PHYSICS TODAY

September 2025 • volume 78, number 9

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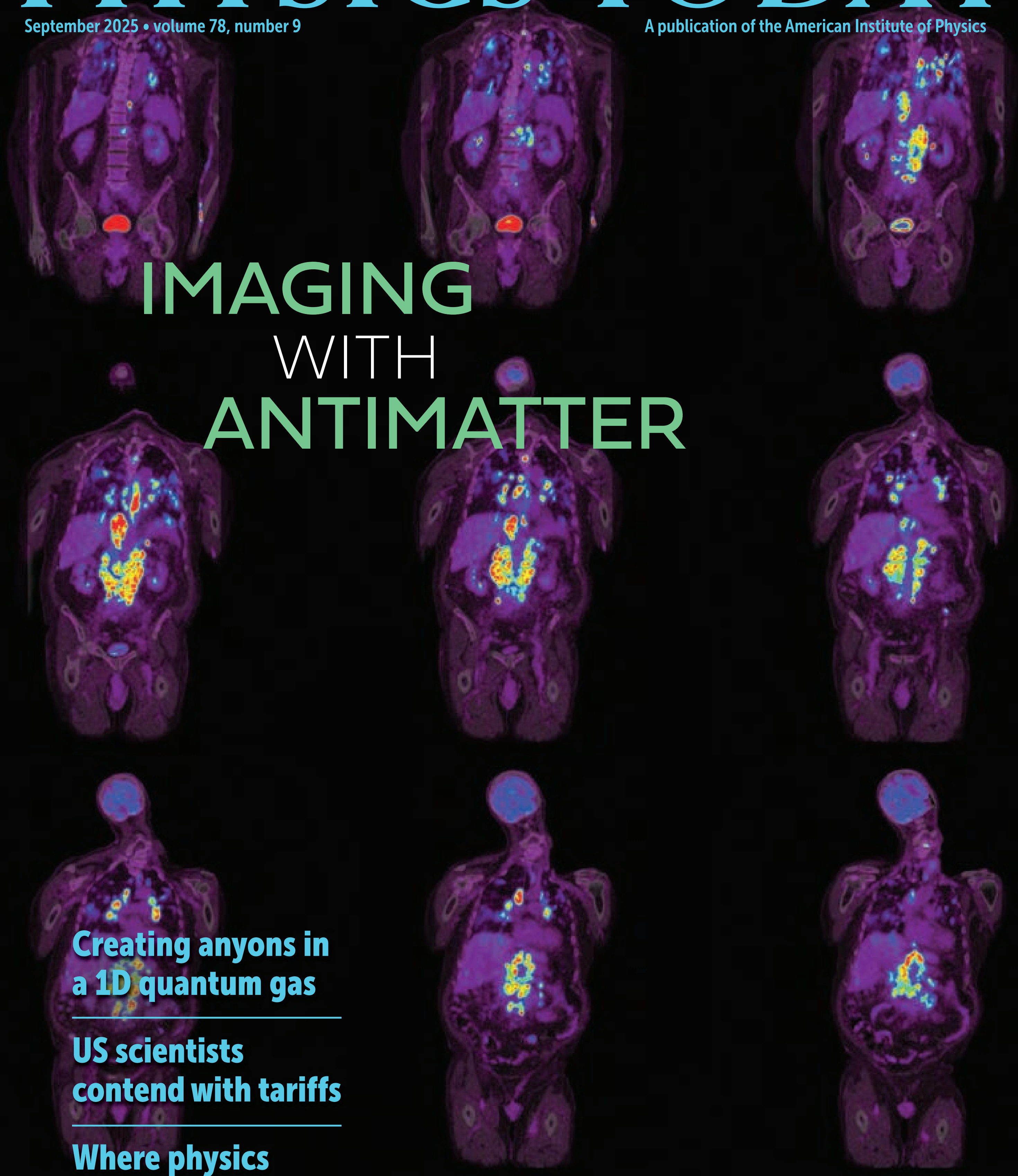

IMAGING WITH ANTIMATTER

Creating anyons in a 1D quantum gas

US scientists contend with tariffs

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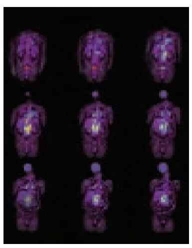
FEATURES



ON THE COVER: Positron emission tomography (PET) scans of a patient with lymphoma reveal the extent of the disease. PET imaging with radioactively labeled tracer molecules is able to map features of the body's biochemistry—here, the rate of glucose metabolism, which is elevated in cancer cells—with high sensitivity. To learn more about PET scans and how they are changing medicine, turn to the article by John Sunderland on **page 28**. (Images courtesy of the University of Iowa department of radiology.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

DAVID ALEXANDER

Space startups

A new initiative at Rice University in Texas is forging international partnerships to advance space technology. Rice paired up with Business France and France's national space agency to create a six-month accelerator program that is familiarizing French space startups with the US market.

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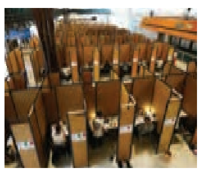

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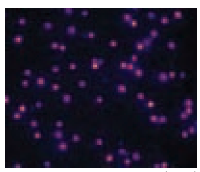
Physics Olympiad

The US was the lone country at this year's International Physics Olympiad to have all five team members receive gold medals. Held this year outside Paris, the annual competition tests high schoolers on theoretical and experimental physics and offers social and cultural activities for participants.

physicstoday.org/Sep2025b



CHENG ET AL., *PHYS. REV. X* (2025)

Measuring NV centers

A new technique developed independently by two groups enables simultaneous precise optical measurements of dozens of nitrogen–vacancy (NV) centers, diamond-crystal point defects that behave like tiny magnetometers. The advance could help make NV centers more useful as quantum sensors.

physicstoday.org/Sep2025c

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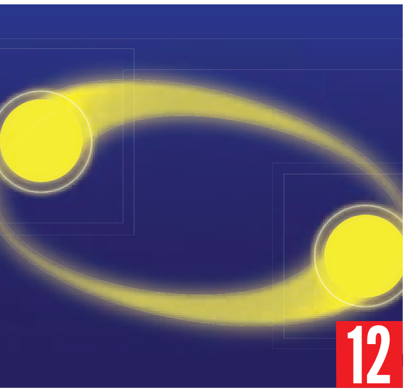

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The Department of Physics and Astronomy at the University of Notre Dame is inviting applications for two faculty positions.

Tenure-Track Faculty Position in Experimental Low-Energy Nuclear Physics

The Nuclear Physics group presently consists of nine experimental and four theoretical tenure-track faculty studying problems in nuclear astrophysics, nuclear structure, fundamental symmetries, and nuclear applications. The successful candidate is expected to develop a research program in low-energy nuclear physics centered around the use of the Notre Dame Nuclear Science Laboratory (https://isnap.nd.edu) or CASPAR (https://caspar.nd.edu). Opportunities also exist for additional experimental programs at nearby facilities such as ATLAS and FRIB.

We seek faculty members committed to developing and sustaining an environment of inclusive excellence in research, teaching, and service. The successful candidate must demonstrate the ability to develop a highly successful research program, attract independent research funding, teach effectively at both the graduate and undergraduate levels, and engage with students from diverse backgrounds. Applicants must have a Ph.D. or equivalent advanced degree. The position is expected to be filled at the assistant professor level, but applications from exceptional researchers at higher ranks will also be considered. The expected start date is August 2026.

Link to apply to this position https://apply.interfolio.com/168722

Assistant Teaching Professor—Physics & Astronomy

We are seeking a physics educator to serve as the instructor of the Modern Physics Laboratory courses and the Introduction to Circuitry and Electronics course for the undergraduate physics majors, and the Methods of Experimental Physics course for the graduate students. Duties will also include maintaining the advanced laboratory equipment in working order, keeping lab manuals up to date, development of new experiments, and maintaining smaller (8”) instructional telescopes.

The successful applicant is expected to have a Ph.D. in Physics. A broad experience with and interest in working with a wide range of experimental equipment is also required.

This is a full-time, 12-month, non-tenure track faculty position. The anticipated starting rank will be Assistant Teaching Professor, though a higher rank may be negotiated based on prior experience. The expected start date is August 2026.

Link to apply to this position https://apply.interfolio.com/171419

The Department of Physics and Astronomy at Notre Dame has 47 tenured and tenure-track faculty, 5 teaching faculty, and another 24 research and concurrent faculty, as well as professors of the practice; more than 100 graduate students; and ~100 undergraduate physics majors. Additional information about the department and the College of Science can be found at http://physics.nd.edu and http://science.nd.edu respectively.

The Department is committed to diversifying its faculty and encourages applications from women and members of traditionally underrepresented groups.

Nonproliferation and the Budapest Memorandum

AN UNIDENTIFIED MISSILE-LAUNCH SITE IN UKRAINE IN MAY 1995. This photo was taken during an inspection team's visit as part of the Ukrainian nuclear dismantlement project. (Photo from the Defense Threat Reduction Agency, Department of Defense/National Archives photo no. 7286446.)

While I found Bill Sweet's article "France's Oppenheimer" (Physics Today, March 2025, page 46) informative and entertaining, I also find it necessary to correct a serious omission in the final paragraph. South Africa is not the only nuclear-armed state to have given up its arsenal. Belarus, Kazakhstan, and Ukraine gave up the nuclear weapons left in their lands following the breakup of the Soviet Union.

Indeed, when the Soviet Union collapsed, Ukraine held the world's third-largest arsenal of nuclear weapons. It denuclearized voluntarily and joined the Treaty on the Non-Proliferation of Nuclear Weapons in 1994. In return, the US, the UK, and the Russian Federation signed the Budapest Memorandum, in which they committed to, among other things, "respect the independence and sovereignty and the existing borders of Ukraine," "refrain from the threat or use of force against the territorial integrity or political independence of Ukraine," and "refrain from economic coercion designed to subordinate to their own interest the exercise by Ukraine of the rights inherent in its sovereignty."[1]

Russia's forced annexation of Crimea in 2014, followed shortly by its promotion of separatist activities in the Donetsk and Luhansk territories, and later its full-scale invasion of Ukraine starting in 2022 violated the Budapest Memorandum. And now doubts among US allies as to the reliability of US security commitments threaten to cause other nations to become nuclear states.[2,3]

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2. G. Chafetz, Z. S. Davis, "The end of nonproliferation?" *Defense One* (16 March 2025).
3. G. Rose, "Get ready for the next nuclear age: How Trump might drive proliferation," *Foreign Affairs* (8 March 2025).

Stephen C. Schiff
Aldie, Virginia

► **Sweet replies:** I take Stephen Schiff's point. I should have said that South Africa was the one country to have developed nuclear weapons and then voluntarily agreed to give them up.

Bill Sweet
(wsenergywise@gmail.com)
New York University
New York City

A question pertaining to Shor's discovery

The recently published interview "Peter Shor on the genesis of Shor's algorithm" (Physics Today, April 2025, page 34), conducted by David Zierler and adapted and annotated by Ryan Dahn, was fascinating. I was interested in Shor's discovery that there is a polynomial-time quantum computer factoring algorithm that violates the Church–Turing thesis, which in Shor's words, says "basically, anything any computer can do in polynomial time, a Turing machine can do in polynomial time." The presentation of the social aspects around this discovery provides an excellent view into the topic's history. Of course, the now well-known implications are also discussed, but in so doing, the article also highlights, by omission, something missing in the field of theoretical computing.

Since the Turing machine is classical, I am left with an obvious but unaddressed question: Is it possible that there is also a quantum Turing machine? I wonder if someone is studying this, but perhaps it is too much to expect that they would make themselves available to discuss it with Dahn for publication in Physics Today. That would only bring unwanted attention and competition to the issue.

Terry Goldman
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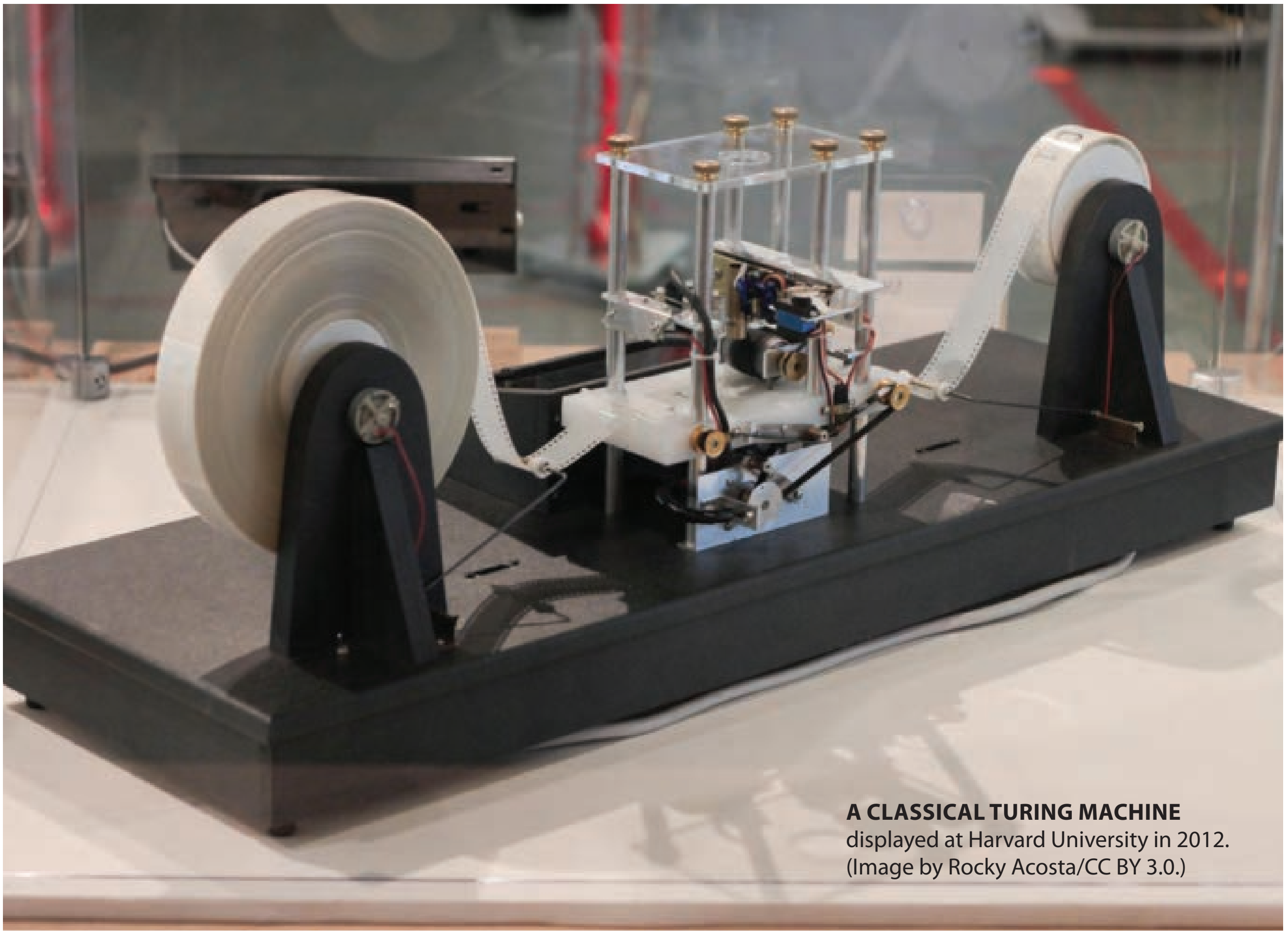
Los Alamos, New Mexico PT



A CLASSICAL TURING MACHINE displayed at Harvard University in 2012. (Image by Rocky Acosta/CC BY 3.0.)

Anyons abound in 1D quantum gases

The statistical behavior of the unusual particles, which are neither fermions nor bosons, is coming under experimental control.

For all the oddities that Edwin Abbott invited his readers to imagine in his classic novella *Flatland*—that women are straight lines, men are polygons, and rain falls from the north—most aspects of physics and chemistry in the fictitious world of two spatial dimensions are the same as in our universe of three. Flatland contains, among other things, trees, gunpowder, food, water, and solid materials: all things that seemingly require the same atoms and molecules that exist in 3D.

Abbott was writing in the 1880s, so he would have had no way to anticipate how dimensionality could affect the nature of matter. It wasn't until the 1920s, with the development of quantum theory, that it started to become clear how much of our everyday world depends on the fact that electrons are spin-½ fermions, no two of which can occupy the same quantum state. That restriction gives rise to atomic shell structure, the periodic table, all of chemistry as we know it, and the fact that matter takes up space.

And only in the 1970s did theorists start to realize that the situation might be different in different numbers of dimensions.[1] In 3D, particles must be either integer-spin bosons or half-integer-spin fermions, but 2D and 1D worlds have no such requirement. Their particles can be anyons—a term coined by Frank Wilczek[2] in 1982—with any spin. If subatomic particles in Flat-

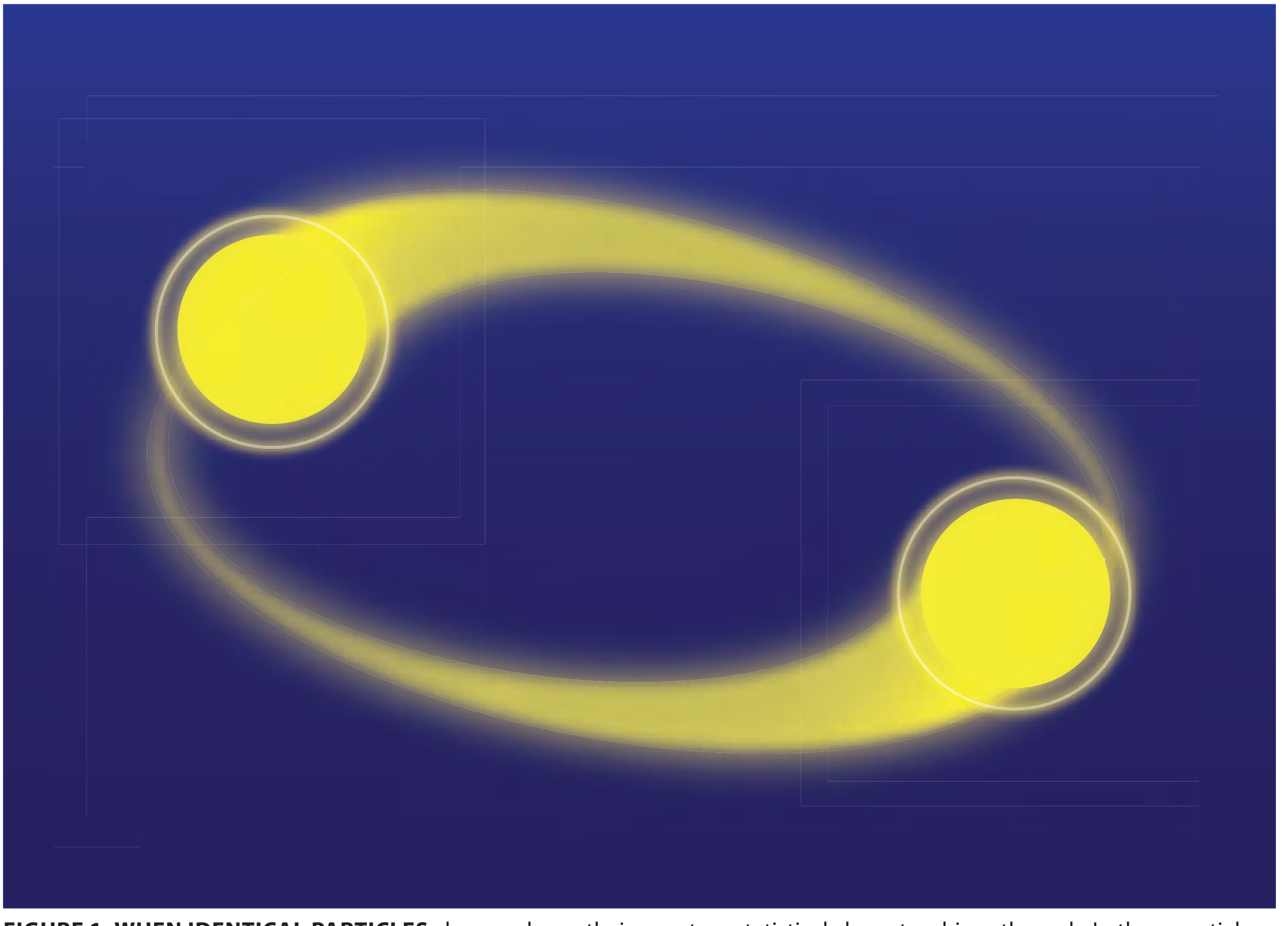


FIGURE 1. WHEN IDENTICAL PARTICLES change places, their quantum statistical character shines through. In three spatial dimensions, exchanging particles twice is the same as leaving them alone, and it follows that particles must be either fermions or bosons. But in reduced-dimensional spaces, there's a spectrum of other possibilities. (Figure by Freddie Pagani.)

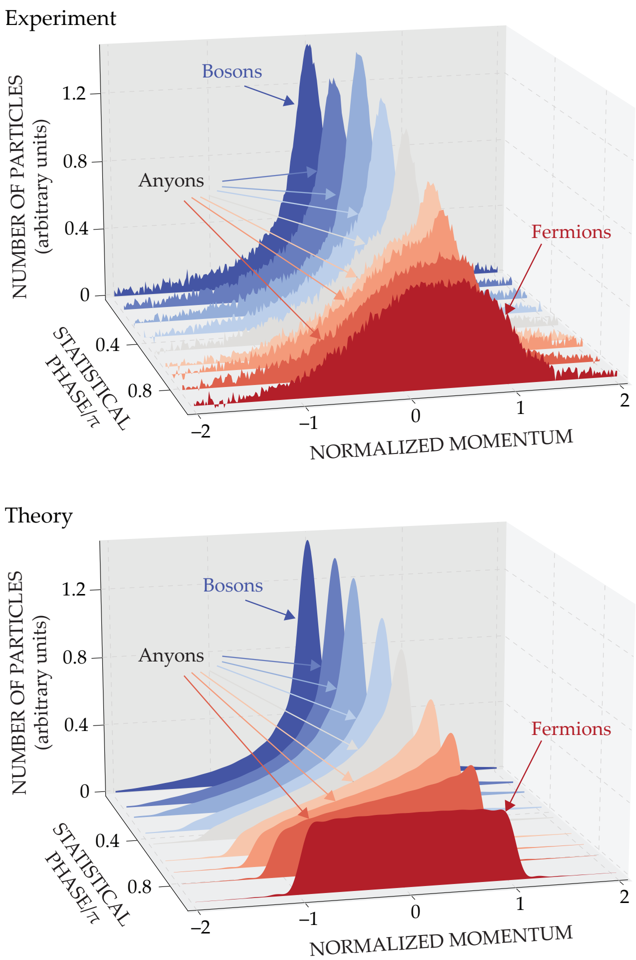


FIGURE 2. THIRTY-SOME ATOMS in a continuous 1D trap can be made to behave like bosons (whose momenta all cluster together), fermions (whose momenta evenly spread out), or any of a continuum of anyonic possibilities in between. (Figure adapted from ref. 3.)

land (or in its 1D counterpart Lineland) had anything other than exactly half-integer spin, there'd be no Pauli exclusion principle, and atoms would look completely different.

Flatland analogies often come up in discussions of the physics of reduced-dimensional systems such as graphene, the one-atom-thick form of carbon (see the article by Andrey Geim and Allan MacDonald, Physics Today, August 2007, page 35). But for the most part, just like in Abbott's story, the inhabitants of those systems are the same fermions and bosons as in 3D. The full spectrum of 2D and 1D peculiarities has remained largely untapped.

But that situation is changing. Two groups—one led by Hanns-Christoph Nägerl[3] at the University of Innsbruck in Austria, the other by Markus Greiner[4] at Harvard University—have now coaxed atoms in 1D quantum gases into behaving like anyons. The experimental implementations differ, but one feature they have in common is that the researchers can tune their particles along the full continuum from fermions to bosons.

Flatland phases

It's a seemingly simple—but deceptively subtle—argument that underlies the rule that particles in 3D must be either fermions or bosons. When two identical particles are exchanged, as in figure 1, the system's wavefunction picks up a phase that depends on the particles' spin: For bosons, the phase is 0, and the wavefunction is unchanged; for fermions, the phase is π, and the wavefunction is multiplied by −1.

Other values of spin would correspond to other phase angles θ that have the effect of multiplying the wavefunction by the complex number $e^{i\theta}$. But, the argument goes, exchanging two particles twice is the same as not exchanging them at all, so applying the phase twice must return the wavefunction to its original value. Because 1 and −1 are the only square roots of 1, fermions and bosons are seemingly the only options.

And in three or more spatial dimensions, that's true. In 2D, however, there are two topologically distinct ways to exchange the particles—by rotating them clockwise or counterclockwise—that can't be smoothly transformed into one another. Two clockwise swaps aren't the same as no swaps, so they needn't return the wavefunction to its original value.

So anyons can exist in 2D—and, in fact, they do. In the fractional quantum Hall effect, a phenomenon that emerges at low temperatures and under strong magnetic fields, fractionally charged quasiparticles form out of a 2D layer of electrons. Theory held that the quasiparticles would also have a fractional phase θ, but that prediction was extremely difficult to experimentally confirm. In a solid-state system, there's no easy way to grab two quasiparticles, manually swap their places, and measure the phase change that results. So although the fractional quantum Hall effect was discovered in the 1980s (see Physics Today, December 1998, page 17), it was only in 2020 that experiments showed that the quasiparticles were indeed anyons.[5]

When the number of spatial dimensions is reduced from two to one, the intuitive picture becomes harder to grasp. The distinction between clockwise and counterclockwise exchanges no longer exists—and neither, for that matter, does the distinction between exchanging the particles and not exchanging them. Particles in 1D can't change places without passing through each other. And because the particles are identical, as soon as they occupy the same space, there's no way to tell whether they really swapped places or merely bounced off each other and returned to their original positions.

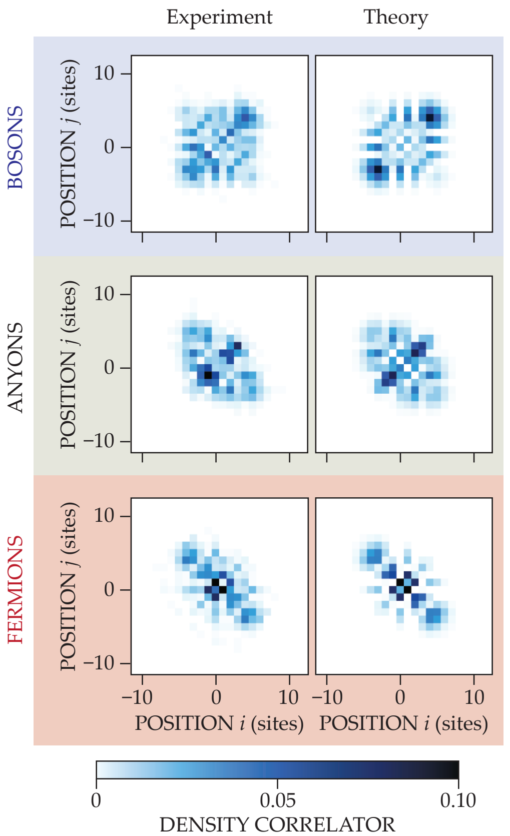


FIGURE 3. WHEN TWO ATOMS hop around freely in a 1D lattice of optical traps, correlations in their positions reflect their bosonic, fermionic, or anyonic character. Although only one anyonic state is shown here—with a statistical phase of $\theta = \pi/2$—the phase can be tuned to any value from 0 to π. (Figure adapted from ref. 4.)

Nevertheless, 1D anyons can exist, as both Nägerl's and Greiner's groups demonstrated through variations on a common theme: Bosons tend to pile up in the same quantum state, whereas fermions spread out into different states. Anyons act in an in-between way—neither bunching nor antibunching—and although the specific nature of that intermediate behavior can be hard to intuit, theorists can predict it.

Quantum gases of ultracold trapped atoms, used by both groups, have proved to be a useful platform for studying many-body phenomena. Atoms in a trap exhibit many of the same behaviors as electrons in a solid, but they can be manipulated and probed in ways that electrons cannot.

Nägerl and colleagues created their anyons by exploiting a phenomenon called spin–charge separation.[6] With a few dozen identical bosonic atoms in a 1D trap, a traveling excitation in the system's spin degrees of freedom creates a phase of $-\theta$ in the spin part of the wavefunction. The charge portion of the wavefunction (really the atomic positions, because the atoms play the role of electrons in a solid) therefore needs to compensate with a phase of θ, which defines the statistical behavior of all the atoms.

The more the spin wave is accelerated, the larger the value of θ becomes, so the researchers can tune it to any value from 0 to π or beyond. They probe the anyonic correlations by abruptly turning off the trap and releasing the atoms. The atoms fly apart with the momentum they had at the moment of their release.

The researchers' momentum measurements are shown in figure 2. As expected from theory, the particles show boson-like bunching into a single momentum state at $\theta = 0$ and fermionic antibunching at $\theta = \pi$. (In the latter case, the experimental data aren't as nicely antibunched as theory predicts, because the experiment averages over many implementations of the system, each with a slightly different range of possible momenta.) Other values of θ yield intermediate—anyonic—momentum distributions.

Whereas Nägerl's group created gases of 30-some anyons, Greiner and colleagues have so far focused on studying just 2. Rather than a continuous 1D trap, they looked at a 1D lattice of discrete sites, into which they loaded two identical bosonic atoms. By driving the system with lasers, they engineered a scenario in which the atoms hopped freely among the sites, and whenever the atoms occupied the same site, the wavefunction picked up a phase: θ if one atom passed the other from left to right, and $-\theta$ if from right to left.

Rather than measuring the momenta, Greiner and colleagues observed fractional exchange statistics by tracking the lattice sites i and j that their atoms occupied, as shown in figure 3. For $\theta = 0$, the atoms showed a bosonic preference to occupy the same site, with an enhanced density along the $i = j$ diagonal. For $\theta = \pi$, they showed a fermionic tendency to be farther apart, with density along the $i = -j$ antidiagonal. Anyons, once again, showed an intermediate behavior.

What for?

The 2D anyons that show up in the fractional quantum Hall effect have tantalizing potential uses in topological quantum computing. Because the system retains information about how many times the anyons have encircled one another, it can be used as a quantum memory. And because the wavefunction phase shifts depend only on the number of particle exchanges, they're insensitive to small changes in the anyons' trajectories, and the memory is robust against noise.

The 1D quantum-gas anyons lack that possible application. But from a fundamental physics perspective, they have the considerable advantage of continuous tunability of the phase θ. (Quantum Hall anyons, in contrast, arise from a discrete set of fractional quantum Hall states that must be prepared one at a time.) So, for example, the researchers could explore the possibility that θ might act as an order parameter that drives a phase transition. Such a transition, if it exists, would be an inherently reduced-dimensional phenomenon; it wouldn't be even conceptually possible in our 3D world, where particles are limited to the binary options of fermions and bosons.

Both groups are also interested in studying interactions between pairs and groups of anyons. Greiner and colleagues have already observed the bizarre and unexpected phenomenon of anyon bound states that travel in only one direction. If they can elucidate the binding mechanism, they could get a step closer toward understanding what atoms and molecules would actually look like in Flatland.

Johanna Miller

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6. R. Senaratne et al., *Science* **376**, 1305 (2022).

Measurements of sea-level rise from melting ice get even more accurate

The Greenland ice sheet has been shrinking faster than any other glacier over the past 30 years.

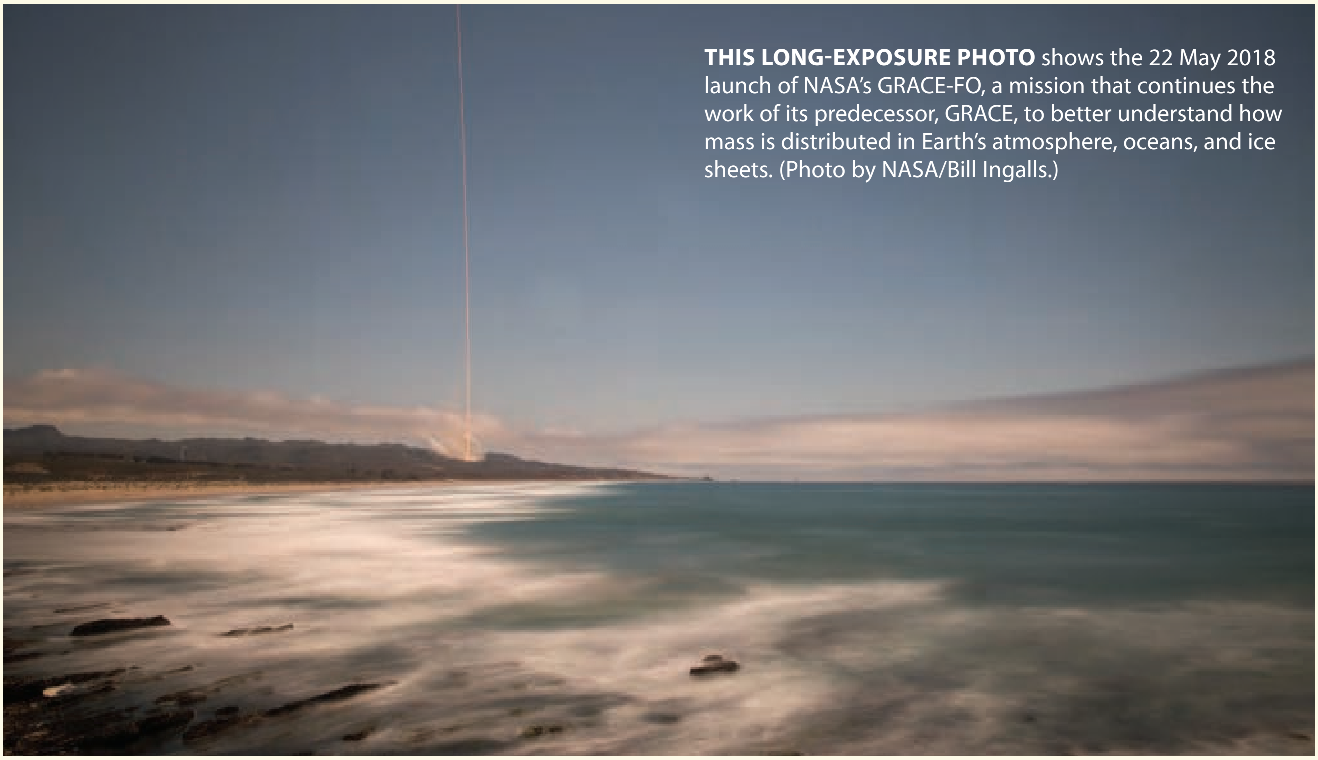
Earth's sea level has been rising at an average of about 3 mm/year since satellite altimetry measurements began in 1993. Most of the change is attributable to ice on land melting into the ocean, which increases barystatic sea level. (The thermal expansion of water is the other cause of sea-level rise.) But because of limitations in ocean-observing networks, estimates of barystatic sea level have included large uncertainties. (See the article by Bruce Douglas and Richard Peltier, Physics Today, March 2002, page 35.)

The situation improved in 2002 with the launch of NASA's GRACE (Gravity Recovery and Climate Experiment) mission to provide, among other data, high-resolution measurements of barystatic sea level. But there's still a one-year gap in observations between GRACE and its successor, GRACE-FO (Follow-On). In addition, one of the two accelerometers on each of the twin satellites suffered malfunctions, which have led some scientists to question the data's reliability. Now Yufeng Nie and Jianli Chen (both with the Hong Kong Polytechnic University) and colleagues have used data from various satellites to make an accurate time series of barystatic sea level that goes back to 1993. Consistent with previous findings, their results show that the barystatic contribution is responsible for 1.9 mm/year of sea-level rise over the past three decades.

The pre-2002 data come from satellite laser ranging. The method measures sea level through gravity-field estimates, which are derived from the time it takes ultrashort pulses of light to travel from a satellite to the ground, then back to the satellite. In the past, the problem with satellite laser ranging has been the lack of spatial resolution. At about 4000 km, the resolution is suitable for researchers to resolve large-scale changes of entire ice sheets, for example, but is insufficient for them to accurately see what's happening at the land–ocean boundary. The inaccurate measure leads to an underestimation of barystatic sea-level rise.

To address that problem, Nie and colleagues put their data into a gridded observational model that corrects for the uncertainty at the land–ocean boundary and thus gives more reliable estimates of long-term barystatic sea level. They find that since 1993, Greenland has contributed to a rise in barystatic sea level of 0.6 mm/year, which is about equal to the combined contribution of all other glaciers on Earth except for those in Antarctica. That result is similar to previous findings, but the independent approach offers a way to better constrain earlier estimates of sea-level rise. The new time series captures the acceleration in global sea-level rise too. Although the barystatic sea level since 1993 has increased by 1.9 mm/year, since 2003 it's climbed to 2.2 mm/year. (Y. Nie et al., *Proc. Natl. Acad. Sci. USA* **122**, e2425248122, 2025.)

Alex Lopatka



THIS LONG-EXPOSURE PHOTO shows the 22 May 2018 launch of NASA's GRACE-FO, a mission that continues the work of its predecessor, GRACE, to better understand how mass is distributed in Earth's atmosphere, oceans, and ice sheets. (Photo by NASA/Bill Ingalls.)

A color-changing material inspired by squid skin

Researchers have fleshed out the details of a mechanism that some cephalopods use to quickly change colors and even become semitransparent.

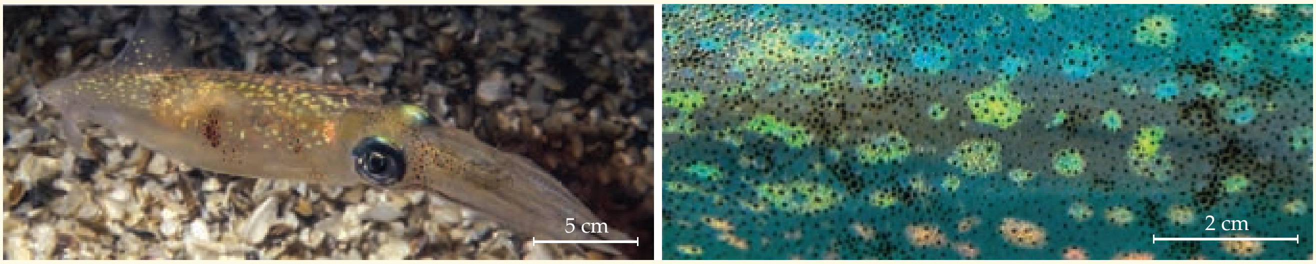


FIGURE 1. SPECIALIZED LIGHT-REFRACTING CELLS in the skin of the longfin inshore squid (*Doryteuthis pealeii*) enable it to iridesce, change color, and even become transparent. The apparent color of the skin depends on the spacing of specialized platelike proteins, known as reflectins, that produce a sinusoidal refractive index gradient. The iridescent blue, green, and orange splotches on the skin are packed with reflectins. The dark brown dots that cover the skin are chromatophores—pigmented cells that can expand and contract to change the skin's appearance. (Images adapted from G. Bogdanov et al., *Science* **388**, 1389, 2025.)

Squids are well known for their camouflaging abilities. Specialized cells in their skin enable them to change color or become transparent at a moment's notice. Now researchers led by Alon Gorodetsky at the University of California, Irvine, have made a synthetic material that uses the same tricks as squid skin to iridesce, change color, and become transparent when stretched or chemically altered. The researchers collected detailed cellular-scale observations of squid skin with a method known as holotomography—3D laser measurement of a material's refractive index. What they found provided the key to replicating the effect.

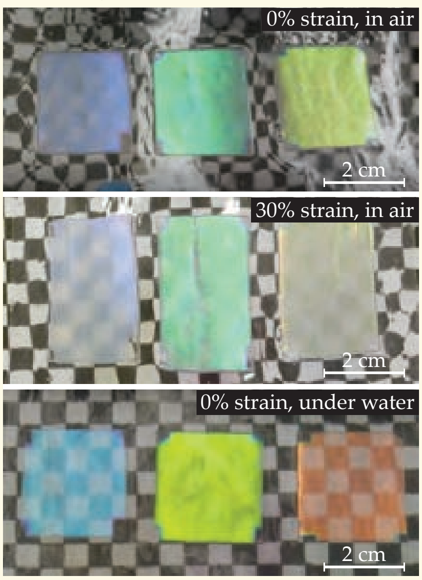


FIGURE 2. A SYNTHETIC MATERIAL mimics the refractive index gradients in specialized squid-skin cells. Changing the view angle, stretching the material, or submerging it in water or other fluids can induce color changes and transparency. (Images adapted from G. Bogdanov et al., *Science* **388**, 1389, 2025.)

The color-changing abilities of some squids and other cephalopods are the result of a variety of specialized cells or cell groups (see the Quick Study by Lydia Mäthger, Physics Today, December 2022, page 62). Cells known as chromatophores contain pigments that are revealed when the cells expand and hidden when the cells contract. Other cells, called iridophores, contain stacks of light-scattering platelike proteins, known as reflectins, surrounded by cytoplasm. Constructive interference of the light transmitted and scattered by the reflectins produces iridescence, as shown in figure 1. Some iridophores have fixed hues, but others can change color or become transparent when the spacing of their platelets is altered.

It was already understood that iridophores' color effects were produced by the distinct refractive indices of the reflectins and cytoplasm. Gorodetsky and colleagues set out to measure those properties in 3D at the cellular level. With the help of researchers at the Marine Biological Laboratory in Woods Hole, Massachusetts, PhD student and co–first author of the study Georgii Bogdanov collected holotomography measurements of iridophores from dozens of squids. He found that most iridophores are packed with winding columns of reflectin platelets. Along the length of those columns, the refractive index varies as a sine function, with reflectins producing high values and cytoplasm producing low values.

Computer simulations show that the refractive index profile's shape is key to the color effects—triangular and rectangular profiles don't produce the color purity or transparency that the sinusoidal profile does. The view angle, platelet periodicity, and surrounding medium also change the perceived color and transparency produced by the reflectin stacks. Using those insights, Aleksandra Anna Strzelecka, a PhD student and co–first author of the study, set about building a material that could replicate the color-changing effects.

The researchers used vapor deposition to build nanocolumns of metal oxides and varied the deposition angle to produce the targeted sinusoidal refractive index profile. The nanocolumns were then attached to a polymer to provide flexibility. The result was a material that changes color depending on what angle it is viewed from, how much it is stretched, and what fluid it is submerged in, as shown in figure 2. The researchers were also able to extend the material's wavelength-manipulating effects beyond the visible part of the electromagnetic spectrum and into IR wavelengths. Though more work is needed to put the material to practical use, the researchers envision potential applications in sensing, display, camouflage, and heat management. (G. Bogdanov et al., *Science* **388**, 1389, 2025.)

Laura Fattaruso PT

Fluctuating tariffs exacerbate US science funding woes

For new faculty and others ordering big-ticket items, the import taxes can be a gut punch.

Since the start of the second Trump administration, the US science community has been confronted with the axing of jobs, the slashing of federal funding, attacks on diversity, and increased visa restrictions. Tariffs are an added twist. On 2 April—which Trump referred to as Liberation Day—new tariffs on many countries went into effect. A roller coaster followed, as rates were raised, lowered, and paused. The threats and negotiations have sowed uncertainty in the science community and beyond about the cost of goods.

Tenure-track experimentalists who are establishing their labs are in a particular bind.

New faculty members receive startup funds, uniquely flexible money that they use for equipment, students and postdocs, conferences, and their own summer salaries. Startup funds in the more expensive areas—notably atomic, molecular, and optical physics, condensed-matter physics, and biophysics—can be as high as $5 million, although around $1.5 million is typical.

Tariffs were not yet a concern for tenure-track faculty who negotiated their job terms in the past few years. But today, as they attempt to establish themselves in their new positions, ponying up tens of thousands of dollars more for big-ticket items can be a hardship—or a dealbreaker.

Sticker shock

In early 2024, a tenure-track physicist at a midsize public university on the West Coast ordered laser equipment from China. It didn't arrive in the US until April 2025, at a time when the tariff rate exceeded 100%. The equipment was stuck in customs, accumulating storage fees, until the physicist could pay the nearly $130 000 import tax. An internal

DACEN WATERS (back) with two of his PhD students, Oliver Schwarm (right) and Zoe Rafter (at computer), in the lab they are setting up. Depending on the tariff rate when the $750 000 dilution refrigerator he ordered is ready for delivery, Waters could end up canceling the order or not having money to pay his graduate students. (Photo by Mark Siemens.)

THE PAYLOAD for a planned long-duration, high-altitude balloon mission to study cosmic star formation at terahertz frequencies was test-flown last year in New Mexico. Jeffrey Filippini, who leads the development of the cryogenic camera for the mission's upcoming Antarctic flight, was slapped with a $10 000 tariff for an infrared filter from the UK. (Photo by Joaquin Vieira, University of Illinois Urbana-Champaign.)

university loan to the physics department saved the day, says the department chair.

The loan means that the new hire can get on with their research, says the chair. But the department will have to scrimp until it repays the money. "We may not be able to invite prospective graduate students to visit," the chair says. "More of our symposia may have to be by video rather than hosting speakers in person. And when equipment breaks, we won't have discretionary funds to step in and help faculty members." (The department chair and others who requested anonymity felt their situations were precarious for visa reasons or wanted to avoid calling attention to themselves and their institutions.)

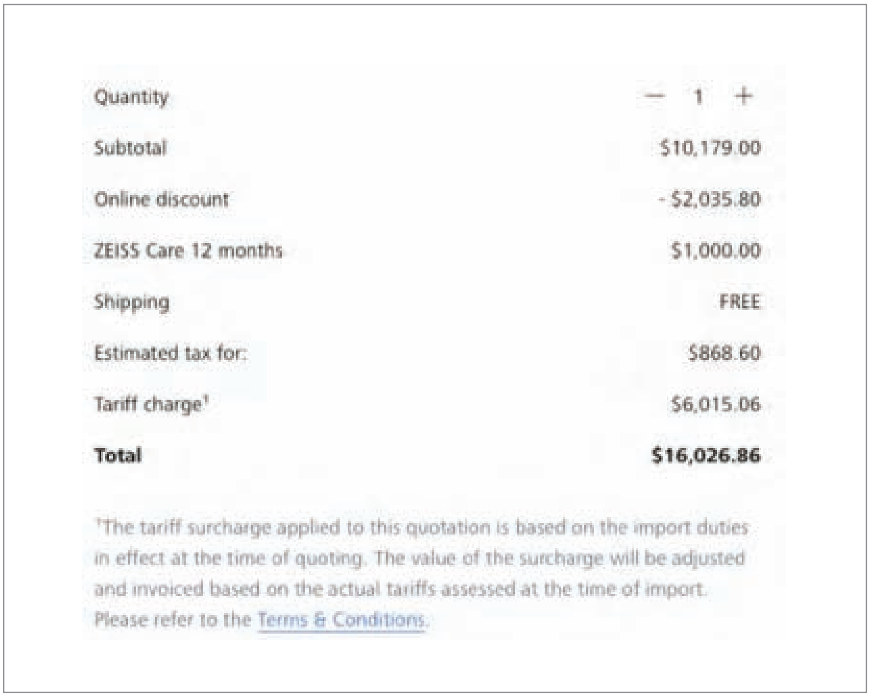
Yulia Maximenko joined the physics department at Colorado State University in 2023, planning to study 2D quantum materials at low temperatures. She was lucky that her most expensive instrument, a $550 000 scanning tunneling microscope from Germany, was delivered in late 2024, before the Trump administration began making changes to tariffs. But this spring, she balked when she saw that she would have to pay a few thousand dollars in tariffs on top of the more than $20 000 price tag for an optical microscope from Olympus, a company headquartered in Japan. Instead, she bought an older model for $8000 on eBay. "It's much cheaper, and there are no tariffs," she says.

Shopping on eBay "is a bit of a shot in the dark," says Maximenko. She relies on sellers' ratings and return policies. She recently bought an electron-beam evaporator for thin-film deposition and an ion pump, both used. "Sometimes I get nice equipment," she says. "And my students and I can fix things." Scrounging for used equipment stretches her money, she adds, "but it slows down research productivity."

Dacen Waters started his tenure-track position at the University of Denver last fall. He studies how electrons behave in 2D materials, work that could eventually feed into quantum computing technologies. Last October, he ordered a dilution refrigerator for about $750 000 from a Finnish company—one of three, all in Europe, where such instruments are available. He had been trying to figure out how to cover $75 000 at a 10% tariff rate. But when Trump threatened a 30% tariff in July, he was panicking. At that rate, he says, he'd have to cancel the order, which per the contract would mean forfeiting $200 000. At press time, the expected tariff had come down to 15%, which Waters says he can make work. "I just need to decide what I will give up to pay the tariffs," he says.

Exemptions for science?

"The tariffs have thrown a nasty curveball into everybody's life," says Walter



Quantity	− 1 +
Subtotal	$10,179.00
Online discount	- $2,035.80
ZEISS Care 12 months	$1,000.00
Shipping	FREE
Estimated tax for:	$868.60
Tariff charge[1]	$6,015.06
Total	**$16,026.86**

[1]The tariff surcharge applied to this quotation is based on the import duties in effect at the time of quoting. The value of the surcharge will be adjusted and invoiced based on the actual tariffs assessed at the time of import. Please refer to the Terms & Conditions.

HIGH TARIFFS, as seen in this screenshot of a price quote for a Zeiss microscope from Germany, led the potential buyer, a physicist who requested anonymity, to buy a simpler, used version in the US.

Silvesky, commercial managing director for the US arm of the German company PI (Physik Instrumente). "It's especially tough for those in the academic sector. Researchers have no mechanism for dealing with extra costs." In some cases, vendors refuse to prepare firm bids because of the uncertainties on their end due to tariffs and inflation. And university purchasing offices sometimes won't approve purchases without a fixed price.

PI, which specializes in micro- and nanopositioning components, is "trying to be fair" about tariffs, says Silvesky. The company may absorb the extra burden of tariffs when "a long-standing customer in the research community is at risk" of having to interrupt their work. But if the cost is too high or "circumstances don't permit," he says, "researchers have to jump through hoops to find money. It's crushing them from the standpoint of time."

Meanwhile, the US branch of PI has sought new international supply chains and domestic sources in order to pay lower tariffs or avoid them altogether. For example, to hold down prices, the company switched to buying some components, such as bolts and screws, motors, and power supplies, outside of China. "It's a balancing act between cost, availability, and performance," Silvesky says.

Many researchers are applying to the US government for tariff exemptions for scientific equipment. Jeffrey Filippini, a cosmologist at the University of Illinois Urbana-Champaign, says he spent "a couple of days preparing 50 pages of documentation" to claim a tariff exemption for $10 000 he forked over for an infrared filter from the UK. The filter is for an astrophysics instrument Filippini's team is building. The team plans to fly it on a balloon slated to launch next year from Antarctica. "The money wasn't in my grant budget," he says. "I had to come up with it out of the last of my startup funds." If he fails to recover the tariff, he adds, "that represents work I can't do, equipment I can't buy, a student I can't pay."

The West Coast department chair says they hope to get back the $130 000 they paid in tariffs by filing for an exemption. And Waters says that on the vendor's advice, he will apply for a tariff exemption for the dilution refrigerator he needs. But the scientists who are applying for tariff exemptions are at best cautiously optimistic: Few report having heard of anyone who has been successful.

Financial and other costs

Scientists are looking for other ways both to cope with tariffs and move forward with their research. At some universities, purchasing offices handle negotiations with companies and the US government. Researchers are looking for US vendors, and in some cases, international companies can skirt tariffs when purchases are made from a US branch.

Ramamoorthy Ramesh, a physicist at the University of California, Berkeley, recently ordered a magnetometer from a company in Switzerland for roughly half a million dollars. "We are going back and forth on how to accommodate the tariffs," he says. Will the company lower the price? Or will the scientists have to eliminate some add-ons? "We are waiting to see who blinks first."

Even paying tariffs on relatively-low-cost equipment and consumables—chemicals, batteries, optical parts, and the like—means something else has to go. So far, Javier Sanchez-Yamagishi, a condensed-matter physicist at the University of California, Irvine, "is eating the cost of tariffs." But, he says, "cheap Chinese scientific equipment has been a big enabler." Low costs keep down the barrier for trying new things, he explains. "We can take more risks."

Harry Levine is an atomic physicist who is getting started at the University of California, Berkeley. He originally had his eye on a high-powered laser from China for atom-trapping experiments, but in response to tariffs, he is instead opting for a lower-powered laser from Germany. It's cheaper, he says, and in the short term, the swap won't compromise the science he can do. In a few years, though, he'll have to find money for the high-powered laser. The tariffs, he says, affect the prices of domestic and overseas equipment, and both the extra costs and their uncertainty have posed the biggest headache in setting up his new lab.

Waters built his own assembly stage for making quantum devices out of single-atom-thick materials. But it didn't save him money, and it cost him time: The one he built and one he ordered from Europe each cost about $30 000, he says. "Could I build things? Yes, but it would take years."

Toni Feder

A radio telescope array takes shape with private funds

At a time when federally supported science is in flux, the Deep Synoptic Array-2000 project in Nevada is moving toward construction with a combination of university and philanthropic support.

THE DESIGN FOR THE DEEP SYNOPTIC ARRAY-2000 calls for 2000 steerable 5-meter-diameter radio dishes placed across 285 square kilometers in a Nevada valley. (Illustration by Chuck Carter/DSA team.)

Along a stretch of Highway 50 in Nevada that's often called the loneliest road in America sits the town of Ely. And an hour drive from that remote site is an even remoter one called Spring Valley. There, if all goes as planned, scientists will begin construction in about a year on a radio telescope currently called the Deep Synoptic Array-2000.

The DSA-2000, in its current conception, is to be composed of 2000 5-meter antennas that work together as one to observe fast radio bursts, pulsars, and other radio-emitting objects with high resolution and sensitivity. Unlike traditional radio interferometers, which require computationally heavy analyses to compile observations, the DSA-2000 should be able to spit out images of the sky in real time.

Led by Caltech, the DSA-2000 team has used NSF funding to support two pathfinder projects, and it has expressed hope that the federal government will someday fund the estimated $10 million annual cost to operate the facility. But so far, the concept development for the DSA-2000 has been supported with funding from the philanthropy Schmidt Sciences and with in-house expertise from Caltech. The private money has allowed the radio array to go from idea to almost reality faster than have telescopes that rely on what has become an increasingly uncertain federal allocation process.

Envisioning a radio camera

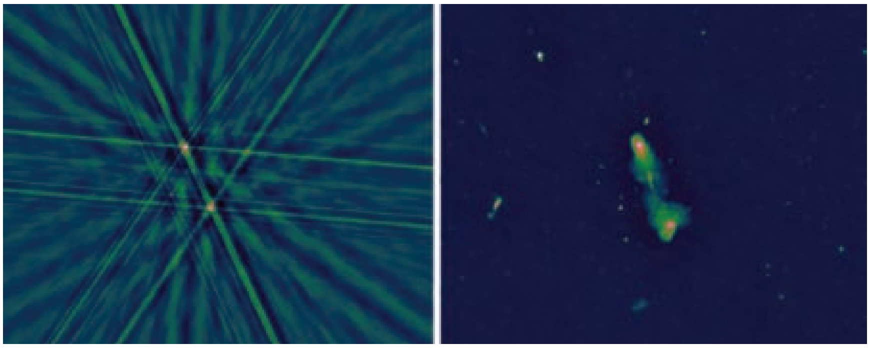
The motivation for building a radio interferometer is that a network of identical antennas can achieve comparable resolution to that of a single gigantic dish and provide a wider field of view. But that convenience comes at the cost of sensitivity: Several dozen small antennas don't have nearly the same photon-collecting area as the gigantic dish and thus can't spot dimmer, more distant radio sources.

The idea for a deep synoptic array hatched around 2013. It would eventually be enabled by technology developed by Caltech radio astronomy engineers, particularly low-cost fiber that could transfer lots of data quickly and relatively inexpensive antennas whose electronics didn't need to be cryogenically cooled. In successive years, researchers began to envision the development of a radio array with thousands of small antennas rather than dozens. An array with that much surface area would have both high resolution and high sensitivity.

"One of the main drivers was to really replicate Arecibo's sensitivity but allow steering over the whole sky," says Vikram Ravi, a Caltech astronomer and the telescope's co-principal investigator, referencing the collapsed telescope in Puerto Rico. With $6.3 million of funding from NSF, the Caltech team made a prototype instrument called the DSA-110, which began operations in 2023.

But large-scale antenna cloning creates another problem: The amount of data scales as the number of antennas squared, says Gregg Hallinan, a Caltech astronomer who is the principal investigator of the DSA-2000. After the data come in, they have to be correlated so that researchers can piece together an image using the collected photons and estimates of the photons that arrived between the antennas. "Because the telescopes measure only a fraction of the incoming signal, we have to use nonlinear techniques to recover, or interpolate, the missing information," says Hallinan.

Buying drives to store data for processing would break the bank. But what if the Caltech researchers didn't have to store all the data? What if they planned their telescope so that its antennas were densely packed enough to closely approximate a single dish? "The number of antennas is large enough that all of the different spatial scales in the image are basically recovered," Hallinan says. If the researchers could make the aggregate smooth enough,



A RADIO CAMERA. At facilities such as the Very Large Array in New Mexico, raw data (simulated at left) need significant processing to generate useful images. In contrast, the raw data collected by the Deep Synoptic Array-2000 (simulated at right) would require less processing, and images would be generated in real time. (Images from the DSA team.)

THE NSF-FUNDED DEEP SYNOPTIC ARRAY-110 at the Owens Valley Radio Observatory in California began operations in 2023. (Photo by Vikram Ravi/DSA team.)

they could use a digital back end to process and calibrate the data in real time to create images using computers with graphics processing units, the same kinds of chips that are often used in AI.

And so the team set out to make the DSA-2000 not a traditional interferometer but a radio camera. An NSF grant for an expansion of the Long Wavelength Array at the Owens Valley Radio Observatory was awarded in 2019. The facility helped prototype some of the snapshot technology.

Private contributions

Around that time, Stuart Feldman, currently the president of Schmidt Sciences, visited Caltech. He was seeking opportunities to invest in science projects that could both happen on fast timelines and potentially result in breakthrough technologies that could decrease the cost of future instruments. Schmidt Sciences was also interested in bringing technology from other disciplines into astronomy. "It's not unlike the startup approach to development in industry," says Hallinan.

By January 2020, Schmidt Sciences was funding an early version of the project. The organization went on to fund the DSA-2000's design, to the tune of about $15 million, and other technology that would be part of the instrument, like the steerable antennas featuring no-cooling-required electronics.

On a timeline that outpaces those for many major science facilities, the DSA-2000 team is planning to start construction in around a year, in Spring Valley if the final environmental assessments permit the project to move forward there. The construction costs are estimated to be around $200 million.

David Kaplan, a professor at the University of Wisconsin–Milwaukee, says part of the DSA-2000's quickness comes from its main institutional affiliation: Caltech is wealthy, and the project is led by the head of its radio observatory. "He has a lot of technical expertise on staff—people who understand every part of a radio telescope, from the foundation to the data analysis," Kaplan says of Hallinan. He can tap them and hire additional experts with the Schmidt Sciences money.

Although the project's prototype technology received NSF money, the team has not had to wait on federal funding cycles to progress to the main project; combined with the startup-style approach, that disentanglement from federal funding has enabled the project to move more quickly than traditional government-reliant projects. The next-generation Very Large Array, for instance, would complement the DSA-2000, but the project doesn't yet have solid NSF funding despite being in the works for years. Construction on the estimated $3.2 billion project won't start until late this decade at the earliest.

"We can tailor things like reviews and funding cycles to fit the project needs rather than have an overarching umbrella process that everybody has to go through," says Arpita Roy, director of Schmidt Sciences' Astrophysics & Space Institute.

The funding model for the DSA-2000 is also notable given the federal government's recent attempts to cut the budgets and staff of science-funding agencies, including NSF, the largest funder of US ground-based astronomical research. The DSA-2000 has evaded some of that uncertainty, although the group hopes that NSF will fund the telescope's operation and still needs to finalize the funding for construction.

Victoria Kaspi, an astrophysicist at McGill University who is not affiliated with the project, notes that Caltech has a long history of projects enabled by private funding, like the Space Solar Power Project. "It would be wonderful to have this be replicable for other projects, since providing resources for the very best science would have the highest impact," she says. But given the necessary special sauce of variables—money, access, and expertise on staff—it could be difficult for other institutions to follow suit.

Looking ahead

With the promise of the DSA-2000 going into action sooner rather than later, collaborators have signed on from national observatories and universities. The telescope's data will be freely available immediately, in contrast to most observatories' data, which have a proprietary period.

Kaplan stands to benefit from the DSA-2000's science. He's a member of the NANOGrav (North American Nanohertz Observatory for Gravitational Waves) collaboration, which uses a net of pulsars tracked by the National Radio Astronomy Observatory's Green Bank Telescope and other facilities to search for gravitational waves. In a collaboration with NANOGrav, the DSA-2000 will time pulsars for 25% of its observing hours.

The bulk of observing time, however, will go to surveys. "Every radio telescope ever built has detected about 10 million sources," says Hallinan. "We'll double that in the first 24 hours." By imaging the entire sky many times over five years of operation, the array should detect more than 1 billion radio sources, he says. Complementing other next-generation telescopes, the DSA-2000 will pinpoint radio counterparts to sources found at other wavelengths with the Vera C. Rubin Observatory, SPHEREx, and others.

With high time resolution, the DSA-2000 should also detect thousands of transient sources. "I think the DSA-2000 is a very exciting project," says Kaspi. "It is likely to have significant impact on understanding fast radio bursts." The observations could also help probe dark matter and galaxy evolution by tracing neutral hydrogen gas.

The DSA-2000's first prototype antennas are now set up at Caltech's Owens Valley Radio Observatory. Says Ravi, "We're very excited to be using them and starting to shake them out and making sure that they do what they need to do."

Sarah Scoles

Solar panels over canals could provide benefits beyond energy

Two projects in the western US are testing the feasibility of installing solar farms over sun-drenched irrigation canals.

Building new solar photovoltaic farms in the US has become cost-competitive with new fossil-fuel projects, but coating the landscape in solar panels can get expensive on in-demand land, especially near population areas and farmland. Finding ways to repurpose existing infrastructure, like parking lots, canals, and rangeland, for solar generation is an active research area globally.

Two newly constructed solar photovoltaic projects over irrigation canals, in California and Arizona, offer insights into a water-based solution. The projects' scientists are conducting cost-benefit analyses of the energy and environmental benefits to see if they outweigh the considerable installation costs.

One of the new projects is a pilot built as part of the Turlock Irrigation District, an agricultural community in California's Central Valley where land comes at a premium. The $20 million solar farm began generating electricity across a 6-meter-wide canal earlier this year, and energy generation at its other site (over a 34-meter-wide canal) will come online later this year. The 1.6-megawatt installation will be enough to power 60 homes for the region's existing customers, says Brandon McMillan of Turlock Irrigation District.

The other pilot is run by Arizona's Gila River Indian Community, which plugged in its $6 million solar project over a 9-meter-wide canal last November. Project director David DeJong says the 1.3-megawatt, nearly 1-kilometer-long installation produces power for the community and offsets costs for its irrigation district. "For the community, land is sacred, and the canal is already disturbed, so placing solar panels over them does not disturb any additional land," says DeJong.

Scientists at both sites are measuring meteorological parameters, solar panel

SOLAR PANELS shade a Turlock Irrigation District canal in Stanislaus County, California. Researchers studying pilot projects in California and Arizona are quantifying the advantages and disadvantages for water and land conservation. (Photo courtesy of Turlock Irrigation District.)

performance, water quality, and other metrics. Solar power over canals could reduce evaporative losses from the canals, according to a 2021 feasibility study in *Nature Sustainability* by Brandi McKuin, of the University of California, Merced, and colleagues. Yet the mounting system for solar power over canals is more costly than that for land-based solar systems, and financing future installations could be more expensive now that Congress has rolled back Inflation Reduction Act funding and solar-farm tax credits through the legislation known as the One Big Beautiful Bill Act.

The data will help researchers determine if the benefits of solar panels over canals outweigh the high costs of the steel, cable-mounting components, and other building materials. The solar panels shade the canal, repressing algal growth that clogs the canal's outlets. In turn, the water cools the air below the solar panels, increasing solar panel efficiency (which decreases at extreme temperatures) and lessening solar panel degradation.

DeJong estimates that mounting solar panels over the canal is 33–40% more expensive than doing so on land, but he argues that the economic and social benefits of water, energy, and land conservation and gains from higher solar panel efficiency will partially or fully offset the cost.

In 2012, India became the first country to install solar power over canals. The 1-megawatt pilot in the state of Gujarat inspired some small-scale copycats within the country, but large-scale projects haven't materialized, partly due to high costs of mounting the panels, according to reporting by *Mongabay India*.

Much of the western US is facing a severe water shortage: Years of overuse along with drought and higher-than-average temperatures exacerbated by climate change have reduced water availability to record lows. Based on their *Nature Sustainability* analysis, McKuin and colleagues project that covering California's 6300 kilometers of canals with solar panels could save up to 240 billion liters of water annually, enough for the homes of 2 million people. DeJong estimates that expanding the Gila River Indian Community's solar pilot project to cover all its Casa Blanca Canal would save enough water to irrigate about an additional third of a square kilometer annually and power 70% of the community's energy needs (excluding its casinos).

University of Exeter renewable energy researcher Aritra Ghosh says that the US projects "serve as a valuable case study not only for solar energy programs in the US but also for academic and research institutions worldwide." Ghosh is not involved with either project.

The final analysis of the California-based project, which is funded by the state and led by the University of California, Merced, is expected to be completed by the middle of next year. National Renewable Energy Laboratory scientists studying the Gila River Indian Community's solar project plan to publish results annually for the next three years as the system is evaluated.

Jenessa Duncombe

Global renewable energy use continues to grow

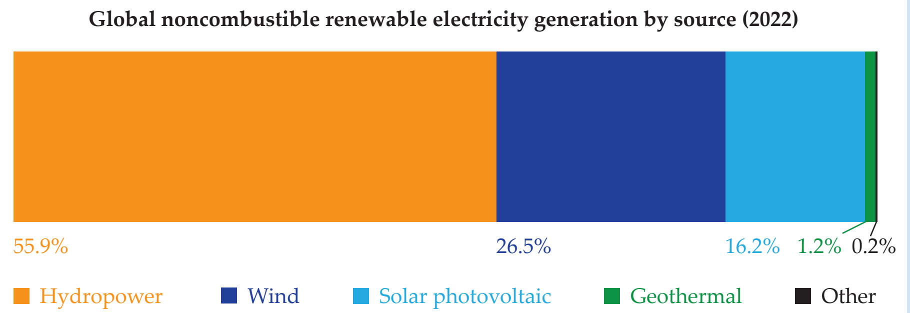
More than 12% of the energy consumed globally in 2021 came from renewable sources, according to the latest data from the International Energy Agency (IEA). That's up from about 7% in 2000.

As shown in the figure, hydropower accounted for the majority of electricity generation from renewables (excluding the burning of biofuels and waste, not shown) in 2022. From 2012 to 2022, annual electricity generation by hydropower grew from nearly 3.8 million GWh to nearly 4.5 million GWh. But the output from solar photovoltaics and wind is surging. The two were the source of about 43% of the noncombustible renewable electricity produced in 2022, up from about 14% a decade prior. Declining manufacturing costs for solar panels and wind turbines have made renewables a more competitive source of electricity generation.

Fossil fuels (coal, oil, and natural gas) accounted for about 65% of the total energy that was consumed worldwide in 2022, according to the IEA. At 30%, industry was responsible for the largest share of global energy consumption, followed by transportation (28%) and residential use (20%). From 2000 to 2022, annual global electricity consumption per capita climbed nearly 50%, to about 3.4 MWh.

For more on global energy generation and consumption, including breakdowns by energy source and use by sector, see the interactive charts at https://www.iea.org/world.

Tonya Gary



(Figure adapted from IEA 2025, "Renewable electricity generation by source (non-combustible), World, 2022," https://www.iea.org/world/renewables, CC BY 4.0. This is a work derived by Physics Today from IEA material, and Physics Today is solely liable and responsible for this derived work. The derived work is not endorsed by the IEA in any manner.)

Q&A: Kathrin Spendier manages the XPRIZE quantum computing competition

Curiosity about snow friction drove the competitive skier to slalom into physics.

When Kathrin Spendier gave up tenure, she switched not only from academia to the private sector but also from biophysics to quantum computing.

Pivoting—and risk-taking—was nothing new for Spendier: She grew up in Austria dreaming of becoming a professional skier, then switched to a career in physics. At the end of high school, she ranked in the top 100 worldwide for slalom skiing but still didn't make the cut for the Austrian team. She was recruited to ski for the University of New Mexico. In 2004, she helped the school win a national ski championship. She later earned her bachelor's and PhD degrees in physics there.

After about a decade as a professor at the Colorado Springs campus of the University of Colorado, she left academia in 2022 and joined the quantum software and computing startup Quantinuum as a quantum evangelist. She oversaw the company's sponsorship and operations of hackathons, explained quantum computing at universities around the country, and worked on building the pipeline for the quantum workforce. It was, she says, "like teaching on steroids."

In 2024, she moved to XPRIZE, which runs competitions that encourage innovation to solve societal problems. Since the foundation got its start in 1994, more than 35 000 people from 173 countries have participated in 30 competitions—offering a cumulative purse topping $519 million—in topics such as tackling water scarcity and enabling private suborbital spaceflight.

Spendier oversees the XPRIZE's competition in quantum applications. Teams compete to develop quantum computer algorithms that can outperform the best classical methods to address problems in climate modeling, drug safety, fusion reactor design, and other areas with societal impact. Currently, 224 teams are participating. Prize money totaling $5 million will be distributed in stages, with up to three winners to be selected in early 2027.

KATHRIN SPENDIER (Photo courtesy of Kathrin Spendier.)

PT: Describe your education path.

SPENDIER: I wanted to do math, but a physics professor at New Mexico who knew I was a skier steered me to physics. He said, "Don't you know that physics and skiing go together?" and told me about friction and snow. Still, athletes have a bad reputation—it took some work to convince the faculty in physics that I was not just there for the ride.

During my junior year, I started building optical microscopes in Jim Thomas's lab. Then I went to grad school.

My first year, I worked at Brookhaven National Lab, in particle physics. But it was too big. I missed tabletop experiments. I went back to Jim. For my PhD, I built a total internal reflection microscope and studied receptor motion. I also did some reaction–diffusion theory.

PT: Why did you leave academia?

SPENDIER: It was a long process to decide to look for something else. At Colorado Springs, I started a biophysics program and taught the whole physics curriculum, which was great. But I was doing too much: I wasn't teaching well, because everything was last minute. In research, I didn't have time to guide the students. And I was always trying to find funding. Once you have tenure, you are automatically asked to do more administrative tasks. And I was not good at saying no.

And the whole time, I felt that I didn't have enough time for my kids. Then one day, I had my computer in the playroom, and my littlest one said, "Mommy, you don't have time for me." It wasn't the first

KATHRIN SPENDIER (third from left) serves on the panel "Applications of Quantum Technologies—Bridging Science, Policy, and Business" at the Women in Tech Summit in Warsaw, Poland, in June. (Photo courtesy of the Perspektywy Women in Tech Summit.)

time, but it finally clicked. I was not joyful anymore. I was grumpy all the time.

PT: Was it scary to give up tenure?

SPENDIER: Yes. At first, I was going to take a leave from Colorado Springs. But they told me they couldn't hire someone if I did that, and I knew they were in dire need of teachers, so I gave up my tenured position. I had an active research grant from NIH at the time, on superresolution microscopy. I retained an affiliation for a while to help a student finish their PhD.

PT: How did you move into the quantum computing arena?

SPENDIER: Biophysics was an elective course, and it was on the cusp of not being offered. I told the graduate students, "Let's do a few weeks of quantum computing in the biophysics class." That got enough of them to sign up for the class to go ahead. And in the class, everyone was excited. They asked so many questions. I stayed up late reading up on quantum computing.

When I started looking for jobs, I had the confidence to look into quantum computing.

PT: How did you make the move?

SPENDIER: I worked a lot with LinkedIn, just applying for jobs, mostly in technical sales in health science and microscopy, and seeing what stuck. I also had interviews for data-science positions, but I typically didn't get far because I didn't have much coding experience.

I realized I would need help. I reached out to a professional resumé writer who helps academics package their skills in 2 pages instead of 15. Academics brag about themselves and their work, but when you look for an industry position, you have to elevate the company.

I ended up with three options. Two were in technical sales, in optics and microscopy. And the third was the job I took: in education outreach for Quantinuum. I thought that was interesting because quantum computing was popping up more and more as a hot topic.

Part of my job was to take algorithms and show students how to compile them and run them on a quantum computer.

PT: How does XPRIZE work, and what is your role?

SPENDIER: XPRIZE is a nonprofit that creates prize competitions to incentivize solutions to humanity's grand challenges. It's all about finding where humanity is stuck in terms of technology and then finding ways to accelerate getting unstuck and making lives better. It could be carbon capture, clean water, or personalized medicine.

XPRIZE finds the barriers and defines the competitions: How long should they last? How much money should we put into it? What types of gadgets do the teams have to build? What should the winning team achieve? We also have to find who in the ecosystem might be interested in donating the prize money. That is what XPRIZE has been doing for 30 years.

As the XPRIZE Quantum Applications director, I serve as the thought leader and the public face of the competition. At the beginning of the competition, I recruited teams. With the help of our advisers, I find judges with the right technical backgrounds and then work with them and the advisers to develop the competition guidelines and judging criteria. I document everything—it's like writing a technical paper.

PT: Do you miss academia?

SPENDIER: I miss my colleagues. And I miss tinkering with equipment. Initially, it was hard not having a lab, and I had to teach myself not to work on weekends. But with what has been happening lately with academia, all the uncertainty they are going through—with federal funding, visas, and attacks on diversity, equity, and inclusion—my former colleagues are worried. I am very sad for them. And I'm glad I am not there.

PT: Do the cuts to federal funding affect you and XPRIZE?

SPENDIER: Not directly, but I believe there will be a trickle-down effect.

The prize money comes after the fact: The teams show that they can do something and then receive additional funding from us. The purse cannot go to anyone in a country sanctioned by the US government. If more countries are sanctioned, we may have teams from a smaller pool of eligible countries. And we have teams from academia. If they have less funding, the teams may be smaller, or there may be fewer teams.

PT: How do you use your physics in your current role?

SPENDIER: Being analytical, problem-solving, seeing patterns and then adjusting what you do according to the patterns is very much needed throughout my work. I have noticed that leaders of companies are very analytical. With a physics degree, you get a problem-solving mindset. You learn how to put things together and make them work. Those skills are very applicable on the business side—more so than you would think.

Toni Feder

FYI SCIENCE POLICY BRIEFS

DOE redirects FY 2025 money to favored programs

Budget details from the Department of Energy reveal the shifting of fiscal year 2025 funds away from wind and solar energy and into water and geothermal technologies. Congress approved $318 million for solar initiatives for FY 2024, but DOE plans to spend only $42 million of it—an 87% cut—in FY 2025. Wind energy initiatives will similarly see a 78% cut. Meanwhile, the department is more than quadrupling funding for geothermal energy from FY 2024 levels, and water power will see a 50% increase.

Congress passed legislation earlier this year that maintained most science agencies' top-line budgets at or near FY 2024 levels but did not specify funding at the program level. In response to the budget details, Democrats overseeing DOE appropriations argued that the spending law carried forward FY 2024 appropriations for solar and wind energy and that DOE's spending plan for FY 2025 is "in defiance" of the legislation.

The department also shifted money between programs in the Office of Science, including a 30% increase to isotope R&D and production and a 22% cut to the workforce development program from FY 2024 levels. Other areas, such as nuclear physics, advanced scientific computing research, and high-energy physics, will see increases, while others, including biological and environmental research and basic energy sciences, will see cuts.

Congress has indicated a willingness to diverge from the administration's budget requests in its funding bills for FY 2026, including an increase for the Office of Science and near-level funding for NSF and NASA. The House Committee on Appropriations bill does not eliminate funding for solar and wind initiatives in DOE's Office of Energy Efficiency and Renewable Energy, as proposed in the president's request, but it still proposes an almost 50% cut to the office. Lawmakers have introduced bills in both chambers directing agencies to pause implementation of caps on indirect costs, and they have shown interest in developing a new indirect cost policy with the research community. —CZ

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

Report on misconduct in Antarctica calls for new standards, training

NSF released a report in July on sexual assault and harassment in the US Antarctic Program (USAP). The report draws on a survey that NSF conducted in 2024 as a follow-up to one conducted in 2021 in the wake of high-profile accusations of sexual violence at USAP facilities. The report recommends installing video monitoring in public spaces, improving training for supervisors, and increasing protections for newer and younger staff. The report also recommends introducing "benchmark standards" for USAP contractors and requiring increased training for their human resources personnel.

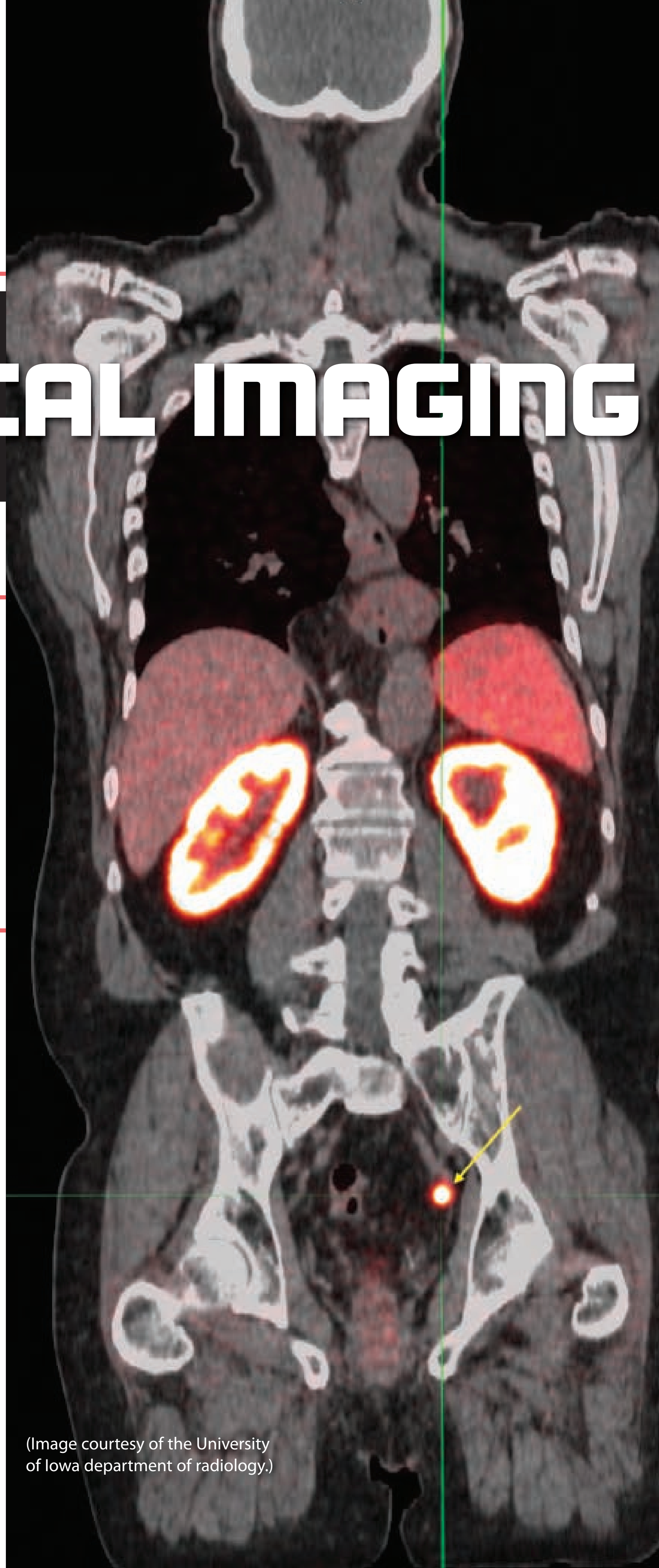
As Physics Today went to press, NSF was reviewing proposals for a new primary contractor to manage its Antarctic facilities. The House Committee on Science, Space, and Technology has accused Leidos, the current holder of the USAP facilities management contract, of failing to prevent sexual violence and lacking basic reporting systems.

The NSF report states that the 2024 survey of recent USAP personnel found that 69% of respondents had observed at least one incident of sexual assault or sexual harassment and 41% had experienced at least one such incident themselves. The survey also found "concerning beliefs that may be associated with a permissive environment" for sexual misconduct. Regarding such beliefs, 43% of respondents said they agree that "sexual jokes and innuendos are a normal part of deployment" within the USAP community, and 10% agreed with the statement "If you want to date/hookup with a USAP community member, it's ok to keep asking until they agree to a date or very definitively say no." The report recommends launching media campaigns aimed at correcting those attitudes and informing staff of reporting procedures. —JT PT

MEDICAL IMAGING

John Sunderland

Positron emission tomography's ability to image the body's biochemistry, not just its anatomy, makes it a powerful tool for detecting diseases.



(Image courtesy of the University of Iowa department of radiology.)

John Sunderland is a medical physicist and a professor of radiology and physics at the University of Iowa in Iowa City. He is also the director of the university's PET Imaging Center.

WITH ANTIMATTER

Most diseases manifest with biochemical signatures well in advance of anatomical changes. The image on the left shows a hybrid positron emission tomography/computed tomography (PET/CT) scan of a prostate cancer patient. The average-sized lymph node in the pelvis indicated by the yellow arrow would look normal in an anatomical image from a CT or magnetic resonance imaging (MRI) scan. But the PET scan shows, definitively, that the lymph node has been invaded by cancer cells: Before the scan, the patient was injected with a positron-emitting radiopharmaceutical that binds to an antigen found on the membranes of prostate cells, both normal and cancerous. PET imaging with disease-specific radiopharmaceuticals is dramatically changing the management of cancer through its remarkable sensitivity in detecting even tiny, remote tumors.

The ability to image biochemical and physiological processes in real time distinguishes PET from medical imaging technologies that primarily visualize anatomy.[1] PET imaging can reveal the molecular signatures of a vast array of diseases and help physicians devise appropriate therapeutic strategies. Over the past four decades, PET has gradually evolved into a mainstream clinical diagnostic tool for cancer and cardiac and neurological diseases. More than 2 million scans are performed in the US annually, and approximately double that are performed worldwide.

A PET scan of glucose metabolism in the body of a breast cancer patient is illustrated in figure 1a. To achieve such an image, the molecular structure of a glucose molecule is subtly altered, as shown in figure 1b, to include a radioactive, positron-emitting fluorine-18 atom, which has a half-life of 110 minutes.[2] The radioactively labeled glucose analog is injected into the patient to provide the signal imaged by PET.

Parts of the body that metabolize glucose appear darker, in proportion to the level of that metabolism. The scan shows normal physiological glucose metabolism in the brain, liver, and heart; intense localization in the urinary bladder and kidneys is because the kidneys recognize the glucose analog as an impostor and gradually filter it into the urine (a similar effect can be seen in the PET/CT scan of the prostate cancer patient). Most importantly, the scan identifies the presence of rapidly dividing metastatic tumor cells that avidly metabolize glucose in lymph nodes around the left armpit.

Basics of positron decay

PET gets its name from the nuclear radioactive decay mechanism—positron emission—that enables the localized measurement of biochemical activity in the body. A positron is an antimatter electron: It has the same mass as an electron but is positively charged. It most commonly comes from the

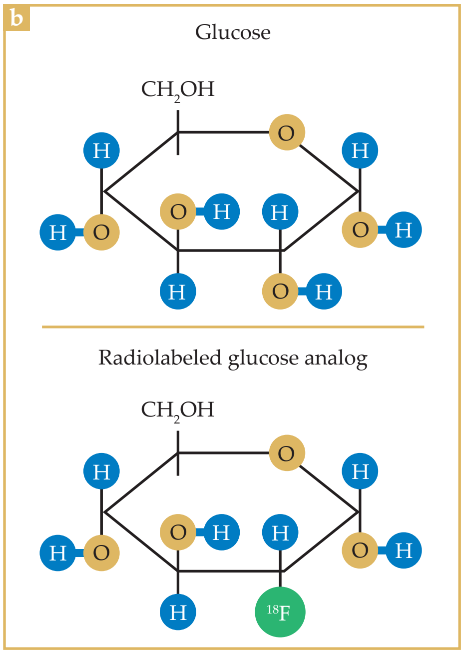


FIGURE 1. ONCOLOGY USING POSITRON EMISSION TOMOGRAPHY. (a) A PET image of glucose (sugar) metabolism in the body of a subject with breast cancer is achieved by injecting a glucose analog radiolabeled with fluorine-18. Parts of the body that metabolize glucose appear darker. The image shows normal glucose metabolism in the brain, liver, and heart; the intense but normal localization in the urinary bladder and kidneys are because the kidneys recognized the analog as an impostor and gradually filtered it into the urine. Crucially, the scan identifies rapidly dividing metastatic tumor cells that avidly metabolize glucose in lymph nodes around the left armpit (red arrow). **(b)** The structure of a glucose molecule and the subtly altered structure incorporating a positron-emitting ^{18}F atom. (Image courtesy of the EXPLORER Molecular Imaging Center/University of California, Davis.)

radioactive decay of a proton-rich nucleus, in which a proton is converted into a neutron, as shown in figure 2. Once created, the emitted positron is not long for this world. Propelled a little by the electrostatic repulsion of the positively charged nucleus, the positron exits the nucleus and then rapidly decelerates. It typically travels less than a millimeter before slowing sufficiently to interact with an ambient electron, its matter counterpart, at which point the particles annihilate each other.

In that annihilation interaction, the electron and positron disappear. In their stead, two 511 keV gamma-ray photons, traveling at 180° from each other, are emitted from the point of annihilation. It is an elegant real-world example of Einstein's $E = mc^2$: The masses of the electron and positron (9.11×10^{-31} kg each) are converted into energy in the form of photons. The photons travel in opposite directions as a result of the conservation of momentum because both the electron and positron are functionally at rest when they interact and annihilate. PET scanners are designed to simultaneously—within about five-billionths of a second—detect both photons to determine the position of the decay event in the body.

Radiopharmaceuticals

The key to PET imaging's remarkable versatility is grounded in its molecular approach. In PET imaging, relatively short-lived radionuclides that decay by positron emission are chemically incorporated into molecules of physiological interest and introduced into the body, usually through an injection. The molecules, commonly called radiopharmaceuticals, could be neuroreceptor ligands designed to bind to dopamine receptors in the brain,[3] or they could be small molecules engineered to attach to specific proteins on the cell membrane of a particular cancer type. Or they could be as simple as radiolabeled glucose molecules used to image sugar metabolism in the body.

To be used in PET imaging, the positron-emitting radionuclide attached to the molecule needs to have a half-life long enough to allow for several steps of production and use: the drug's radiochemical synthesis, subsequent quality control to ensure its safety and purity, its administration to a patient, and its sufficient circulation through the body to reach its molecular target and be imaged. Ideally, the half-life is tens of minutes to several hours. But sometimes, the physiological process being imaged requires days, in which case a longer-lived positron-emitting radionuclide, like zirconium-89 with a half-life of 78 hours, is necessary.

PET is a tracer-imaging methodology. Although it involves injecting drugs into a patient, the actual amount of the radioactive drug is incredibly small, far below the threshold of what would induce any kind of measurable pharmacological effect. For example, the mass of a standard clinical dose of the ^{18}F-labeled glucose used for a PET oncology scan is about one-billionth of a single grain of sugar. That is enough to generate an excellent clinical-quality image, with more than 100 million pairs of annihilation photons detected in a typical 15-minute scan. The use of trace quantities of such drugs allows for the probing of biochemical distributions in the body noninvasively without perturbing the biochemical mechanisms that are being studied.

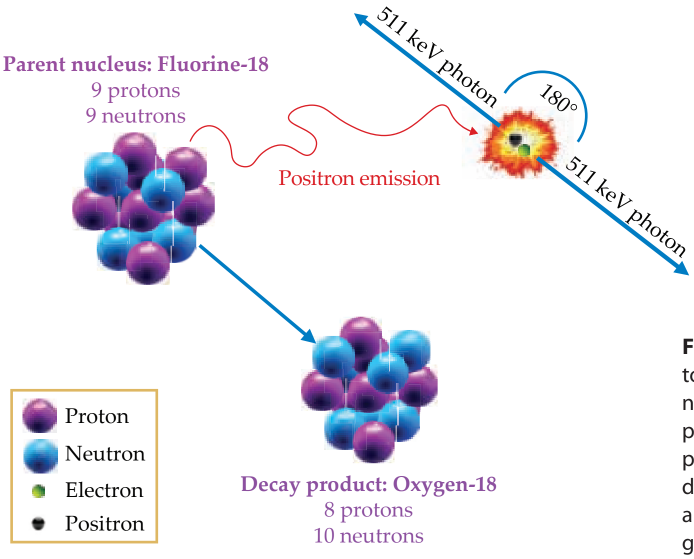


FIGURE 2. POSITRONS ARE EMITTED in the decay of fluorine-18 to oxygen-18 when a proton in the ^{18}F nucleus gets converted to a neutron. Within less than a millimeter of its original location, the positron will annihilate with an ambient electron. That annihilation produces two 511 keV gamma-ray photons, traveling in opposite directions, that can be detected by scintillation crystals in the ring of a PET scanner. Tens of millions of photon detections are compiled to generate PET scan images.

Approximately 90% of PET scans are performed to help diagnose and stage various kinds of cancer and to help monitor patients' responses to treatment. The remaining 10% of clinical cases are split evenly into cardiac and neurological applications. The technology is also used extensively in drug development with specially designed ultrahigh-resolution PET scanners for small animals, especially rats and mice.

PET, CT, x-ray, and single-photon nuclear medicine imaging all use ionizing radiation to generate diagnostic images that help physicians manage their patients' treatment. The amount of radiation energy deposited in organs and tissues with each of those procedures is well known and understood, and each procedure and protocol is optimized to provide diagnostic-quality imaging with the lowest associated radiation dose. For all those diagnostic procedures, the radiation doses received by a patient are orders of magnitude below any that could potentially cause a short-term adverse radiation effect. The primary concern about low radiation doses in diagnostic procedures is an exceedingly low increased risk of the patient developing a downstream cancer years later. It is a basic tenet of medical imaging that the benefit of the tests far outweighs any remote potential risk.

How a PET scanner works

A PET scanner is designed to generate a 3D map of the radiopharmaceutical's distribution in the body. To achieve that, the scanner needs to identify the location of each positron decay event in 3D space with as much precision and efficiency as possible. The higher the precision with which the origin of the decay can be determined, the better the resolution can be of the resulting image. And with a higher detection efficiency, less of the radioactive drug needs to be injected to create a diagnostically satisfactory image.

Because the emitted positron travels only a short distance (less than a millimeter for ^{18}F) before annihilation, detecting the positron itself is out of the question. The two gamma-ray photons produced by the positron–electron annihilation, however, are highly penetrating. A reasonable fraction of the photons escape the body, unscathed by either Compton scattering or photoelectric-effect absorption. It is the efficient simultaneous detection of those photon pairs that is at the heart of the PET scanner's design.

A modern-day PET scanner consists of multiple contiguous detector rings that contain thousands of tiny scintillation crystals, typically about 4 mm × 4 mm on the face and 15–25 mm in depth, as shown in figure 3. Those small, individual radiation detector elements are all connected in electronic coincidence with one another. During a PET scan, when one of the small scintillation detectors measures a 511 keV gamma-ray photon through energy discrimination, it sends to a central location a fast electronic signal that uniquely identifies both its precise location in the detector ring and the precise time at which the detection event took place (to within about 0.2–0.3 ns).

Following the detection of any single 511 keV photon, the PET system patiently waits about 5 ns for a second such photon. If a pair of 511 keV photons are detected within that 5 ns window, then the system concludes that the photons must have come from the same annihilation event, one that happened somewhere along a straight line between the two detectors, as illustrated in figure 4a. Exactly where the event occurred along that line, though, remains unknown.

Coincidences are rejected if one of the photons has an energy of less than 511 keV, which signals that the lower-energy photon was scattered. If two 511 keV photons are detected but not within the 5 ns coincidence window, they are rejected because they must have originated from different decay events. It is possible that two independent decays occur within 5 ns of each other and that unrelated 511 keV photons are simultaneously detected, which creates an accidental or random coincidence. The random coincidence, if left uncorrected, would create the illusion that a decay event

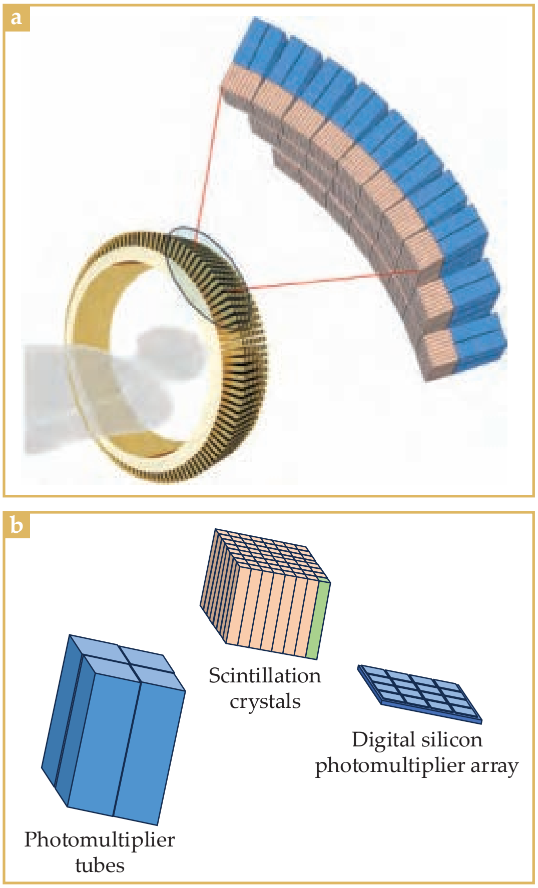


FIGURE 3. A PET DETECTOR RING. (a) A zoomed-in section of the detector ring shows that it is made of many detector modules. **(b)** A traditional detector module is made of approximately 64 scintillation crystals (one here highlighted in green) that are optically coupled to photomultiplier tubes (PMTs). When a gamma-ray photon triggers a burst of scintillation light in a crystal, the relative amounts of light detected by each of the four PMTs will determine which crystal was involved in the event. New scanners couple the same scintillation crystal block matrix to a digital silicon photomultiplier array instead of to PMTs. Because fewer crystals are coupled to each photodetector, crystal identification is more reliable.

occurred along the dotted line in figure 4b. PET systems are designed to statistically account for and remove random events to the greatest degree possible.

A deeper dive into detection

There are three main components to the detector modules used in PET: the scintillation crystal that converts the gamma-ray energy to visible light, the photodetector that converts the visible light to an electrical signal, and the detector electronics that measure the absorbed energy and record the precise time and position of the detection event. The three components need to work together to detect the origin of the radioactive decay with high spatial resolution, high efficiency, high energy resolution, and high temporal resolution.

As shown in figure 3a, each of the radiation-detecting rings of the PET scanner consists of a number of discrete detector modules. Each module consists of a matrix of small, discrete scintillation crystals, typically five to eight across. Those crystal matrices are optically coupled to photodetectors that convert the scintillation photons into an electrical signal. Historically, photomultiplier tubes have been used as the photodetectors, as sketched in figure 3b, but digital silicon photomultiplier arrays have recently come into use. They are more compact and can provide both better timing resolution and more precise localization of the crystal interaction.

Detector modules are configured in multiple contiguous rings to allow simultaneous collection of imaging data along the length of the patient. Most PET scanners can image between 20 and 25 cm along the axis of the scanner at a time, though designs are moving toward the inclusion of more rings and therefore a larger axial coverage beyond 25 cm. The patient is slowly moved through the scanner to image as much of their body as is medically necessary.

To precisely identify the location from which the positron–electron annihilation event originates, PET requires simultaneous gamma-ray detection with high spatial resolution. High resolution is primarily achieved by decreasing the size of the face of the individual scintillation crystals. Modern PET systems typically have square crystal faces with sides measuring 3 to 4 mm and a depth of about 15 to 25 mm. With crystals that size, clinical resolution can approach 4 to 5 mm. The longer the crystals are, the higher the probability that an incoming 511 keV photon interacts with them. But longer crystals have a higher risk of the photon crossing over from one crystal into an adjacent crystal before interacting, which will result in a small misplacement of where the annihilation event occurred and a slight decrease in resolution.

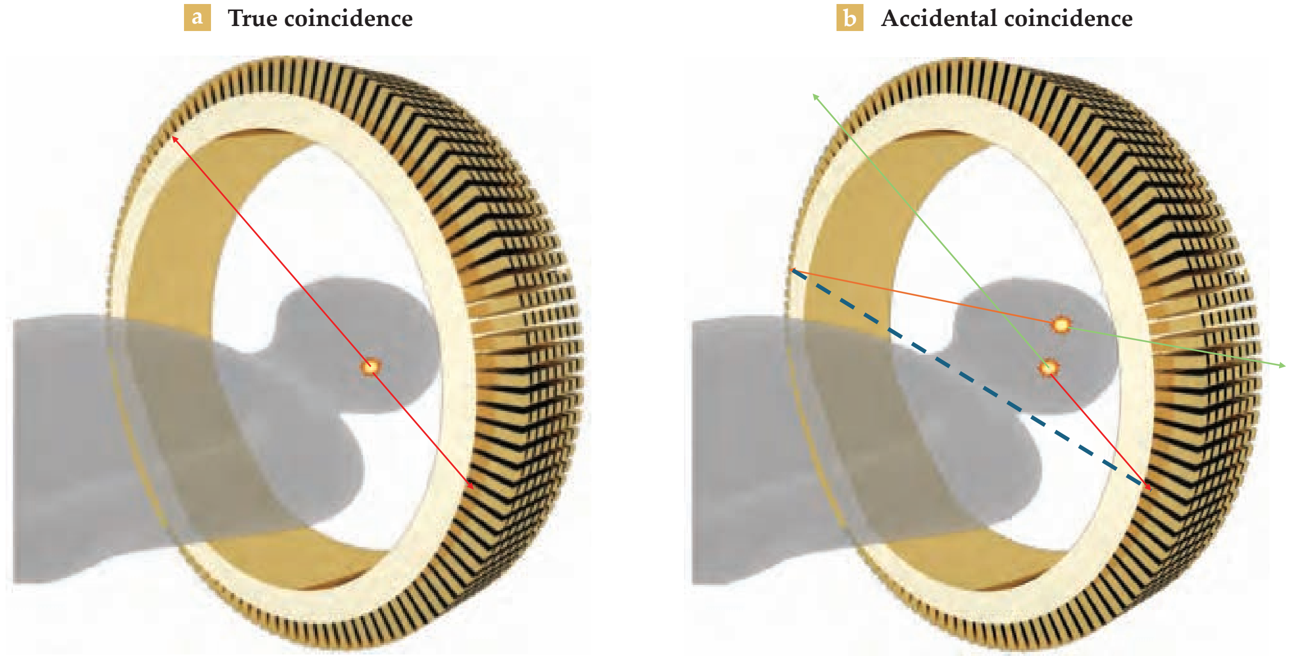


FIGURE 4. PHOTON COINCIDENCE DETECTION in a PET scanner. **(a)** When two 511 keV gamma-ray photons are detected within 5 ns of each other, they are presumed to have formed from the annihilation of a positron and an electron somewhere along a straight line between the two detection locations. That measurement corresponds to a true coincidence event. **(b)** It is possible for two discrete annihilation events to randomly occur within 5 ns of one another such that two unrelated 511 keV photons are detected at the same time. Those accidental coincidence events are indistinguishable from true events, but they can be approximated statistically and subtracted at the end of a scan.

The more efficient the radiation detectors are in a PET scanner, the less radioactive material needs to be injected into the patient to still achieve a diagnostic-quality image. High detection efficiency is achieved by using scintillation crystals with a high average number of protons in the nucleus and high physical density. Detection efficiency is further enhanced by simply using thicker crystals. A PET crystal with a depth of 20 mm has about an 80% probability of detecting a 511 keV gamma ray.

When a scintillation crystal is hit with a single high-energy photon, it can fully absorb that energy through the photoelectric effect and convert the energy into several thousand visible-light photons that produce a rapid flash inside the crystal. The number of generated visible-light photons is proportional to the energy absorbed, so by measuring the amount of light produced, one can indirectly measure the energy of the incoming photon. That capability is critical because photons that experience inelastic Compton scattering on the way to the detector will have lower energy and can thus be filtered out.

PET image reconstruction

PET images are created through image-reconstruction algorithms that use the tens of millions of 511 keV photon pairs detected during the scan. At the foundation of PET reconstruction is the concept of back projection. If an annihilation event is sensed between two detectors, the position of the annihilation event is assigned an equal probability over the entire length of the line connecting them. That back projection is done for each detected event. Where events' individual back projections spatially overlap, their probabilities are summed. When all detected events are collected and overlapped, it results in a first approximation of the radioactivity distribution.

The smaller the detectors and the finer the angular sampling, the higher the resolution of the resulting image. And although coincidence windows of about 5 ns are typically used, modern PET detection systems can achieve timing resolution on the order of 200–300 ps. Light travels only about 6 cm in 200 ps. By measuring the difference in arrival times between two coincident photons, the position of the annihilation event can be reasonably localized to within several centimeters along the line connecting the two detectors. The refined localization based on that time-of-flight information greatly enhances the probability-based reconstruction algorithm so that substantially better images are produced from fewer detected events.[4]

Back projection is only the first step of what is a much more complex reconstruction process. The entirety of the collected projection data is corrected for photon attenuation within

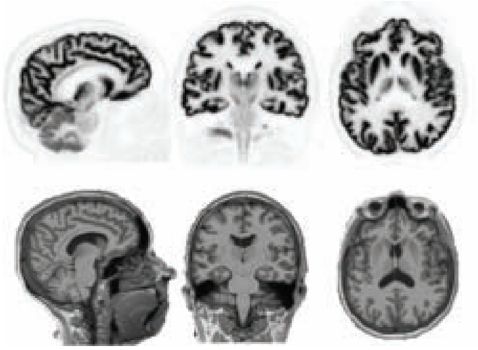


FIGURE 5. IMAGE SLICES OF THE BRAIN of a healthy control participant (top row), acquired 60–90 minutes after injection of a radiolabeled synaptic density marker. The images were made using a new dedicated human-brain PET imager, NeuroEXPLORER. Matching MRI anatomical images were also captured (bottom row). The ultrahigh resolution and sensitivity of the NeuroEXPLORER provide exquisite delineation of the folds of the brain's cerebral cortex and structures deeper in the brain. (Image courtesy of Richard Carson on behalf of the NeuroEXPLORER consortium.)

the body, electronic dead time, accidental coincidences, and scattering. Finally, just before the back-projection step, the projection data from each angle—that is, all the parallel lines connecting opposite detectors at a given angle—are processed through a spatial filter that largely removes the artificial blurring introduced in the back-projection step. That processing step is also used for other tomographic imaging methods, including CT scans. (See reference 5 for an excellent animated demonstration of the back-projection method.) Reconstruction steps are typically performed iteratively to converge on the highest-quality clinical images.

When all those steps are performed on a calibrated PET system, the resulting image is a quantitative map of radioactivity concentration, which reveals the spatial distribution of the radiopharmaceutical in the body. Each voxel, or 3D pixel, in the image is in units of becquerels per cubic centimeter, where the becquerel is one radioactive decay per second. In well-calibrated systems, measurements can be accurate to better than 2%. Beyond being remarkably useful medical imaging tools, PET scanners are amazing measurement devices, and for decades, they have provided accurate pharmacokinetic measurements of numerous physiological processes.

Necessary infrastructure

The clinical use of PET scanners has experienced continuous growth over the past 30–35 years; millions of diagnostic scans are currently being performed annually. That number, however, is one to two orders of magnitude lower than the number of annual CT and MRI scans being performed. Growth of PET usage has been more gradual than for its CT and MRI counterparts largely because of infrastructural and regulatory barriers.

PET radiopharmaceuticals are considered drugs by the US Food and Drug Administration and other worldwide regulatory agencies. As such, before clinical use, a PET radiopharmaceutical must undergo testing in phase 1, 2, and 3 clinical trials to prove both safety and clinical efficacy. Clinical trials cost tens of millions of dollars to perform, and approval of a radiopharmaceutical for human clinical use can easily take 5–10 years.

Additionally, PET drugs are radiolabeled with relatively short-lived radionuclides that have half-lives typically on the order of an hour or two, which means that they must be synthesized near to both the time and place they are used. A PET-dedicated cyclotron is typically necessary to produce the positron-emitting radionuclides that are incorporated into the PET radiopharmaceuticals. For PET to be widely available requires a network of commercial radiopharmacies equipped with cyclotrons, radiochemistry laboratories, clean-room facilities for drug manufacturing and quality control, and centralized distribution infrastructure.

It has taken some time to build that infrastructure. At present, there are hundreds of PET-dedicated cyclotrons around the world, daily producing carbon-11 (a half-life of about 20 minutes), ^{18}F (a half-life of about 110 minutes), copper-64 (a half-life of about 13 hours), and ^{89}Zr (a half-life of about 78 hours) to supply the thousands of worldwide PET scanners.

The cutting edge

PET imaging continues to grow and evolve. It has become increasingly useful in clinical medicine. One area of advancement is through technical innovation—making PET scanners with higher resolution, more sensitivity, and enhanced image quality through better time-of-flight resolution and use of AI in the image-reconstruction phase.

One trend in new commercial equipment is to have more detector rings to produce a longer axial field of view. With the additional rings, oncology patients can be scanned faster and with improved image quality. Or the image quality and scan time can be kept the same and smaller radiopharmaceutical doses used, which is especially important for reducing radiation exposure in pediatric patients. Some commercial PET systems on the market have axial fields of view of 1–2 meters that can image a patient's entire body in just a few minutes; the scan in figure 1a was obtained with such a system.[6] Imaging nearly the entire body at once also enables dynamic imaging of the pharmacokinetic properties of new drugs by taking images of the biodistribution at set time intervals, as rapidly as every few seconds.

Meanwhile, developments in electronics and photosensor technologies for silicon photomultipliers continue to improve time-of-flight resolution, which now is better than 200 ps and provides enhanced image quality.[7]

New brain-only imaging units are being developed with an unprecedented isotropic resolution that approaches 2 mm^3, which is comparable to but not quite as high as that of MRI. PET brain images, like those shown in figure 5, reveal the biochemical distribution of radiopharmaceuticals that enables the detailed probing of, for example, specific neuroreceptors, amyloid deposition in Alzheimer's disease, and even synaptic densities.

The true power of PET imaging lies in its ability to probe the specific physiology of disease processes. In the clinical domain, only about 20 PET radiopharmaceuticals are approved for clinical use. But those well-studied and proven drugs only scratch the surface; hundreds of PET radiopharmaceuticals under development are aimed at new molecular targets. Drugs under later-stage development include a class that specifically binds to fibroblast activation protein, a marker found on cells in the tumor microenvironment of a broad array of cancers.

Another area of growth is the use of PET to image and monitor the body's immune response.[8] There are several strategies to do that, but one of the more direct ways is to label and monitor monoclonal antibodies, which are synthetic proteins similar to the body's natural antibodies. Monoclonal antibodies are used to treat cancer because they bind to specific antigens on cells and trigger immune responses. Because they are typically large molecules that have slow kinetics, they sometimes take days to localize, so longer-lived positron emitters, such as ^{89}Zr, are often used to allow for imaging several days after injection.

Neurological and psychiatric radiopharmaceuticals are also clinically available, with more under development. With the recent approvals of new treatments for Alzheimer's disease, demand for PET imaging to more definitively identify candidates for therapy is rising dramatically.[9] On the research and drug-development front, radiopharmaceuticals designed to measure the pharmacokinetics and distribution of positron-emitter-labeled molecules targeting dopamine and serotonin receptors are popular targets for study. And direct measurement of neuroinflammation with PET has applications in studying the biophysiology and biochemistry of stroke, Parkinson's disease, and traumatic brain injury, among other disorders.

Molecular imaging with PET is poised for continued rapid growth, driven by advancements in imaging technology, an increasing array of disease-specific radiopharmaceuticals, and its alignment with the worldwide focus on personalized medicine.

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PT

FROM RADIO WITH LOVE

A Cold War astronomical collaboration

To construct an interferometer with a baseline spanning the planet, US radio astronomers reached out to their Soviet counterparts.

REBECCA CHARBONNEAU

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The 140-foot telescope at Green Bank Observatory, pictured in 1965. (Photo by J. Baars, courtesy of NRAO/AUI/NSF/CC BY 4.0.)

In 1969, with East–West tensions high, scientists from the US and the USSR carried out an unprecedented cross-border experiment in radio astronomy. Designed to push the limits of a new technique called very long baseline interferometry (VLBI), it required trust and cooperation between both sides. Overcoming a host of political, cultural, and logistical hurdles, US and Soviet astronomers connected two radio telescopes—one in Green Bank, West Virginia, and one in the Ukrainian peninsula of Crimea—to create a single virtual telescope with a baseline as large as the distance between them. The result was not only a historic leap in observational capabilities but also a surprising collaboration between rivals.

Invented in the mid 1960s, VLBI is at the heart of cutting-edge astronomical observations even today. The black-hole images published by the Event Horizon Telescope since 2019, for example, were made possible by the technique (see "A portrait of the black hole at the heart of the Milky Way," Physics Today online, 12 May 2022). VLBI allows astronomers to improve the resolution of radio telescopes by linking multiple dishes across great distances and using the time difference in signal arrival at each telescope to simulate a single, much larger dish.

In fact, the widely separated radio antennas need not even be physically connected to achieve unprecedented angular resolution. With radio telescopes scattered across the globe, VLBI has imaged the radio emission from astronomical objects that would otherwise be impossible to resolve, such as distant quasars, neutron stars, and supermassive black holes. But because the technique relies on precise synchronization and data sharing across political borders, it often involves as much diplomacy as astrophysics.

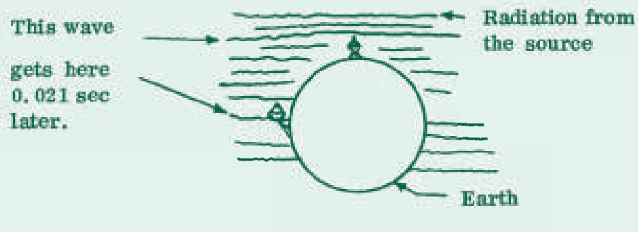
A new spectrum

Radio astronomy emerged in the 1930s, when Karl Jansky, working at Bell Labs, accidentally discovered radio waves emanating from the center of the Milky Way while he was investigating static interference in transatlantic telephone signals. That unexpected discovery enabled a new way of observing the universe—one that would eventually reveal objects and phenomena that were previously unrecognized, such as pulsars, quasars, and the cosmic microwave background.

At the heart of a radio telescope's sensitivity is its collecting area. Large parabolic dishes gather radio waves and focus them into a feed horn, a funnel-shaped component that directs the signal to a receiver that amplifies the faint waves and converts them into electrical signals for analysis. But because radio wavelengths, which range from millimeters to meters, are so much longer than those of visible light, achieving fine angular resolution requires radio telescopes to be far larger than their optical counterparts.

Until the mid 1960s, radio astronomers were able to improve their observational capabilities by building ever-larger radio dishes. The Arecibo telescope in Puerto Rico, completed in 1963, for example, had a whopping 305-meter diameter. But as the decade wore on, the community began facing a technological limitation. Not only were large telescopes expensive and difficult to build, but at a certain point, the effects of gravity made it impossible for a telescope to support itself and maintain its parabolic shape. Observing distant, faint objects in the radio spectrum would require telescopes with far better resolution than a single dish could provide.

Enter interferometry and aperture synthesis. Building on techniques they had learned developing radar during World War II, Martin Ryle and others realized that by combining signals from multiple telescopes spread out across a distance, they could simulate a much larger telescope and get significantly higher resolving capabilities. The technique became a staple in radio astronomy and earned Ryle a share of the 1974 Nobel Prize in Physics.



A SCHEMATIC DIAGRAM illustrating the principles of very long baseline interferometry. A wave approaches Earth and is measured by two radio telescopes at different locations. To combine the measurements, astronomers need to know the precise time at which each observation was taken. (Image from J. Broderick, "VLB Interferometry," *The Observer*, January 1970, p. 7.)

But combining signals from distant telescopes isn't straightforward. As illustrated in the diagram above, radio waves hit each telescope at a slightly different time, depending on how far apart the telescopes are. Astronomers needed to precisely align those signals to measure that time difference. As early as the 1940s and 1950s, researchers were able to achieve that task for telescopes positioned close enough that they could be connected by coaxial cable. But doing so would be far more complicated for telescopes that were many hundreds or thousands of kilometers apart—perhaps even located on different continents—and thus too distant to be physically networked. The payoff promised to be immense. By increasing the distance between telescopes, called the baseline, astronomers could dramatically improve angular resolution: An interferometer comprising two telescopes 1000 kilometers apart can achieve a resolution approximately 10 000 times as fine as that of a single 100-meter dish.

Simultaneous invention

The story of VLBI does not hinge on a single breakthrough but rather a convergence of technological advances and scientific ambitions during the Cold War. In the US, radio astronomers sought sharper resolution to study distant quasars and map Earth's rotation with greater precision. In the USSR, astronomers had limited access to large single-dish antennas and pursued interferometry to enhance observational power using existing infrastructure. Researchers in both countries were aided by several crucial new technologies, including highly stable atomic clocks and high-speed tape recorders. Those innovations, which arose nearly simultaneously in several countries, spurred several groups to independently begin experimenting with using disconnected telescopes for long baseline interferometry.

The idea of a collaborative East–West VLBI experiment emerged early on, in 1963, when UK astronomer Bernard Lovell discussed the idea with Soviet astrophysicist Iosif Shklovsky

THE 22-METER RADIO TELESCOPE at the Simeiz Observatory in Crimea used in the 1969 US–USSR VLBI experiment. (Photo by K. Kellermann, courtesy of NRAO/AUI/NSF/CC BY 4.0.)

and others during a trip to the USSR. The two signed an agreement to test the concept, but the proposed experiment never got off the ground. Two years later, Soviet scientists Leonid Matveenko, Nikolai Kardashev, and Gennady Sholomitskii published an article proposing the use of atomic clocks to synchronize signals from widely separated telescopes that could not be physically connected.[1] Calling the technique *radiointerferometr s bolshoy bazoy* ("radio interferometry with large baselines"), they envisioned that the telescopes could be positioned virtually anywhere—even on different continents—and that extraordinary resolutions could be achieved. But because it appeared in a Russian-language journal with limited distribution in the West, and the journal's English translation was just getting off the ground, the paper went largely unnoticed by the astronomical community.

The first VLBI experiment arguably took place in January 1967, when scientists at the University of Florida in Gainesville and Florida Presbyterian College in St. Petersburg combined tape-recorded signals from two disconnected antennas to observe Jupiter's radio bursts. The team was able to synchronize the data by placing at each telescope a crystal oscillator, which time-stamped and stabilized the frequency of the incoming signals. Although the baseline of 218 kilometers wasn't especially long, the innovative experiment ushered in the core technique of VLBI: synchronizing and correlating data from separated instruments. But the paper announcing the results didn't appear until 1968,[2] so the work had little immediate impact. Around the same time, a team of Canadian researchers used a similar technique to perform an experiment with telescopes separated by just 200 meters. That group published its findings in June 1967.[3]

One month later, teams working at the National Radio Astronomy Observatory (NRAO) and the Naval Research Laboratory (NRL) published the results of a collaborative VLBI experiment that they had conducted that May.[4] Their independently operated telescopes, located in Green Bank and the Maryland Point Observatory, were separated by 220 kilometers—approximately the same baseline as the Florida experiment—but because their observations were made at a frequency more than 100 times as high as the Florida group's were, the images produced had much better resolution. The idea for the experiment famously came about over a lunchtime pitcher of beer: A fittingly collaborative and spontaneous origin for a project that would go on to revolutionize astronomy.

US AND SOVIET ASTRONOMERS CELEBRATE with glasses of cognac after the first successful VLBI observations were made at the Simeiz Observatory in October 1969. Standing, from left, are observatory director Ivan Moiseyev, John Payne of the NRAO, and Victor Efanov, one of the observatory's support staff. Seated in front is another, unnamed observatory employee. (Photo by K. Kellermann, courtesy of NRAO/AUI/NSF/CC BY 4.0.)

So who deserves credit for inventing VLBI? The answer is less about a single inventor and more about parallel innovation and simultaneous invention: Several groups from different countries arrived at the same idea around the same time. The result was not just a new technique but a new kind of radio astronomy—one that reflected the collaborative, globally distributed nature of the field itself.

Planning the experiment

To build on the experiment done with the NRL telescope, the NRAO scientists sought to collaborate with researchers from observatories around the world. Their first international collaboration was in January 1968 with a Swedish team, during which the two teams successfully linked telescopes over 6000 kilometers apart.[5] Encouraged by that success, the NRAO researchers set their sights on achieving an even finer resolution, which required a combination of long baselines and telescopes that could observe at low frequencies with sufficient sensitivity. They first hoped to work with Australian astronomers, but facilities such as the large radio telescope at Parkes Observatory in New South Wales weren't yet fully equipped for the demands of VLBI.

The team soon realized that some of the best options were in the USSR, which had invested heavily in radio astronomy and possessed several large dishes suitable for VLBI experiments. So in February 1968, NRAO radio astronomer Kenneth Kellermann and Marshall Cohen, then at the University of California, San Diego, sent a letter to Soviet scientist Viktor Vitkevich of the Lebedev Physical Institute in Moscow, in which they pitched a collaborative experiment that would use the NRAO's 140-foot radio telescope in Green Bank and an antenna in the USSR.

The Soviets agreed to collaborate and suggested using the 22-meter radio telescope at the Simeiz Observatory in Crimea. So in late 1968, the NRAO team jumped into planning mode. The VLBI experiment would be one of the earliest high-profile examples of US–Soviet scientific collaborations made possible during détente, the period during the late 1960s and 1970s when Cold War tensions eased and the two superpowers promoted cooperation in science and technology. The thaw in relations opened channels for collaboration that had been closed for decades and enabled joint projects that would have been politically unthinkable just a few years earlier.

In an internal report outlining the scientific goals of the collaboration, Kellermann and his NRAO colleagues explained why it would be ideal to use the Crimean telescope: Not only was it well situated for achieving the long baselines necessary for high-resolution observations, but it was one of only a few non-US telescopes that could observe at the required wavelengths with the necessary sensitivity for the demanding experiment.[6]

The report highlighted two major challenges that the collaboration would face, which would need to be smoothed out with careful preparation. The first was communication: To quickly resolve the inevitable technical issues the teams would face, researchers in the US and USSR needed to constantly be in touch. Language barriers compounded the challenge: Few US scientists spoke Russian, and vice versa. To complicate matters further, both US and Soviet scientists needed to visit each other's facilities to familiarize themselves with the other team's equipment and procedures, which meant that they came up against Cold War travel restrictions.

Even during détente, personnel exchanges between the US and the USSR remained rare and were subject to strict political oversight. On the Soviet side, often only scientists who were Communist Party members or in good political standing were permitted to travel. And both governments encouraged or required their scientists to report both on foreign visitors and on their own experiences during visits abroad. The atmosphere of surveillance and political caution complicated the smooth functioning of the collaboration.

The second hurdle was gaining permission to export technically sensitive instrumentation to the USSR. One of the most critical pieces of equipment for the experiment was an atomic clock, which helped precisely synchronize signals between the telescopes in Green Bank and Crimea, separated by more than 5000 kilometers. The NRAO team needed to bring the clock from the US to the Simeiz Observatory, which required clearance from the Office of Export Control in the Department of Commerce. But that wasn't all: The Department of Defense had national security concerns about conducting VLBI because the technique was also used in geodesy—the scientific study of Earth's shape, orientation, gravitational field, and movement.

Geodetic information is also vital for guiding intercontinental ballistic missiles. At the time, VLBI could locate radio antennas' positions to within a few meters, which alarmed the DOD. The department feared that if extremely precise geodetic data regarding the NRAO 140-foot telescope's exact location were shared with the USSR, it might help the Soviets improve their ability to accurately aim missiles at high-value US targets in the general vicinity of Green Bank, including Washington, DC. At one point, representatives from the DOD visited the NRAO to voice their concerns.[7] But in the end, the DOD did not object to the experiment: Both the US and USSR were already launching spy satellites into Earth's orbit that provided comparably precise geodetic measurements.

AN ATOMIC CLOCK similar to the one used in the 1969 US–USSR VLBI experiment. (Courtesy of NRAO/AUI/NSF/CC BY 4.0.)

Overcoming difficulties

Even after receiving official permission to export the atomic clock, physically transporting it across the Atlantic Ocean and within the USSR proved to be an ordeal. Packed into a large, unmarked crate, the clock looked suspiciously like an oversized bomb to Soviet airport security. Out of concern that the term would evoke nuclear anxieties to Soviet customs officials, the US astronomers were careful not to call their device an "atomic" clock. But even without the word atomic, transporting the large device caused concern. As Kellermann later recalled in a retrospective essay for *The Observer*, the NRAO's internal newsletter: "Imagine a Russian trying to get on a flight from Miami to New York carrying a strange looking box (ticking, of course) with wires and batteries, and having only a voltmeter, pair of plyers, and a large screwdriver for luggage, and you get the picture."[8]

After several delays and intense scrutiny, the team finally arrived in the USSR with the clock. But the challenges didn't end there. At the Pulkovo Observatory near Leningrad, the team members synchronized the clock with a Swedish reference, but the internal battery started running low during their flight to Crimea. That posed a major problem because the atomic clock needed continuous power to preserve its precise time calibration. They hooked it up to a car battery they had brought as a backup and, after landing, loaded the ungainly contraption into a car to drive to the Simeiz Observatory. But that battery, too, began to falter midway through the trip. Improvising, they hooked up the clock to the car's battery for power and ultimately managed to arrive at the observatory before that also died.

Although the team expected to face communication challenges, maintaining contact between Green Bank and Crimea

A SELECTION OF THE WHIMSICAL CARTOONS drawn to accompany Kenneth Kellermann's three-part 1970 article in the NRAO's newsletter, *The Observer*, that recounted the story of the 1969 VLBI experiment. (Cartoon of the radio dish and clock by Peggy Weems, and cartoons of the international clock test and the calendar with vodka by Shelton Reid, all courtesy of NRAO/AUI/NSF/CC BY 4.0.)

proved even more difficult than expected because of a series of unforeseen issues. The team members originally planned on communicating via TWX machines—a precursor to fax technology—but that method failed. Telephone lines went down. As a last resort, they turned to telegrams, but even those faced near-comedic hurdles. As Kellermann recounted, "It took a while to explain [to a representative at the Soviet telegraph office] that Green Bank was not a major U.S. city and the telegram went off—or so we thought. Four days later the telegraph office called me at the hotel. They still wanted to know where Green Bank was." The communication ordeal between the two nations was so great that the collaboration earned the unofficial nickname the "Russian–American International Clock Test."[8]

Cultural differences and language barriers posed further challenges. The US team needed to install sensitive electronic receivers on the 22-meter telescope that would capture and amplify the faint radio signals from distant quasars before recording them on magnetic tape. Although the local mechanics were capable, they seemed unconcerned about the urgency of the project. John Payne, a member of the US team, was "having considerable trouble getting them organized," Kellermann later recalled. "They kept telling him that this was Russia, not America, and he should relax, have some Vodka, and not be in such a hurry."[9] Despite the setbacks, the team was ready for its main observing run by October. After successfully making the first set of observations, the scientists celebrated with food, vodka, cognac, and declarations of Soviet–US friendship before heading back to the hotel.

But then a telegram arrived from the NRAO with dire news: The frequency on the 140-foot telescope in Green Bank had been set incorrectly, and the run needed to be repeated from the start within the next two hours while the quasar the team was observing was still visible. Payne and Kellermann rushed back to the observatory only to find that the mechanical crew had decided to declare an impromptu holiday and were busy celebrating. Fortunately, the delay meant that the electronic receivers for that portion of the VLBI experiment hadn't yet been removed from the telescope. With the help of Soviet radio astronomer Ivan Moiseyev, the director of the Simeiz Observatory, Payne and Kellermann were able to correct the error in time.

The joy of success

The team sent the tapes from the Crimean observations to Green Bank so the two sets of signals could be correlated. But they never arrived in West Virginia. In *The Observer*, Kellermann speculated that "somewhere either in Moscow, Washington, or both, teams of experts at the CIA or KGB were unsuccessfully trying to decode a magnetic tape containing a sequence of 150 million random numbers which had apparently been smuggled out of the USSR."[10] Although the tapes were eventually located, the US astronomers' suspicions that the Soviet intelligence agency was interested in their visit proved prescient: Kellermann revealed in a 2001 epilogue to his account that a trip to some tourist destinations in Central Asia "was arranged so that KGB engineers could have an uninterrupted week to reverse engineer our recorder, receivers and atomic clock."[11]

After a few more hiccups—at one point, in rapid succession, Green Bank's hydrogen maser failed and a power transformer on the facility's telescope exploded—the team was able to successfully complete the experiment in late October 1969.[12] Kellerman later described the joy of success after the myriad challenges the experiment had faced:

> In a little over a month we had dispatched various shipments of people and equipment between Stockholm, Moscow, Lenningrad [sic], and Crimea by air, rail, and road. We had made unprecedented demands on transportation and communication facilities, and had apparently cornered the market on all the storage batteries in the Soviet Union.…
>
> …You can therefore imagine the general joy and relief when the telegram arrived announcing strong fringes on 3C 454.3. Vitkevich was at first speechless, but rapidly recovering he cried,

> "BRING THE VODKA!" Remembering that we still had two days of observing left the celebration was, however, postponed.[13]

The target, 3C 454.3, an extremely luminous and distant quasar powered by a supermassive black hole, is cataloged in the Third Cambridge Catalogue of Radio Sources (hence the "3C"). It was selected because it appears as a strong, compact radio source, ideal characteristics for testing VLBI's ability to achieve the best possible angular resolution. The scientists realized that they had been successful when they saw the telltale fringes—namely, the interference pattern created when the signals from both telescopes are combined and overlaid.

The experiment's legacy

What are the lessons from this problem-riddled yet ultimately successful experiment? Scientifically, it demonstrated that VLBI could indeed be conducted across continents and at frequencies needed to obtain high resolutions. It also set the stage for tremendous leaps in observational capabilities in radio astronomy and paved the way for international VLBI networks that would later expand to include telescopes from around the world. But it was more than just a technical achievement: The experiment opened the door to collaborations between the US and the USSR—and, after 1991, Russia—that continued well into the 21st century. From 2011 to 2019, for example, Russian radio astronomers incorporated NRAO telescopes into the RadioAstron program, a VLBI experiment involving a satellite and several ground-based observatories that extended radio interferometry baselines to near-lunar distances and to an angular resolution of a few tens of microarcseconds. The Green Bank–Crimea observations, in contrast, had a resolution of 400 microarcseconds.

Today, however, collaboration between Russian and Western scientists has reached a nadir. Russia's 2014 annexation of Crimea significantly strained international scientific collaborations that until then had been alive and well for almost five decades. Many of those efforts were completely fractured after Russia commenced a full-scale invasion of Ukraine in 2022, a conflict that remains ongoing (see Physics Today, June 2022, page 22). Along with the rest of the Crimean peninsula, the Simeiz Observatory is now considered by the international community to be under an illegal occupation. The contrast between the optimistic internationalism of the 1969 experiment and the current situation serves as a sobering reminder of how drastically the foundations of scientific diplomacy can shift.

The scientists at the NRAO and the Simeiz Observatory were motivated to collaborate largely for practical reasons: Their experiment demanded cooperation across great distances. But it pushed the researchers to forge alliances even in the face of great logistical, cultural, and political divides. Their "science first" mentalities created a shared purpose that transcended those otherwise discouraging circumstances.

But they were not so single-mindedly focused on the experiment that its social and political implications escaped them. In his *Observer* essay, Kellermann explained that the experiment's true success lay not only in the scientific results but also in proving that even during an era of profound geopolitical tension, collaboration could triumph over division: "Perhaps in some small way," he wrote, "we have contributed to an increased understanding between Soviet and American people, and demonstrated that scientific cooperation between the U.S.A. and the U.S.S.R. is possible."[14]

That lesson feels especially urgent today. As global tensions rise and political winds shift—and with federal science funding threatened, international trust eroded, and collaborative global research initiatives increasingly at risk—the achievements of early VLBI pioneers remind us of what can be lost. Triumphs in VLBI such as the Event Horizon Telescope, which comprises a network of stations across the globe, show how far the collaborative spirit can take us. But those achievements were made possible not just by technology or funding but also by openness, risk-taking, and a belief in the value of knowledge shared across borders. In an age when the foundations of global science are being tested, we might look back to this Cold War collaboration as both a technical milestone and a model for the courage that will be required to meet the challenges ahead.

This article is dedicated, with much gratitude, to Ken Kellermann, who has served as my mentor for nearly eight years. Ken remains a gift not only to radio astronomy but to its history. His firsthand accounts of this groundbreaking experiment—both preserved in the NRAO's archives and personally shared with me during countless conversations—made this research possible. Ken's continuing dedication to documenting the human stories behind scientific breakthroughs has ensured that future generations can learn not just what was discovered but also how discovery happens: through collaboration, persistence, and the occasional act of diplomatic courage.

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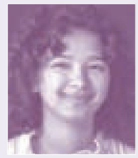
PT

Where physics meets poetry

Defying the often-perceived incompatibility between the two subjects, some physicists are using poetry to communicate science and to explore the human side of their work.

MAIA CHANDLER

Maia Chandler is a recent graduate of Swarthmore College, where they majored in biophysics and minored in educational studies. They interned at Physics Today this summer.



The path between physics and poetry is often painted as a one-way street. Myriad poets have turned to the physical sciences for inspiration. Jane Hirshfield, for example, illustrates a fundamental concept of quantum mechanics in the poem “Entanglement”; Walt Whitman’s “When I Heard the Learn’d Astronomer” celebrates stars; and Tracy K. Smith muses about outer space in “My God, It’s Full of Stars.” Physicists, however, are commonly perceived as analytical, unwilling to be clouded by the romanticism of a pursuit such as poetry.

Despite that perception, poetry and physics are not disparate subjects. They are both mechanisms for knowing the world more intimately. They both humanize the ineffable and savor everyday phenomena, and their practitioners grapple to articulate what we know about the world around us. When I ask physics students what makes physics special, they tell me how it provides elegant structures for finding logic and meaning in a seemingly meaningless, illogical universe. They share how physics combines rigorous scientific thought with a wonder and humility for our place in the cosmos and how it gives us a reason for why things are the way they are.

In the space where poetry and physics overlap, science is personal. The physicists and poets who exist at that intersection are motivated by curiosity, wonder, and the spirit of exploration. They use poetry as a mode of science communication, and they write it for pleasure, using observation and imagination to clarify their experience and celebrate what they describe.

To begin to navigate that creative landscape, Physics Today spoke with Sam Illingworth, a physicist-poet who started both a peer-reviewed journal and an annual competition dedicated to science and poetry. Accompanying the interview is a selection of physicist-written poetry. Some of the poems are sourced from Illingworth’s endeavors. All of them remind us that science is human.

Drying the Spine

SAM ILLINGWORTH

What slipped
was not a flood –
no clean edge
or single rupture –
but a drawn-down
thread,
sucked from the grip
of root-treads and
clay-cradle.
A thirst took
the curve of years
and held it,
tightening
until the skin cracked.
Not drought,
but the absence
of return.

(ILLUSTRATION BY THREE RING STUDIO.)

Q&A: Sam Illingworth unites poetry and science

After finishing his atmospheric physics PhD program, Sam Illingworth took a sharp turn away from his research, which involved using satellites and aircraft to measure greenhouse gases. In 2010, he moved to Japan, where he spent two years exploring the relationship between science and theater. That experience, he says, helped him realize he "loved communicating science and was probably better at communicating science than doing science." Now that's his job.

As a professor of creative pedagogies at Edinburgh Napier University in the UK, Illingworth researches how poetry and games can be used to facilitate dialogue between scientists and society. He runs science poetry workshops with students, asylum seekers, and mental health organizations.

Illingworth has built on his interest in poetry and background in developing undergraduate curricula that use theatrical techniques for effective communication. He has a weekly blog, *The Poetry of Science*, where he writes poems based on recent scientific publications. Rather than trying to explain quantum entanglement or dark matter, he tries to write from a place of curiosity. Five years ago, he founded the first science and poetry peer-reviewed journal, *Consilience*, which has a yearly readership of 100 000. Illingworth also started an international poetry competition, Brilliant Poetry, that explores scientific wonder and discovery. This year's competition invites poems inspired by the International Year of Quantum Science and Technology.

A Rubric for Heat

SUNAYANA BHARGAVA

Staring aimlessly out of a crowded train,
I begin to wonder about the heat death of the Universe

That runaway descent into disorder,
like thread unspooling.
All work eventually undone

What is more romantic than labour
that fights the prophecy of its extinction?

Earlier I watched people assemble
like particles, charged
against a death less inevitable than heat

To read the Riot Act
to those who are already dispersed
is perhaps another kind of entropy

After we said goodbye,
I reimagined the city as a heat map

The train tracks molten,
spilling under slick blue buildings,
The residual warmth you left in my hands
given away by an infrared eye

What if heat, like language,
is not the firmness of ground
but the cracks that bloom under it?

There is a way to rescue order;
rake in the wasteland of energy and
bring it to rest: absolute zero

The wilderness of space is too warm.
The coldest place we have is here on Earth.

I question laws that speak of bodies
without first surviving in one
or stopping one from feeling illegal

On the cusp of equilibrium;
I can feel the incapacity of my hands
as you slip through them. The gentle stasis
of unrest under a darkening sky

An entire history of transfer, lost,
the moment two properties become equal.

Sunayana Bhargava is a postdoctoral fellow at the Côte d'Azur Observatory site in Nice, France, where she searches for galaxy clusters. She is an editor for *Consilience*. This poem was inspired by the four laws of thermodynamics and was originally commissioned by IF Oxford.

On First Looking Into Dirac's *Quantum Mechanics*

JOSEPH CONLON

No show; no poetry, no eloquence.
Lines of austere unpolished truth unroll
On logic-chiselled tracks. A sneaking sense
Of felt emotion flits then fades. The whole

Of human culture is reduced to this:
Evolving quantum states of phi and psi
Churning unceasingly down the abyss
Where Greek and Roman classics come to die.

From death comes life; these cold equations change
To living fire, as algebra unfolds
To understanding. Symbols rearrange
And make the Megas Basileus that holds
Our universe in thrall. Its chthonic roar
Razes the squeaks of Homer's village war.

Joseph Conlon, a professor of theoretical physics at the University of Oxford in the UK, has enjoyed (and memorized) poetry since childhood. He was captivated by the direct, unadorned style of Paul Dirac's book *The Principles of Quantum Mechanics*. This poem was short-listed in the 2024 Brilliant Poetry competition.

PT: Describe your work.

ILLINGWORTH: My research involves three different strands: poetry, games, and generative AI. How can I help to democratize and diversify science? I found a way through poetry. This involves using poetry to disseminate knowledge and to more effectively establish a dialogue between scientists and nonscientists so that the nonscientists can contribute their expertise, tacit knowledge, and lived experience to frontier research and future research directions. I also explore how we can use poetry as a pedagogic tool within higher education.

PT: What is the process of transforming a research article into a poem?

ILLINGWORTH: The idea behind *The Poetry of Science* is that science is societally important, interesting, weird, scary, and fun but often written in language that nonscientists can't engage with. So can I take the science and write a poem about it to bring people in?

I look through press releases to see what I think is going to be interesting. I've written about wildfire suppressants, merging galaxies, crow sight, and quantum biology. I then write a lay summary and write the poem about it. That sounds like a huge leap. I used to write poetry that followed a very particular form, like a villanelle, a sonnet, or a sestina. I don't do that as much anymore, but because I did that for so long, it helped me find my poetic voice. So the poem just kind of comes a lot of the time.

I used to feel like the poem had to tell the exact science story, whereas it now has this nonspecialist summary that offers a new lens through which to view the science. If a poem opens a question or gives someone pause to consider something differently, then it has already done more than a didactic summary ever could.

I always email a copy of the poem to the scientists whose work I have featured, and almost without exception, they reply. Many express thanks and often note how interesting it is to see their research reframed through poetry. Several have mentioned that it prompted them to think differently about how they communicate their work—which for me, is a quiet but meaningful outcome.

PT: You do a lot of work on climate change and poetry. Why?

ILLINGWORTH: I think the climate crisis lends itself to poetry. The way that we've communicated the climate crisis has failed. Poetry is a way of reminding people of the human centeredness of the crisis—that this is caused by humans, affecting humans, and ultimately is only going to be solved by humans.

PT: Why poetry? Could another art form serve a similar purpose?

ILLINGWORTH: People can feel intimidated by scientists. Poetry creates this set base of "Oh, there's a professor. And they might be good at science, but they're not very good at poetry."

Doing science, you're taught to be very objective about it. That's fine when conducting science, but when talking about it, it's okay to display pathos. Scientists find that hard because they're not really trained to do it. Writing a poem about those experiences gives the scientists permission to display this level of emotion that they're not normally "allowed" to display.

Of course, there are elements of physics that are complex and detailed. When using poetry to explore physics, I think the most important thing is to communicate a sense of wonder and uncertainty—that science is a process, not just a set of results.

PT: You mentioned the importance of establishing a dialogue between scientists and nonscientists. What does using poetry as dialogue mean?

One Hundred One Thousand Meters

IRIS VAN ZELST

At the surface
of the Earth,
rocks are
strong
A little
lower,
a little
less
Then strong again
and then
they
get
w
e
a
k

Iris van Zelst is a Patience Cowie Research Fellow at the University of Edinburgh in the UK. She studies the geodynamics and seismology of Venus. She thinks poetry is playful and is a creative outlet, and she encourages people to look at science in an unexpected way. The shape of this poem mirrors the structure of its subject matter: the strength of Earth's crust and upper mantle.

Physics for the unwary student

PIPPA GOLDSCHMIDT

1. Imagine that you are trying to balance on the surface of an expanding balloon. List all the different ways in which this resembles reality.
2. Thousands of sub-atomic particles stream through you night and day. Does this account for those peculiar flashes of light you sometimes see?
3. You are trapped in a lift which is plummeting to the ground. Describe what you feel.
4. You are in a spaceship travelling towards a black hole. As you pass the event horizon and become cut off from the rest of the Universe, what do you observe?
5. What happens if you stop believing in gravity? Will you slide off the Earth?
6. What happens if you stop believing?

Pippa Goldschmidt has a PhD in astronomy and a master of letters in creative writing. She is an honorary fellow in the Science, Technology and Innovation Studies unit at the University of Edinburgh in the UK. This poem was inspired by thought experiments in physics that ask us to consider what happens in various extreme situations.

ILLINGWORTH: What people share in poetry dialogues varies widely depending on the group and context. In a session with asylum seekers, participants wrote poems reflecting on visibility and air—not just as pollution, but as something that can't be escaped, that is inhaled regardless of choice or status. Their needs, expressed through poetry, often center on being heard and being safe. These are not easily summarized in a policy report but are deeply felt and politically charged.

Poetry creates a space where these needs can be articulated without having to conform to institutional or scientific language. We use that as the starting point for conversations with experts in that area of physics or research. It's about making those relationships.

People first need to feel encouraged to write poetry and realize that it really is for everybody. It's a very accessible art form when discussed and introduced in the right way.

PT: What parallels do you see between poetry and physics?

ILLINGWORTH: I think at their core, they're both trying to make sense of the world in which we live. They're just doing it in different ways. Certainly, since the turn of the 19th century, when science became a proper discipline and moved away from being an amateur field, it feels to some extent that science has had a monopoly on what original thought is. But science doesn't have all the answers. Poetry and physics have complementary pieces of the same jigsaw.

PT: How do you approach doing poetry versus doing physics?

ILLINGWORTH: When I'm doing poetry or physics, I feel as though I'm engaging the same part of my brain. It's problem-solving, just using a different set of tools. There's precedent to this. Physicist- or scientist-poets write about the fact that it's scratching the same itch and that a lot of the time, society forces them to pick whether they're a scientist or poet. Most of the time, they've felt as though they've had to pick the scientist part to be taken seriously. But the overlap is why I think it's important to involve creatives in scientific work.

I think that for me, thinking physically or thinking scientifically is about the facility to ask questions. A lot of the work I do in terms of developing people's science literacy isn't necessarily about feeding them facts. It's about empowering them to ask questions. PT

Focus on lasers, imaging, microscopy, and photonics

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.

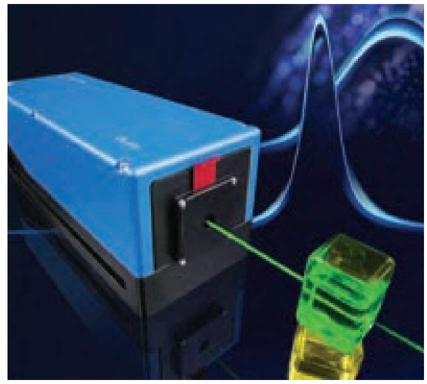
Andreas Mandelis

Ultralow-outgassing Faraday isolator

Excelitas has launched its latest Linos ultralow outgassing Faraday isolator, which advances optical isolation technology and extends laser-system lifetimes by minimizing photocontamination. With a patented, glue-free design, the isolator outgasses less than previous low-outgassing versions and standard Faraday isolators, according to the company. Eliminating adhesive components reduces the risk of volatile organic contaminants degrading optical performance over time and ensures system cleanliness and reliability. According to the company, the Linos Faraday isolator delivers high performance with optimal isolation and high transmission, ensuring reliability and longevity even in demanding environments. It is suitable for high-vacuum environments, high-power laser applications, industrial solid-state systems, semiconductor manufacturing, and space applications. ***Excelitas Technologies Corp***, *2545 Railroad St, Ste 300, Pittsburgh, PA 15222, www.excelitas.com*

X-ray microscope

According to Bruker, its new X4 Poseidon 3D x-ray microscope (XRM), a benchtop system that uses micro–computed tomography, offers advanced capabilities comparable to larger, floor-standing systems. It makes fast, high-resolution 3D x-ray microscopy accessible for demanding XRM applications in materials science research and industry. Those areas include the geosciences, pharmaceutical R&D, composite materials, renewable energy, and microelectronics. It is also suitable for life sciences applications such as bone and dental research, soft-tissue imaging, and plant and animal biology. According to Bruker, the x-ray source in the X4 Poseidon has a 3D resolution more than an order of magnitude higher than that of similar instruments. The system's large field-of-view, high-efficiency detector can optionally be combined with a high-resolution scientific CMOS detector for multivision analytical flexibility. The X4 Poseidon is designed for low maintenance and is field upgradable. ***Bruker Corporation***, *40 Manning Rd, Billerica, MA 01821, www.bruker.com*



Ultrastable tunable diode laser

Toptica developed its DL pro BFY tunable diode laser for applications in which hands-off operation is required. It is equipped with temperature stabilization and can withstand pressure fluctuations and high winds. The hermetically sealed butterfly package and compact design of the resonator allow for the best passive-mode stability and robustness of all the lasers within the company's DL pro family. Ultrastable against temperature and acoustic variations, the DL pro BFY features the DLC pro's digital control for output precision and low noise. The DL pro lasers are reliable external-cavity diode lasers for operation at almost all wavelengths between 369 and 1770 nm. They offer power of up to 400 mW and a free-running linewidth down to 0.6 kHz. The graphical user interface makes remote access easy. ***Toptica Photonics Inc***, *1120 Pittsford Victor Rd, Pittsford, NY 14534, www.toptica.com*

Ultrastable frequency comb

Vescent Technologies has brought to market its RUBRIComb, a low-size, low-weight, and low-power optical frequency comb, and RUBRIColor, a companion wavelength extender that extends the RUBRIComb platform wavelength coverage from 490 to 2000 nm. They were developed to enable smooth, efficient experiments with high reliability, even in the field, in areas including atomic clocks and time transfer, quantum computing, and dual-comb spectroscopy. The RUBRIComb offers low-noise, turnkey operation and a long life. Having passed demanding shake, vibration, and thermal tests, the rugged laser is environmentally robust and sustains femtosecond-level stability, remaining locked for months with precise control. It also mode locks at every startup. Vescent's unique oscillator design makes it easy to precisely factory match the repetition rate of several of its combs for multicomb-spectroscopy solutions. According to the company, its modular design and compact footprint make it adaptable and scalable to any quantum system. ***Vescent Technologies Inc***, *14998 W 6th Ave, Ste 700, Golden, CO 80401, https://vescent.com*

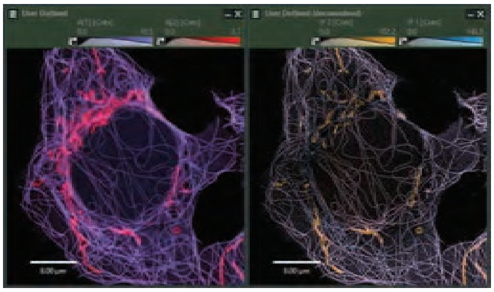
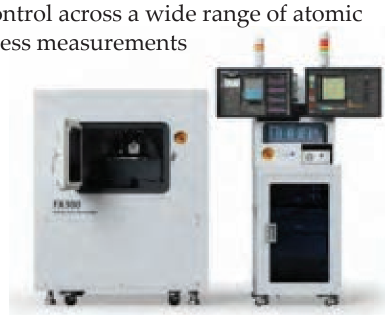


Image-scanning-microscopy analysis software

PicoQuant has released its NovaISM software for fluorescence-lifetime imaging microscopy (FLIM) and image scanning microscopy. The software is designed to advance FLIM by delivering superresolved spatial details and improved contrast. Seamlessly integrating with the company's Luminosa confocal microscope, NovaISM is optimized for the company's PDA-23 single-photon avalanche diode (SPAD) array detector. Key features for enhancing FLIM include pixel reassignment, which refines spatial resolution, and one-click deconvolution, which restores fine details and reduces noise. Those improvements ensure sharper optical sectioning, better signal quality, and image resolution up to 1.7 times as high as that of conventional confocal-microscopy images. State-of-the-art computational sectioning and lifetime species separation improve contrast and resolution. According to the company, with NovaISM, FLIM users can achieve a high level of clarity in cellular biophysics, protein interactions, and metabolic imaging. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

Atomic force microscopes for large samples

Building on its Park FX200 model, Park Systems has enhanced its FX Large Sample atomic force microscope (AFM) series. The Park FX300 for 300 mm wafer analysis delivers advanced capabilities for R&D and quality control across a wide range of atomic force microscopy techniques. Specialized features include a sliding stage for long-range flatness measurements of copper pads in semiconductor postprocessing and an off-axis optics system for improved sample visualization. A fan filter unit ensures the AFM is contamination-free, making it suitable for use in clean rooms. The FX200 IR and FX300 IR models for nanoscale chemical analysis integrate Fourier transform IR spectroscopy with atomic force microscopy. They use photo-induced force microscopy to enable chemical identification with a spatial resolution of less than 5 nm. Users can analyze the chemical composition of nanoscale structures without damaging wafer surfaces. According to the company, that capability opens new possibilities for material characterization in semiconductor, polymer, and life sciences applications. ***Park Systems***, *3040 Olcott St, Santa Clara, CA 95054, https://parksystems.com*



Compact laser for flow cytometry

Hübner Photonics has unveiled the Cobolt Kizomba, a new addition to the Cobolt 05-01 laser series. The compact, robust laser offers 349 nm output at 50 mW and is designed for use in flow cytometry and other applications, including holography, interferometry, ion trapping, Raman spectroscopy, superresolution microscopy, and semiconductor inspection. The CW diode-pumped Cobolt 05-01 series lasers offer single-frequency operation, providing an ultranarrow linewidth of less than 1 MHz (greater than 100 m coherence length) and excellent spectral purity. The wavelength stability is less than 1 pm (over ±2 °C and 8 h) and the noise is low, at less than 0.1% rms. All Cobolt lasers are manufactured using HTCure technology for compact, hermetically sealed packaging, which ensures a high level of reliability and immunity to varying environmental conditions. ***Hübner Photonics Inc***, *2635 N First St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com* PT

Ruben Zakine is a postdoctoral fellow at the Hydrodynamics Laboratory (LadHyX) and a member of the EconophysiX research group, both at École Polytechnique in Palaiseau, France. **Michael Benzaquen** is a CNRS research scientist at LadHyX, head of EconophysiX, and a professor of economics at École Polytechnique.

A tasty introduction to packing problems

Understanding how particles of all kinds fill space has applications in physics, engineering, materials design, and even machine learning.

Ruben Zakine and Michael Benzaquen

Imagine that you've just cracked open and enjoyed a bunch of pistachios. You're now left with double their number of empty shells. How big of a container do you need to hold the shells without having them overflow or cramming them in?

Although our pistachio problem may seem frivolous, the underlying mechanisms that govern the packing of geometric shapes are remarkably complex. How objects pack together has intrigued scientists for centuries because the problems are often simple to formulate but usually tremendously difficult to resolve. In 1611, for example, Johannes Kepler conjectured that equally sized spheres have the highest average density when they're packed in a face-centered cubic arrangement or a hexagonal close-packing pattern. It took nearly 400 years to formally prove, with computer-assisted methods, that Kepler's seemingly intuitive idea is correct.

Substantial progress has been made on understanding the packing of spheres and ellipsoids. M&M's candies are almost true ellipsoids, and their packing behavior has been successfully predicted with theory. Yet real-world particles rarely have such simple, regular shapes. Most particles—like pistachios and their shells—are irregular, nonconvex, and elongated. The prediction of how such objects fill space remains a largely open problem.

Jamming and rigidity

Packing problems lie at the intersection of geometry, mechanics, and statistical physics. Packings of irregularly shaped particles are essentially amorphous solids and glasses. They lack crystalline order and, at the microscopic level, resemble liquids. The particles become mechanically rigid above a certain density and undergo a jamming transition in which they cease to move. That transition depends on how the particles are compacted. Spherical particles can exhibit different arrangements that lead to jamming. The compaction protocol is even more significant for complex or anisotropic shapes, such as rods, ellipsoids, and other exotic geometries. For those shapes, the jamming transition can occur over a range of densities and ultimately depends on the directions in which the particles nest, align, and obstruct one another.

The shape of constituent particles influences not just how densely they can pack but also how they transmit forces and resist motion once jammed. In turn, the jamming threshold and the emergence of rigid behavior in packed particles constrain which packing patterns and macroscopic packing phases are stable and prevalent in natural and engineered materials. The study of jamming transitions sheds light on how materials deform, fracture, and resist flow under external forces.

The jamming of irregularly shaped particles is critical for various phenomena in soft condensed matter and biology, such as densely organized DNA in a cell nucleus, macromolecular crowding in cytoplasm, and spatial arrangements of tissue cells. In addition, soft-matter and biological systems often have further complications. Some systems are sensitive to stickiness, which is characterized as short-range attractions between particles, or to friction, in which energy is dissipated when objects are in contact. Stickiness and friction naturally enrich the phenomena that eventually emerge in systems of packed objects.

Pistachios have many characteristics that make their packing behavior complicated. A simple experiment helps illustrate why.

Packing pistachios

To explore how efficiently pistachios and their empty shells can be packed, we first loosely filled a graduated cylinder with 613 pistachios, with visible gaps between them. Next, we gave the cylinder a good shake and a few rolls to settle the pistachios into a dense arrangement. We repeated the same process with the empty pistachio shells.

We observed that the unshelled pistachios in the loose and dense states have about the same packing density, about 320 pistachios per liter. For the empty shells, however, the difference is significant: After shaking, the packing density is 27% higher. The increase makes sense: Unlike the unshelled pistachios, the nonconvex shells partially nest and interlock, especially when shaken, as shown in the image.

The container for the empty shells, therefore, can be smaller than the bowl for the unshelled pistachios. If you are feeling a bit lazy and toss the shells in loosely, you will need a container roughly three-quarters (73%) the size of the original bowl. But if you pack the shells tightly by shaking the container, it needs to be only a little more than half (57%) the size of the original.

Beyond physical particles

Besides its importance in soft-matter and biological systems, packing behavior is essential in materials science. The inter-

EMPTY PISTACHIO SHELLS are densely packed in this graduated cylinder. Because the shells nest and interlock—which can easily be seen around the 500 mL level—they occupy a volume that's only 57% of the volume taken up by whole pistachios.

nal structure formed by packed particles directly influences the mechanical, thermal, and flow properties of materials.

In ceramic processing, the way powders are compacted before being melted determines the final material's density and strength. In concrete and asphalt production, the packing of aggregates affects durability, porosity, and load-bearing capacity. In additive manufacturing, the compaction and flow of irregular metal or polymer particles help determine the material's structural performance. Each of those examples relies on controlling how disordered, nonspherical particles organize when constrained. Observations and models are often necessary to understand how to control the particles.

Finally, the statistical behavior of disordered packings has inspired connections beyond materials science. In machine learning, the training of neural networks exhibits characteristics that are also present in glassy systems, such as numerous local energy minima, geometric frustration, and nontrivial correlations. Powerful tools that were developed to study packing and jamming have been adapted to better understand AI and neuroscience models. The work of Giorgio Parisi, who was awarded the 2021 Nobel Prize in Physics, in understanding spin glasses helped enable the fruitful transfer of knowledge from statistical physics to computer science (see Physics Today, December 2021, page 17).

What may appear then to be a simple geometric problem—how many objects fit in a container—turns out to have far-reaching implications across physics, engineering, computational science, and even snacking.

Additional resources

▶ A. Donev et al., "Improving the density of jammed disordered packings using ellipsoids," *Science* **303**, 990 (2004).

▶ S. Torquato, "Perspective: Basic understanding of condensed phases of matter via packing models," *J. Chem. Phys.* **149**, 020901 (2018).

▶ M. S. Viazovska, "The sphere packing problem in dimension 8," *Ann. Math.* **185**, 991 (2017).

▶ P. Charbonneau et al., "Glass and jamming transitions: From exact results to finite-dimensional descriptions," *Annu. Rev. Condens. Matter Phys.* **8**, 265 (2017).

▶ M. Geiger et al., "Jamming transition as a paradigm to understand the loss landscape of deep neural networks," *Phys. Rev. E* **100**, 012115 (2019).

PT

BACK SCATTER

Fingerprinting a supernova explosion

Type Ia supernovae, such as the young supernova remnant (SNR) 0509-67.5 shown here, are integral to understanding how the universe expands. Because of their predictable luminosity, they're called standard candles, and astronomers use them to measure the distances of astronomical objects from Earth. The uniform luminosity was previously thought to be because white dwarfs explode at a standard 1.44 solar masses, the Chandrasekhar mass limit. Now it is hypothesized that white dwarfs become supernovae at masses significantly below that limit. SNR 0509-67.5, as captured by the European Southern Observatory's Very Large Telescope, detonated at a low mass. Studying it can help researchers understand how type Ia supernovae occur.

The artificially enhanced colors in this image reflect the remnant's chemical composition: calcium in blue and hydrogen in orange. SNR 0509-67.5 has an unusual structure, with two concentric calcium rings in a hydrogen shell that marks the supernova's boundary. The structure is consistent with a previously theorized double-detonation mechanism, in which the supernova explodes twice. For double detonation to occur below the Chandrasekhar mass limit, excess helium around SNR 0509-67.5 had to condense into a thin, unstable blanket that ignited an initial explosion. The resulting shock wave traveled inward to the white dwarf's core and triggered a second detonation, which caused stellar material to plow into the surrounding interstellar gas. (P. Das et al., *Nat. Astron.*, 2025, doi:10.1038/s41550-025-02589-5; image by ESO/P. Das et al., background stars [*Hubble*] from K. Noll et al.) —MC

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