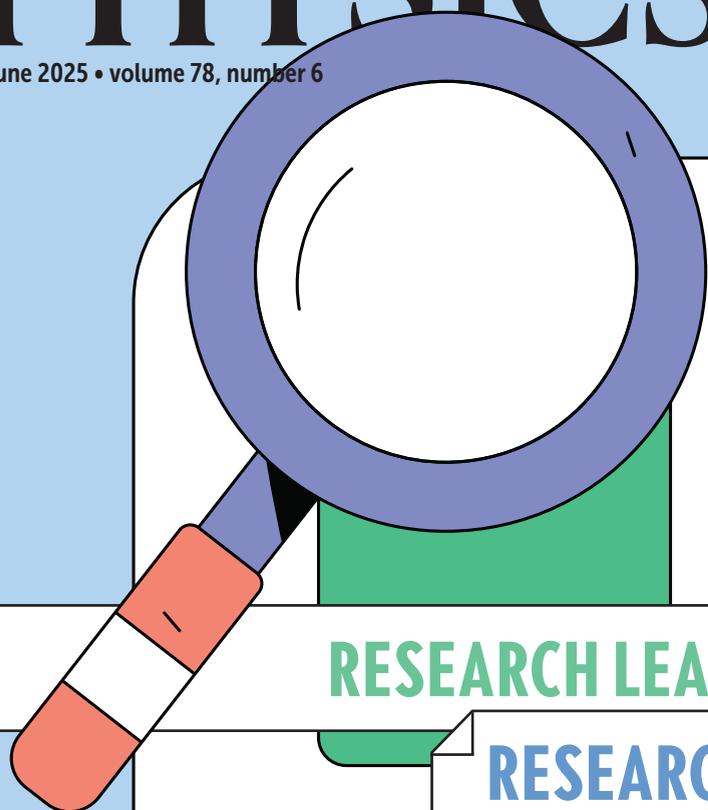


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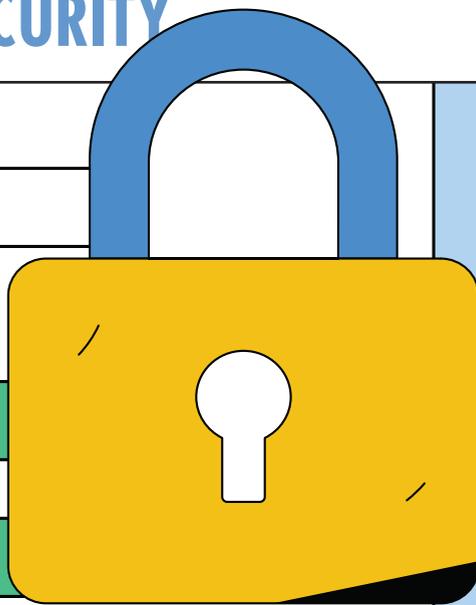
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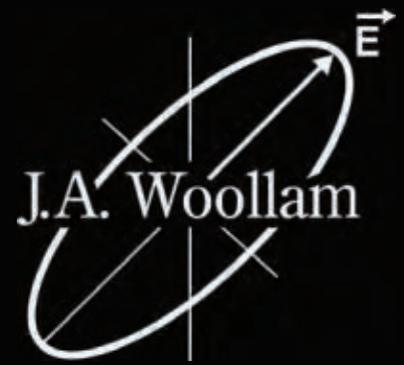
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PHYSICS TODAY

June 2025 | volume 78 number 6

FEATURES



26 Hippies, Bell tests, and a career studying quantum entanglement

David Kaiser

Investigating a group of maverick physicists who studied the foundations of quantum mechanics in the 1970s led one physicist-historian to help create a new test of entanglement.



36 Re-remembering Benjamin Whiso Lee, promoter of gauge theories

Eun-Joo Ahn

The Korean American physicist made the framework underlying the standard model accessible to a generation of particle physicists.



44 How stars shape galaxies

Matt Orr, Shyam Menon, and Blakesley Burkhardt

The energy and momentum that stars inject into the gas that surrounds them dramatically influences subsequent star formation.



ON THE COVER: The US government's growing concern over potential foreign influence on research and researchers is intended to protect commercial and national interests. But the varying security requirements often leave researchers burdened, confused, and intimidated. Many scientists worry that they will lose collaborations—especially with colleagues in China—and that the clampdown will erode US scientific leadership. For more on the evolving research-security scene, see the story on **page 16**. (Cover image adapted from iStock.com/lucky_sun.)

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Neutrino masses

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Carbon on Mars

Today, Mars's atmosphere is thin and cold. But carbonate minerals found by NASA's *Curiosity* rover suggest that the planet once had a thick atmosphere that was rich in carbon dioxide. The result implies that ancient Mars had a carbon cycle, which could have helped sustain liquid water on the surface. physicstoday.org/Jun2025b



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Women in quantum

A soon-to-be-released book that was prepared for the International Year of Quantum Science and Technology presents profiles of Katharine Way and 15 other women in the history of quantum physics. A *PHYSICS TODAY* photo essay highlights some of those influential physicists. physicstoday.org/Jun2025c

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DEPARTMENTS

9 Readers' forum

Letters

10 Search & discovery

A small ancient galaxy started reionizing its surroundings early • Updates: Putting holes in a sail to reach the stars / A rumbling truck enables a clearer view of Yellowstone's most active magma chamber



16 Issues & events

US research enterprise seeks to retain leadership while upping security • Humor helps convey science, study suggests • Q&A: Graduate student Ari Jain strives to better the world through research and leadership • Physics, astronomy graduate admissions in the US expected to shrink amid funding uncertainty • DOE eases regulation of national laboratories • FYI science policy briefs

51 New products

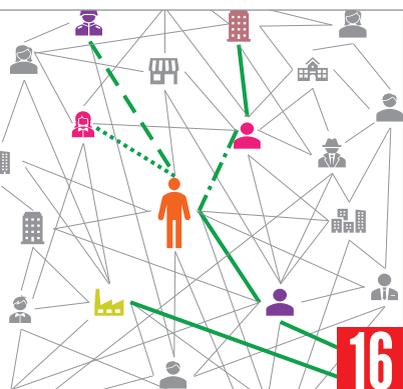
Focus on test, measurement, quantum metrology, and analytical equipment

54 Quick study

A new twist on the quantum vacuum — *Jeremy N. Munday*
From the archives: October 2019

56 Back scatter

Soft touchdowns for tiny robots



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6 PHYSICS TODAY | JUNE 2025

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*Pold, J., & Mulvey, P. J. (2025). Physics Bachelor's Initial Employment: Academic Years 2020–21 and 2021–22. American Institute of Physics.

Wu, Shaknov, and the EPR dilemma

At the risk of gilding the lily that is the article “Chien-Shiung Wu’s trailblazing experiments in particle physics” by Chon-Fai Kam, Cheng-Ning Zhang, and Da Hsuan Feng (*PHYSICS TODAY*, December 2024, page 28), I would like to add a note relating to the theoretical work of John Wheeler,¹ Wu and Irving Shaknov’s experiments on the polarization correlations of entangled gamma-ray photons produced in positronium annihilation,² and their implications for the Einstein-Podolsky-Rosen (EPR) “dilemma.” In September 1993, I wrote to Wheeler asking whether he or anyone else “considered these correlations in the EPR context” or if the time around which these papers were published was “just not ripe for such considerations.” He answered, “no one I knew of” and “right,” respectively.

I also asked “whether Einstein knew of [Wheeler’s] work,” to which he answered “no.”

As noted by Kam, Zhang, and Feng in their reply in the April 2025 issue (page 7), “Wu and Shaknov’s experiment was done only about 15 years after Albert Einstein, Boris Podolsky, and Nathan Rosen first brought the concept of quantum entanglement to light in what’s known as the EPR paper.” The first connection of the work to EPR that I can find is in a paper by David Bohm and Yakir Aharonov, published seven years after the Wu-Shaknov paper. They remarked that the Wu-Shaknov experiment “is explained adequately by the current quantum theory which implies distant correlations, of the type leading to the paradox of [Einstein-Rosen-Podolsky],

but not by any reasonable hypotheses implying a breakdown of the quantum theory that could avoid the paradox of ERP.”³

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2. C. S. Wu, I. Shaknov, *Phys. Rev.* **77**, 136 (1950).
3. D. Bohm, Y. Aharonov, *Phys. Rev.* **108**, 1070 (1957), p. 1075.

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Another Fowler

The recent letter to the editor from Victor van Lint (*PHYSICS TODAY*, December 2024, page 11) warrants a follow-up: There was yet another Fowler at Los Alamos, Joseph L. Fowler, who during the 1940s used measurements of magnetic-flux compression to discern the dynamics of explosively driven metal shells. That work was a precursor to magnetic-flux-compression generator development led by Clarence “Max” Fowler around 1960. Max remarked to me around 1971 that Fowler was a very common name, but not as generally common as variations on “Martin,” such as “Martino” and “Martinez.”

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CHIEN-SHIUNG WU around 1975. (Photo from the AIP Emilio Segrè Visual Archives.)

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A small ancient galaxy started reionizing its surroundings early

As the *James Webb Space Telescope* looks back at the universe's first billion years, surprises continue to turn up.

In the context of the universe, the matter around us is unusual: It's made up of neutral atoms. Of all the baryonic matter in existence (that is, disregarding dark matter and dark energy, whose forms are unknown), the vast majority is ionized. Much of the ionized matter is in stars—more than 99% of the mass of our solar system is in the Sun—and even more is in the intergalactic medium (IGM), the desolate expanse between galaxies with a matter density as low as a single atom per cubic meter.

Or rather, because the IGM is mostly hydrogen and overwhelmingly ionized, each cubic meter contains not a bound-state atom but a lone proton and a lone electron, doomed to forever search for one another in the emptiness of space. Because intergalactic distances are so vast, the particles with that lonely fate represent the majority of all baryonic matter.

Their situation used to be different. Neutral hydrogen was the norm for hundreds of millions of years in the early history of the universe. Protons and electrons combined into atoms at the same time that the cosmic microwave background formed, some 380 000 years after the Big Bang, and they remained stable until stars were consistently producing enough light to ionize them all again.

Reionization—the last phase transition that the universe underwent as a whole—didn't happen everywhere at the same time, but it was thought to have been a fairly quick process, cosmologically speaking: beginning 600 million or 700 million years after the Big Bang and wrapping up by 1 billion years after the Big Bang. Now, however, Joris Witstok (of the Cosmic Dawn Center at the University of Copenhagen) and colleagues have found evidence in data from the

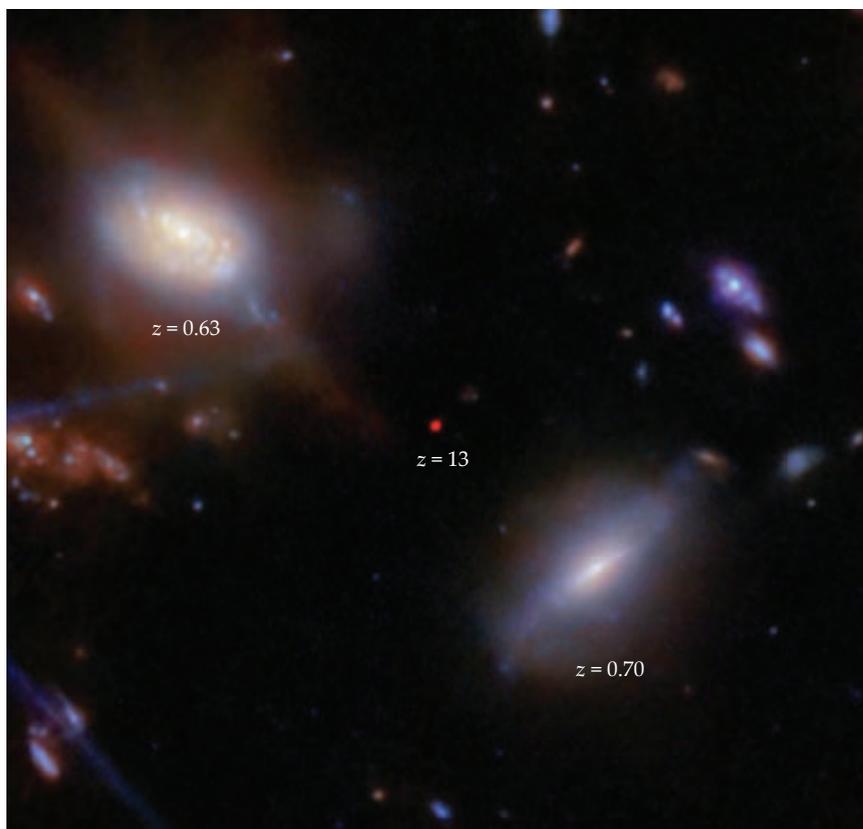


FIGURE 1. GALAXIES AT MANY DISTANCES appear together in the images captured by the *James Webb Space Telescope*. They're distinguished by the wavelengths at which they appear: The galaxy shown as the red dot in the center of the image is so old that the expansion of the universe stretched the visible and UV light it emitted all the way into the IR. Its redshift, $z = 13$, means that we see it today as it existed 330 million years after the Big Bang. (Image by ESA/*Webb*, NASA & CSA, JADES collaboration, J. Witstok, P. Jakobsen, A. Pagan/STScI, and M. Zamani/ESA/*Webb*.)

James Webb Space Telescope (JWST) that reionization started as early as 330 million years after the Big Bang, at least in the vicinity of one galaxy they observed.¹

The observation is just one data point. But it contains valuable clues about the kinds of galaxies that got reionization started—and the kinds of stars that they may have contained.

Intergalactic ions

Astronomers know that the IGM must be ionized because they can see so clearly

through it. If the IGM were a gas of neutral atomic hydrogen, it would absorb strongly at the characteristic wavelengths—the Lyman series—that correspond to the excitation energies from hydrogen's ground state to its infinitely many excited states.

In the rest frame, Lyman-series resonances are all in the UV. They start at 122 nm, the Lyman- α excitation to the first excited state, and they converge to the Lyman limit at 91 nm. Photons with still shorter wavelengths have enough energy to rip hydrogen atoms apart.

Over cosmic distance scales, though, the picture is complicated by the fact that the universe is expanding. When light travels for billions of years from a distant galaxy, its wavelength is stretched, or redshifted, by the time it's seen by an Earthly observer. For a galaxy with a redshift of $z = 3$ —meaning that its light gets stretched by a factor of $z + 1 = 4$ —its Lyman- α resonance shows up not at 122 nm but at 486 nm. Along the way, it traverses the whole continuum between those wavelengths. If all of space were filled with Lyman- α -absorbing hydrogen atoms, that whole swath of the galaxy's spectrum would be wiped out.

That's not what astronomers see. Plenty of UV and blue light reaches Earth from $z = 3$ sources. Their spectra are attenuated by a thicket of discrete absorption lines, called the Lyman- α forest. But that's what's expected of light that's passed through many isolated patches of neutral gas—which are known to exist, especially in and around galaxies—rather than through a continuous neutral IGM.

Above a redshift of about 6—more than 13 billion years ago, or less than 1 billion years after the Big Bang—the situation changes. The observed spectra of such ancient, distant sources do have regions, just blueward of their redshifted Lyman- α resonances, where their light is completely absorbed (see *PHYSICS TODAY*, October 2001, page 17). Those objects, therefore, must date from a time when at least part of the local IGM hadn't yet been fully ionized.

Why the difference? So early in the universe's history, starlight—specifically, the UV light capable of ionizing hydrogen atoms—was much scarcer than it is today because the epoch of peak star formation was still a couple of billion years in the future. At the same time, the universe was smaller, so intergalactic hydrogen was denser, and it was easier for protons and electrons to find one another and pair up. In the competition between the Coulomb forces that drive atoms to form and the ionizing radiation that rips them apart, the former used to have the edge. Now the latter does.

Hunting early galaxies

The end of the reionization transition had been observed in the early 2000s, but looking back much deeper into the

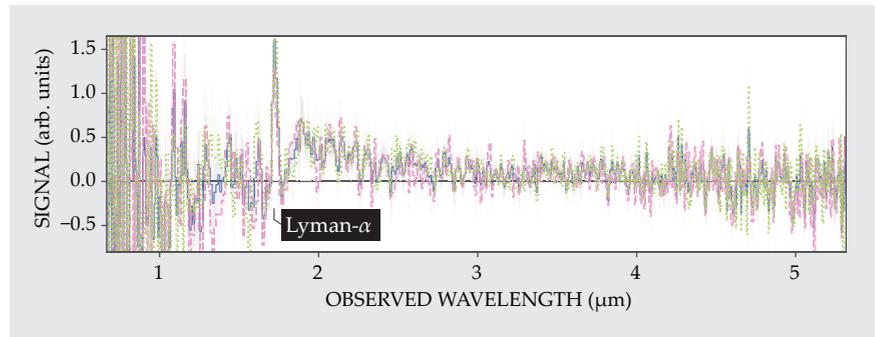


FIGURE 2. THE IR SPECTRUM of the $z = 13$ galaxy from figure 1 contains a surprise: a sharp peak at the redshifted Lyman- α wavelength of 1700 nm. If the galaxy were surrounded by a gas of neutral hydrogen, light at that wavelength would have been immediately absorbed and would never have reached Earth. The pink and green lines were obtained during two independent observation periods, designed to eliminate the effects of instrumental artifacts. The blue line is the average spectrum with outlying data points removed. (Figure adapted from ref. 1.)

transformation's history had to wait for the advent of the *JWST*. Above a redshift of about 7, the Lyman- α wavelength is stretched so far into the near-IR that it runs into atmospheric absorption bands, so it can't be observed with ground-based telescopes. The *Hubble Space Telescope*, too, was optimized for observing in the visible range, not the IR. "Purely, this was possible only because of *JWST*'s instrumentation," says Witstok. "We need instruments that can work at long wavelengths, and we need *JWST*'s huge 6-meter mirror because the galaxies are so incredibly faint."

Roughly speaking, the *JWST* observation process has two stages. In the first, the telescope captures images of an entire swath of sky, including the region shown in figure 1, through various wavelength filters. Researchers use the filtered images to identify pre-reionization galaxy candidates: If a speck of light is visible in a long-wavelength image but it disappears completely in shorter-wavelength images, that's a good sign that it might be a high-redshift galaxy that had part of its spectrum zeroed out by a neutral IGM.

Through that method, *JWST* observers have identified several candidates for extremely early galaxies.² Among them was the red dot in the middle of figure 1, estimated to have an astonishingly high redshift of 13, which dates it to 330 million years after the Big Bang. "It stood out for its enormous redshift; there wasn't really any more to it than that," says Witstok. "We didn't know there was anything particularly special about it just

yet." They advanced the object, and others, to the next stage of the observation process: detailed spectral analysis.

From the spectra, shown in figure 2, the researchers realized that the $z = 13$ object was truly unusual. As they expected, the spectrum was zeroed out, albeit noisy, at wavelengths shorter than the redshifted Lyman- α wavelength of 1700 nm. At longer wavelengths, it showed a broadband emission. So far, so good: The shorter-wavelength light would have been absorbed by a neutral IGM during the early part of its trip across the cosmos, and the longer-wavelength light would have passed through.

What was completely unexpected, however, was that at the Lyman- α wavelength itself, the spectrum showed a sharp, intense peak. If the galaxy had been surrounded by a neutral IGM, such an emission would have been immediately absorbed and would never have reached Earth. For a $z = 13$ galaxy to exhibit the spectrum that the researchers observed, it would have to have been surrounded by a sizable reionized region so that its light would not have encountered any neutral IGM until its Lyman- α emission spike was safely redshifted out of reach.

Small and mighty

The natural explanation for how a $z = 13$ galaxy came to be surrounded by reionized IGM is that it performed the reionization itself. If so, that's an important clue about the types of galaxies that were responsible for reionization. The $z = 13$ object is extremely compact, with an estimated radius of tens of parsecs. In

contrast, the Milky Way's radius is thousands of parsecs. "There's a debate over whether reionization was due to many smaller galaxies or fewer big ones," says Witstok. "This points toward smaller galaxies, which could exist earlier on."

The observation also raises the question of how the galaxy generated such an intense Lyman- α emission in the first place. "It doesn't line up with our standard models of stars," says Witstok. Even without encountering a neutral IGM, he points out, between 90% and 95% of the Lyman- α light was likely absorbed on its trip toward Earth. "So it must have started out incredibly luminous. Something in that galaxy is very powerful—maybe hot massive stars, or maybe a black hole that's accreting."

The earliest stars and galaxies must have been different from the ones that formed more recently because they formed from different material. Stars such as our Sun were forged from the leftovers of previous generations of stars, and they contained a mix of chemical elements from the start. But the universe's first generation of stars, known to astronomers as Population III, formed directly out of the primordial material

that emerged from the Big Bang: mostly hydrogen, a little helium, and a trace of lithium. And their formation process would have been qualitatively different.

Perhaps counterintuitively, the first step toward star formation is cooling: For a mass of material to coalesce to the density needed to trigger nuclear fusion, it needs to shed its excess energy. That happens through collision and radiation: Atoms collide, promote one another into excited states, and relax back to the ground state by hurtling photons out into space. The process is much easier with some heavier elements, such as carbon and oxygen, in the mix because of their rich spectra of low-energy excited states. To radiatively cool a gas of just hydrogen, the collisions would have to pack enough of a punch to excite the Lyman- α transition—a tall order.

Population III star formation has never been observed directly. All that researchers have are computer models of how the process would have played out and what the resulting stars would have looked like. The models suggest that Population III stars would have been much hotter and more massive than the Sun, and they would have shone brightly

at the Lyman- α wavelength. Although the resemblance to the $z = 13$ object is tantalizing, it's far too tenuous a case for the researchers to conclude that that's what they've observed.

Whatever the Lyman- α was inside the $z = 13$ galaxy, it had an influence on the universe far beyond its galactic home: The researchers estimate that the ionized region around the galaxy must have had a radius of at least 200 000 parsecs. The connection across scales—from the hot, dense environment of stars and black holes to the enormous desolation of intergalactic space and ultimately the universe as a whole—is what Witstok finds inspiring about reionization. "It's a very important transition that the universe goes through, and it's controlled by the physics of how stars form inside galaxies," he says. "It's important to understand how these processes connect from one scale to another."

Johanna Miller

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1. J. Witstok et al., *Nature* **639**, 897 (2025).
2. See, for example, B. Robertson et al., *Astrophys. J.* **970**, 31 (2024).

UPDATES

Putting holes in a sail to reach the stars

Sails made of photonic crystal membranes may one day propel spacecraft to Alpha Centauri.

The Planetary Society, a nonprofit space organization, in 2019 launched a solar-sail-powered spacecraft that orbited Earth. Its reflective mylar sail used only the energy of solar photons to push it through space. The society demonstrated that solar-powered light sails can work locally, but more energy is needed for them to quickly travel greater distances. A high-powered laser fired for less than an hour from Earth's surface could provide enough momentum to accelerate a sail to a fifth of light speed and reach Alpha Centauri within 20 years (see figure 1). All that's re-

quired is a sail that is optimized to reflect as much light as possible and is lightweight enough to make use of the resulting energy. A research team working as part of the Breakthrough Starshot initiative has designed a new photonic crystal reflector that the team believes does just that.

Photons reflect off the sail, which is then propelled because of conservation of momentum. But as the sail picks up speed, the laser light becomes Doppler shifted. To reflect for as long as possible—and accelerate as much as possible—before getting out of range of the laser, a sail needs to reflect across a range of wavelengths. When designing the latest sail, Richard Norte (Delft University of Technology in the Netherlands) and his group targeted a range of 1.55–1.86 μm , where atmospheric ab-

sorption is low. That wavelength window provides a wider range than other theoretical designs so as to account for the Doppler-shifted wavelength of the proposed laser. Thus, the sail has lower reflectivity over a wider waveband compared with designs that have high reflectivity within a narrower waveband.

To reach relativistic speeds, the payload and the sail need to have masses of no more than 1 g each. The ultimate goal is a microchip payload carried by a 10 m^2 sail, so the material needs to be lightweight yet strong. Previous lightsail designs have been multilayered to increase the broadband reflectivity at the expense of mass. Norte set his sights on a single-layer silicon nitride photonic crystal with subwavelength holes in the membrane that would determine what wavelengths are re-

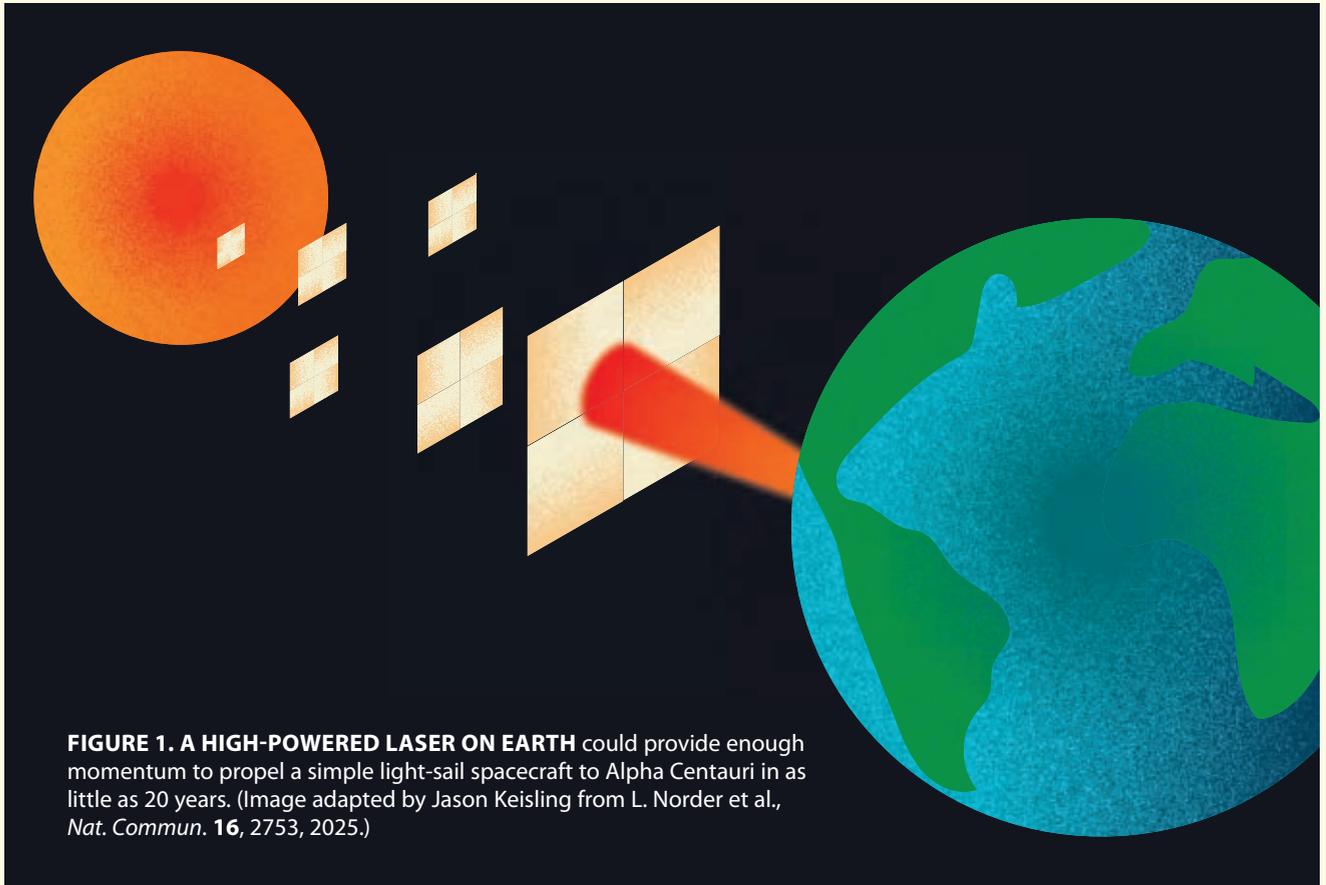


FIGURE 1. A HIGH-POWERED LASER ON EARTH could provide enough momentum to propel a simple light-sail spacecraft to Alpha Centauri in as little as 20 years. (Image adapted by Jason Keisling from L. Norder et al., *Nat. Commun.* **16**, 2753, 2025.)

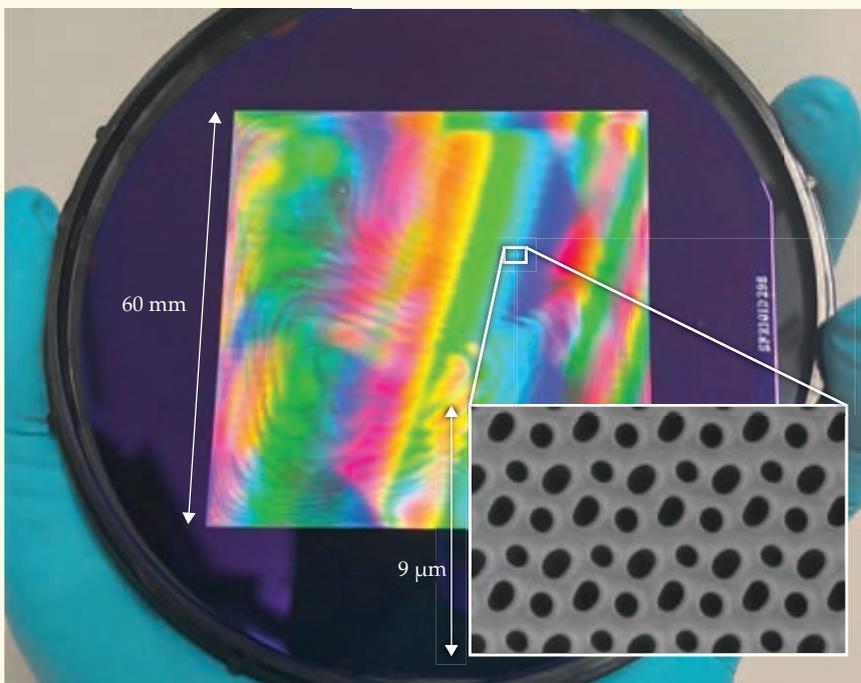


FIGURE 2. THIS 60 × 60 MM SAIL MEMBRANE has a repeating pattern of potato-shaped holes, as seen in the inset, imaged by a scanning electron microscope. Different hole sizes reflect different wavelengths of light, which allow the sail to continue reflecting laser light even when it is Doppler shifted. (Image adapted from L. Norder et al., *Nat. Commun.* **16**, 2753, 2025.)

flected. To design the pattern of holes, Miguel Bessa (Brown University in Rhode Island) used neural topology optimization to balance ideal hole sizes and arrangement for precise reflection against real-world manufacturing constraints. The result was a configuration featuring potato-shaped holes with slightly varied forms and sizes (see the inset in figure 2), each with a different wavelength at which maximum reflectance is achieved.

The pentagonal lattice pattern of holes lends strength to the membrane because its homogeneity creates a stable, crack-free suspension when unfurled. The repetitive pattern mask used to create the holes also reduces the manufacturing time of their 60 × 60 mm sail when compared to hole-by-hole fabrication. Although many technological advances are still needed before the meter-scale sail can be created, the thin sail material is projected to require a drastically reduced manufacturing time and be a promising final design for future light sails. (L. Norder et al., *Nat. Commun.* **16**, 2753, 2025.)

Jennifer Sieben

A rumbling truck enables a clearer view of Yellowstone's most active magma chamber

Seismic imaging reveals that the chamber is just 3.8 km belowground and capped by a layer of volatile-rich magma.

The Mud Volcano section is one of Yellowstone National Park's most hydrothermally active regions. Gas and hot fluids percolate up from deep underground to form the unique muddy features that give the region its name. The ground inflates and deflates, movement of magma beneath the surface creates swarms of small earthquakes that last months or years, and emissions of helium isotopes from Earth's mantle signal an even deeper driver of all the activity near the surface. Until recently, estimates of the depth belowground to the top of the magma chamber spanned the rather large range from about 3 km to 8 km. That's because underground imaging relied on signals from distant earthquakes that couldn't provide a high-resolution view. But for Earth scientists trying to understand the region's eruption hazard, the difference between 3 km and 8 km has major implications for how magma behaves.

Now a study by Chenglong Duan and Brandon Schmandt, both at Rice University, and their colleagues has shown that the top of the magma chamber is on the shallower side, at about 3.8 km down, and is capped by a thin layer of magma that contains supercritical volatiles, including water, sulfur, and carbon dioxide. "Yellowstone is famous for its hydrothermal features and gas emissions. That makes sense if you have a really shallow magma reservoir with its top at 4 kilometers," Schmandt says. The researchers obtained their clearer view by creating their own seismic waves rather than relying on those from earthquakes.

In 2020, they deployed about 650 small cable-free seismometers along a stretch of road that crosses the edge of the Sour Creek dome, as shown by the densely clustered black dots in figure 1. Then, along the same stretch of road,

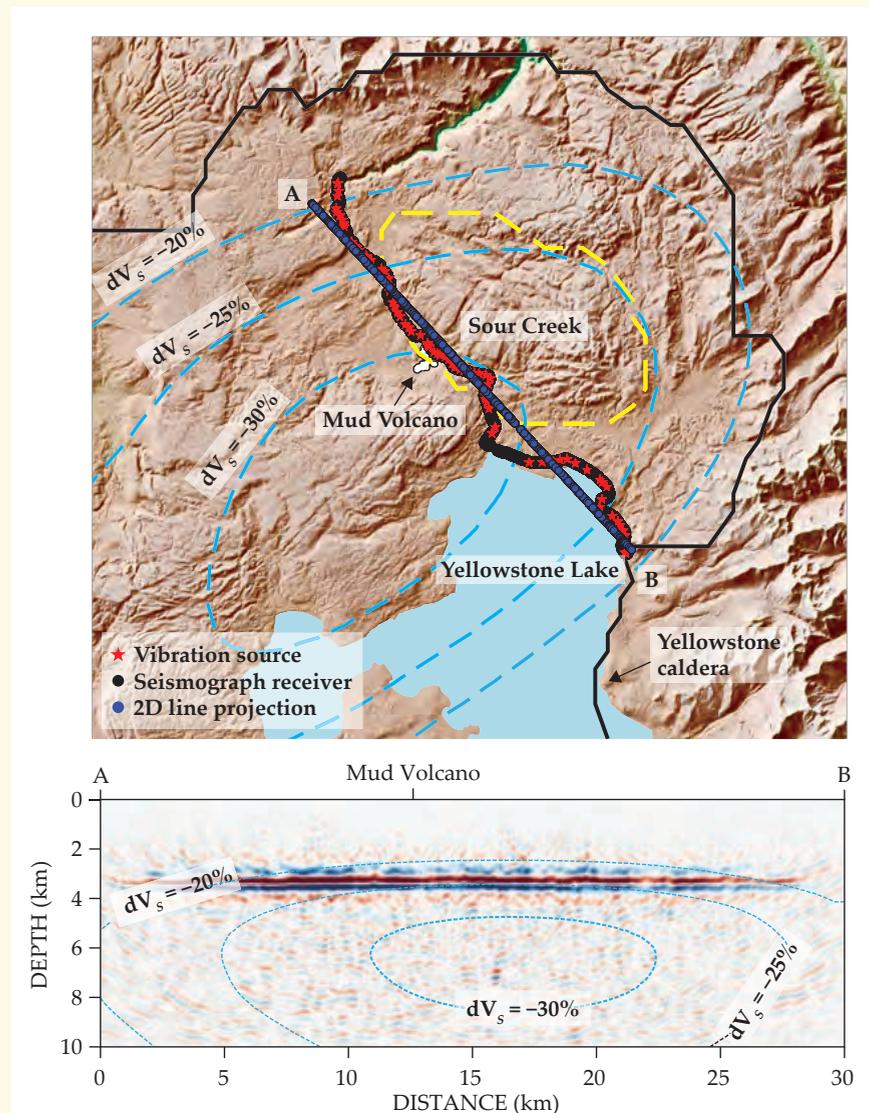


FIGURE 1. THE MAGMA RESERVOIR beneath the Sour Creek resurgent dome (upper panel, yellow dashed line) in Yellowstone National Park was imaged in unprecedented detail using vibrations sent into the ground along a 30 km stretch of road. Seismic imaging revealed an abrupt roof to the magma chamber about 3.8 km underground, and the researchers determined that the top of the reservoir contains a mixture of supercritical water, magma, and solid mineral crystals (lower panel, red line). The Mud Volcano section of the park exhibits the most chemical evidence of ongoing input of deep magma, as measured from gases and fluids that come to the surface. Previous studies used signals from distant earthquakes to estimate the density of the magma chamber, averaged over large areas. Those measurements of decreasing shear wave velocities (dV_s), which indicate higher fractions of melt, are contoured with blue dashed lines (both panels). The edge of the Yellowstone caldera—a depression left after the volcanic system's last super-eruption about 630 000 years ago—is outlined in black (upper panel). (Figure adapted from C. Duan et al., *Nature* **640**, 962, 2025.)



FIGURE 2. A TRUCK-MOUNTED METAL PLATE uses about 220 000 N of force to send vibrations into the ground across a frequency sweep of 6–30 Hz. Analysis of how the high-frequency vibrations move through the ground has provided a refined view of the Yellowstone magma reservoir in the northeast section of the park. (Photo courtesy of Brandon Schmandt, taken under Yellowstone National Park research permit YELL-2020-SCI-8146.)

they created the vibrations for their measurements: A large truck, shown in figure 2, lowered a metal plate to lift it off the ground and use almost its full weight to send the signal into the earth. The plate vibrated through a range of frequencies over a span of 40 seconds, and the process was repeated 20 times at each site. All of the measurements were collected at night both to avoid bothering

visitors to the park and to reduce extra noise from traffic.

The high frequencies used—from 6 to 30 Hz—enabled the researchers to get a sharper picture of what is happening below. But extracting an accurate view requires a lot of data processing to see through the noise. Active-source seismic imaging of volcanic systems has excelled in ocean settings: A ship can send well-

defined signals into the water, which carries the vibrations in a predictable way, and tow a line of receivers behind it to collect measurements. But on land, there are more confounding factors: A road is needed, the vibrations scatter off the surroundings in less predictable ways, and more sources of noise obscure the targeted signals. The unique setting of the national park, with easy access to roads, was part of what made the latest study possible. Improvements in the past decade to small, easily deployed seismometers and to data processing methods also enabled the work.

The study's finding doesn't change the current hazard assessment for the region, but it does provide better context to understand future monitoring data. Decompression of magma as it moves up in the crust can lead to a buildup of volatiles that will sometimes trigger eruptions. But for now, the imaging suggests that the magma chamber is channeling fluids and gases to its surface in a manner that promotes stability. (C. Duan et al., *Nature* 640, 962, 2025.)

Laura Fattaruso [PT](#)

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US research enterprise seeks to retain leadership while upping security

Uncertainty shrouds research-security measures and how to comply with them.

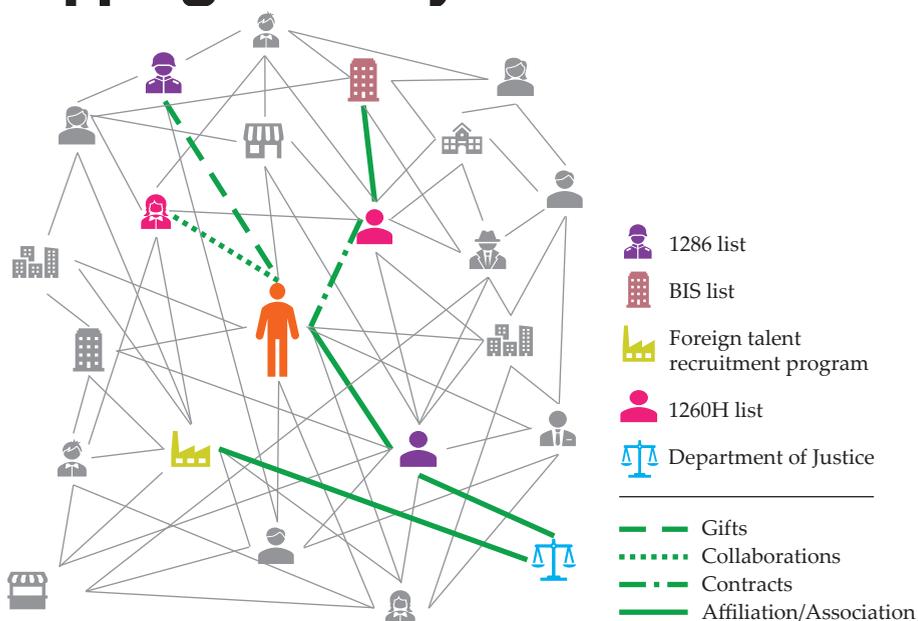
The vetting of US scientists and their work by the federal government for potential foreign influence concerns—willful or otherwise—for decades was mostly limited to research with near-term national security or commercial implications. Now, scrutiny is starting to be applied more broadly and more strictly. Connections with China are especially under the microscope.

The aim of increased scrutiny, explains Tam Dao, associate vice president of campus safety and research security at Rice University, is to ensure that international collaborations are transparent, ethical, and mutually beneficial. Research-security officials support researchers in “assessing potential risks of undue foreign influence,” he says. “We work hard on early intervention and education. We are not waiting for someone to do something bad and then nail them.” International collaboration, he adds, “is critical to research success.”

Scientific collaborations between the US and China have skyrocketed, notes Caroline Wagner, a professor of public policy at the Ohio State University who studies international collaborations. In the early 2000s, she says, 2–3% of US international collaborations were with China; by early this decade, it was 20–25%. A very small number of researchers in the US system are “bad actors,” she says. “My real concern about the tightened measures is the harm it could do to US science and technology—both reputationally and in the sense of knowledge-creation opportunities that could evaporate under enhanced scrutiny.”

Directives

The turning point for tightening research security came nearly a decade ago, says Dao, who back then was a Federal Bu-



ASSESSING THE CONNECTIONS of researchers applying for grants is part of research-security efforts. Ties to people and institutions that are on various US government lists can lead to requests for mitigation measures, including severing ties, for funding to be approved. In this diagram, a hypothetical principal investigator (center, orange) is revealed to have connections with various entities of concern. The Department of Defense’s 1286 list includes foreign institutions that the department says are engaging in activities related to technology transfer and talent recruitment that threaten national security; the 1260H list highlights Chinese military companies operating in the US; the Bureau of Industry and Security (BIS) list contains names of businesses, research institutions, government and private organizations, and individuals that are subject to federal licensing requirements; and foreign talent recruitment programs targeting science and technology professionals and students can lead to conflicts of commitment. The Department of Justice generally oversees research-security transgressions. (Figure adapted from an image provided by Tam K. Dao/Rice University.)

reau of Investigation special agent focusing on economic-espionage investigations. “Intelligence agencies started to share materials with federal funding agencies to inform them there were issues with undue foreign influence,” he says. Since then, government entities have picked up the pace in defining, tightening, and increasing enforcement of research-security measures.

In 2019, JASON, a group of scientists that advises the government on sensitive science and technology issues, pro-

vided NSF with recommendations on research security. In a March 2024 update, JASON noted that “recent efforts of the People’s Republic of China (PRC) to preferentially direct fundamental research toward military needs, and its decision to restrict the flow of information out of the country, may severely limit the benefits of collaborations with research organizations within the PRC.”

In January 2021, President Trump issued a memorandum directing the strengthening of protections for US-



RESEARCH-SECURITY OFFICERS from around the country identify needs they'd like to see addressed by the new SECURE (Safeguarding the Entire Community of the U.S. Research Ecosystem) center. The exercise took place in February at a conference of the Academic Security and Counter Exploitation program in College Station, Texas. (Photo courtesy of Mark Haselkorn.)

government supported R&D “against foreign government interference and exploitation.” The following year, the CHIPS and Science Act codified into law the memorandum’s requirements for research-security provisions and included directives intended to protect US commercial and national security interests and to help with their implementation.

Universities want to comply with the security requirements, says an administrator at a large public university who requested anonymity. “But it’s complicated. And the consequences of failing to comply are substantial.” Last year, for example, the US government filed suit against Georgia Tech for allegedly violating cybersecurity regulations.

“We fret about increased costs to comply in a time when funding may shrink due to outright cuts and to reduced overhead funds,” the administrator says. Extra costs could come, for example, from requirements to mandate training, fill out forms, cordon off areas for confidential unclassified work, and maintain separate, secure computer systems.

For many university faculty members, details about the implementation of research-security measures remain fuzzy. And uncertainty both about what is permitted and how the measures play out has cast a chill over research communities.

The requirements “are a moving target,” says Kenny Evans, who studies research security at Rice University’s Baker Institute for Public Policy. “There is a ton of confusion about what constitutes risk.” The US government has designated China, Iran, North Korea, and Russia “countries of concern.” Yet for the past few decades, the US has benefitted from attracting large numbers of international graduate students, including ones from those countries.

The theft of intellectual property and technology does happen. Michael Shannon was a longtime government investigator and since 2022 has been at IPTalons, a startup that offers services in research-security risk assessment. Shannon estimates from company data that 95% of US-funded researchers have international connections and that 75–80% of them have failed to report something. Most of the omissions are paperwork violations that can be fixed, he says, but 3–5% are “deliberate.”

Many US researchers acknowledge that increased security measures are needed. But such measures “have to be applied carefully so as not to hurt the competitiveness of US science and scientists,” cautions a physics professor originally from China whose institution requested anonymity because of the

topic’s sensitivity. Many researchers worry that the US is, as Evans puts it, “fueling China’s abilities” by pushing people out and that the blanket application of increased security measures could compromise US standing in science.

Risks and reactions

A major challenge, the university administrator says, “is the lack of harmonization between agencies.” The Department of Defense, for example, has well-established research-security measures. The same goes for the Department of Energy weapons labs and other funders. But the measures differ from agency to agency.

Complicating matters is that some states are superimposing their own security measures on research. And faculty members are accustomed to independence. “They value open science and have not seen sharing information as a threat,” the administrator says.

At many institutions, researchers must file annual disclosures that include names of collaborating scientists and their affiliations, past and planned travel, monetary gifts and sources of funding, and potential conflicts of interest. Researchers provide similar information when they apply for grants from federal agencies. In the past, institutions could



TAM DAO, associate vice president of campus safety and research security at Rice University, addresses participants at the first global workshop on “research on research security,” held at Rice in May 2024. (Photo from Michael Stravato, Baker Institute for Public Policy, Rice University.)

say they were in legal compliance as long as they had collected the requested information, Shannon says, but “nowhere in the oversight process was the veracity checked.” That’s changing.

When disclosures raise flags, Dao says, his job is to provide researchers with accurate information about agency rules so they can make an informed decision through the lens of national security. A researcher’s decision could boil down to implementing mitigation measures or forgoing funding. Mitigation might include taking additional research-security training, ceasing a particular collaboration, refusing money or travel perks from some foreign source, or meeting with counterintelligence representatives from the funding agency. Getting flagged is common, Dao says. The agencies, he adds, “have made it clear that their goal is to get to ‘yes.’”

Still, many researchers find the increased scrutiny cumbersome and even scary. Some Chinese-origin faculty members say they have stopped applying for grants from the US government. And many researchers have minimized or discontinued their professional connections with colleagues in China.

While on a personal trip to China in 2023, the physics professor whose institution asked not to be identified was in-

vited to give an academic talk at a university in Shanghai. The professor paid out of pocket for local travel and lodging to avoid having to explain—to their institution and funding agencies—accepting money from a Chinese entity. As a precaution, the professor has also stopped collaborating with Chinese colleagues—often former postdocs or graduate students. “I won’t publish with colleagues if they include an affiliation in China,” they say. “That is a loss for me as a researcher. The reduced collaborations in fundamental science between the two countries is a huge loss for the whole scientific community.”

Peter Littlewood, a physicist at the University of Chicago and former director of Argonne National Laboratory, says that “it’s not regarded as a conflict of interest” when an institution in the US pays his travel expenses to give a seminar. But when traveling to a country of concern, the same behavior “is treated differently.” A few years ago, he says, he “got the message” to reduce travel to China. DOE officials “didn’t say don’t go,” he says. “But the number of questions you had to answer was growing, and they made it clear you’d save the legal department a lot of time if you did not travel to China.”

Condensed-matter theorist Steven

Kivelson of Stanford University says he jumped through hoops to get funding to attend a conference in China last fall. A non-Chinese US scientist who requested anonymity says they no longer respond to emails from China because they “don’t want to be flagged as a risk.” And many scientists express worry that US faculty members will become hesitant to take on students from China and other countries of concern because of the difficulties that future collaborations may bring.

New measures, long-term effects

Last summer, NSF announced a pilot program called Trusted Research Using Safeguards and Transparency. Initially limited to quantum-related studies, TRUST applies an extra layer of scrutiny to proposals that receive high rankings from peer reviewers. NSF wouldn’t say what that scrutiny involves, although a spokesperson wrote that “the TRUST process has no implications for the nationality of who can work on quantum-related projects funded by NSF.”

Rice’s Dao says, “We don’t know the details except that [NSF] will likely assess active appointments, positions, research support, and instances of non-disclosure.” In any case, says Sophia

Economou, director of Virginia Tech's Center for Quantum Information Science and Engineering, the extra scrutiny will cause delays. "That could lead to big gaps in funding and can affect younger faculty who have the pressure of the tenure clock," she says. "I worry about them."

Another new research-security measure stems from the National Defense Authorization Act (NDAA) that was signed into law last year. It bars scientists who are from the four countries of concern and don't have US resident status from working at the National Nuclear Security Administration (NNSA) labs. Foreign nationals at those sites work on unclassified, often fundamental science.

In February, around 60 non-US citizens, mostly from China, lost access to the campus of Lawrence Livermore National Laboratory, one of the three NNSA labs. They now spend workdays in a building off-site. One of them is a physicist who has been at Livermore for several years. That physicist says they can still run simulations and analyze data, but some other scientists lack the apparatuses necessary to continue experiments. The physicist says they feel isolated and uncertain about their future; they asked not to be identified because they fear retribution and hope to find either a solution at Livermore or other employment in the US.

The physicist and others also question the necessity of the exclusion. The security checks and rules for working at the NNSA labs are extensive. For example, says the physicist, "There are specific computers I am allowed to touch, and I am not the administrator of my own computer." Sometimes their students' computers were off-limits, they add.

Shutting out Chinese and other foreign researchers "is a move in the wrong direction," says Siegfried Hecker, who was director of Los Alamos National Laboratory from 1986 to 1997. The law specifies that waivers are possible but, he says, "the way the government works, that never happens." To stay "at the top of the game," he adds, "you have to attract the smartest people. Then you have to manage risk. And places like Los Alamos know how to do security."

"The effects of the NDAA changes will have a long lead time to understand how devastating they will be," says Hecker. "With research security, it

will be years before we understand the harm to US science."

Spokespeople from the nation's three NNSA labs said only that the labs are complying with the NDAA. They did not respond to questions about how many people are affected or how the loss of those scientists affects the labs' research.

New center serves as liaison

To help bolster research security, the CHIPS and Science Act calls for measures to aid in implementation. The 400 or so universities that receive more than \$50 million annually from the federal government are now required to set up research-security offices. (Several universities are creating master's degree programs to prepare people for careers in those offices.)

And an NSF-backed center, Safeguarding the Entire Community of the U.S. Research Ecosystem (SECURE), is ramping up to serve as a bridge between government funding agencies and the research community. Headquartered at the University of Washington, with an analytics branch at Texas A&M and partners at other universities, SECURE is funded through the CHIPS and Science Act with \$67 million over five years. The aim, says center director Mark Haselkorn, is to enable researchers and research administrators "to be secure and to protect the value of what they create while also sustaining the collaborative open environments in which research thrives."

Working with the research community, the SECURE team has come up with priorities that include providing tools to interpret and navigate research-security policies, reducing the burden of agencies' various security requirements for researchers, and developing guidance for managing foreign travel. This summer, Haselkorn says, the center will roll out a virtual environment where researchers and research-security officers can share information. The center is also creating a condensed version of a research-security training course that will satisfy requirements for all federal funding agencies.

"SECURE will do a service by making it clear what's in and what's out," says Ohio State's Wagner, leader of the new center's evaluation team. "That could make people less fearful about collaborations."

Toni Feder

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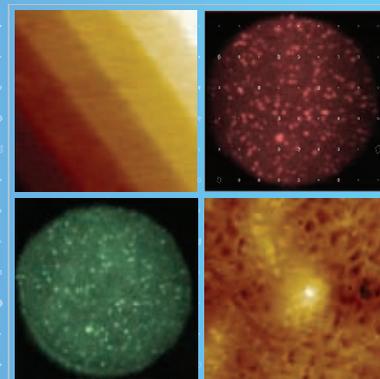


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Humor helps convey science, study suggests

Most Americans trust scientists, according to a 2024 Pew Research Center survey, but about half believe that scientists are not good communicators. In a recent study in the *Journal of Science Communication*, four communications researchers found that humor on social media correlates with a more positive public perception of science and scientists.

In an October 2020 online survey, the researchers measured the reactions of more than 2000 participants in the US to different versions of a mock Twitter (now called X) post from the fictional and gender-neutral scientist “Dr. Jamie Devon.” Each post features a cartoon about the complexity of designing AI systems that account for human behavior and error (see image). The posts use either satire, anthropomorphism, both types of humor, or no humor. Participants viewed one post and then an-

swered questions about the post’s legitimacy as a source of information and about the fictional Devon.

Respondents rated how funny they found each post on a scale of 1 to 7. Those who viewed posts they considered funnier rated Devon as more likable and the scientific information as more legitimate than did participants who viewed posts they considered less funny. “Our research suggests that funny scientists can be well liked and still regarded as valid sources of information, at least among American audiences,” says lead author Alexandra Frank, a doctoral student at the University of Georgia’s Grady College of Journalism and Mass Communication.

Applying the findings beyond the small-scale study has limitations, write the authors. The research can’t demonstrate that humor was the reason for the better perceptions of the posts. The study

also dealt with one particular topic (self-driving cars) and used lighthearted humor. Finally, Devon represents an unknown scientist rather than a public figure who could sway people’s reactions.

Coauthor Michael Cacciatore, a professor at the University of Georgia’s Grady College, says that physicists can take something away from the study. “I don’t see why the same conclusions wouldn’t apply with a physics pun or sprinkling in some satire or anthropomorphism in that realm,” he says.

Helen Pilcher, a science and comedy writer with a PhD in neuroscience who was not involved with the study, says modern science communication emphasizes interacting with audiences rather than lecturing them: “Sharing a laugh with somebody, making somebody smile, is the most lovely form of interaction that you can get.”

Jenessa Duncombe



MOCK SOCIAL MEDIA POSTS for a science communication study on humor. The comical post (**left**) was rated as a more legitimate source of information by survey participants than the humorless post (**right**). (Figure adapted from A. L. Frank et al., *J. Sci. Commun.* **24**, A04, 2025.)

Q&A: Graduate student Ari Jain strives to better the world through research and leadership

Awarding travel grants, organizing conference sessions, and lobbying the government have afforded him a close-up view of how the science enterprise works.

“You can’t be a pilot—it’s dangerous.” That’s what Ari Jain’s mom told him when he was a small child and wanted to become one. So, instead of flying planes, he decided in middle school he would design them. Says Jain, “The passion never went away.”

Jain earned his bachelor’s and master’s degrees in aerospace engineering. Now he’s working on his doctorate at Georgia Tech and expects to graduate in December 2026. Alongside his experimental research on combustion engines, Jain is active in three professional societ-

ies: He is the past chair of the American Physical Society (APS) Forum on Graduate Student Affairs (FGSA), the deputy director for young professionals for the American Institute of Aeronautics and Astronautics Region II (which covers the southeast US), and the vice president for the Georgia Tech Aerospace Engineering Graduate Student Association.

His participation in governance, he says, has helped him grow as a leader and develop his network. It also builds confidence: “I see that I can make an impact, and I shouldn’t feel I have any-

thing less to offer than someone who is later in their career.”

PT: Describe your research.

JAIN: I work on combustion for commercial gas-turbine engines—the type you see on the planes that you fly on. I work on advancing the technologies that lower pollutants—nitrous oxides and nonvolatile particulate-matter emissions.

Part of my research is on the combustion side of things, the actual physics. The other side is the diagnostics and how we measure and analyze flows of combustion products.

PT: How do you decrease pollutants?

JAIN: In gas-turbine emissions broadly, carbon dioxide makes up about 80% of emissions, and non-CO₂ emissions are the other roughly 20%. To decrease CO₂ emissions, there are sustainable aviation fuels made from alternative feedstocks. The current jet fuel in the US is called Jet A. You are allowed to mix Jet A in a 50-50 ratio with sustainable aviation fuels and deploy that on an aircraft. The goal is to get to 100% sustainable fuel.

For non-CO₂ emissions, like nitrous oxides and nonvolatile particulate matter, one of the mitigation strategies is to burn fuel lean—that is, increase the air-to-fuel ratio. However, burning fuel lean inherently has more risks. We need to continue understanding how the sustainable fuels and lean burning affect engine performance and operability.

PT: What type of risks?

JAIN: The risk is that combustion is not sustained and the engine goes out. That’s not a good thing at 40 000 feet.

PT: Tell me about your governance activities.

JAIN: I think of the roles I have as being on two different levels. There is the local campus level and the society level. Being a part of both gives me an opportunity to be clued in to what’s happening in



ARI JAIN WENT TO WASHINGTON, DC, to lobby for the RESEARCHER Act and other policy issues through the American Physical Society’s Congressional Visits Day this past January. (Photo courtesy of Adhiraj Bhagat.)

both arenas and to be able to make an impact. As an undergraduate, I served on the executive committee for the American Institute of Aeronautics and Astronautics student branch at my campus, the University of Illinois Urbana-Champaign. Once I got to grad school, I could apply my leadership skills at a broader level.

PT: What are examples of what you do in your current roles?

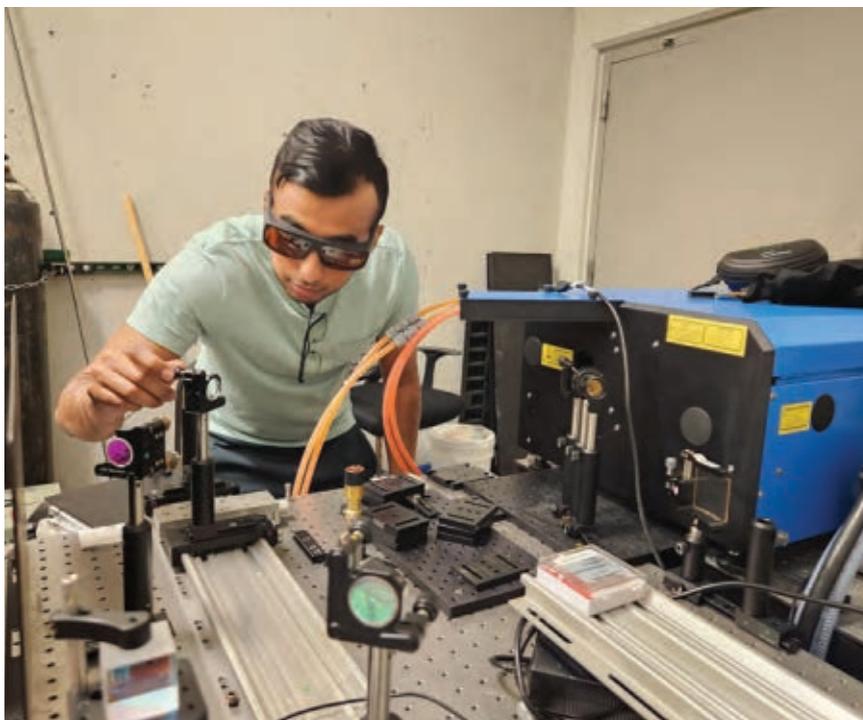
JAIN: Some are little things. Georgia Tech's qualifying exams for the PhD program in aerospace engineering are notoriously tough. The aerospace graduate student association provides exam takers with resources to ease the anxiety of taking that big exam: We connect them with people who can give them mock exams, and there is a massive study bank for them to look at notes from previous years. When I was studying for my exam, that bank helped me a lot, so I know it's important to maintain it.

For APS, the FGSA administers travel awards to students who need support to get to conferences. I am one of the people who goes through the applications. This year, we funded 19 students—a handful of which were international students—to go to the Global Physics Summit in March. Being able to give those students a chance to present their work and take advantage of networking is very rewarding.

The APS FGSA also organizes sessions for the Global Physics Summits. We curate the topics, invite speakers, and make it happen. It's an annual thing. This year, the topics were ethics and publishing, graduate students as changemakers, and a career panel that we cosponsored with a couple other APS units. And, because it's the International Year of Quantum Science and Technology, we had a quantum-focused session.

PT: How did you, as an engineering student, become involved in APS?

JAIN: My master's degree was more in the pure fluid-dynamics space, so I joined APS for their division of fluid dynamics. My work is very physics adjacent: I am applying fluid-dynamics concepts in a combustion setting. That's why, although I am not a physicist per se, I stay involved with APS.



REDUCING POLLUTION FROM AIRPLANE COMBUSTION ENGINES is the focus of Ari Jain's doctoral studies at Georgia Tech. He uses lasers to monitor where flames and combustion chemicals are. (Photo courtesy of Adhiraj Bhagat.)

PT: How did you get into APS governance?

JAIN: Of all the units that the APS has, the Forum on Graduate Student Affairs is the most important and relevant to me. When they put out a call for serving on their executive committee, I threw my hat in the ring. I was elected.

PT: What appeals to you about serving in the leadership of professional societies?

JAIN: I know that we are impacting individual students in a big way.

Last year, there was a bill in Congress called the RESEARCHER Act, which directs the White House Office of Science and Technology Policy to gather data on graduate student and postdoc stipends and develop new, more robust guidelines for how federal agencies should suggest grant allocations toward such stipends when they put out calls for proposals.

Through APS, we launched a nationwide grassroots campaign. Eight hundred letters were sent to senators and House of Representatives officials. We were able to arrange trainings for constituents for how to talk to lawmakers. And we arranged six meetings. Based on

those meetings, two additional congressmen signed on to cosponsor the bill.

With the end of that session of Congress, the bill died. It will have to go through the process again. The last I heard is that it's close to being reintroduced.

The thought that "Hey, I can help other graduate students and postdocs get fair compensation, get more money," is probably the most rewarding thing I've done in my governance positions.

PT: How much time do you invest in your society activities?

JAIN: Like 10 hours a week. I don't know how I make time for them, but I do. And I would encourage other graduate students to get involved. You will get as much out of it as you put into it.

PT: What are your plans for after you finish your PhD?

JAIN: I'm currently in two frames of mind. I may like to work at an R&D center in industry. And, because of my activities with the RESEARCHER Act, I want to explore aerospace policy, or science policy in general, as a possible career path.

Toni Feder

Physics, astronomy graduate admissions in the US expected to shrink amid funding uncertainty

The predicted decrease is larger than pandemic-era disruptions, according to a survey of university departments.

Because of recent federal cuts to science, about 600 fewer first-year physics and astronomy graduate students are expected to enroll in the US this fall compared with the fall 2024 semester. The estimate, from a new report from the American Institute of Physics (AIP; publisher of *PHYSICS TODAY*), is based on survey responses from the chairs of 115 physics and astronomy departments in the US in April 2025. The report is among the first to quantify declines in graduate school admissions caused by federal funding reductions.

Many universities withheld offer letters to first-year graduate students this year because they anticipated less money from federal grants, says report coauthor Susan White, AIP's statistical research director. Federal grants typically support graduate student stipends.

More than one-third of responding departments expect first-year admissions to decrease. In analyzing the estimates that the respondents provided, AIP projects a 13% drop in first-year enrollment in fall 2025 compared with fall 2024. That would be a sharper decrease than in any other year in the past decade, including during the COVID-19 pandemic, which saw a 7% year-to-year drop.

One in six of the responding chairs reported that at least one faculty member in the department has had their federal grant funding reduced or canceled, and one in four anticipate funding disruptions in the next six months. "The expectations of coming cuts [are] very concerning and [are] causing everyone to be more cautious," wrote one chair.

The admissions reductions and funding impacts are more severe at private universities than at public ones. More than half of private school departments forecast a smaller incoming class, compared with one-quarter of public

(2) Has the number of first-year graduate students you plan to enroll in the fall 2025 been influenced by recent funding policy changes instituted by the current White House administration?

No, we plan to enroll the same number of graduate students we had initially planned.

Yes, we plan to enroll *fewer* graduate students than we had initially planned.

Yes, we plan to enroll *more* graduate students than we had initially planned.

Please elaborate (optional):

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MORE THAN 100 CHAIRS of physics and astronomy departments at US universities answered questions such as this one in a recent survey. (Image courtesy of Susan White, AIP.)

school departments. And nearly two-thirds of the department chairs at private universities reported having faculty that have experienced or anticipate facing funding disruptions in the next six months compared with roughly one-third of the public university department chairs.

White says the report's findings are relevant to other STEM departments: "I personally suspect enrollment reductions are going to be similar throughout all STEM disciplines because they face the same funding cuts."

In the survey's write-in box, department chairs lamented hiring freezes, cancellations of undergraduate internships, and a demoralizing environment. "One cannot work like this—all energy goes in[to] thinking how to survive," one chair wrote.

Several respondents noted the strains on international students, who face threats of visa revocations and deportations by the Trump administration. One department chair wrote that they

could foresee a future decrease in international enrollment "simply because it seems it'll be harder to secure a visa." International graduate students have been a main driver of the growth in science, engineering, and health graduate program enrollment in recent years, according to a report from NSF's National Center for Science and Engineering Statistics.

The AIP survey was largely conducted before the reports of new federal funding changes, including NSF's pause on the awarding of new grants and its termination of existing grants that are related to combating misinformation and that support diversity, equity, and inclusion initiatives.

The department chairs surveyed said that sharper admissions cuts may come in 2026. Wrote one respondent, "It is almost certain we will have to shrink the size of our graduate program in future years due to the anticipated reduction in federal funding."

Jenessa Duncombe

DOE eases regulation of national laboratories

Lab directors praise the new flexibility, while Democratic appropriators probe the risks of reduced oversight.

An order issued in March by US Energy Secretary Chris Wright eases regulations on both construction projects and workforce policy for national laboratories. It incorporates ways to improve lab efficiency, which were proposed by all 17 national lab directors in response to a Department of Energy request for such ideas.

The top Democratic appropriators for DOE, however, have expressed concern that the order reduces oversight of major construction projects and could lead to cost overruns and project delays. They have asked the Government Accountability Office (GAO) to study the matter.

The order reduces the number of projects that will be subject to DOE's review process for capital assets. The process previously applied to projects with total costs of more than \$50 million but will now cover only those with costs above \$300 million. The order also reduces the number of independent reviews that will be required of projects with costs between \$300 million and \$1 billion.

John Wagner, director of Idaho National Laboratory and chair of the National Laboratory Directors' Council, tells *FYI* that the lab directors proposed \$300 million as the threshold for projects that are sufficiently complex to require more oversight. The DOE review process, he says, "adds a variety of approvals and additional rigor into projects that do come at a time-and-cost expense. That makes sense for very big, complicated projects and adds less value for small, more routine projects." He contrasts the complexity of building a new spallation neutron source with the routine work of building new office space. "Over time, \$50 million doesn't buy what it used to," he says. "And we decided for projects roughly under \$300 million, the cost wasn't worth the benefit."

Projects between \$300 million and \$1 billion will use a "graded approach" to the review process based on their details, Wagner says, though DOE and the



US ENERGY SECRETARY CHRIS WRIGHT meets earlier this year with the directors of all 17 national laboratories. (Photo by Donica Payne/DOE.)

labs are still working out the exact rubric for that approach.

Wagner says that some labs had been looking to ease the regulations since around the beginning of the first Trump administration. Similar areas of improvement were identified then, but progress "to this degree" was not achieved, he says. "What's really encouraging right now is how quickly the secretary acted on these issues."

Meanwhile, the top Democratic appropriators for DOE, Senator Patty Murray of Washington state and Representative Marcy Kaptur of Ohio, have cautioned that inadequate supervision over past DOE projects led to "significant delays and project overruns."

"The Department's own tracking confirms the risk," Murray and Kaptur wrote in a letter to the GAO. They added that 53% of the department's total project portfolio, representing more than \$24 billion, is not meeting targets for cost or time efficiency: "Without sufficient oversight, there is a higher likelihood that projects will not meet their cost estimates or will fail to be completed within the allocated timelines."

Wright's order also removes some DOE requirements for subcontractor construction companies regarding workers' exposure to potentially dangerous materials. Wagner says that contractors have had to meet those requirements even for projects such as office

buildings, where they may not be applicable. Typically, contractors are not familiar with the additional requirements and so are less inclined to take on a project, Wagner adds.

Removing those requirements "will increase the number of construction companies that can bid on work at [Los Alamos National Laboratory] and provide a more competitive bidding process that will assist in lowering the costs of construction," Los Alamos director Thom Mason said in an April DOE press release. The order states that the labs will instead implement a "tailored, graded approach" to meet legal requirements for worker safety and health and notes that a similar framework has been used by the National Nuclear Security Administration.

The order also removes some oversight of labs' employee compensation plans, which covers how much the lab will spend on salary increases, bonuses, relocation, and retention. Under the previous process, those plans required annual reviews, and any changes were subject to DOE approval. In the DOE press release, Kimberly Sawyer, director of the Thomas Jefferson National Accelerator Facility, said that revising the compensation clauses "could result in up to 40% time savings in onboarding key personnel" and gives the lab "the flexibility needed to attract and retain top-tier talent."

Clare Zhang

FYI SCIENCE POLICY BRIEFS

Federal commission calls for multibillion-dollar biotech funding boost

Congress must take urgent action to strengthen the US biotechnology industry or risk irrevocably falling behind China, warns a recent report from the National Security Commission on Emerging Biotechnology. The report urges Congress to disburse billions of dollars in federal funding over the next five years to grow the domestic biotech industry, end supply-chain dependencies on China, and protect US intellectual property from theft.

The report's final recommendations are organized into six focus areas: making biotechnology a national priority, mobilizing the private sector, maximizing the benefits of biotechnology for defense, out-innovating strategic competitors, boosting the biotechnology workforce, and working with allies and partners. The report authors also propose what they call grand research challenges: One focuses on "making biotechnology predictably engineerable," and the other is centered on "making biomanufacturing scale-up predictable, rapid, and cost-competitive."

Federal science agencies play a key role in the report's recommendations. The report proposes, for example, that NIST become a "hub" for biotechnology, biometrology, and biological data standards and that NSF administer a national biotechnology coordination office to be housed in the Executive Office of the President. The report also suggests providing the Department of Energy with \$1.2 billion to establish six centers for biotechnology within the existing network of national laboratories and another \$700 million over five years to create a biological data repository for researchers.

The bipartisan National Biotechnology Initiative Act was introduced in both the

House and Senate in April to support some of the proposals in the report. —LM

STEM professionals face hurdles procuring US visas, report finds

The US visa process presents numerous administrative obstacles for scientists, engineers, and medical professionals looking to enter the country, according to a new report commissioned by the National Academies of Sciences, Engineering, and Medicine. The conclusions come from a survey of more than 1200 respondents in 95 countries. It was conducted last fall, meaning it chronicles challenges from the COVID-19 pandemic but not the effects of policies the Trump administration began deploying earlier this year.

Almost a third of respondents expressed reluctance about applying for US visas. The most cited hindrance to obtaining a visa was the interview process; others included administrative delays and the perceived difficulty of applications.

The report focuses on four types of visas that can be used to stay in the US for short periods: B-1 business visitor visas, F student visas, J-1 exchange program visas, and H-1B temporary specialty worker visas. Most survey respondents were applying for B-1 or B-2 (tourist) visas, and almost two-thirds of them were coming from an academic institution.

The US also has a visa waiver program that allows citizens or nationals of a select group of countries to visit the US for 90 days without a visa. But the survey found that 19% of the 148 respondents who should have been eligible for that program still missed professional activities because of visa problems.

Almost one-third of the survey respondents were from China or India. The data show that respondents from those countries were more likely than the overall sampled population to face visa challenges, especially with scheduling interviews.

More than 60% of respondents found that their experiences applying for a US visa were more difficult than applying for one from other countries. And more than 25% said they have stopped or avoid collaborating with partners in the US because of visa challenges. —HD 

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



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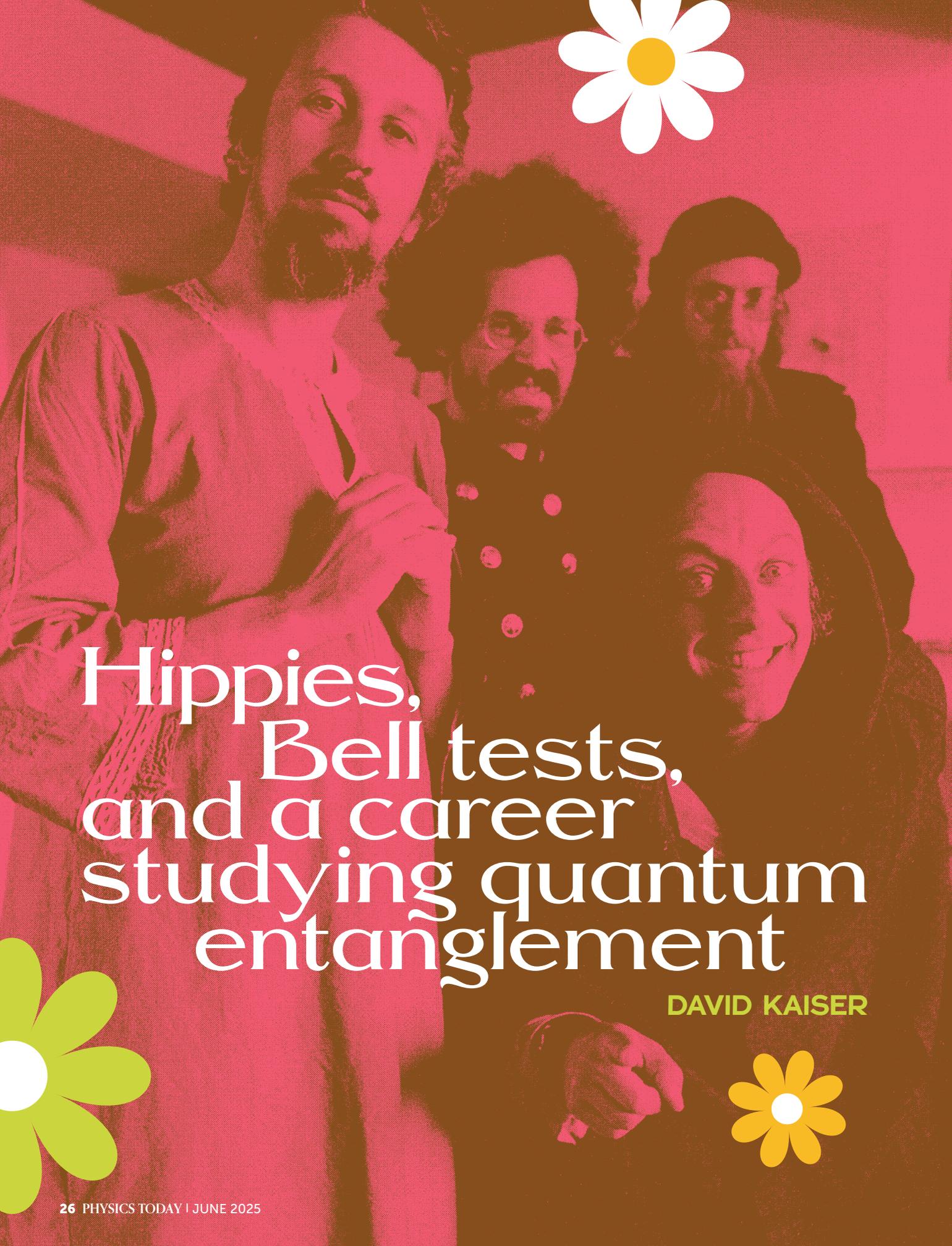
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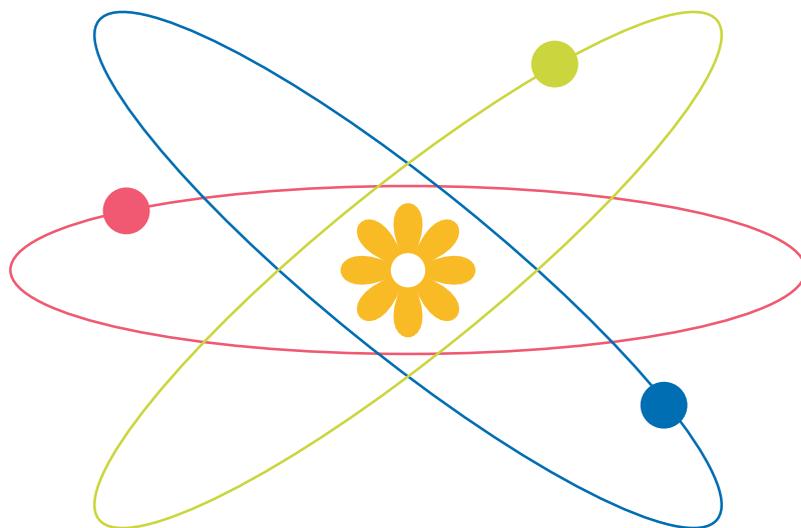
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Hippies, Bell tests, and a career studying quantum entanglement

DAVID KAISER



Investigating a group of maverick physicists who studied the foundations of quantum mechanics in the 1970s led one physicist-historian to help create a new test of entanglement.

My fascination with quantum entanglement began in high school, when I stumbled upon a cheap paperback of physicist Fritjof Capra's *The Tao of Physics*.¹ The book had first been published in 1975; by the time I found the copy in a used bookstore about a decade later, it had long since become an international bestseller. I was immediately captivated by the book's discussion of bizarre-sounding features of quantum theory and the subtle dance of subatomic particles. Capra's earnest discussions of various Eastern spiritual traditions—and what struck him as parallel suggestions, comparable to those from modern physics, about the nature of physical reality—left less of an impression on me. But few could miss his passion for quantum strangeness.

Inspired by some marvelous high school teachers and books like Capra's, I entered college determined to study physics. Soon, other books grabbed me—I can still picture the tiny cubicle in the library where I spent hours tightly gripping a copy of Bernard d'Espagnat's *Conceptual Foundations of Quantum Mechanics*.² Meanwhile, my academic adviser, an expert in general relativity whose diverse reading habits included literature, art, and history, sparked my interest in the history of science. Before long, I was delving into classes in both physics and history. I became fascinated by the history of quantum entanglement and contemporary physicists' efforts to grapple with it. I decided to pursue doctoral studies in both theoretical physics and the history of science.

During my doctoral studies, my physics department stipulated that PhD students in theoretical physics had to complete one semester of an undergraduate laboratory course. I grumbled the whole time, except when my long-suffering lab partner and I worked on a benchtop experiment to test entanglement. We were clumsily redoing a classic experiment, first conducted in 1972 by John Clauser and Stuart Freedman, that

A GROUP OF OFFBEAT BERKELEY PHYSICISTS began meeting during the 1970s to discuss foundational questions in physics, such as quantum entanglement, that were then considered passé. Pictured here are four members of the self-proclaimed Fundamental Fysiks Group. Standing, left to right, are Jack Sarfatti, Saul-Paul Sirag, and Nick Herbert; kneeling is Fred Alan Wolf. (Photo courtesy of Fred Alan Wolf.)

HIPPIES AND BELL TESTS

attempts to measure correlations in the polarizations of pairs of photons.³ (Clauser shared the 2022 Nobel Prize in Physics for his pioneering efforts to test entanglement.) Freedman had been a graduate student at the time and Clauser a young postdoc, newly arrived at Lawrence Berkeley Laboratory.

About 10 years after stumbling through that experiment, I learned that during the 1970s, Clauser had been one of the founding members of a spirited, informal discussion group in Berkeley whose members called themselves the Fundamental Fysics Group. Capra had also been a member, right around the time he published *The Tao of Physics*. Between Capra's book and Clauser's experiment, I was hooked, and I wanted to know more. The exploration led to my 2011 book, *How the Hippies Saved Physics*.⁴ And then, in a wonderful twist, my *Hippies* book helped catalyze one of the most memorable adventures of my career: working with an international collaboration to design and conduct novel tests of entanglement, which we dubbed the cosmic Bell experiments.

The International Year of Quantum Science and Technology offers opportunities to ask how some of the most central ideas of quantum theory were introduced, debated, tested, and ultimately accepted (see *PHYSICS TODAY*, April 2025, page 38). As I found while working on my *Hippies* book and the cosmic Bell tests, physicists' decades-long efforts to discern whether entanglement is a robust feature of the world have been anything but straightforward.

Articulating entanglement

Erwin Schrödinger, Albert Einstein, and several other architects of quantum theory identified entanglement as a prediction of the still-new quantum formalism back in the 1930s. Tickle a particle here, the equations seemed to suggest, and somehow the measured properties of its distant twin would

be affected, no matter how far apart the particles had traveled. To Schrödinger and Einstein alike, that hypothetical behavior seemed too strange to be true. Surely, they convinced themselves, real bits of matter in the real world could not behave that way.

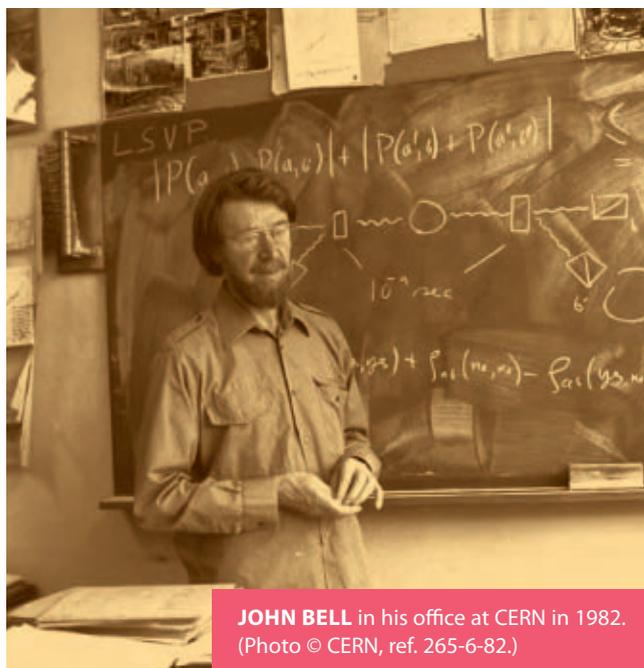
In a now-famous article published in May 1935, Einstein, Boris Podolsky, and Nathan Rosen asserted that predictions like entanglement revealed that quantum mechanics must be incomplete.⁵ A more proper theory, they concluded, would enable physicists to specify properties of each particle rather than imagining that one particle's properties somehow depended on something that happened to its distant partner (see the article by David Mermin, *PHYSICS TODAY*, January 2025, page 28). If such spooky connectedness were a prediction of quantum mechanics, perhaps it was time to search for another theory.⁶

Niels Bohr's 1935 defense of the new quantum theory and its strange-sounding predictions like entanglement,⁷ a paper he wrote in response to Einstein, Podolsky, and Rosen, seemed to satisfy many physicists at the time. Their relief came not necessarily because Bohr's arguments seemed clear but because another giant of the field had stepped into the fray and declared that all was well in the quantum realm.

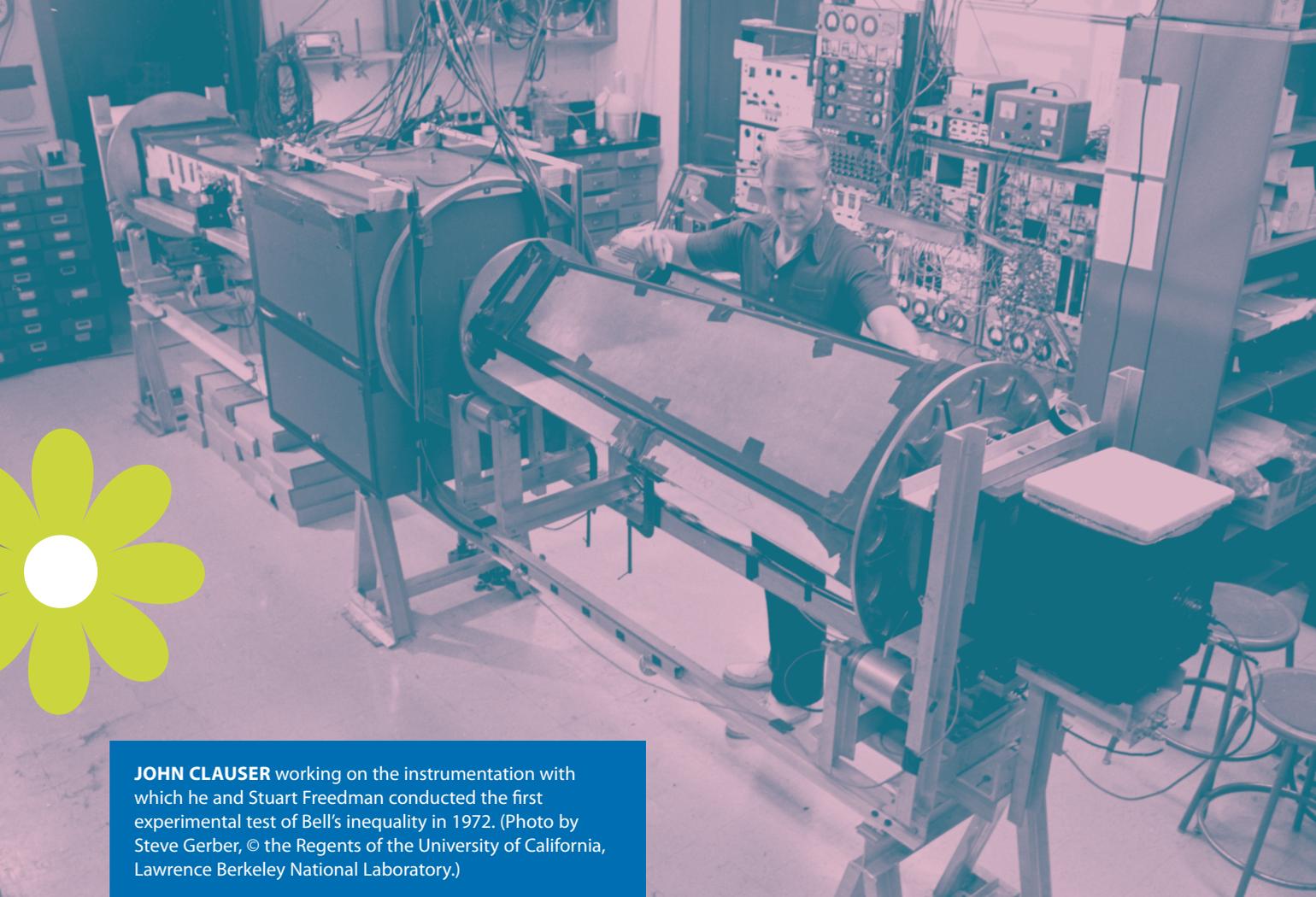
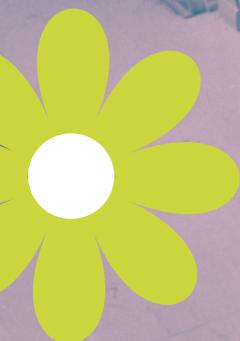
Nearly 30 years elapsed before the stalemate over entanglement began to shift. In 1964, physicist John Bell published his now-famous inequality⁸ (see the box on page 30). In an elegant, six-page article, Bell derived a constraint on the behavior of any physical system that obeyed the two reasonable postulates that Einstein, Podolsky, and Rosen had introduced in their analysis—namely, that a particle should possess definite values for various properties even when no one tries to measure those properties and that no force or signal could travel faster than the speed of light. Given those postulates, Bell demonstrated that there must exist an upper limit to how strongly correlated the outcomes of measurements could be on pairs of particles that had once interacted and then traveled arbitrarily far apart.

In just a few more lines, Bell demonstrated that according to quantum mechanics, the outcomes of measurements on such particle pairs could be more strongly correlated than the Einstein-like limit would allow. Bell's work thus identified a measurable difference between predictions from Einstein-like theories and those from quantum mechanics—a difference that, in principle, might be testable in a laboratory. Near the conclusion of his landmark paper, Bell emphasized that the strong correlations predicted by quantum theory sit rather uneasily with Einstein's relativity: For entangled systems, quantum theory seemed to suggest, local causes need not yield only local effects.

Today, entanglement and Bell's inequality are at the heart of quantum computing, quantum teleportation, quantum encryption, and more. Yet all that lay far in the future when Bell published his remarkable analysis. His paper was published in the first volume of an obscure journal, *Physica Physique Fizika*, which folded a few years later. The article garnered one citation in the worldwide scientific literature over the next three years, and that was a self-citation in one of Bell's other papers.⁴



JOHN BELL in his office at CERN in 1982.
(Photo © CERN, ref. 265-6-82.)



JOHN CLAUSER working on the instrumentation with which he and Stuart Freedman conducted the first experimental test of Bell's inequality in 1972. (Photo by Steve Gerber, © the Regents of the University of California, Lawrence Berkeley National Laboratory.)

Around that time, Clauser stumbled across Bell's article in a library at Columbia University, where Clauser was working on his PhD. Clauser's dissertation adviser urged him to stay away from such "philosophy."^{4,9} Disappointed, Clauser made a mental note of Bell's work. A few years later, as he was completing his dissertation and getting ready to start his postdoc at Berkeley Lab, Clauser reached out to Bell to see if any physicists had conducted the type of experiment that he had proposed. As Bell later recalled, Clauser's letter from February 1969 was the first response he had received about his work. Delighted that an experimentalist was showing interest, Bell dashed off his reply: No one else seemed to have noticed the work, and if Clauser could manage to measure a deviation from the quantum predictions, that would "shake the world!"^{4,9}

Quantum carnivalesque

By the time Clauser had made his way to Berkeley, he had struck up a new collaboration with Abner Shimony and Michael Horne. Shimony was then a professor of both physics and philosophy at Boston University, and Horne was his curious physics PhD student. Shimony had also stumbled on Bell's 1964 paper and become intrigued. Before long, Shimony and Horne spotted a brief abstract that Clauser had submitted to the *Bulletin of the American Physical Society*. Taking into account details like finite apertures and limited detector efficiencies, Clauser proposed to translate Bell's pristine alge-

bra into quantities that could be measured in a real experiment. Shimony tracked Clauser down by telephone in early 1969, and they arranged to chat at a meeting of the American Physical Society that spring. Horne, Clauser, and Shimony became fast friends, and they delved into the intricacies of entanglement and Bell's inequality in collaboration with experimentalist Richard Holt.

Clauser soon picked up other discussion mates in Berkeley. Some, including Elizabeth Rauscher and George Weissmann, were PhD students studying nuclear and particle physics at the University of California, Berkeley; others, like Capra, Nick Herbert, Jack Sarfatti, and Fred Alan Wolf, were a few years past their doctorates; another, Saul-Paul Sirag, had taken a detour from his physics studies to pursue theater and other passions. A few more senior researchers—staff scientists at Berkeley Lab like Henry Stapp and Philippe Eberhard—rounded out the group.

Each member of the group had entered graduate school in the years after the Soviets launched the *Sputnik 1* satellite, a time when generous federal funding drove skyrocketing physics enrollments. Each, in turn, found that their broad curiosity about the foundations of physics and the nature of reality had been stunted amid the overcrowded classrooms and narrow research agendas of their professors—much as Clauser had felt the sting when his Columbia adviser had steered him away from Bell's work.



FRITJOF CAPRA, author of *The Tao of Physics*, in November 1977. (Photo by Roger Ressmeyer/Corbis/VCG via Getty Images.)

TESTING BELL'S INEQUALITY

In his 1964 article, John Bell derives an inequality that limits how strongly correlated the outcomes of measurements on two or more particles can be if the outcomes of each measurement are independent of actions undertaken at arbitrarily distant locations. Further, he confirms that quantum mechanics predicts that measurements on particles in entangled states can be more strongly correlated than his new inequality would allow.^{8,13}

Incorporating an earlier suggestion by David Bohm, Bell focuses on dichotomic observables—that is, observables for which the measured outcomes can be only one of two values. Such is the case for an electron's spin. To measure it, a physicist must select a basis—namely, they must choose to measure the electron's spin along the x -direction, along the y -direction, or along any orientation in between. No matter which basis is selected, a measurement of the electron's spin along that direction yields only spin up (labeled $+1$) or spin down (-1).

The group members' main misfortune was to be seeking careers in physics during the early 1970s, just as the discipline was undergoing the steepest decline in its history (see "PHYSICS TODAY ads track employment boom and bust," *PHYSICS TODAY* online, 7 May 2018). As late as 1963, even amid exponential growth in the number of physics PhD students across the US, jobs for young physicists had been outpacing the number of graduates. Then a series of rapid-fire developments sent the physics profession into a tailspin: the escalation of fighting in Vietnam and the subsequent removal of draft deferments for students; widespread economic uncertainty compounded by oil shocks and stagflation; and a sharp reversal of funding priorities in the US Department of Defense and related federal agencies, which until the late 1960s had underwritten research and training in physics even for open-ended, basic research. By 1971, the number of PhD-holding physicists in the US seeking jobs outstripped the number of jobs on offer by a factor of 20.⁴

With newfound time on their hands and a rekindled passion to engage with the kinds of questions that had attracted them to physics in the first place, the ragtag collection of Berkeley physicists formed the Fundamental Fysiks Group, which met on Friday afternoons in a spare classroom on UC Berkeley's campus. They threw themselves with gusto into such topics as quantum entanglement, even as several of them struggled to make ends meet. In fact, during a time when few physicists paid much attention to Bell's work, nearly 90% of the research articles on Bell's inequality published through 1980 and written by US-based physicists came from members of the group or from authors who thanked group members for introducing them to the topic or clarifying various subtleties.⁴

Bell then sketches how an idealized version of an experiment to test his new inequality might go: A source σ emits pairs of particles that travel away from it in opposite directions, as seen in the figure. At each detector, a physicist selects a basis (\mathbf{a} for detector A, on the left, and \mathbf{b} for detector B, on the right) in which to perform a measurement; once each particle has reached its respective detector, the detector yields a measurement outcome (A, B). For spin, A and B could be only ± 1 , no matter which of the two bases the physicist had selected.

Bell then introduces correlation functions $E(\mathbf{a}, \mathbf{b}) = \langle A(\mathbf{a}) B(\mathbf{b}) \rangle$, where the brackets indicate averaging over many experimental runs in which pairs of particles were measured in the bases (\mathbf{a}, \mathbf{b}) . Given the fact that each measurement outcome $A(\mathbf{a})$ and $B(\mathbf{b})$ could be only ± 1 , the correlation function for any pair of bases (\mathbf{a}, \mathbf{b}) would satisfy $-1 \leq E(\mathbf{a}, \mathbf{b}) \leq +1$.

Next, Bell constructs a conditional probability $p(A, B | \mathbf{a}, \mathbf{b})$ to find the pair of measurement outcomes A and B given the selection of bases \mathbf{a} and \mathbf{b} . He defines it in terms of the conditional probability for detector A to yield measurement outcome A when performing a measurement in basis \mathbf{a} and the conditional probability for detector B to yield measurement



With newfound time on their hands and a rekindled passion to engage with the kinds of questions that had attracted them to physics in the first place, the ragtag collection of Berkeley physicists formed the Fundamental Fysiks Group.

Members of the Fundamental Fysiks Group pored over entanglement and Bell’s work while immersed in a burgeoning counterculture. Mainstream newspapers like the *San Francisco Chronicle* were reporting on such unorthodox topics as mind-reading experiments and tests of extrasensory perception, or ESP. Some group members began to wonder whether quantum entanglement—with its spooky, long-range connections between particles—might help to explain the latest reports. After Israeli stage magician and self-proclaimed ESP aficionado Uri Geller underwent testing at Birkbeck College in London in 1974 under physicist David Bohm’s direction,¹⁰ group member Sarfatti announced that entanglement, with its intrinsically nonlocal character, left “ample room for the possibility of psychokinetic and telepathic effects.”¹¹

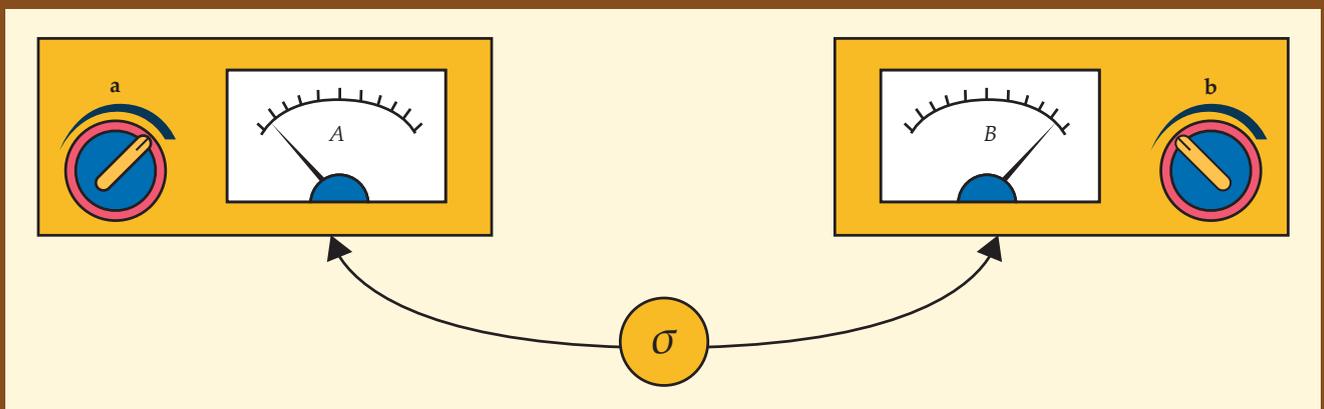
To pursue their unusual research topics, some group members sought cash from unlikely sources, including the Central Intelligence Agency and the self-made entrepreneurs in California who had become fascinated by such subjects as

the nature of human consciousness and whether quantum theory could help unlock human potential. The physicists became regulars at the Esalen Institute, the central gathering spot for New Age enthusiasts, nestled among the seaside cliffs in Big Sur, California. With help from an eccentric supporter named Ira Einhorn—a counterculture gadfly who was famous for hanging out with such flower-power advocates as Abbie Hoffman and was later convicted for the grisly murder of his girlfriend—they shared preprints across an underground network, even as Capra and a few others became bestselling authors.

Along the way, the group members inspired some fascinating work that, stripped of its original packaging, has since entered the physics mainstream. Take the no-cloning theorem, for example. A fundamental feature of quantum theory, the theorem was discovered in 1982 independently by Wojciech Zurek and Bill Wootters, by Dennis Dieks, and by GianCarlo Ghirardi and Tullio Weber. It stipulates that it is impossible to make exact copies, referred to as clones, of an unknown quantum state (see the Quick Study by Bill Wootters and Wojciech Zurek, *PHYSICS TODAY*, April 2025, page 46). It quickly became the linchpin for the first quantum encryption protocol.⁴

The physicists arrived at the theorem in the process of refuting a particularly clever entanglement-related thought experiment published by Fundamental Fysiks Group member Herbert earlier in 1982. As physicist Asher Peres wrote many years later—unmasking himself as having been one of the referees for Herbert’s paper and thus as having missed a subtle flaw in Herbert’s proposal that the no-cloning pioneers identified—Herbert’s “erroneous paper was a spark that generated immense progress.”¹²

By the time the Fundamental Fysiks Group had disbanded



outcome B when performing a measurement in basis \mathbf{b} :

$$p(A, B|\mathbf{a}, \mathbf{b}) = \int d\lambda p(\lambda) p(A|\mathbf{a}, \lambda) p(B|\mathbf{b}, \lambda).$$

Here, λ represents some shared properties of a given particle pair (often dubbed hidden variables) that could help deter-

mine the measurement outcomes at each detector. Bell assumes that there would be some probability distribution $p(\lambda)$ for a given value of λ to be selected each time a new pair of particles is created.

By design, Bell’s construction incorporates locality: The probability of finding measurement outcome A at detector A , written

HIPPIES AND BELL TESTS

in the late 1970s, it had left some remarkable legacies, given its humble platform. During their playful, creative romps, group members applied their disciplined physics training outside the usual institutions and remained open to out-of-left-field curiosities. In the process, they nurtured a focus on entanglement and Bell's inequality before many other physicists took notice.

Chasing loopholes

While writing my *Hippies* book, I learned about the early experimental tests of Bell's inequality. In a typical Bell test, a source emits pairs of entangled particles that move in opposite directions; physicists decide to perform a particular type of measurement on each particle, and then they identify correlations in the outcomes of those measurements. Learning more about Bell tests also introduced me to a series of loopholes that physicists, including Bell, Clauser, Shimony, and Horne, had identified over the course of the 1960s and 1970s—circumstances that, in principle, could account for the strong correlations measured in tests of Bell's inequality, even if the particles obeyed a model consistent with the postulates put forward in the 1935 paper by Einstein, Podolsky, and Rosen.

In their correspondence during 1969, for example, Bell and Clauser zeroed in on the timing of when various events should occur in a Bell test. They concluded that, ideally, the type of measurement to be performed at each detector should be selected such that no information about the selections could reach either the particle source or the distant detector until after each measurement had been completed. Otherwise, any correlations among the measurement outcomes could be attributed to the local flow of information during a given experimental run, all consistent with Einstein's postulates and with no need to invoke quantum entangle-

ment.⁹ That scenario was soon termed the locality loophole. Implementing fast switching of measurement selections proved too difficult in the early 1970s when Clauser and Freedman conducted their first experiment, but 10 years later, Alain Aspect led a team in France that accomplished just such a feat.¹³ (Aspect shared the 2022 Nobel Prize with Clauser and Anton Zeilinger.)



In an ironic twist, given my grumbling in grad school about needing to complete a lab course, we soon set to work designing a new type of experiment that could test Bell's inequality.

As described in the box, within a few years, Clauser, Shimony, and Horne identified another possible flaw in a Bell test, one that is now known as the freedom-of-choice loophole. Unlike the locality loophole, which deals with the flow of information during a given experimental run, the freedom-of-choice loophole concerns whether some common cause might have nudged or previewed in advance the sequence of measurements to be performed. If that were the case, the common cause could have shared that information with the particle source before any particles were emitted, without requiring any direct communication among parts of the experimental apparatus.¹³

I began thinking about the freedom-of-choice loophole in

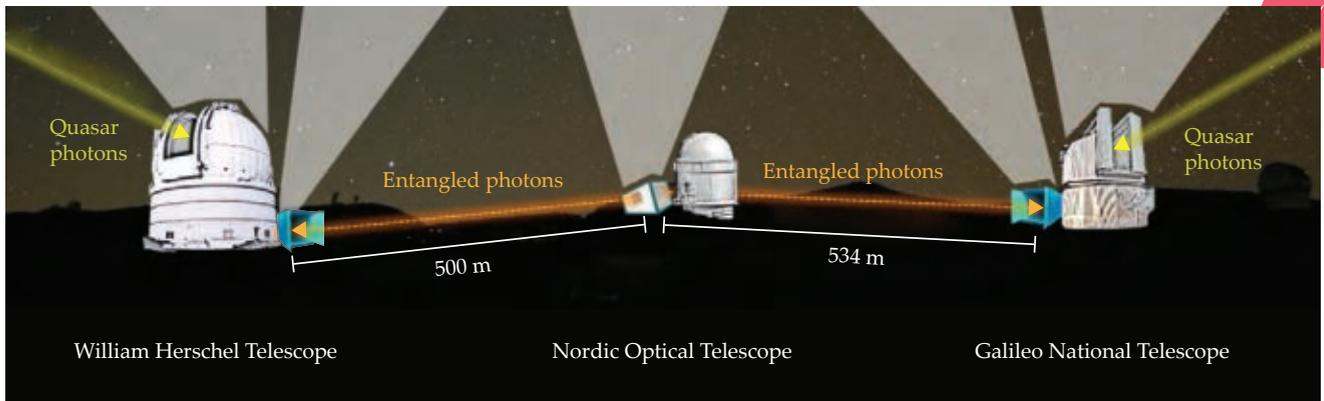
as $p(A|\mathbf{a}, \lambda)$, depends on the local properties carried by each particle (λ) and on the basis \mathbf{a} at detector A, in which the measurement would be performed. The probability does not depend, however, on either the basis \mathbf{b} or the measurement outcome B at the distant detector. Similarly, the converse is true for the probability of finding measurement outcome B at detector B: It does not depend on basis \mathbf{a} or the measurement outcome A at the other detector.

In 1969, soon after they began collaborating, John Clauser, Michael Horne, Abner Shimony, and Richard Holt cast Bell's inequality in a simpler form. In what was later termed the CHSH paper, they consider experiments in which each particle would be subjected to measurement in one of two bases: either \mathbf{a}_1 or \mathbf{a}_2 at detector A and either \mathbf{b}_1 or \mathbf{b}_2 at detector B. Then they consider a particular combination S of correlation functions, as one toggles the bases at each detector:¹⁸

$$S = |E(\mathbf{a}_1, \mathbf{b}_1) + E(\mathbf{a}_2, \mathbf{b}_1) - E(\mathbf{a}_1, \mathbf{b}_2) + E(\mathbf{a}_2, \mathbf{b}_2)|.$$

The innocent-looking minus sign in front of the third correlation function makes all the difference. In just a few lines of algebra, Clauser and colleagues—much like Bell before them—demonstrate that for any model of the particles' behavior that could be put in the form of Bell's conditional probability $p(A, B|\mathbf{a}, \mathbf{b})$, the Bell-CHSH parameter S must obey the inequality $S \leq 2$.

Again following Bell's lead, Clauser and his colleagues demonstrate with a brief calculation that quantum mechanics predicts violations of the inequality $S \leq 2$. They considered two-particle quantum states, such as $|\psi\rangle = (|+1\rangle_A |-1\rangle_B \pm |-1\rangle_A |+1\rangle_B)/\sqrt{2}$, which represents a superposition of two possible outcomes: Particle A will be measured as spin up (in a particular basis) and particle B as spin down (in that same basis), or particle A will be measured as spin down and particle B as spin up. (The factor of $1/\sqrt{2}$ comes from normalization: The quantum state needs to satisfy $\langle\psi|\psi\rangle = 1$.) For specific choices of the angles between measurement bases $\mathbf{a}_1, \mathbf{a}_2, \mathbf{b}_1$, and \mathbf{b}_2 , measurements on pairs of particles prepared in that quantum state should exceed the limit $S \leq 2$; in



A SCHEMATIC OF THE COSMIC BELL EXPERIMENT conducted in January 2018 at the Roque de los Muchachos Observatory on the island of La Palma in the Canary Islands. A team in a makeshift laboratory next to the Nordic Optical Telescope generated polarization-entangled particles that were emitted in opposite directions toward detector stations at the William Herschel Telescope and the Galileo National Telescope. Teams at those two telescopes also performed rapid measurements of the color of distant quasars. The result of each color measurement determined which one of two polarization bases an entangled particle would be measured in. The findings revealed a substantial violation of Bell's inequality and confirmed that the predictions of quantum mechanics are correct.

2012, about a year after my *Hippies* book had been published. Andy Friedman, then a new postdoc at MIT, had planned to work with me on research projects in early-universe cosmology. Perhaps intrigued by the funny-sounding title, he read my book on a lark and began brainstorming with Jason Gallicchio, his good friend from graduate school. As Andy and Jason recognized, cosmologists had learned a remarkable amount since the 1970s about the expansion history and large-scale structure of our universe, stretching all the way back to the Big Bang. With a fuller understanding of the varying rate at which the universe has expanded over time, astrophysicists and cosmologists could now map causal relationships across the vast sweep of cosmic

history—determining, for example, which discrete events in space and time could possibly have exchanged a single light signal with other spacetime events and which could not.

Andy and Jason shared their early ideas with me, and in an ironic twist, given my grumbling in grad school about needing to complete a lab course, we soon set to work designing a new type of experiment that could test Bell's inequality while shielding against both the locality and freedom-of-choice loopholes. Our basic idea: Turn the universe itself into a pair of rapid-cadence random-number generators. We proposed to use the results of real-time astronomical observations of distant objects, such as high-redshift quasars, to select

fact, the maximum value, according to quantum theory, is $2\sqrt{2}$.

A dozen years after Bell derived his inequality, Shimony, Horne, and Clauser pointed out a subtlety that Bell had overlooked: something known to statisticians as the law of total probability, which is similar to the chain rule in ordinary calculus.¹³ In constructing $p(A, B|\mathbf{a}, \mathbf{b})$, Bell had integrated the λ parameters over a probability distribution $p(\lambda)$ rather than over a conditional probability $p(\lambda|\mathbf{a}, \mathbf{b})$ —that is, the probability for parameters λ given the selection of measurement bases (\mathbf{a}, \mathbf{b}) . The conditional probability would account for any statistical correlations between the selection of measurement bases (\mathbf{a}, \mathbf{b}) on a given experimental run and the properties of the emitted particles λ . Such correlations could arise, in principle, from some shared common cause without any direct communication between parts of the experimental apparatus.

The possibility that $p(\lambda|\mathbf{a}, \mathbf{b}) \neq p(\lambda)$ has been dubbed the measurement-dependence loophole, also known as the freedom-of-choice loophole. Additional recent theoretical work has demon-

strated that only a minuscule amount of statistical correlation between λ and the bases (\mathbf{a}, \mathbf{b}) would enable a local, Einstein-like model to mimic all the correlations predicted by quantum mechanics for measurements on an entangled quantum state. (See reference 13 and references therein.)

To get an intuitive feel for Bell's inequality, one may simplify a bit and replace the averaged correlation functions with the products of measurement outcomes for a single experimental run. In their 1935 paper, Albert Einstein, Boris Podolsky, and Nathan Rosen had insisted that (at least in some situations) particles carry definite values for various properties prior to and independent of their measurement.⁵ So the three physicists might have imagined that the particle heading toward detector A had specific values for spin

HIPPIES AND BELL TESTS

measurements to perform on each member of a pair of entangled particles. By carefully arranging the spatial alignment of our Bell-test instrumentation on the ground, we could ensure that information about which measurement would be performed on each particle would be inaccessible to both the particle source and the detector for the other particle until both particles had been measured.¹⁴

As we were finalizing our proposal for the new “cosmic Bell” tests, we had good luck: None other than Anton Zeilinger, a renowned expert in experimental quantum optics and a leading figure in the long history of experimental tests of Bell’s inequality, visited MIT to give a colloquium at the physics department. I secured time on Zeilinger’s busy schedule, and at our appointed hour, Andy and I pitched to him our idea of using uncorrelated, astronomical sources of randomness for Bell tests. Within a few minutes, Zeilinger’s smile was as broad as Andy’s and mine. He and his group in Vienna had recently completed a major project related to the freedom-of-choice loophole, and he appreciated the novel twist that Andy, Jason, and I had in mind. In the meantime, Andy and I convinced cosmologist Alan Guth, my MIT friend and colleague, to join our project. And so our international cosmic Bell collaboration was born.

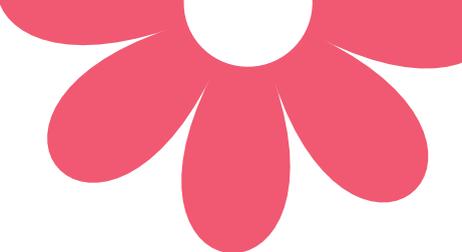
After we conducted a successful pilot test in Vienna in April 2016 using small-scale telescopes trained on bright Milky Way stars,¹⁵ Zeilinger managed to secure telescope time for our group at the Roque de los Muchachos Observatory, on the island of La Palma in the Canary Islands. At the observatory during January 2018, one team set up at the William Herschel Telescope while another team took over the Galileo National Telescope—both world-class optical telescopes with roughly 4-meter mirrors. A third team worked near the Nordic Optical Telescope in a makeshift laboratory, placed about 500 meters from each of the other telescopes, in which the members used a pump laser and a nonlinear crystal shipped from Zeilinger’s lab to generate about 1 million polarization-entangled photons per second. The entangled particles were beamed through the night sky, in opposite directions, toward detectors at the Herschel and Galileo Telescopes.

along both orientations \mathbf{a}_1 and \mathbf{a}_2 , even if a given measurement revealed only one of those values. If we denote A_1 as the value of the particle’s spin in basis \mathbf{a}_1 , then $E(\mathbf{a}_1, \mathbf{b}_1)$ becomes simply $A_1 B_1$, and so on. Then the Bell–CHSH factor S would take the form:

$$[A_1 B_1 + A_2 B_1 - A_1 B_2 + A_2 B_2] = [(A_1 + A_2) B_1 - (A_1 - A_2) B_2].$$

Since each spin value can only equal ± 1 , then either $(A_1 + A_2) = \pm 2$ while $(A_1 - A_2) = 0$ or vice versa. And since B_1 and B_2 likewise only equal ± 1 , the parameter S should obey $S \leq 2$.

A violation of the Bell–CHSH inequality implies that particles do not carry definite values of all relevant properties prior to measurement or that measurement outcomes at one detector



“Within a few minutes, Zeilinger’s smile was as broad as Andy’s and mine.”

While a pair of entangled photons was in flight, the Galileo Telescope team would perform a rapid measurement of the color of a distant quasar, whose light had been traveling toward Earth for the past 8 billion years. If, during a microsecond-long window, the quasar light happened to be redder than its average color, that would trigger the neighboring equipment to prepare to measure the incoming entangled photon (still zooming across the island) in one polarization basis. If the quasar measurement instead had been bluer than its average color, then the entangled particle would be measured in a second polarization basis. Meanwhile, the same procedure—triggering off a different quasar, on the opposite side of the sky, whose light had been traveling toward Earth for 12 billion years—unfolded at the Herschel Telescope.

We measured about 30 000 pairs of entangled particles that night on the mountaintop, each time selecting new measurement bases, predicated on updated inputs from the quasars, at each detector (see the box). Our results yielded a significant violation of Bell’s inequality—exactly as predicted by quantum theory—even as our experiment addressed both the locality and freedom-of-choice loopholes. To account for those results, any Einstein-like mechanism that could have exploited a modest statistical correlation among detector settings and particle properties would need to have been set in motion at least 8 billion years ago, long before any physicists were around to ponder such wonderful topics as quantum entanglement.¹⁶

Entanglement today

Since 2015, several groups around the world have tested Bell’s inequality while addressing various pairs of loopholes

are not independent of actions taken (such as the selection of a particular measurement basis) at a distant detector. Even though both of those postulates seem quite reasonable—we can go about our daily routines confidently assuming that the objects we encounter have definite properties on their own and that information obeys Einstein’s relativistic speed limit—they do not both hold in quantum mechanics. And thanks to more than 50 years of experimental tests of Bell’s inequality, we now know that the quantum prediction holds up: The Bell–CHSH inequality is routinely violated in careful experiments, which means that we indeed live in an entangled quantum world.¹³



THE COSMIC BELL COLLABORATION, nourished by a lunch near MIT, takes form in October 2014. From left to right are Andy Friedman, Jason Gallicchio, Anton Zeilinger, and David Kaiser.

(see *PHYSICS TODAY*, January 2016, page 14). Like our cosmic Bell tests, each of those experiments has measured significant violations of Bell's inequality, exactly as predicted by quantum theory. Over the past decade, the new generation of multi-loophole-closing experiments has demonstrated beyond dispute that quantum entanglement is a basic fact of our world.¹³

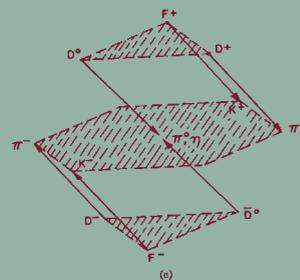
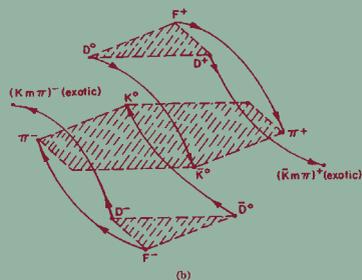
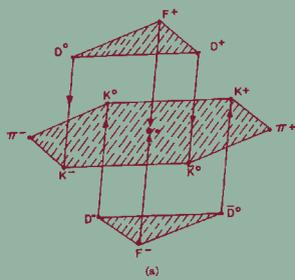
Some of the most ambitious and audacious Bell tests—including a breathtaking experiment by Jian-Wei Pan and his group that involved measuring, at detector stations roughly 1200 km apart, pairs of entangled photons emitted from a satellite in low Earth orbit¹⁷—have been central to testing quantum encryption infrastructure.

Efforts to understand quantum entanglement and to test or constrain various alternatives have enabled generations of physicists to explore the fundamental strangeness of quantum theory. At the same time, as topics like entanglement and Bell's inequality have wandered into and out of the mainstream, they enable us to chart the changing boundaries in the field of physics and the shifting place that physicists have occupied in our wider cultures—an evolution that we can ponder from many perspectives as we celebrate the International Year of Quantum Science and Technology in 2025.

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RE-REMEMBERING BENJAMIN WHISOH LEE

PROMOTER OF GAUGE THEORIES

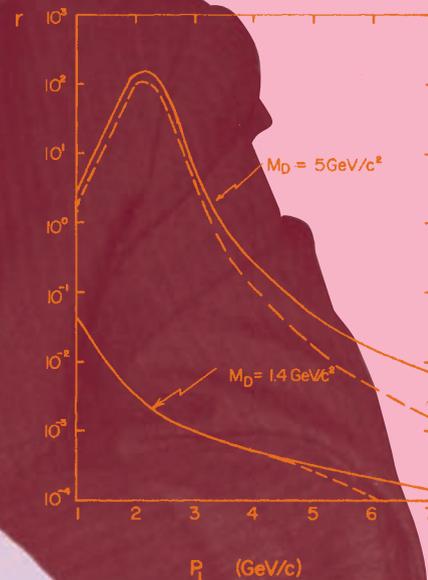
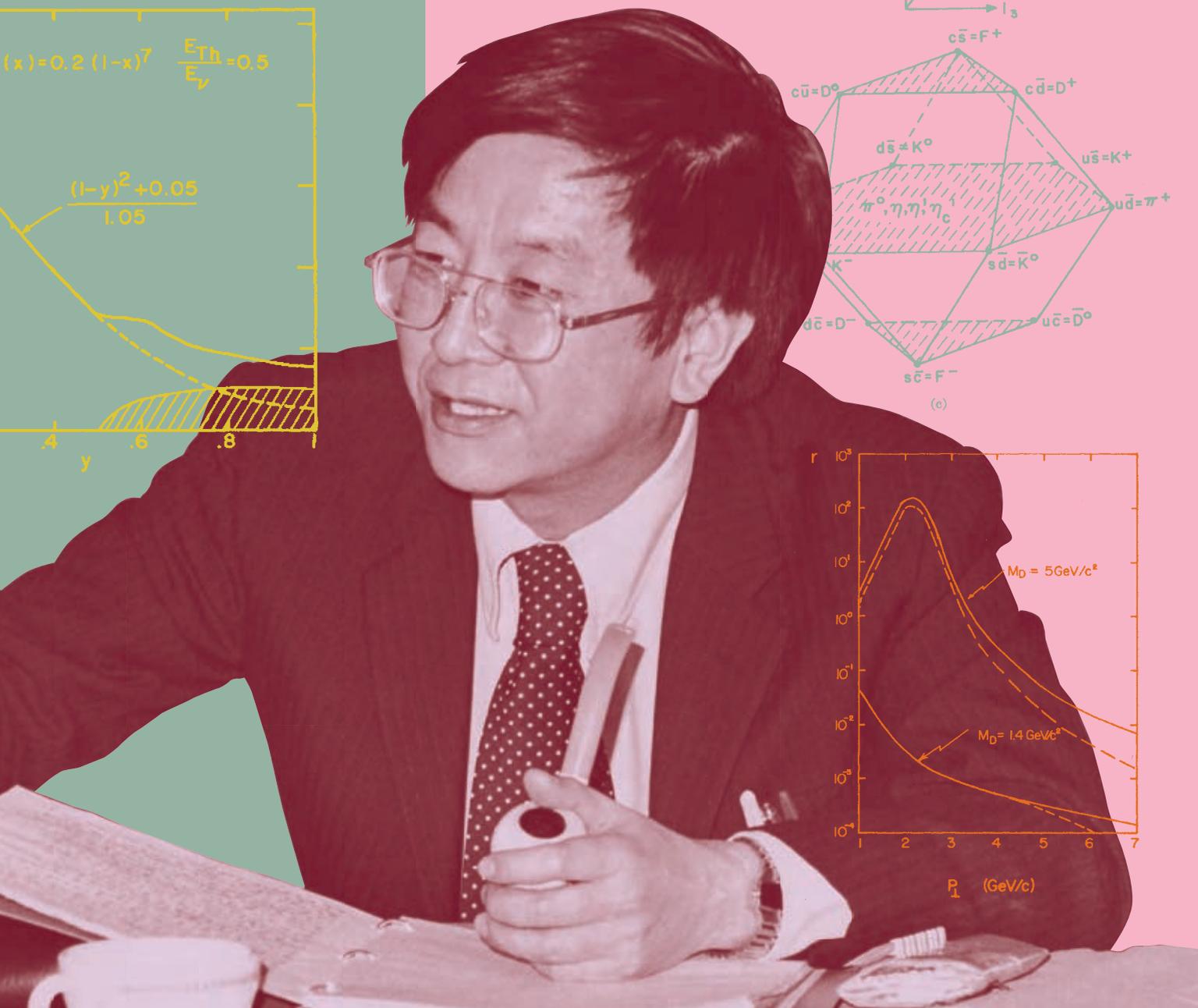
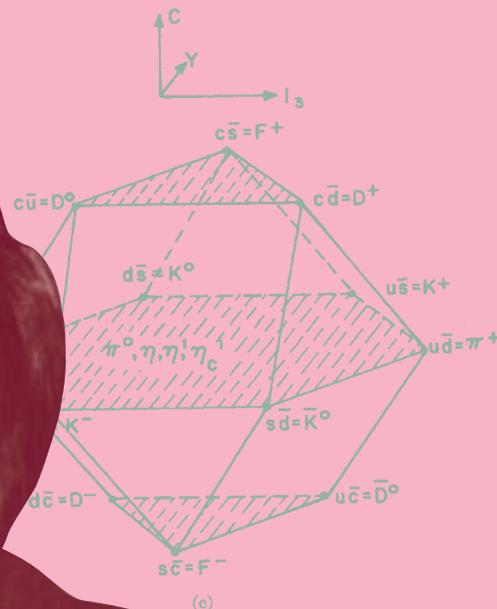
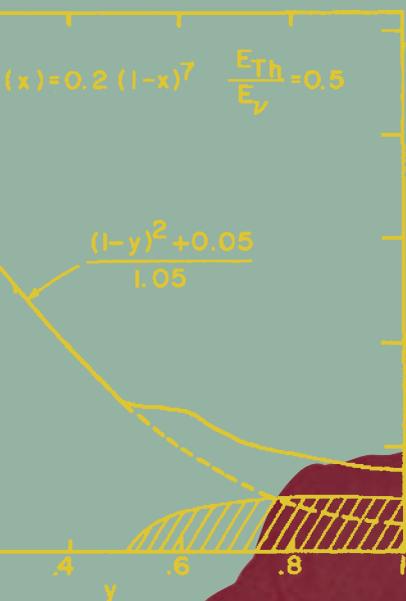


The Korean American physicist made the framework underlying the standard model accessible to a generation of particle physicists.

Eun-Joo Ahn



Eun-Joo Ahn is a lecturer and Presidential Visiting Fellow in the department of physics and a faculty fellow at the Center for the Study of Race, Indigeneity, and Transnational Migration at Yale University in New Haven, Connecticut. She holds a PhD in history from the University of California, Santa Barbara, and a PhD in astronomy and astrophysics from the University of Chicago.



Ben Lee giving a lecture titled "Development of Unified Gauge Theories: Retrospect" at the 1977 American Physical Society meeting held in Chicago. (Photo courtesy of Fermilab; figures adapted from ref. 11.)

RE-REMEMBERING BENJAMIN WHISOH LEE



A FAMILY PHOTO IN SEOUL, KOREA, taken in 1943 shows Benjamin Whiso Lee (right) at age 8. His mother Park Soonhui (left) holds his youngest brother Moo-Un, and his sister Youngja stands beside her. His grandmother holds his brother Chulwoong. (Photo © Korea University Museum.)

Gauge theories use the mathematics of symmetries to explore how subatomic particles behave. The theories have been used to predict the existence of elementary particles, including the Higgs boson, well before they've been observed and to unfurl details about the first few seconds of the universe's existence. To this day, researchers in cosmology and particle physics benefit from Benjamin Whiso Lee's contributions to the development and dissemination of gauge theories.

Well versed in mathematical and theoretical work, Ben Lee (as he was better known to his colleagues) made the demonstration of a renormalizable electroweak theory—the unified description of weak interaction and electromagnetism—accessible to other physicists. (See the article by Steven Weinberg, *PHYSICS TODAY*, April 1977, page 42.) Most physicists of the late 20th century studied his lectures rather than the original papers.¹ Lee's work was crucial, akin to Freeman Dyson's efforts to make quantum electrodynamics accessible to the physics community in the 1950s.² (See the article by Dyson, *PHYSICS TODAY*, September 1952, page 6, and reprinted January 2025, page 18.)

Lee was born in Korea in 1935 and went to the US at age 20 to study physics as an undergraduate transfer student at Miami University in Ohio. Within 10 years, he became a tenured professor at the University of Pennsylvania. Later, he

was a professor at SUNY Stony Brook and then at the University of Chicago, and he also headed the theoretical division of Fermilab. Lee's scientific contributions permeated theoretical and experimental particle physics in the 1960s and 1970s. His untimely death in 1977 in a car accident was met with shock by the international physics community. (See his obituary in *PHYSICS TODAY*, September 1977, page 76.) Though he is still warmly remembered by close friends and colleagues, his early death perhaps contributes to his obscurity today.

We can honor Lee's memory by remembering his scientific contributions in a societal context. At a time of unprecedented expansion in elementary particle physics, Lee enabled a generation of physicists in the field to embrace gauge theories. He also embodied the student immigrant who, during the second half of the 20th century, went to a wealthier and more powerful country to gain knowledge and seek a better life.

Growing up in Korea

Lee Whisoh (his given name) was born in Seoul during the period when Korea was colonized by Japan, which lasted from 1910 until the end of World War II. His family—Lee, his three younger siblings, his grandmother, and his parents—lived comfortably off the income from the medical practice of his mother, Park Soonhui. Despite an increase in doctors trained in Western medicine after Japan and Western powers forced the opening of the Korean border in the late 1800s, women doctors were still rare. Park, who specialized in pediatrics, obstetrics, and gynecology, worked at a charity hospital and later opened a private practice. The family's financial security was rare among Korean families, who suffered under the repressive and exploitative Japanese occupation.

At age six, Lee entered elementary school. The colonial government's education policy in Korea was aimed at producing useful subservient labor for the Japanese Empire, which led to a segregated education system: a superior one for Japanese citizens that was on par with the education standards in Japan and an inferior one for Koreans that emphasized loyalty to the Japanese emperor. Unlike most Korean children, Lee attended a school intended for Japanese children. There is speculation, but no proof, that Park formed connections through her medical practice that enabled her son to attend the elite school.

Two years after Korea's 1945 liberation from Japanese rule, Lee took the entrance exam for the top academic secondary school in Seoul and was accepted. His academic trajectory straddled privilege and turmoil. After liberation, despite many Koreans' hope for a unified country, Korea was partitioned along the 38th parallel, with the Soviet Union administering the North and the US administering the South. The North established a Communist regime, and the South formed a democratically elected government that quickly became increasingly authoritarian. The clash between the two Koreas culminated in the 1950–53 Korean War.

In 1951, Lee's family evacuated to the Pusan Perimeter in southeast Korea, the area that South Korean, US, and United Nations forces were holding against the advancing North Korean forces. During the war years, the family maintained relative stability. Lee's parents worked as doctors, and Lee resumed attending his secondary school, which had relocated to inside the perimeter. In those times of starvation and devastation, education was a luxury denied to most families. The war took a toll on Lee and his family, especially with the loss of his father. That loss contributed to Lee hastening to finish his secondary school studies and to take the entrance exam for Seoul National University, which also had been moved inside the perimeter. In 1952, he started in the university's most prestigious and popular department: chemical engineering.

Three years of war destroyed Korea's infrastructure and left the country heavily reliant on foreign aid to provide food against famine and to rebuild the country. In South



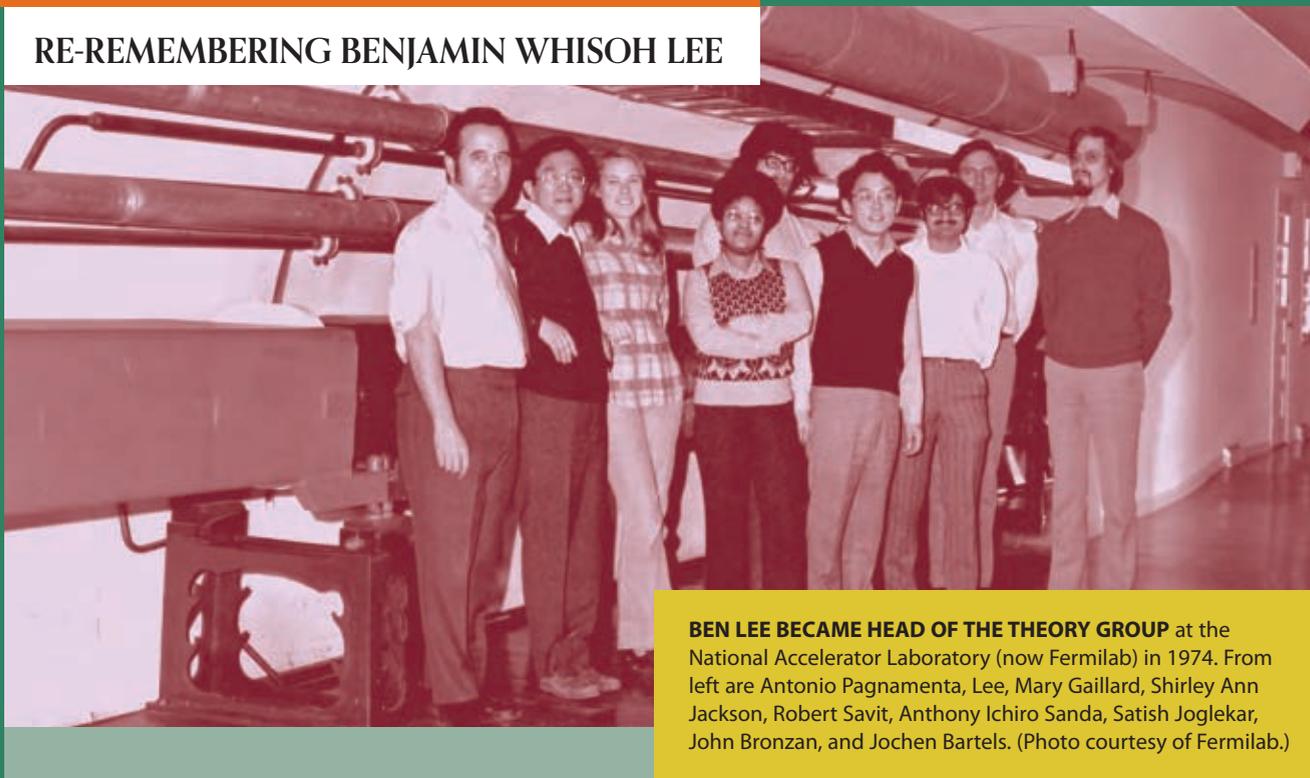
AFTER GRADUATING FROM MIAMI UNIVERSITY in 1956, Ben Lee went on to study theoretical particle physics in graduate school. He then earned an MS degree from the University of Pittsburgh in 1958 and a PhD from the University of Pennsylvania in 1960. Lee is shown here reading a textbook in the late 1950s. (Photo © Korea University Museum.)

Korea, chemical engineering was prized as a discipline that could accelerate industrialization through development of existing textile factories and agricultural production. Physics, on the other hand, was regarded as less helpful.³

But when he returned to Seoul after the armistice of 1953, Lee became increasingly drawn to physics. Despite being the best university in South Korea, Seoul National University lacked the teachers, textbooks, and lab instruments to properly teach science. Courses in chemical engineering focused on the application side, but Lee found fundamental chemistry and basic principles more interesting. By his third year, Lee was studying quantum mechanics on his own and sought to transfer to the physics department. But he was in the College of Engineering, and the physics department was part of the College of Liberal Arts and Sciences. University regulations did not allow transfer between colleges. Ordinarily, his only option would have been to retake the entrance exam. Yet the war that devastated Korea ironically provided an alternative path for Lee to pursue physics.

That path came in the form of scholarships that were available for students to study abroad. Considered humanitarian aid, the scholarships were made available by private foundations and nongovernmental organizations, mostly in the US, that were affiliated with Christian missionaries or with military personnel. Though the scholarships were privately sponsored, they were nevertheless designed to expand US soft power and to help stop the spread of Communism in South Korea. The scholarships were often merit based and required applicants to take a test. As a student at the nation's premier university, Lee was well positioned to apply for one.

RE-REMEMBERING BENJAMIN WHISOH LEE



BEN LEE BECAME HEAD OF THE THEORY GROUP at the National Accelerator Laboratory (now Fermilab) in 1974. From left are Antonio Pagnamenta, Lee, Mary Gaillard, Shirley Ann Jackson, Robert Savit, Anthony Ichiro Sanda, Satish Joglekar, John Bronzan, and Jochen Bartels. (Photo courtesy of Fermilab.)

Lee received a scholarship sponsored by the spouses of military officers. After getting accepted as a transfer student to major in physics at Miami University, he left South Korea in January 1955 on a student visa. From the devastated grounds of Korea in the 1950s, an education in the US was a privilege only a few could attain. Lee joined other members of the emerging Korean middle class in using education to navigate the turbulent period.

A Korean student in the US

Lee did his best to acclimatize to life in the college town of Oxford, Ohio. It was his first time seeing so many white people and being on a coed campus. In an effort to better fit into US society, he gave himself an English name: Benjamin, after the American polymath and founding father Benjamin Franklin, whom Lee had learned about in Korea and admired for his empirical turn of mind.

For Lee and fellow Korean students, studying abroad generated mixed feelings of homesickness, appreciation of opportunity, and ambition to study hard. Simple chores such as going to the laundromat brought out the contrast with Korea, where laundry was still washed by hand. Regular correspondence between Lee and his family at that time reflects how much he missed them. He wrote to them about the times he got together with other Korean students on campus, visits made by Korean students from nearby cities, and homesick children he helped while working as a summer camp counselor. As the eldest son, he felt the duty to oversee his younger siblings' upbringing, even from far away, and would remind them to mind their mother and not cause trouble.

Lee studied hard and was determined to be at the top of

his class. He had outstanding professors, including George Arfken, who would go on to write the well-known textbook *Mathematical Methods for Physicists*, and took up the challenge of advanced mathematics courses. In his third and last semester, Lee became the top physics student and applied to graduate school. In 1956, Lee graduated summa cum laude and started his physics graduate studies at the University of Pittsburgh, where he had secured a teaching assistantship.

As a graduate student, Lee developed a preference for theoretical work and became interested in quantum field theory. With his adviser, Edward Gerjuoy, he systematically studied scattering processes, which became the basis of his master's thesis. Building on that work, Lee published his first scientific article demonstrating a new dispersion relation for particle scattering.⁴ Gerjuoy recommended that Lee transfer to the University of Pennsylvania to work with Abraham Klein, who was an expert on field theory and had studied under Julian Schwinger. After receiving his MS degree from Pittsburgh in the summer of 1958, Lee moved to Philadelphia. At Penn, Lee continued working on the dispersion relations of particle scattering for his PhD thesis.

Lee and his family regarded his studies in the US as an investment in a better financial and sociocultural future for them all. Though he took on some part-time jobs, especially at the start of his time at Miami University, Lee regularly asked his mother to wire him funds so he could focus on his studies. Her income was not enough to support Lee and his siblings, and the family faced increasing financial difficulties. Lee was sensitive to the hardship he was causing. In graduate school, he would send money home whenever he could spare it from his fellowship stipend or assistantship salary.



Becoming a Korean American physicist

When he first traveled to the US, Lee expected to return to South Korea with a physics degree. As time went by, though, he remained in the US. His rise in the physics community, the availability of jobs, politics in both South Korea and the US, and personal choice all shaped his ultimate decision to stay.

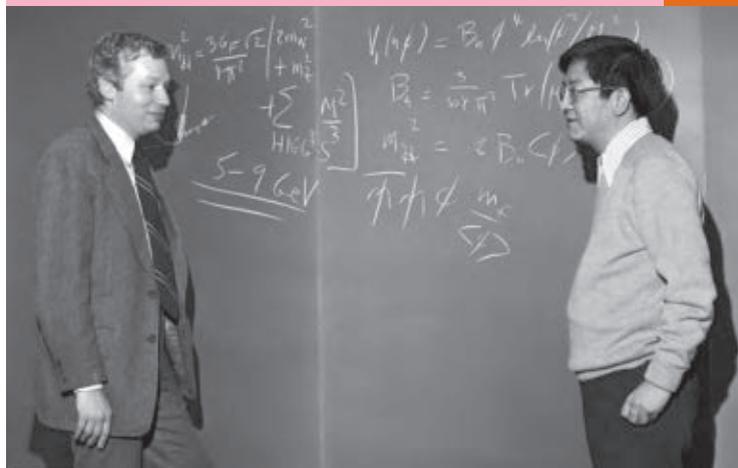
Lee's interest in elementary particles expanded in breadth and depth. Experimental physicists used increasingly powerful accelerators to further probe the nature of subatomic particles. Lee studied with mathematical rigor how particles such as kaons, pions, and nucleons scatter or interact via resonances. At Penn, he worked not only with his adviser but also with other professors, postdocs, and fellow graduate students in the department. Those collaborations led him to write eight articles—an extraordinary number for a graduate student—that were published in several high-profile journals. After filing his PhD thesis in October 1960, Lee was offered an assistant professorship at Penn. Before starting, he took a year of leave at the Institute for Advanced Study in New Jersey. There, Lee widened his pool of collaborators and continued to study dispersion relations and phenomena in strong interactions.

The opening sentence in a 1962 *Review of Modern Physics* article by Lee and colleagues aptly captures his perspective at the time: “One of the most natural questions when one looks at the mass of uncorrelated data on elementary particle interactions is whether a systematic pattern is emerging from this complexity.”⁵ Lee used his impressive mathematical skills to search for and explore the consequences of those patterns. Back at Penn, he became increasingly interested in spontaneous symmetry breaking.⁶ In 1966, Nobel laureate Chen Ning Yang recruited Lee to the newly formed Institute for Theoretical Physics at Stony Brook.

Lee's academic brilliance was no doubt essential to his ascendance in the field. The state of physics during that time was also an important factor. In the aftermath of World War II, and with the onset of the Cold War, physics was perceived to hold the key to US security and prosperity.⁷ The sentiment was exacerbated when the Soviets launched the first artificial satellite, *Sputnik I*, in 1957. The scope of physics research expanded: Physicists advised the government, government agencies provided generous research funding, and graduate training in physics was deemed critical.⁸ Fueled by unprecedented funding, physics departments throughout the country expanded, awarded many PhDs, and hired faculty as never before.

Meanwhile, in South Korea, the anti-Communist president Syngman Rhee led an authoritarian and corrupt government. Rhee was ousted in a citizen-led revolution in 1960 that brought hopes of democracy. Such hope was extinguished the following year by a military coup led by Park

STEVEN WEINBERG AND BEN LEE, pictured here at Fermilab, had a fruitful collaboration that produced an early calculation of the lower bound of heavy neutrinos' mass. (Photo courtesy of Fermilab.)



Chung Hee, who established a dictatorship. Yet Korean students in the US were never regarded as political refugees the way Chinese students were when the Communist Party gained control of mainland China in 1949. Despite human rights abuses and crackdowns on democratic movements in South Korea, the US regarded the firmly anti-Communist government as a close ally.

Changes to US immigration laws opened the channel for foreign students, particularly those from Asia, to become US citizens. Legislation from the late 1800s and early 1900s had effectively banned Asian immigration. The 1952 Immigration and Nationality Act restricted global immigration in response to national security concerns fueled by the Cold War. But the legislation also abolished the earlier bans on Asian immigration, although it still retained a stringent quota. Influenced by both the civil rights movement and Cold War geopolitical concerns, the US government passed an act in 1962 that facilitated application for permanent residency by skilled workers, and in 1965, it passed the Immigration and Nationality Act that eliminated racial quotas. Korean students with advanced degrees had a choice of either returning to their home country or applying for US citizenship.

Because of those changes, Lee obtained permanent residency in 1962 and became a US citizen in 1968, the year the 1965 Immigration and Nationality Act took full effect. Lee had both personal and professional reasons to stay in the US. He had become a prominent figure in the US particle-physics community, and he kept up with new theoretical and experimental developments. If he had returned to South Korea, he would have had to build a professional community essentially from scratch. Also, his wife Marianne, a Chinese Malaysian medical student, and their children would have been treated as perpetual foreigners. At the time, those considered foreigners—which included people who were half Korean—faced sociocultural hostility and discrimination upon settling down in South Korea.

An impactful career

After the 1956 discovery that the weak force does not operate with mirror symmetry (see the article by Chon-Fai Kam, Cheng-Ning Zhang, and Da Hsuan Feng, *PHYSICS TODAY*, December 2024, page 28), the particle-physics community began investigating the suspected connection between weak and electromagnetic interactions. Working independently, Sheldon Glashow, Abdus Salam, and Steven Weinberg developed a formalism that unified electromagnetism and weak interactions. That work would later earn them the 1979 Nobel Prize in Physics (see *PHYSICS TODAY*, December 1979, page 17). But the model required renormalization—a mathematical redefinition of calculated quantities such as mass—to make the infinities that arise in the calculations become finite.

By the early 1970s, the community started to recognize how the Glashow-Weinberg-Salam theory could be renormalized. Lee had the breadth of knowledge needed to examine mathematical approaches, including his own contributions, that laid the groundwork for unified gauge theories. With Jean Zinn-Justin, he published a series of articles that demonstrated the renormalizability of spontaneously broken gauge theories.⁹

Lee was one of the first physicists to recognize the significance of work by Gerard 't Hooft and Martinus Veltman, who received the 1999 Nobel Prize in Physics for demonstrating the renormalizability of the Yang-Mills theory (see *PHYSICS TODAY*, December 1999, page 17), which describes electroweak and strong interactions. With the depth of knowledge needed to grasp the complexities of the work and to synthesize a coherent explanation of gauge symmetries, Lee gave a series of lectures at Stony Brook on gauge theories. Based on those lectures, Lee and his colleague Ernest Abers compiled a review article that became the authoritative source for the study of gauge theories.¹

The long boom of US physics research in the 1950s and 1960s, enabled by generous funding from government agencies because of the Cold War and the space race, was followed by a bust in the early 1970s. In the face of a costly Vietnam War, détente with the Soviet Union, and economic stagnation, federal funding for defense and education declined, and government agencies rapidly decreased physics funding. Research money dried up, and faculty and post-doctoral job openings disappeared.

Even during those hard times, Lee was in demand. In the suburbs of Chicago, experimental particle physicist Robert Wilson was leading construction of the National Accelerator Laboratory (now Fermilab) in the face of retrenchment. Wilson and deputy director Edwin “Ned” Goldwasser were eager to recruit Lee to head the nascent theory department. Well versed in the theoretical and experimental developments related to gauge theories and weak interactions, Lee considered it an attractive opportunity.

A photograph taken at Fermilab in 1974 (see page 40) shows some of the members of the theory group, which was more diverse than most particle-physics groups at the time. According to colleagues at Fermilab, Lee did not discriminate based on gender or race; he wanted group members of the highest caliber. The small group cannot fully represent a cross section of the demographics of particle physicists in the 1970s, but it does show that the US physics community was far from homogeneous. What cannot be shown is the myriad discriminatory barriers faced by members of marginalized groups who sought to become research physicists.

Fermilab’s theory group thrived. Lee’s extensive knowledge of theoretical and experimental work in particle physics drew many visitors and collaborators. Chris Quigg and William Bardeen joined the department as senior members, which further enriched the research program. A collaboration between Lee and Mary Gaillard formed spontaneously when the latter was a visiting scientist at Fermilab. Together they produced a number of influential works, including an evaluation of the effects of strong interaction on weak decay of mesons and a prediction in 1975 of the charm quark mass.^{10,11}

“One of the most natural questions when one looks at the mass of uncorrelated data on elementary particle interactions is whether a systematic pattern is emerging from this complexity.”

Robert Shrock found the ambience of the Fermilab theory group exhilarating, and he was greatly inspired by Lee in the collaborative research they did together. Their work included examining the interaction of charged and neutral leptons. They showed that the electroweak theory naturally suppresses flavor mixing, and that condition extends to cases for neutrinos with nonzero mass.¹² In another area, Bardeen, Lee, and Shrock obtained nonperturbative results for the nonlinear sigma model.¹³ Such work expanded the understanding of the standard model of particle physics.

Weinberg, who typically preferred working alone, recalled that he made an exception for Lee, with whom he enjoyed collaborating.¹⁴ One of Lee’s last projects was with Weinberg; they derived a lower bound for the mass of stable cosmological leptons, which include neutrinos and other neutral particles that may constitute dark matter. Known as the Lee-Weinberg bound, it informs today’s dark-matter searches.¹⁵

Lee was at the top of the world in particle physics. Gaillard cited Lee’s “rare combination of a familiarity with formal



A FEW MONTHS AFTER BEN LEE'S UNTIMELY DEATH, the particle-physics community celebrated his memory and accomplishments at the Ben Lee Memorial International Conference on Parity Nonconservation, Weak Neutral Currents and Gauge Theories on 22 October 1977 at Fermilab, outside Chicago. (Photo courtesy of Fermilab.)

mathematical techniques and a close touch with experimenters and experimental results" as attributes that enabled him to stay at the forefront of a wide range of research topics.¹⁶

As his career advanced, Lee remained ambivalent about his relationship with South Korea. Disapproving of Park Chung Hee's dictatorship, he kept few to no professional contacts in the country. Even so, in 1974, he helped with an evaluation conducted by the US Agency for International Development that explored strategies to help Seoul National University develop graduate education. Self-described in that report as "Korean—by birth, and an American—by choice and citizenship," Lee combined his insights about the Korean university environment and US higher education. He offered recommendations that spanned issues like faculty salaries, graduate coursework, and library resources.¹⁷

Lee's legacy

On 16 June 1977, Lee died in a car accident on his way to the Fermilab Program Advisory Committee meeting in Aspen, Colorado. He was one of the organizers of a meeting on weak interactions and gauge theories that was going to be held at Fermilab in October of that year. The conference name was changed to the Ben Lee Memorial International Conference on Parity Nonconservation, Weak Neutral Currents and Gauge Theories. His family and colleagues established the Dr. Benjamin Lee Memorial Scholarship at Miami University in his memory. Electroweak theory became an accepted component of the standard model of particle physics, greatly aided by Lee's promotion and teaching of it to his colleagues. Yet Lee's name nevertheless slowly faded away in the physics community.

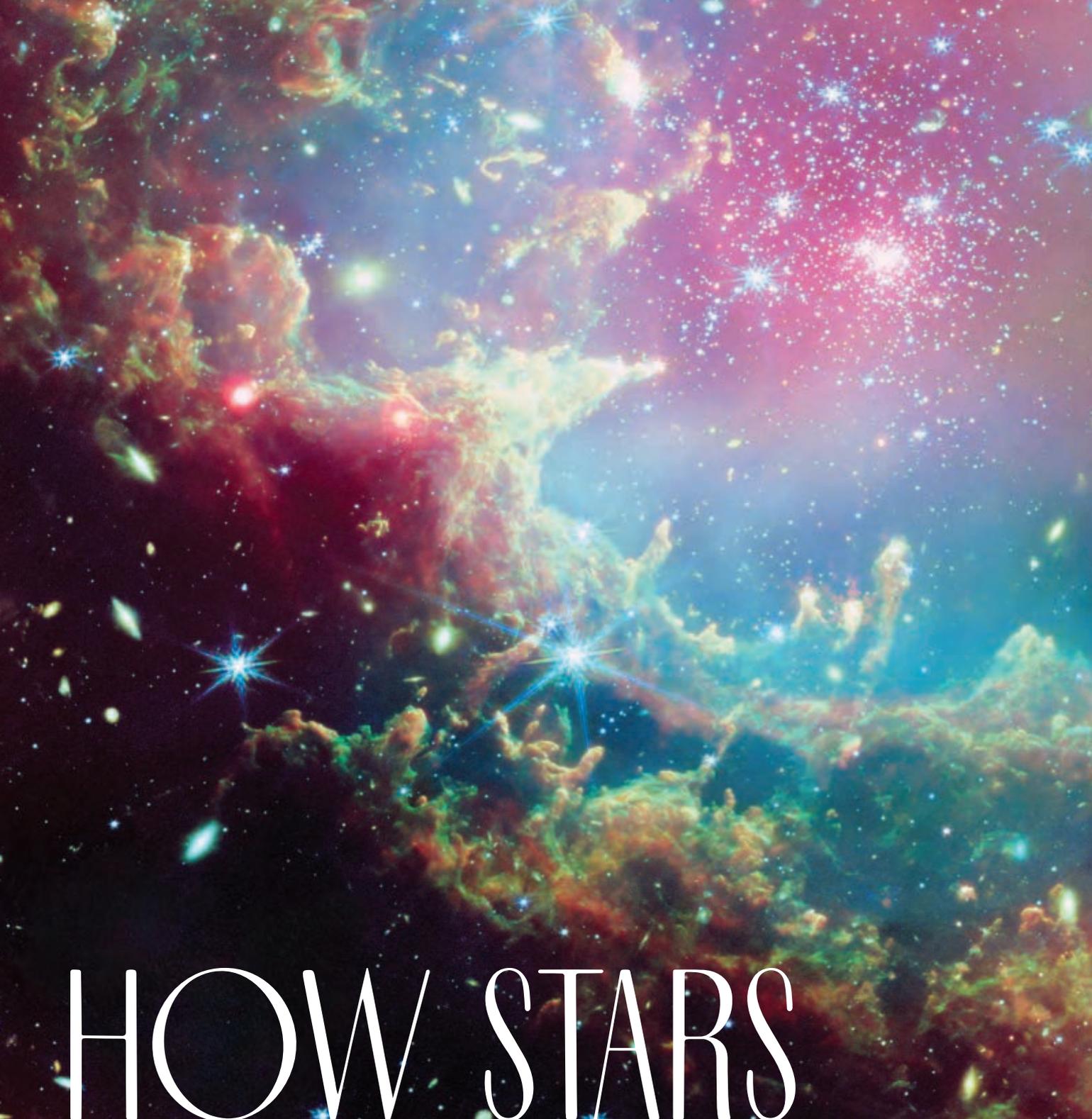
Lee's remembrance took an unusual turn in South Korea decades after his death. Sometimes exaggerating his achievements and sometimes conflating the field of theoretical particle physics with nuclear physics or engineering, scientists and media portrayed him as a genius patriot whose untimely death tragically precluded him from receiving the Nobel Prize in Physics and helping with the development South Korea's science and engineering programs. Scholars have pointed out that Lee's life was mythologized into a Korean success story, in which he overcame his home country's impoverished circumstances to become a world-leading authority in an impossibly difficult field.¹⁸

Calling Lee a genius who missed out on the Nobel Prize captures only a narrow slice of who Lee was. Even the description of him as the promoter of gauge theories acknowledges just one of his facets. He was eager to advance the field and treated his colleagues equally regardless of gender, race, or position. Weaving together his numerous contributions to the development of today's standard model of particle physics with his navigation of the geopolitical and sociocultural landscape offers a richer understanding of how physics knowledge is made.

I am grateful to Robert Shrock, Liz Quigg and Chris Quigg, and Marge Bardeen and Bill Bardeen for sharing their memories of Ben Lee. I am also grateful to Ned Goldwasser and Lizzie Goldwasser who, before their passing, shared their recollections of recruiting Lee to Fermilab. I thank the anonymous reviewer and Valerie Higgins at Fermilab Archives.

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HOW STARS SHAPE GALAXIES



Matt Orr and **Shyam Menon** are postdoctoral fellows working with **Blakesley Burkhart** at Rutgers University in New Brunswick, New Jersey, and at the Flatiron Institute in New York City to study the process of star formation and how it is influenced by stellar feedback, physical mechanisms, and magnetic turbulence.

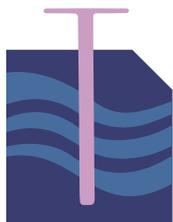


UV radiation and stellar winds from the young star cluster NGC 602 have created an expanding hole of low-density gas in the surrounding nebula. (Image composite: x-ray image from NASA/CXC; IR image from ESA/Webb, NASA and CSA, P. Zeidler, E. Sabbi, A. Nota, and M. Zamani; image processing by NASA/CXC/SAO/L. Frattare and K. Arcand.)

The energy and momentum that stars inject into the gas that surrounds them dramatically influences subsequent star formation.

MATT ORR / SHYAM MENON / BLAKESLEY BURKHART

HOW STARS SHAPE GALAXIES



The birth of stars is a complex process. Far from being an isolated event, star formation is strongly influenced at every stage by the surrounding dust and gas that make up the interstellar medium (ISM) in a galaxy. And those new stars also dramatically shape their galactic environments through processes known collectively as stellar feedback. That complexity is on display in the Small Magellanic Cloud, a dwarf galaxy that is falling into our own Milky Way. Inside, the young star cluster NGC 602 is rapidly destroying the molecular cloud that birthed it: Hot stellar winds and ionizing radiation from massive stars in the cluster are blasting away the surrounding gas. The changed environment is unlikely to undergo continued star formation, but localized regions that have been compressed are more likely to form a new generation of stars.

Interactions between young stars and their environment are fundamental to the evolution of stars,¹ galaxies,² and the greater universe. Turbulence, magnetic fields, and gravitational instabilities can all compress a molecular gas cloud, and that compression, in turn, can trigger a new round of star formation.³ Yet those same dynamics can also disperse gas and inhibit star formation.

There are multiple mechanisms through which stellar feedback influences the ISM, as detailed in box 1. Radiation pressure, stellar winds, and jets produced by new stars push against the surrounding gas and reshape the environment. Those outward pressures primarily inhibit subsequent star formation in the immediate vicinity. Particularly massive stars produce large amounts of photoionizing radiation that ionizes and heats the surrounding gas, a process that also prevents nearby star formation. Supernovae are the dominant source of stellar feedback because of the vast amounts of energy and material that spread throughout the ISM and sometimes reach beyond the confines of the galaxy. Supernova explosions also create cosmic rays, which can deeply penetrate nearby molecular clouds, heat their interiors, and set off complex chemical processes. The various forces at play in stellar feedback make it a challenging and fascinating problem for researchers building predictive models of galaxy evolution.

Star-formation inhibition

The effects of stellar feedback range from triggering individual star-forming sites in a molecular cloud to setting the stage for later generations of stars across an entire galaxy. Feedback mechanisms are critical in driving the dynamics of gas. By

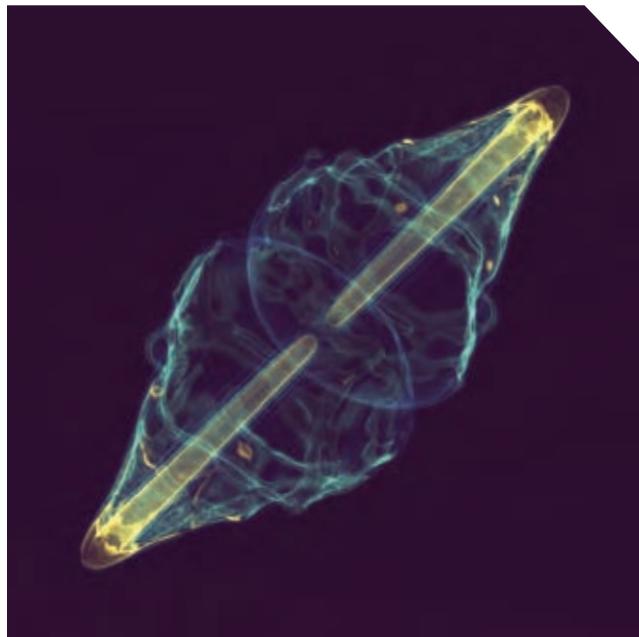


FIGURE 1. A VOLUME RENDERING OF A STELLAR JET.

Numerical simulations can help visualize an idealized jet. This one shows the distribution of gas around a bipolar protostellar jet caused by a star of 5 solar masses. Shock waves have pushed gas away from the jet. A real jet is much more complex. (Visualization by Sabrina Appel.)

regulating the availability of gas on small and large scales, they shape galaxy evolution as much as accreting flows of gas from outside the galaxy do.

The formation of a generation of stars in a molecular cloud takes only a few million years, a brief span of time when compared with the many-billion years that a star like our Sun lives. In fact, Sun-like stars are barely considered to be stars in their first few million years because hydrogen has not yet begun to fuse in their cores. In contrast, stars of more than 8 solar masses (M_{\odot}) evolve faster and take only a few hundred thousand years to initiate nuclear fusion in their cores. They are already radiating starlight while the surrounding molecular cloud is still forming additional stars.

Those massive stars, however, can quench nearby star formation. Because of their high surface temperatures, they emit significant UV radiation that is readily absorbed by gas and dust grains in the surrounding ISM.⁴ The transferred energy heats and ionizes the atoms and molecules, and the transferred momentum simultaneously imparts an outward force. Both effects prevent further star formation. The thermal pressure from the hot, ionized gas provides support against self-gravitational collapse and drives the expansion of ionized bubbles. The outward force pushes dense gas away from star-forming sites.

Additionally, the UV radiation gets absorbed by metal ions—those heavier than hydrogen—in the atmosphere of massive stars. The ions' large effective cross sections result in

significant forces that launch stellar winds exceeding 3000 km/s. When the winds slam into the surrounding ISM, they produce shocks and generate bubbles hotter than 10^7 K that expand and impart significant momentum against gravitational collapse.

Feedback from less massive stars also moves gas away from where they were formed, albeit on a more local scale. A young star is surrounded by a disk of gas that rotates because of conservation of angular momentum. Strong magnetic fields near the protostar can funnel gas into powerful outflows, directed perpendicular to the disk. Those outflows can reach speeds of a few hundred kilometers per second and take on a biconical shape, as seen in figure 1.

Protostellar outflows expel gas that would otherwise contribute to the growth of the star and impart momentum to the surrounding region; they thus can potentially cut off the disk's gas supply. As a result, they play a crucial role in regulating the final mass of stars. But because of the outflows' narrow geometry and limited momentum, their effects are mostly confined to the immediate region.

Collectively, the radiation and winds from clusters of young, massive stars in the same stellar nursery are strong enough to create large-scale expanding bubbles that halt star formation locally and across entire molecular clouds.^{5,6} The destructive shredding of such molecular clouds is stunning. As seen in the opening image, the dense portions of clouds are blown away and have evaporated, revealing the young star cluster inside.

But it's not all bad news for future star formation: The interaction of expanding bubbles with the surrounding ISM also produces localized compression that can trigger new sites of star formation. The Pillars of Creation in the Eagle Nebula are an iconic example of that phenomenon. The prevailing view among astronomers is that triggered star formation is localized and that the overall impact of radiation and stellar-wind feedback is in limiting the fraction of gas in a molecular cloud that can form stars. The remainder of the gas is dispersed elsewhere in the galaxy, where it may eventually cool, condense, and be recycled to form stars.

Subsequent generations of stars are crucially affected by violent stellar feedback in the form of supernovae. The most massive stars—those with masses greater than about $8 M_{\odot}$ —begin to exhaust their fuel for nuclear fusion when they are a few million years old. After using the available hydrogen in their cores, those stars rapidly consume more-massive elements in an attempt to sustain fusion. Ultimately, they are unable to support themselves against the crushing pressure of gravity. The core collapses and triggers a supernova, one of the most violent types of explosions in the universe. A core-collapse supernova produces cosmic rays and injects into the ISM about the same amount of energy that our Sun produces in 8 billion years. The explosion distributes heavier metals throughout the galaxy, and subsequent generations of stars can form with those materials already incorporated.

Box 1. The many forms of stellar feedback

As stars evolve, they inject energy and momentum back into their surroundings. The various forms of that feedback influence the interstellar medium (ISM) and subsequent generations of stars. Stellar feedback is a catchall term that encompasses several processes.

* **Photoionizing radiation.** Massive stars emit intense UV radiation that ionizes and heats surrounding gas, creating ionized areas known as H II regions. By altering the gas temperature and pressure, the radiation can both trigger and inhibit star formation, depending on the local conditions. H II regions are often seen around young star clusters and can drive complex interactions in the ISM.

* **Radiation pressure.** Radiation pressure from young, massive stars can push against the surrounding gas, particularly dust grains, and affect gas distribution and dynamics. The pressure can disperse star-forming regions or compress gas in other areas, potentially initiating new star formation. The influence of radiation pressure becomes significant when massive stars exert enough force to disrupt gas clouds, thus reshaping the stars' environment.

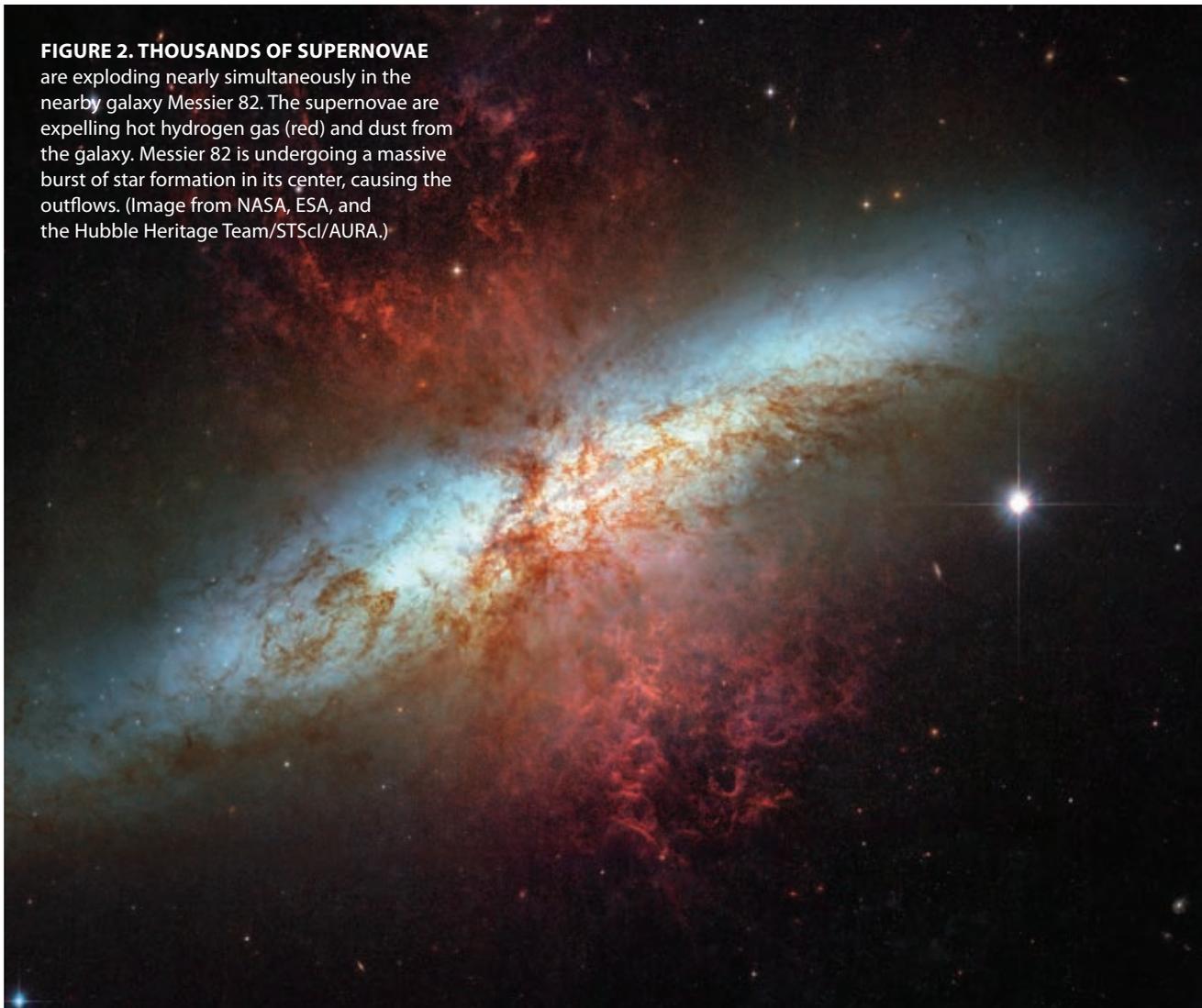
* **Stellar winds and jets.** Stellar winds, particularly from massive stars, inject momentum and energy into the ISM. They can carve out cavities in the surrounding gas, thereby creating in clouds such structures as bubbles and shells that impact the formation of new stars. Additionally, young stars often produce jets that collide with nearby gas, reshape the stars' natal environments, and affect the formation of nearby stars.

* **Supernovae.** When massive stars—specifically those with a mass greater than about 8 solar masses (M_{\odot})—end their lives in supernova explosions, the shock waves release vast amounts of energy and material throughout the ISM. The explosions can compress nearby gas and lead to new star formation, or they can disperse gas and inhibit star formation in the vicinity.

* **Cosmic rays.** High-energy particles accelerated primarily by supernovae but also by other energetic processes can ionize gas and influence its temperature and pressure. Such cosmic rays are often considered as a separate form of feedback from supernovae because they can penetrate deep into molecular clouds, where other forms of feedback cannot reach, and affect the chemistry and dynamics of star-forming regions.

FIGURE 2. THOUSANDS OF SUPERNOVAE

are exploding nearly simultaneously in the nearby galaxy Messier 82. The supernovae are expelling hot hydrogen gas (red) and dust from the galaxy. Messier 82 is undergoing a massive burst of star formation in its center, causing the outflows. (Image from NASA, ESA, and the Hubble Heritage Team/STScI/AURA.)



Explosive regulation

Star formation, in its strictest sense, is the result of gravity compressing gas to ultrahigh densities in clouds. Were gravity left to its own devices, that process would occur 50–100 times as fast as we observe in the nearby universe.⁷ The relative inefficiency of star formation that we see in most galaxies today is because of energy and momentum injected into the system by feedback that opposes gravity.

Supernovae are incredibly efficient at returning energy to the ISM. Over the course of a few days or weeks, the supernova explosion of a single star releases more energy in its burst of light and high-velocity ejecta—which can approach 10% of the speed of light—than the light output of entire galaxies over the course of weeks or months. (Locally, the Crab Nebula is a remnant of one such explosion; when the supernova occurred in AD 1054, it shone so brightly that it appeared briefly as a star in the daytime sky.) As shock waves

from supernovae expand into the surrounding ISM, they sweep up gas and dust into a swiftly moving shell that imparts energy and momentum back into the ISM.

The rapid influx of energy from only a small number of supernovae is sufficient to power the dissipation of turbulent energy throughout the ISM on galactic time scales. A mere trickle of star formation is required to maintain a balance between the pull of gravity and the stirring action of turbulence on the scale of kiloparsecs. Thankfully, less than 1% of stars end their lives as supernovae; most exhaust their hydrogen cores in a more tranquil fashion. Too many supernovae would tip the balance and lead to galaxies tearing themselves apart via explosions.

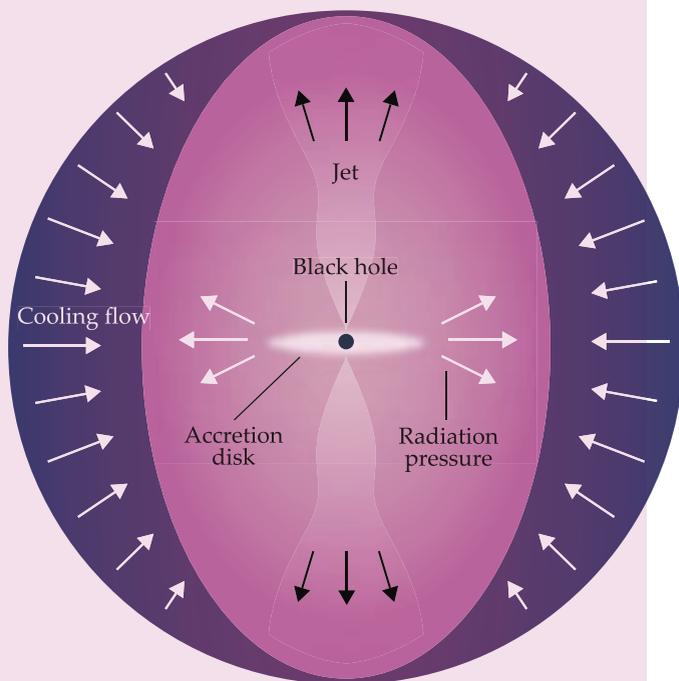
One spectacular feature of supernova feedback comes from processes of star formation and stellar feedback on smaller scales. Stars form around the same time in tight clusters in a molecular cloud, so supernovae are also clustered in time and space. For example, the largest molecular clouds

Box 2. Feedback from active galactic nuclei

In addition to stellar feedback processes, feedback from active galactic nuclei (AGNs) is one of the most significant mechanisms shaping the evolution of galaxies. It often regulates star formation on larger scales than stellar feedback alone. AGNs are disks of material that surround supermassive black holes at the centers of galaxies and expel copious amounts of radiation. The two primary types of AGN feedback, distinguished by the dominant form of energy released, are the radiative (or quasar) mode and the mechanical (or radio) mode.

High-luminosity AGNs release most of their energy through intense radiation from the accretion disk; that radiation heats the surrounding interstellar medium (ISM) in the galaxy and circumgalactic medium (CGM) in the galaxy's immediate vicinity. The heat prevents the CGM from cooling and collapsing into the galaxy and, subsequently, from creating star-forming regions. Additionally, the radiation can drive powerful outflows of gas and expel the gas from the galaxy altogether. Those outflows can remove large reservoirs of cold gas, effectively limiting the fuel necessary for stars to form. That quenching is responsible for transforming blue, star-forming disk galaxies into elliptical galaxies colloquially referred to as “red and dead.” Such galaxies are characterized by little to no new star formation because of the lack of cold CGM gas falling into the galactic ISM.

In the mechanical mode, AGNs eject high-velocity jets of relativistic particles and winds from the vicinity of the supermassive black hole. The jets can extend well beyond the galaxy, into the surrounding CGM, and even into the intergalactic medium (IGM) that permeates the space between galaxies. The interaction of the jets with the surrounding gas



(Illustration by Jason Keisling.)

creates shock waves that heat the CGM and IGM, further preventing the cooling and inflow of gas. By heating and disrupting the CGM, AGN feedback can prevent cold gas from replenishing the galaxy's ISM, effectively halting star formation in the galaxy.

AGN feedback is a key factor in galaxy evolution models and causes many massive, gas-rich galaxies to cease forming stars. Without fresh cold gas entering a galaxy, star formation cannot continue, and the galaxy transitions into a quiescent phase. Furthermore, AGN feedback is believed to regulate the size and structure of galaxies, playing a role in limiting the growth of the most massive ones by curbing star formation and expelling gas.

span a few hundred light-years and form stars with a combined total mass of $10\,000\text{--}100\,000 M_{\odot}$. From those stars, hundreds to thousands of supernovae are expected. The explosions often occur in such tight temporal and spatial proximity that the shock fronts overlap to form a single expanding shell, known as a superbubble.⁸

Unlike an individual supernova, a superbubble can grow to fill the entire height of the ISM. When a bubble reaches the edge of the galaxy and ruptures, it drives dramatic outflows of multiphase gas that, in turn, propels matter thousands of light-years outside the galaxy, as seen in figure 2. Energy and momentum from superbubbles are injected both into the ISM and directly into the halo of gas that surrounds galaxies. Feedback from superbubbles and active galactic nuclei—compact, highly luminous regions

surrounding supermassive black holes at the centers of galaxies—have the widest-reaching effect on star formation. (See box 2 for more detail on feedback from active galactic nuclei.)

Spiral galaxies like the Milky Way have maintained a consistent increase in their stellar mass for more than half of the age of the universe. Scenarios that consider different gas dynamics underscore how delicate the balance was that created the universe we see today. If a galaxy didn't have any additional gas supply, the gas reservoirs needed to form new stars would have been depleted within a few billion years. The intergalactic medium—gas outside the galaxy—is able to supply gas at a rate comparable to the rate that gas gets incorporated into stars and so maintains a consistent amount of gas in the ISM. Without supernova

HOW STARS SHAPE GALAXIES

feedback, however, all the gas would be converted to stars in a few tens of millions of years, a time scale not even reaching back to the extinction of dinosaurs on Earth. Simply put, gas would not last long enough to form an ISM. There would be almost no gas in galaxies and no active star formation; nearly all observable matter in the universe would be found in stars.

In some extreme environments with exceptionally large amounts of gas in a local region, stellar feedback can fail to regulate star formation: The sheer amount of collapsing material around a young, massive protostar is able to absorb the effects of photoionizing radiation, stellar winds, and nearby supernovae without being pushed away or the protostar dissipating.

In such conditions, star formation is accelerated. Gas collapses into stars until so much is consumed that the remaining material can no longer fully absorb the momentum and energy of the stellar feedback. At that point, the dregs are finally blown away, and stars no longer form. The stars do not tend to drive massive outflows because their feedback has been largely contained. Such exotic cases were likely a common mode of star formation in the early universe and may have produced the ancient globular clusters seen in our galaxy.⁹

Challenges of simulating feedback

The multiscale nature of feedback-regulated star formation presents significant numerical challenges for simulations. Ideally, a model would accurately capture processes ranging from small-scale turbulence to galaxy-wide feedback effects, a span of at least nine orders of magnitude. Simultaneously resolving the physics across that range is far beyond the limits of current technology. Researchers often focus their efforts on a couple orders of magnitude at a time to maximize the ability of their models to resolve different aspects of stellar feedback. At each scale of simulation—from individual star-forming clouds to whole galaxy clusters—researchers must choose how to treat the physical processes of feedback and at what resolution to apply them.

Various groups have found success with that approach. Simulations that model large volumes with comparatively coarse resolution in any individual galaxy have been able to match many of the properties of galaxy populations observed in massive surveys, such as the Sloan Digital Sky Survey. Groups whose simulations focus on individual galaxies have pushed the goalposts further: They match the observed properties and structures within galaxies. Figure 3 shows one such comparison between a nearby spiral galaxy imaged with the *James Webb Space Telescope* and dense gas and dust structures of a spiral galaxy from a simulation by the FIRE (Feedback in Realistic Environments) collaboration.¹⁰ On still-smaller scales, theorists who look at patches of galaxy disks or at individual star-forming clouds have begun to advance our

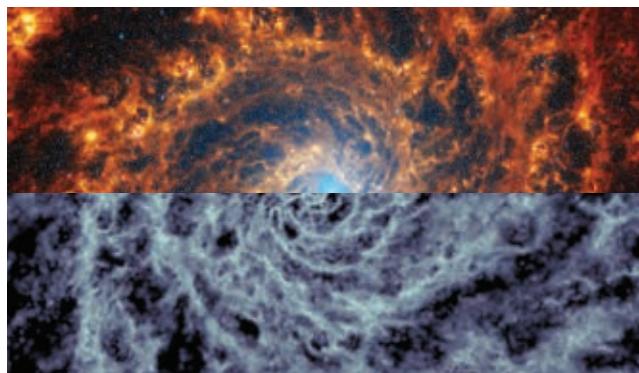


FIGURE 3. SIMULATIONS VERSUS OBSERVATIONS. New simulations, such as those by the FIRE (Feedback in Realistic Environments) collaboration,¹⁰ can now intimately match galaxies' observed internal properties, such as holes in spiral arms caused by photoionizing radiation, stellar winds, and clusters of supernovae. At top is an IR image of the spiral galaxy NGC 628 by the *James Webb Space Telescope*; at bottom is a FIRE simulation of the gas content in a Milky Way analogue. The close match in overall structure demonstrates strong qualitative agreement between theory and observations. (Top image by NASA, ESA, CSA, STScI, and the PHANGS Team; bottom simulation by the FIRE collaboration.)

fundamental understanding of the interplay between star formation and stellar feedback on the scale of individual stars. The IR imaging capabilities of *Webb* have opened up vital comparison observations at all scales.

Feedback in its various forms is a critical part of the story of star formation and the evolution of galaxies. As a catchall term for the physical processes that return energy, momentum, and mass back to the surrounding gas, feedback covers many length and time scales, from parsecs to megaparsecs and from hours to hundreds of millions of years. Astronomers and astrophysicists have spent the better part of the past century piecing together the impact and centrality of feedback and are approaching the ability to model it accurately on galaxy scales.

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Andreas Mandelis



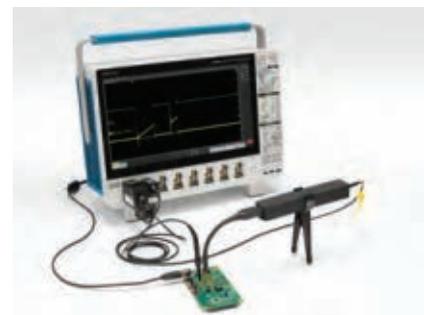
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to a PC via USB for live readout and logging of digital data from the sensor. A robust application programming interface (API) supports .NET Framework 4.8.1 (C#, VB.NET) and native C++ (ISO C++ 20). The API encapsulates the device's protocol, simplifying communication and integration. It is fully compatible with the 64-bit versions of Windows 10 (version 1607 and later) and Windows 11. To accelerate development and streamline integration into users' software, code examples for C++, C#, and VB.NET are provided. **Bartington Instruments Ltd**, 10 Thorney Leys Business Park, Witney, Oxon OX28 4GG, UK, www.bartington.com

Vector network analyzer

Rohde & Schwarz has expanded its vector network analyzer portfolio with the R&S ZNB3000, a high-precision instrument suitable for use in RF laboratories and production facilities. With frequency ranges from 9 kHz to 4.5, 9, 20, and 26.5 GHz, the R&S ZNB3000 addresses applications in the communications, electronic goods, and aerospace industries and in the design of digital high-speed printed circuit boards and cables. It has a dynamic range of up to 150 dB, which, according to the company, is the highest in its class, and an excellent trace noise of less than 0.0015 dB rms. It also offers its class's highest output power—for example, +11 dBm at 26.5 GHz—which yields better setup loss compensation. The frequency can be easily upgraded to meet fast scale-up requirements. Using external switch matrices, the instrument can be scaled up for multipoint measurements up to 48 ports. **Rohde & Schwarz GmbH & Co KG**, Muehldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com



Isolated current probes

The TICP series IsoVu isolated current probes from Tektronix deliver high-bandwidth, low-noise current measurements in applications that require greater power capacity and efficiency. According to the company, the new probes are the first to use RF isolation, and they deliver high precision and safety when measuring fast-changing currents across low- and high-voltage systems. They provide complete galvanic isolation between measurement systems and devices under test, therefore eliminating ground loops. They also offer a common-mode rejection ratio (CMRR) that is more than 30 times as high as that of traditional differential voltage probes: 140 dB CMRR at DC and up to 90 dB at 1 MHz. In a 1× configuration, the 50 Ω input offers very low noise of less than 4.7 nV/√Hz (less than 150 μV at 1 GHz). Available in three models with bandwidths of 1 GHz, 500 MHz, and 250 MHz, the probes allow oscilloscopes to capture accurate measurements of fast-changing currents across a wide voltage range—from microamps to kiloamps—in nanoseconds. **Tektronix Inc**, 13725 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com



Residual gas analyzers

Stanford Research Systems has announced its RGA120 series of residual gas analyzers, which build on the previous RGA100 series. The 120, 220, and 320 amu analyzers have increased mass range, better performance, and new capabilities such as built-in analog input and output. For increased sensitivity and faster scan rates, the company offers an optional electron multiplier that detects partial pressures down to 5×10^{-14} torr.

The RGA systems include a probe consisting of an ionizer, a quadrupole mass filter, and a detector. Its simple design, with few parts, minimizes outgassing and reduces the introduction of impurities into vacuum systems. All the electronics needed to control the RGA head are densely packed into the electronics control unit; a real-time Windows software package facilitates probe control, data acquisition, and analysis and supports multiple head operation. The RGA120 series is suitable for applications involving gas analysis, leak detection, and vacuum processing. **Stanford Research Systems**, 1290 Reamwood Ave, Ste D, Sunnyvale, CA 94089, www.thinksrs.com

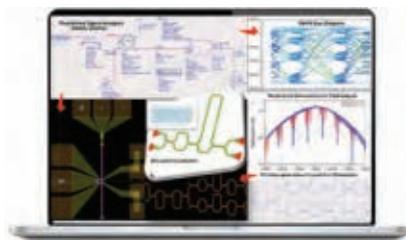
Sampler-extended real-time oscilloscope

Pico Technology has added the PicoScope 9404A-25 model to its PicoScope 9400 series. The new high-performance oscilloscope features a 25 GHz bandwidth on four channels and the company's sampler-extended real-time oscilloscope technology, which combines the advantages of traditional real-time acquisition with sampling oscilloscope capabilities. The scope can trigger directly on the signal and record pretrigger data while also achieving the extremely high time and amplitude resolution of a sampling scope. The PicoScope 9404A-25's high-speed internal trigger up to 18 GHz eliminates the need for an external trigger or clock-recovery circuit, making it versatile and convenient for challenging high-speed signal analysis. With a real-time sampling rate of 500 MS/s, the oscilloscope can capture lower-frequency, nonrepetitive signals or single-shot events. For higher-speed repetitive signals, it uses random equivalent-time sampling to achieve effective rates of up to 5 TS/s. **Pico Technology**, 320 N Glenwood Blvd, Tyler, TX 75702, www.picotech.com



Software for photonic circuit design

Keysight Technologies developed its Photonic Designer software to help users optimize the performance of photonic integrated circuits through advanced physics-based simulation. Photonic Designer integrates real-world measurement data directly into the simulation workflow to optimize models and streamline compliance and validation. The software enables users to avoid costly iterations by ensuring compatibility with foundry process design kits. Providing an intuitive interface for circuit design and layout generation, the software makes pure optical and combined electrical-optical workflows more efficient. With its photonic design automation tool, it eliminates fragmented workflows and improves accuracy. The software's optical finite-difference eigenmode solver, accessed either via a graphical user interface or directly within passive optical components, automatically calculates optical modes for each component during simulations, ensuring precision in circuit performance analysis. **Keysight Technologies Inc**, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com 



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INTERNATIONAL YEAR OF
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A new twist on the quantum vacuum

Jeremy N. Munday

A subtle macroscopic effect in the space between two birefringent plates produces a measurable Casimir torque.

Editor's note: We continue our celebration of the International Year of Quantum Science and Technology with this archival Quick Study on a quantum effect with potential technology applications.

One usually imagines a vacuum as empty space devoid of any matter. That picture isn't quite accurate when quantum mechanics is taken into account. Emptiness turns out to be an illusion: The real vacuum is full of activity in the form of quantum fluctuations—sometimes thought of as virtual particles that appear and disappear so quickly that they don't violate Heisenberg's uncertainty principle. In this Quick Study, I discuss how electromagnetic fluctuations can give rise to forces and even torques between macroscopic objects without the need for any other interactions. Indeed, the quantum mechanics of a vacuum may prove to be an exciting tool for engineering nanoscale devices.

Forces from nothing

In the late 1940s while working at the Philips Laboratory in Eindhoven, the Netherlands, Dutch physicist Hendrik Casimir developed a theory to describe the interaction forces he observed in colloidal suspensions. Intrigued by the notion of quantum fluctuations of electromagnetic fields and by conversations with Niels Bohr, Casimir considered what would happen in a different scenario involving two parallel, uncharged, metallic plates.

In a classical vacuum, nothing happens. But in a quantum vacuum, he realized, the presence of the closely spaced plates—essentially an optical cavity—would influence the fluctuating fields (see, for example, the Reference Frame by Daniel Kleppner, *PHYSICS TODAY*, October 1990, page 9, and *PHYSICS TODAY*, November 2011, page 14). More specifically, conductive plates force the electric and magnetic fields to go to zero at the boundaries, and only a subset of the fluctuations can exist between the plates; the largest wavelengths are excluded simply because they do not fit.

The plates effectively reduce the energy density, often called the zero-point energy, associated with those quantum fluctuations. The closer the plates, the lower the zero-point energy. Because nature likes to minimize the energy of a system, the two plates should be attracted to each other—an interaction referred to as the Casimir effect.

Within 10 years of Casimir's prediction, an experiment by Dutch physicist Marcus Sparnaay confirmed the existence of the Casimir force between two parallel plates. In Sparnaay's own words, the experiments "do not contradict Casimir's theoretical prediction." That humble phrasing reflected the difficulty of measuring such small forces while keeping the plates parallel and in close proximity—typically below a micron—and removing electrostatic interactions and other artifacts.

Around the same time, 1956, Russian chemist Boris Derjaguin realized that replacing one of the plates with a sphere would simplify the measurement: Researchers would no longer need to worry about keeping the plates parallel. Although the sphere-plate geometry did improve detection, not until the 1990s did modern measurement techniques usher in a new wave of Casimir force experiments. (See the article by Steve Lamoreaux, *PHYSICS TODAY*, February 2007, page 40, and *PHYSICS TODAY*, February 2009, page 19.)

From forces to torques

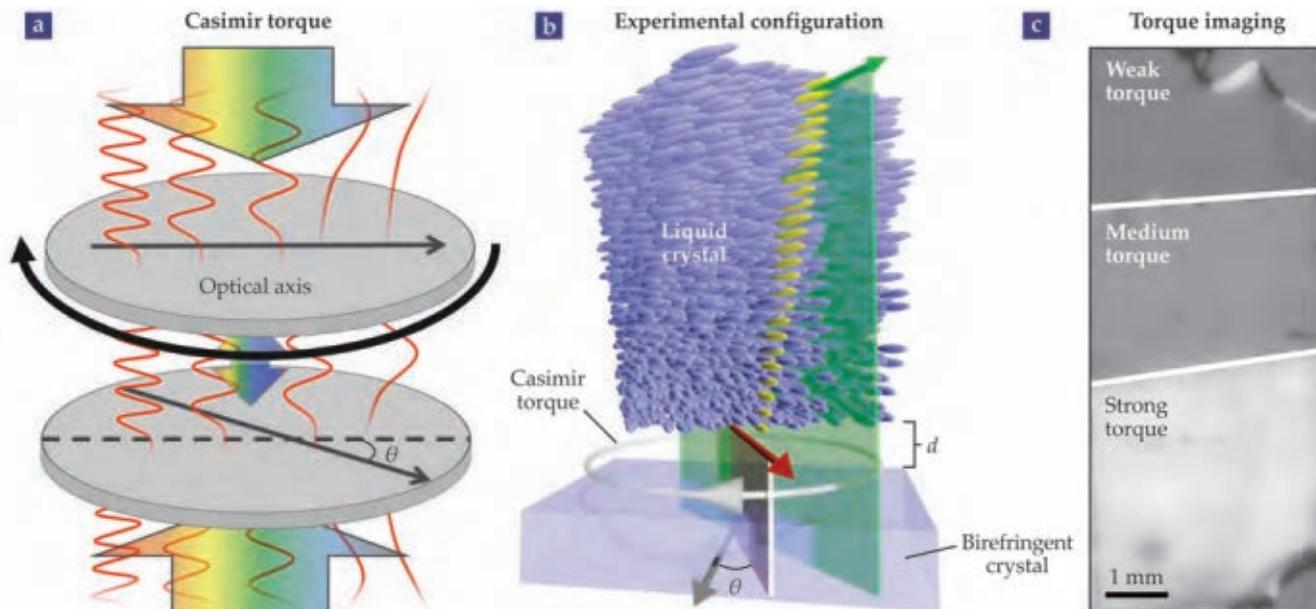
Casimir's theory describes the force between metal plates. But what happens when the plates are not perfect conductors? Theorists Igor Dzyaloshinskii, Evgeny Lifshitz, and Lev Pitaevskii answered that question in 1961 when they generalized Casimir's result to the case in which the plates are described by arbitrary, isotropic dielectric functions. Today their theory is used in comparisons to experiment; the optical properties of the actual metals used in the experiments are incorporated as variables into the theory.

In the 1970s a new configuration was considered: What if the optical properties of the plates are anisotropic—for example, when using birefringent crystals such as calcite? In that case, the total free energy of the system depends not only on the separation between the two parallel plates but also on the angle θ that defines their relative orientation. The system should exhibit a torque that causes the plates to rotate into a position of minimum energy—a Casimir torque.

Minimum energy is reached when the optical axes with the highest refractive index align. The theory for that idea was worked out by Adrian Parsegian and George Weiss and independently by Yuri Barash. For relatively small separations, generally less than a few tens of nanometers, they found that the torque has a $\sin 2\theta$ dependence and is inversely proportional to the separation squared.

As with the Casimir force, several technical issues complicate measuring the Casimir torque. Two relatively large-area plates need to be kept parallel and at submicron separations. One plate also needs to freely rotate relative to the other, and that rotation must be detectable above background noise and artifacts. A way to perform such an experiment is to suspend one birefringent plate above another using a torsion rod.

The twisting of the rod induced by the Casimir torque could be measured optically or electronically to determine the rotation angle. But parallelism, dust removal, and surface imperfections turn out to be difficult to control in that setup. Another possibility is to perform experiments in which one plate is levitated above another either using optical tweezers in vac-



IMAGING THE TWIST FROM VACUUM. (a) When two optically anisotropic plates form a narrowly spaced optical cavity, the energy associated with quantum fluctuations between them depends on their orientation. To minimize the free energy of the system, the Casimir torque rotates one plate relative to the other until their optical axes align. (b) This configuration illustrates my group's recent experiment to measure the Casimir torque between a liquid crystal and a solid birefringent crystal. A thin isotropic layer of material separates the crystals by a variable distance d . The yellow rods illustrate the extent to which the liquid-crystal sample twists from top to bottom; the green and red arrows show the average direction of the liquid at the two endpoints. The dark gray arrow in the birefringent crystal depicts the crystal's optical axis. (c) Shining polarized light through the liquid and solid crystals offers a way to reveal the Casimir torque. A sample is prepared with three spacing-layer thicknesses that separate the liquid crystal from the solid birefringent crystal. Viewed between crossed polarizers, the image brightness is proportional to the strength of the torque. A thinner spacing layer d results in a stronger torque and hence a brighter image.

uum or using electrostatic or dispersion forces in a fluid. Unfortunately, those setups suffer from many of the same problems as experiments involving torsion rods.

To circumvent those problems, my group developed an alternative experiment that enabled the first quantitative measurement of the Casimir torque. The trick was to replace one of the birefringent plates with a liquid crystal, as shown in the figure. Liquid crystals contain birefringent molecules that can have local and long-range order. They behave much like solid birefringent crystals but can also wet another surface and rotate at the molecular level.

For our experiment, we used a solid birefringent crystal on which we deposited a thin—less than 30 nm—optically isotropic layer of aluminum oxide. That layer separates the solid crystal from the liquid crystal, much like the vacuum gap in Casimir-force experiments. Once the liquid crystal is placed atop the aluminum oxide, it wets the surface to form a three-layer stack: a solid birefringent crystal, aluminum oxide, and liquid crystal. The thickness of the spacer layer determines the distance between the solid and liquid crystals, and it can be varied by making multiple samples. The Casimir torque then rotates the liquid crystal so that its optical axis aligns with that of the solid crystal. We detected the rotation by measuring the polarization rotation of an incident light beam using an optical microscope.

The experiment, published in 2018, confirmed many of the predictions made by Parsegian, Weiss, and Barash. It showed that the torque decays with a power-law dependence on the separation and has a $\sin 2\theta$ dependence on the angle. The optical properties of the crystal substrate and of the liquid crystal affect the magnitude of the torque and its sign (clockwise or counterclockwise rotation). My lab has measured

torque densities as small as a few nanonewton meters per meter squared on surfaces separated by tens of nanometers.

Quantum effects in the real world

Beyond a confirmation of a quantum effect predicted decades ago, the measurement of the Casimir torque sets the stage for engineering vacuum fluctuations to modify how nanoscale and microscale devices work. In the world of microelectromechanical systems (MEMS), the Casimir force and the related van der Waals force are thought to have an important effect on surface-adhesion phenomena that cause devices to break. Reducing, eliminating, or even reversing the Casimir force among MEMS devices could ameliorate the problem.

Rather than being hindrances, the Casimir force and torque may perhaps give rise to more sensitive accelerometers and torsion sensors. What's more, the fact that the Casimir torque can affect liquid crystals—a staple of modern display technologies—suggests that liquid-crystal applications may also be on the horizon. Among the possibilities is ultralow-power switching that requires merely a tiny voltage to break the alignment of the liquid crystal and allow light to pass or be absorbed when the crystal is placed between crossed polarizers.

Additional resources

- ▶ V. A. Parsegian, *Van der Waals Forces: A Handbook for Biologists, Chemists, Engineers, and Physicists*, Cambridge U. Press (2005).
- ▶ D. Iannuzzi et al., "The design of long range quantum electro-dynamical forces and torques between macroscopic bodies," *Solid State Commun.* **135**, 618 (2005).
- ▶ D. A. T. Somers et al., "Measurement of the Casimir torque," *Nature* **564**, 386 (2018).

PT



Soft touchdowns for tiny robots

For insect-scale flapping-wing robots, landing is perhaps the most dangerous portion of flight. Close to the ground, the wings generate unpredictable air vortices that often cause hard or crash landings. The rigid, single-segment legs that researchers typically use on the robots struggle to reliably cope with the collision forces generated during landings, which can easily damage fragile components such as the wings or the piezoelectric or electromagnetic actuators that power the devices.

To create robots that can achieve smoother landings, a team led by Nak-seung Hyun of Purdue University and Christian Chan of Harvard University looked to the crane fly, a larger cousin of the mosquito. With its long, flexible legs, the crane fly is known for its ability to land gracefully on various surfaces. The insect's legs comprise two joints and two deformable segments—the upper tibia and the lower tarsus. Both the joints and the flexibility of the segments help the insect's legs dissipate energy on landing.

To emulate crane fly legs, Hyun, Chan, and their team fitted an existing insect-scale robot, the Harvard RoboBee, with two deformable joints made of carbon fiber and polyimide film and rigid leg segments made of carbon fiber. The joints were laminated with a thermoplastic elastomer that served as a damping element. After experimenting with varying lengths for the tibia and the tarsus, the researchers found that the optimal leg design was one like the crane fly's, in which the tarsus makes up 60% of the leg's total length. The photo shows the prior iteration of the RoboBee (second from left) and the new version with deformable legs (second from right), alongside a US penny and a crane fly specimen for scale.

Like the insect that inspired it, the new RoboBee can successfully take off and land on the leaf of a plant. The researchers hope that with additional refinement, insect-scale robots will be able to help live bees pollinate flowers. (N.-S. P. Hyun et al., *Sci. Robot.* **10**, eadq3059, 2025; photo courtesy of Harvard Robotics Lab/Christian Chan.)

—RD

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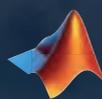
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