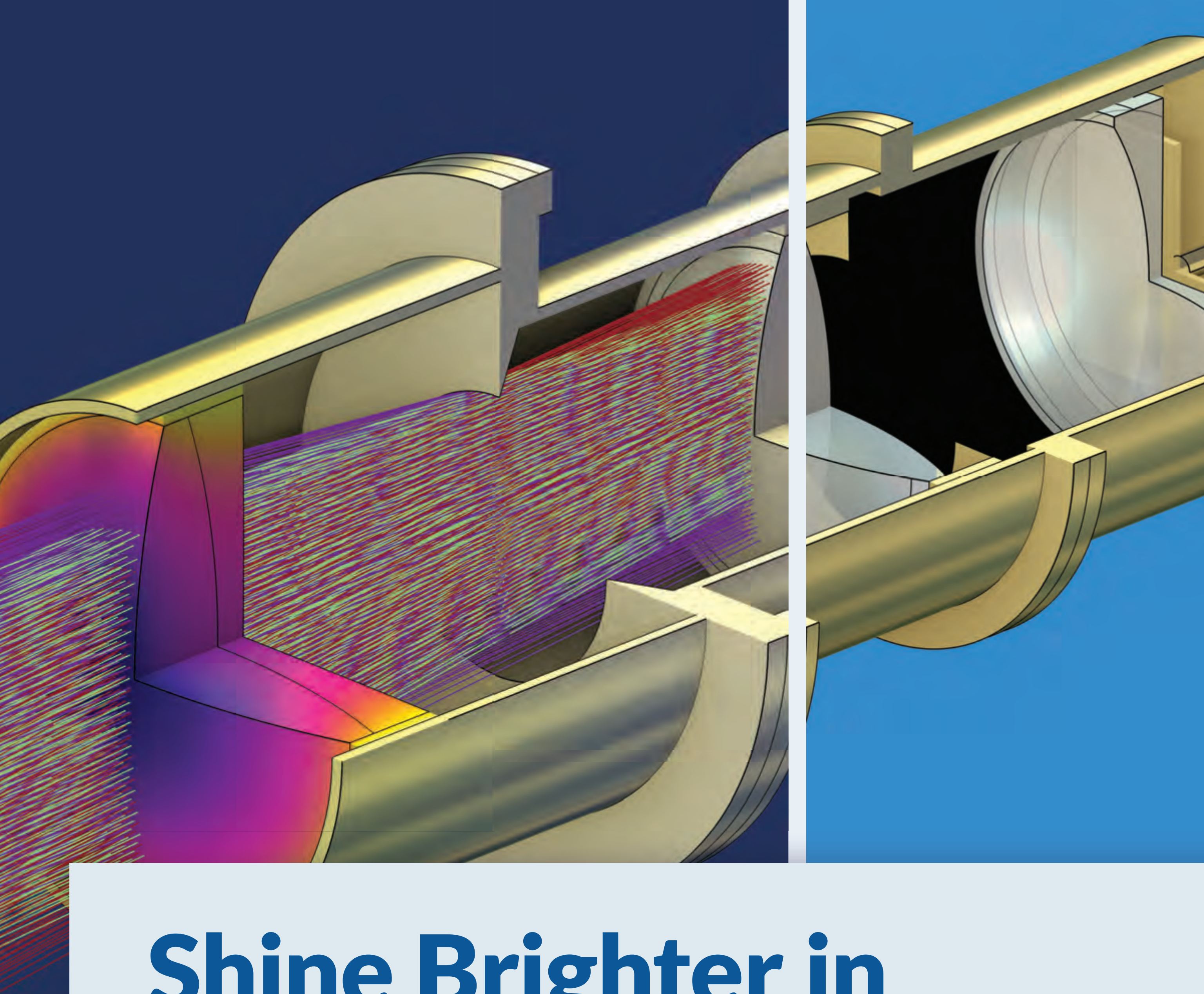

# PHYSICS TODAY

May 2023 • volume 76, number 5

A publication of the American Institute of Physics

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# PHYSICS TODAY

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## FEATURES



**ON THE COVER:** This photo, captured from the International Space Station, shows Hurricane Florence as it made landfall in North Carolina on 14 September 2018. The category 1 storm killed 52 people and caused some $24 billion in damages. On **page 28**, Caroline Muller and Sophie Abramian dive into how multicloud structures such as Florence are formed in the atmosphere and what advances have been made in observing and simulating cloud dynamics and convective storm systems. (Photo courtesy of NASA.)

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### PT at 75

How did Physics Today hatch? How have the magazine's ads reflected the state of the field? Why wasn't there an obituary for Albert Einstein? After exploring Physics Today's history on page 42, visit our website to learn more about the evolution of the magazine since its May 1948 debut.

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KEVIN NUCKOLLS

### Magic-angle graphene

In 2018, MIT physicists discovered that two sheets of graphene become superconducting at low temperature when they are stacked with an offset of 1.1°. Five years later, researchers are still finding exciting new behaviors in multilayered graphene, even as they struggle to explain the underlying mechanism.

***physicstoday.org/May2023a***

NASA/JPL/UNIVERSITY OF ARIZONA

### Naming moons

Back when astronomers knew of only a handful of moons in our solar system, they designated each one by number. The mythology-inspired naming convention that is still in use today started in the 1800s to keep national rivalries out of the sky—although more personal motivations were also at play.

***physicstoday.org/May2023b***

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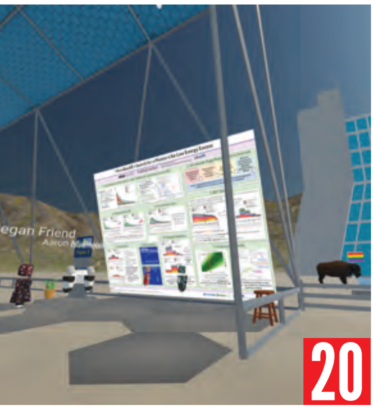

## DEPARTMENTS

# Science in Ukraine and in Iraq: Two sides of the same coin

Toni Feder deserves kudos for her report on the impact of the war in Ukraine on science and scientists in that country and its wider reverberations across physics research (see Physics Today, June 2022, page 22). The topic of the most recent invasion, which was launched by Russia in February 2022, rightfully took pride of place in that issue, with a photograph of a demolished Ukrainian school displayed on the cover. Science is a universal enterprise, and those engaged in it are its trustees. It is proper to speak up in support of scientists who face impediments and restrictions on their activities.

Physics Today also on many occasions supported scientists in the Soviet Union during that era by publishing voices speaking out against persecution. But as we mark the 20th anniversary of the US invasion of Iraq, I want to point out that the magazine has been mostly silent when it comes to the obliteration of Iraqi science, physics included, and the persecution and murder of scientists in the country.

Iraq used to boast a vibrant scientific community, but with the onset of the brutal Iran–Iraq War (1980–88), academic activity in the country declined: "Promising students ceased being sent abroad to the US and the UK for their higher degrees, and funds dried up for purchases of books and journal subscriptions," wrote the Islamic and Middle East specialist Jeff Spurr (as quoted in Physics Today, November 2005, page 24). Scores of young minds were killed in the war, and that was happening with the support of the US, which was operating under a "the enemy of my enemy is my friend" mindset.

After the Persian Gulf War (1990–91), Iraq suffered under a dictatorship and crippling sanctions from the United Nations. Many scientists attempted to flee, though travel was severely restricted. The academic enterprise in the country was gutted. Iraq could not even import pencils because they contained

**A MAN GATHERS BOOKS** from the ruins of Baghdad's National Library and Archive during the US invasion of Iraq in April 2003. (Image from Gleb Garanich/Reuters/Alamy Stock Photo.)

graphite and were therefore classified as a material with potential military applications.

The US-led war that began in 2003, initiated partially on the false grounds that Iraq possessed weapons of mass destruction, added insult to injury. It unleashed violence that specifically targeted scientists. By January 2005 about 300 university administrators and academics had been murdered,[1] including a former president of the University of Baghdad, Mohammed al-Rawi, who was killed in his medical clinic. Iraq, its academic institutions, and its scientists continue to suffer the consequences of misguided US foreign policies.

**Science is a universal enterprise, and those engaged in it are its trustees. It is proper to speak up in support of scientists who face impediments and restrictions on their activities.**

The effects on science caused by the wars in Ukraine and Iraq are two sides of the same coin. I applaud Physics Today for drawing attention to the travails of scientists across the globe, but I encourage inclusivity in that reporting.

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# Newton's "force" and fake doors: The "geometric spirit" in the arts

The science of Isaac Newton became a major part of the larger intellectual milieu during the long 18th century. Newton's influence dominated all areas of human concerns—scientific and otherwise—as scientific principles were applied to all aspects of life in the Enlightenment.[1] "The geometrical spirit is not so tied to geometry that it cannot be detached from it and transported to other branches of knowledge," proclaimed the French polymath Bernard le Bovier de Fontenelle[2] in 1699. This "century of lights" could just as well have been called "the century of Newton": The poet Alexander Pope once wrote in an epitaph for him, "God said, *Let Newton be!* and all was light."

The art of the 18th century reflects a renewed interest in classical form with Newtonian symmetry and balance, an emphasis that earned the period the name neoclassicism.[3] That classical revival, which followed on the heels of the French and English Baroque period, began in the second half of the century and extended well into the following century. The period saw a transition from the fanciful, overdecorated ornamentation of the Baroque to the unpretentious, balanced style of neoclassicism—in which the emphasis was on symmetry and the pureness of form. In the UK, that classical revival was marked by the metamorphosis of highly ornamented Stuart architecture into reasoned, properly proportioned styles and Palladian supersymmetry. In an age rebelling against excess, Cartesian

**THE PRADO MUSEUM** in Madrid, Spain. (Courtesy of Emilio J. Rodríguez Posada, CC BY-SA 2.0.)

ROBERT FLECK

**THE OLD PENNSYLVANIA SUPREME COURT CHAMBER** in Philadelphia's Independence Hall.

swirls yielded to Newtonian balance and simplicity.

Newtonian neoclassical balance is evident in several monumental buildings of the period, which display on a rather ostentatious scale the century's vogue for mathematical regularity in architecture. Examples include Vienna's Schönbrunn Palace, remodeled in neoclassical style starting in 1743; the Circus, a ring of townhouses built beginning in 1754 in Bath, England; and Madrid's Prado Museum (see page 11), designed in 1785.

Lesser known is the interior of the old Pennsylvania Supreme Court Chamber, which I photographed when I visited Philadelphia's Independence Hall (see above)—itself a building symmetrical and balanced in design, like much of Georgian colonial architecture. Here, the door on the left is real and functional; the one on the right, however, is fake: It is inoperable, but necessary to preserve the overall symmetry of the room. The English architect-scientist and Newton contemporary Christopher Wren declared that "the geometrical is the most essential part of architecture."[4]

While connections between science and the cultural expressions of society are interesting in and of themselves, appreciating them helps bridge the science–humanities "two cultures" divide. As emphasized by the American Association for the Advancement of Science, science literacy "includes seeing the scientific endeavor in the light of cultural and intellectual history."[5] Recognizing that relationship enhances and enlivens education in and awareness of STEAM (science, technology, engineering, arts, and mathematics) and, at the very least, helps humanize science.

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## Correction

**April 2023, page 30**—Panels a and b are mislabeled in the figure 3 caption. Figure 3a is a cross-sectional image of a pre-eclamptic placenta, and figure 3b is a cross-sectional image of a normal placenta. PT

# Fluorescence microscopy watches proteins at their own scale

Visible light can track molecules with nanometer and millisecond resolution, even amid the complexity of a living cell.

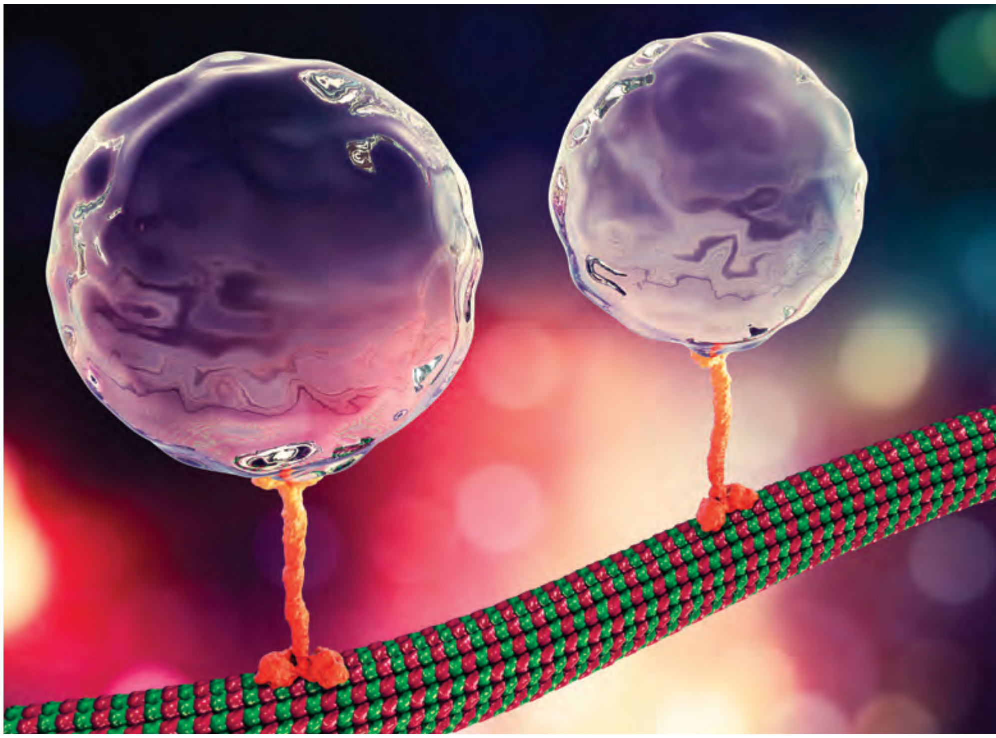

**FIGURE 1. KINESIN,** shown in this artist's illustration in orange, is a motor protein that carries cargo (transparent spheres) around inside a cell. The kinesin walks along a microtubule (part of the cell's cytoskeleton, shown in green and red) by moving its feet alternately, one in front of the other. But until now, its movement was too fast to be directly studied in detail. (Image by Kateryna Kon/Shutterstock.com.)

Sometimes what looks like a fundamental physical limitation isn't so insurmountable after all. An example is the diffraction limit: Light can't be focused to a spot smaller than half its wavelength, so it might seem to be impossible to use visible light to image features smaller than 200 nm. But researchers took on the diffraction limit and won, as highlighted by the 2014 Nobel Prize in Chemistry (see PHYSICS TODAY, December 2014, page 18). The three laureates—Eric Betzig, Stefan Hell, and William Moerner—and others developed ingenious ways to use optical fluorescence microscopy to obtain images with resolution of around 20 nm. And the resolution revolution was just getting started.

One can see a lot at 20 nm resolution. In biological systems—the most appealing imaging target because of all their unknown nanoscale complexity—that's the scale of organelles, protein complexes, and many other supramolecular structures (see, for example, PHYSICS TODAY, May 2015, page 14). But a lot remains unseen. Many important features are an order of magnitude smaller, including the shapes and conformations of individual proteins. And still images completely leave out what's arguably the most important thing about living systems: the way they change over time.

In the years since the Nobel, superresolution researchers have pushed to improve the resolution in both space and time. They've now reached the point of achieving nanometer and millisecond precision simultaneously—good enough to watch the motions of proteins in real time—as shown in new work by two groups in Heidelberg, Germany, one led by Jonas Ries of the European Molecular Biology Laboratory (EMBL)[1] and the other led by Hell at the Max Planck Institute for Medical Research.[2] Both groups used MINFLUX, a technique Hell and colleagues unveiled[3] in 2017, and both studied the motor protein kinesin, illustrated in figure 1, whose job it is to carry cargo from place to place inside a cell.

The exquisite precision comes with a trade-off: The researchers don't obtain a complete moving image of kinesin and all of its surroundings. Instead, they track the position of just one fluorescent molecule, called a fluorophore. But through judicious choice of where to attach the fluorophore to the kinesin, they can obtain detailed insights into how the molecule moves—and perhaps a similar understanding of other proteins that operate on the same time scales.

## Why so slow?

One of the key insights that make superresolution imaging possible is that although a dense bunch of fluorophores blur together, the position of a single isolated fluorophore, with no other light sources around, can be pinpointed precisely. There are various ways of doing that, the simplest being just taking a picture with a camera. The fluorophore appears as a diffraction-limited blob, hundreds of nanometers across. But the center of the blob—and thus, presumably, the position of the fluorophore—can be determined with much greater precision.

Single-fluorophore localization predates the Nobel-winning superresolution work by several decades (and in fact was the basis for early work on the kinesin mechanism, described below). The Nobel Prize honored the development of a suite of techniques for building up large numbers of single-fluorophore detections into complete images of complicated structures. Unsurprisingly, the imaging takes a long time—on the order of minutes. That's far too slow to study any kind of biological dynamics.

But localizing even a single fluorophore from its diffraction-limited blob can still be impractically slow, and its spatial precision in practice falls far short of the theoretical ideal. To pinpoint the center of a blob of light with nanometer precision, one needs to know its shape extremely well, which requires collecting thousands of photons. All those photons are fluorescence emissions from the same fluorophore, which must be cycled thousands of times between the same two quantum states.

Not all fluorophores can even endure that much cycling—they get damaged by the laser or fall into a nonfluorescing quantum state long before they've emitted enough photons—and for those that can, the process takes tens to hundreds of milliseconds. Localization can be performed faster and more gently on fluorophores, but at the cost of spatial resolution.

Furthermore, camera-based localization has a systemic limitation, no matter how many photons are detected. Fluorophores absorb and emit light as dipoles, so their fluorescence doesn't emanate equally in all directions. If a fluorophore doesn't rotate freely over the exposure time, the center of the fluorescence blob on camera may be several nanometers removed from the fluorophore's true location, which hampers the imaging resolution.

Other techniques are capable of studying biomolecules with high spatial precision. There's cryoelectron microscopy (which garnered its own Nobel Prize; see Physics Today, December 2017, page 22) and its cousin cryoelectron tomography, but they require specimens to be frozen. Tethering a molecule to a bead held in an optical trap can track molecular motions on scales of nanometers and microseconds (see Physics Today, June 2016, page 14), but there's no guarantee that the force exerted by the tether doesn't interfere with the molecule's natural movement. The appeal of fluorescence imaging is that it's comparatively benign and noninvasive, so it's compatible with living cells. But it hadn't yet reached its potential for studying cellular machinery in motion.

## In the dark

With MINFLUX, Hell's idea was to detect fluorophores not from the photons they emit, but from the ones they don't. "You still need a lot of photons to localize a molecule to within a nanometer," he says. "That follows from the uncertainty principle, and you can't get around it. But we can put the burden of the required number of photons on the laser, not the fluorophore. And there's no shortage of laser photons."

In the original MINFLUX (not an acronym, but an abbreviation for "minimal fluorescence photon flux"), a molecule is illuminated by a laser beam with a doughnut-shaped profile.[3] When the molecule is exactly in the center of the doughnut, it emits no fluorescence. Even one fluorescence photon is enough to show that the molecule is slightly off-center.

It's a little tricky to determine in what direction it's off-center. But Hell and colleagues developed an algorithm, a version of which is shown in figure 2a, to scan the beam's position and home in on the molecule quickly and efficiently: The localization precision scales exponentially with the number of fluorescence photons detected. (In contrast, the resolution of a camera-based localization scales with the square root of the number of fluorescence photons.) "That's a major thing," says Hell. "That's why this is so effective."

MINFLUX could provide complete—but slow—images of whole specimens labeled with many fluorophores. But it was also well suited, for the first time, for tracking single fluorophores with simultaneous nanometer and millisecond precision.

The MINFLUX apparatus is specialized and a bit complicated, and at first it existed only in Hell's lab. But he quickly commercialized the technology through his spin-off company, Abberior Instruments, to make the technique available to the broader community. The first commercial prototype went to EMBL, where Ries had already collaborated with Hell on MINFLUX applications in biology. "We were looking for an application that wouldn't be possible with any technology other than MINFLUX," says Ries, "and quickly we identified motor proteins in living cells, specifically kinesins."

Hell, meanwhile, was also studying kinesin, not in living cells, but as a test system for a new version of MINFLUX his group had developed. As shown in figure 2b, the new MINFLUX microscope replaces the doughnut beam with a linear interference pattern, which is shifted left and right to localize a fluorophore in the horizontal direction. The process needs to be repeated with an orthogonal interference pattern to find the molecule's vertical position. But because the intensity profile is better suited than the doughnut beam to fast and precise localization, the result is an improved resolution in space and time—and an unprecedented look at how kinesin moves.

## Walk like a kinesin

From illustrations such as figure 1, it's hard not to see kinesin's resemblance to

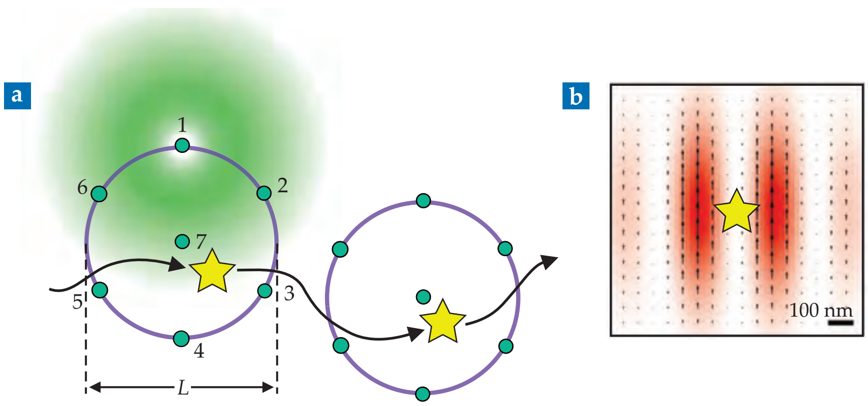


**FIGURE 2. MINFLUX,** an optical fluorescence technique, finds the positions of fluorescent molecules (yellow stars) quickly and precisely, using minimal fluorescence photon flux. In its original, recently commercialized version **(a)**, a doughnut-shaped light beam (green) probes several positions around a circle that's thought to contain the molecule. The circle diameter *L* is iteratively reduced to find the molecule with nanometer precision. In a newly developed version of the technique **(b)**, the doughnut beam is replaced with a linear interference pattern (red). Even though the molecule must now be localized in the horizontal and vertical directions separately, the localization is faster and more precise. (Panel a adapted from ref. 1; panel b adapted from ref. 2.)

a stick figure. The molecule has two feet that walk along a microtubule (part of the cell's cytoskeleton) and two hands that grasp cargo to carry it around the cell. But the resemblance in form doesn't necessarily mean that kinesin moves like a human does. For a long time, researchers debated whether kinesin really walks—taking alternate steps with its two feet, putting each in front of the other—or whether it shuffles along like an inchworm, with the same foot always leading.

That question was first answered in 2004 by the University of Illinois at Urbana-Champaign's Paul Selvin and colleagues using a technique called FIONA (which stands for "fluorescence imaging with one-nanometer accuracy," although it doesn't produce complete images, and the resolution in practice is coarser than 1 nm). They attached a robust fluorophore to a kinesin foot and collected the requisite thousands of photons to localize its position. It was already known from other methods that the kinesin body moves 8 nm with each step. Selvin and colleagues found that the foot moved 16 nm at a time, a clear sign that the feet moved alternately in a walking motion.[4]

To get that result, they had to slow the kinesin down by starving it of fuel. Kinesin walking at full speed can take tens of steps per second, whereas a single FIONA localization took 0.33 seconds. Like most cellular machinery, kinesin runs on adenosine triphosphate (ATP). In their *in vitro* experiment, Selvin and colleagues supplied an ATP concentration a thousandth of that found in cells, which reduced the kinesin speed to less than one step per second, slow enough for them to measure.

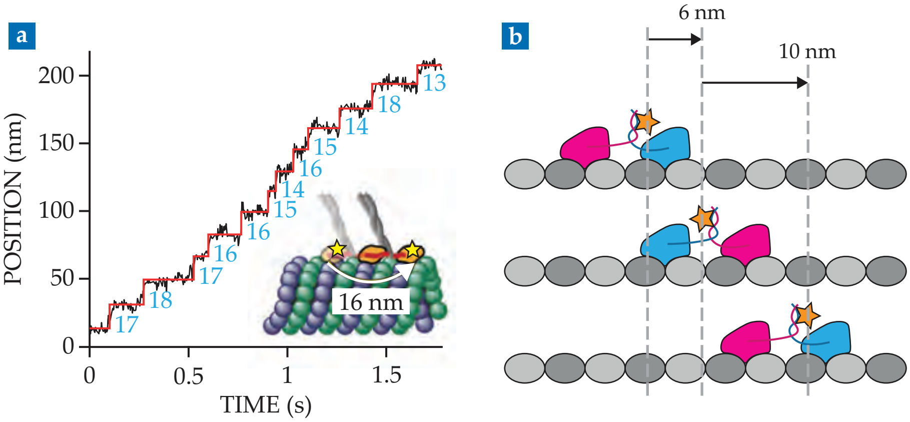


**FIGURE 3. ATTACHING FLUOROPHORES** (yellow stars) to different parts of a kinesin molecule probes different aspects of the molecule's movement. **(a)** A fluorophore on the kinesin foot reveals the average stride length of 16 nm. Because the kinesin body moves 8 nm with each step, the stride length is a clear sign that the kinesin feet step alternately. The data shown here were recorded in a living cell. **(b)** A fluorophore on the side of the kinesin stalk shows that the stalk rotates 180° between steps. The finding addresses, but doesn't definitively resolve, the question of whether kinesin walks facing forward or twirls like a ballerina. (Panel a adapted from ref. 1; panel b adapted from ref. 2.)

Ries and colleagues have now replicated those measurements in living cells—not because they were expecting to find anything significantly different, but because "it's important, in general, to bring insights from *in vitro* studies into physiological conditions and verify them," Ries says. "And from the technology side, it's important to demonstrate that nanoscale dynamics can be studied in live cells, even with all the complexities and background. We hope we'll encourage other researchers to study protein dynamics at more natural conditions." Figure 3a shows just one of the data tracks they obtained.

Merely knowing that kinesin steps with alternate feet doesn't explain everything about its mechanism. Does it really walk facing forward, with the right foot staying on the right and the left foot on the left, or does it twirl like a ballerina, with each foot passing the other on the same side? It's questions like that, among others, that Hell and colleagues hoped to address with their improved higher-resolution MINFLUX measurements.

In a twirling kinesin, the stalk would rotate 180° with each step, with the front of the stalk becoming the back and the back becoming the front. The stalk itself is too thin for even MINFLUX to resolve its front from its back. But because a fluorophore has nonzero size, the technique can distinguish a fluorophore attached to the front of the stalk from one attached to the back. As shown in figure 3b, a fluorophore on a rotating kinesin stalk would be seen to take alternate steps of 6 nm and 10 nm, even though the stalk itself advances by a steady 8 nm each time.

When Hell and colleagues performed that experiment, the alternating step sizes are just what they found. The result isn't definitive evidence of a twirling mechanism—kinesin could still walk facing forward while twisting from side to side—but it doesn't rule it out.

## Next steps

Both groups' MINFLUX experiments focus on tracking the position of a single fluorophore, with no information about the dynamics of anything else in the system. That capability works for studying kinesin, because the microtubules don't move much on the time scales of the experiments, even in living cells. But a more powerful tool would be one that simultaneously tracks the positions of two fluorophores that fluoresce in different colors. A two-color experiment could monitor protein interactions or conformations; with one fluorophore on each foot of a kinesin, it could settle the question of whether kinesin walks or twirls. "That's exactly what we're working on establishing next," says Ries.

For Hell, the next MINFLUX frontier is pushing the technique's resolution even further. The spatial resolution is already as good as it can be, because it's limited by the size of the fluorophore, but the temporal precision still has room to run. "The limiting factor is the fluorophore brightness," says Hell. A molecule that fluoresces more efficiently provides the same positional information in much less time. "With brighter fluorophores, we could get from one nanometer per millisecond down to one nanometer per ten microseconds," he says. "There's no reason that shouldn't be possible."

**Johanna Miller**

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# Trapped-atom analysis pushes calcium-41 onto the radiometric dating scene

With recent advances in laser technology and cold-atom methods, the technique's sensitivity to the isotope has reached environmental levels.

When Willard Libby and colleagues developed radiocarbon dating in the late 1940s, they faced an experimental obstacle: No radiation detection tool was sensitive enough to detect carbon-14 at its expected environmental concentrations—about 1 out of every $10^{12}$ carbon atoms.

To overcome that obstacle, Libby and coworkers built a sample chamber surrounded by multiple Geiger counters and significant shielding. It removed some background signal and allowed them to calibrate for still more, thereby enabling them to pick out the $^{14}$C signal.

As the field of radiometric dating has expanded to include isotopes with longer half-lives, lower abundances, and trickier contaminants, so has the range of experimental challenges. Calcium-41 was identified in the late 1970s as a potentially useful radioactive tracer for studying biochemical and geochemical cycles because of its prevalence in both biological organisms and Earth's crust. And because $^{41}$Ca has a longer half-life than $^{14}$C—nearly 100 000 years rather than around 5700 years—it could date older specimens. But its low natural baseline abundance, about 1 out of every $10^{15}$ Ca atoms, kept $^{41}$Ca dating out of experimental reach.

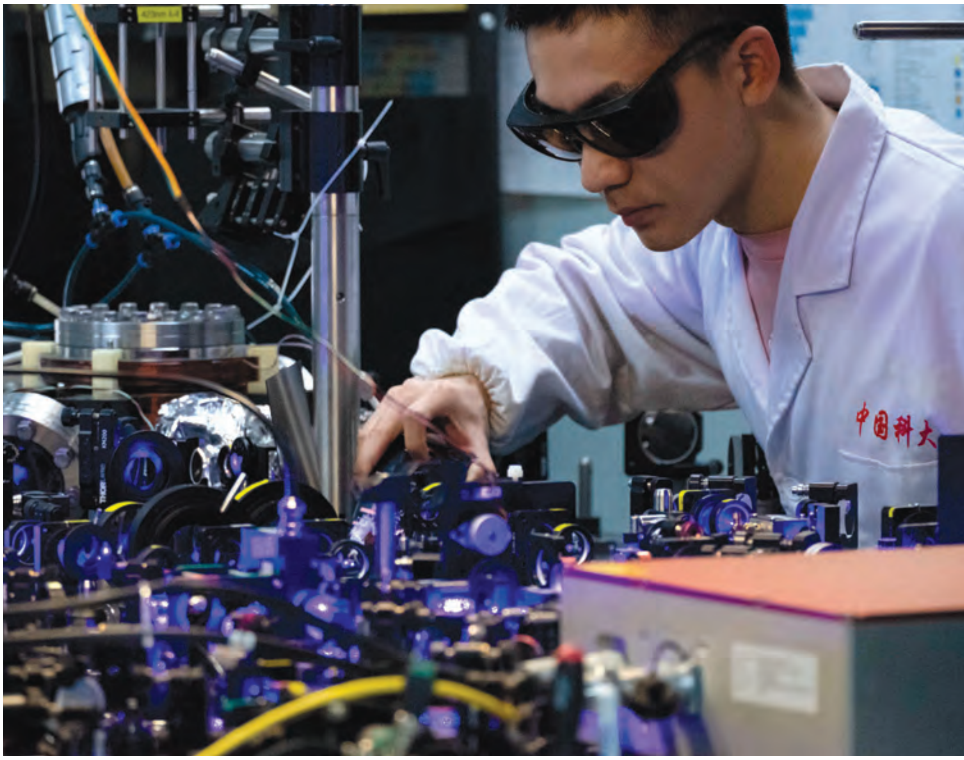


**FIGURE 1. WEI-WEI SUN,** a graduate student in the Laser Laboratory for Trace Analysis and Precision Measurements at the University of Science and Technology of China, adjusts the blue laser that slows and traps calcium atoms in the group's atom-trapping setup. (Courtesy of Wei-Wei Sun.)

Now Tong-Yan Xia, Wei-Wei Sun, and colleagues in Zheng-Tian Lu's group at the University of Science and Technology of China in Hefei have built an atom-trap trace analysis (ATTA) setup[1] (see figure 1) that can measure $^{41}$Ca at abundances of less than $10^{-16}$. They've demonstrated their system's ability to measure $^{41}$Ca in natural samples of granite, seawater, and bone, and they are now collaborating with glaciologists and other experts to test the isotope as a tracer for radiometric dating.

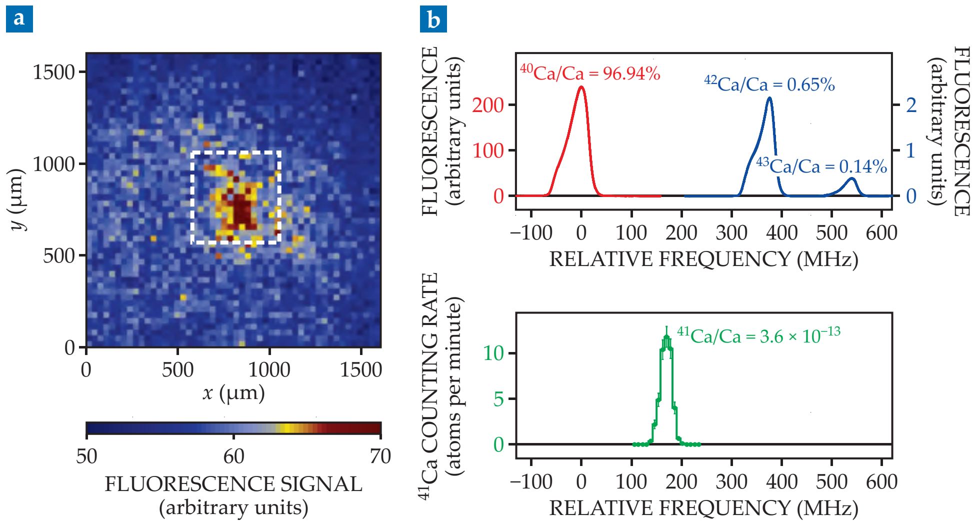


**FIGURE 2. INDIVIDUAL CALCIUM-41 ATOMS** are picked out of a Ca beam by atom-trap trace analysis. **(a)** The fluorescence from a single trapped $^{41}$Ca atom is recorded as a CCD image. The pixels in the region of interest (ROI) are used to measure the signal. **(b)** When the laser frequency is tuned to be resonant with the electron transitions in $^{40}$Ca, $^{42}$Ca, or $^{43}$Ca, the beam traps many atoms at once, which produces a bright fluorescent signal (top panel). But when it's tuned to $^{41}$Ca, it rarely catches more than a single atom at a time (bottom panel). (Adapted from ref. 1.)

## Isolating isotopes

A major disadvantage of using Geiger counters to measure a radioactive isotope's abundance is that the atoms are detectable only when they decay. So it revolutionized the field when researchers started using accelerator mass spectrometry (AMS) for carbon dating[2] in the 1970s. The technique uses a magnetic field to sort ions in a beam by mass, so researchers could measure the abundance of a particular isotope directly instead of waiting to detect a decay product. As a result, measurements take less time and can use much smaller samples.

A challenge for mass-spectrometry techniques is separating rare isotopes from common ones of the same mass. Radioactive $^{14}$C may be easily distinguished from $^{12}$C, but it's basically indistinguishable from nitrogen-14. To separate those isotopes, researchers have to give the species different charges so that they behave differently in the magnetic field. Carbon-14 atoms accept electrons to form a negatively charged beam, but $^{14}$N atoms don't. So that technique solves the problem for carbon dating.

But for other elements, including Ca, the trick of making a negatively charged beam doesn't work well. That's where ATTA comes in.[3] Introduced in 1999, the technique filters atoms based on their electronic structure rather than their mass.

An ATTA sample is first vaporized in an oven to create a neutral beam of atoms. Those atoms are then slowed by Doppler cooling and, eventually, loaded into a magneto-optical trap so that their fluorescence can be imaged (see figure 2a).

The main reason why AMS measurements of $^{41}$Ca can't reach natural environmental levels is because of potassium-41 contamination; the species have the same atomic mass, and even after purification, the stable isotope is always present at the same low level as $^{41}$Ca. But the two have entirely different electronic structures. So when the ATTA laser is tuned to a $^{41}$Ca transition, it has no effect on $^{41}$K, and the contaminant is no longer an issue.

The problematic contaminants in ATTA are isotopes of the same element. Slightly different nuclear masses and dipole moments alter the isotopes' energy levels and shift the electronic transition frequencies. But those shifts can be small, so isolating a particular transition can be tricky.

## Picking out a peak

Figure 2b shows the ATTA spectra for the four Ca isotopes that Xia, Sun, and their colleagues measured. When they tuned their laser to the resonance of the more abundant isotopes (top panel), they caught so many atoms in the trap at once that the measurement yielded only an overall fluorescent signal. But at the $^{41}$Ca resonance, rarely was there more than one atom in the trap at a time, so the researchers could count individual atoms.

The fact that ATTA looks at only one isotope at a time differentiates it from typical spectroscopy measurements and is crucial for its success with rare isotopes. The $^{40}$Ca fluorescence peak is 16 orders of magnitude taller than the $^{41}$Ca peak, and the two are separated by only about 200 MHz. If they were measured together, the smaller peak would be completely swallowed by the tails of the larger one. Trapping the $^{41}$Ca atoms separately allows them to be measured in isolation and their tiny peak to emerge.

For dating studies, though, the quantity of interest isn't just how many $^{41}$Ca atoms are present; it's the ratio $^{41}$Ca/Ca. To figure out the Ca beam's intensity, the researchers looked at the stable isotope $^{43}$Ca, which has the same hyperfine structure as $^{41}$Ca and is therefore trapped with a similar efficiency. Its isotopic abundance is 0.135%, which is too high for counting individual atoms. But the researchers extracted the trapping rate—how many atoms were caught per second—by turning the $^{43}$Ca trap on and off and analyzing the slope of the fluorescent signal.

Lu was part of the team that first developed ATTA and has been successfully applying the technique for years to dating glacier ice cores with argon and krypton isotopes. (See the Quick Study by Lu, Physics Today, March 2013, page 74.) Noble gases present the same challenge to AMS as Ca does—they don't form negative ion beams, so it's hard to separate the radioisotopes from more stable isotopes of the same nuclear mass.

So why did it take so long to apply ATTA to $^{41}$Ca? Researchers, including Lu, did attempt those experiments shortly after the technique's development.[4] And it was successful in applications for which the concentration could be raised above the natural background level of about $10^{-15}$. But it couldn't measure lower levels.

Lu credits advances in lasers in part for their current setup's improved performance: "Laser power is a lot higher, and laser frequency control is better—everything got better." Whereas it was difficult to pinpoint an isotope's transition frequency for cooling in earlier experiments, doing so is straightforward with modern lasers. Add to that an increase in power from about 60 mW to 3 W and an ATTA setup can reach a loading rate that is four orders of magnitude higher than it was in the technique's early days.

Advances over the past 15 years in modern cold-atom experimental techniques were also necessary to improve the trap's efficiency at capturing and holding atoms. One particularly important technique is so-called repumping: Each time an atom is excited in the Doppler-cooling process, it has a small chance of falling back to a state other than the ground state. When that happens, it can no longer be cooled by the laser and is lost. A repump laser directs the rogue atoms back to the ground state, thereby keeping more atoms around. It also helps the trap hold them long enough for imaging, which takes about 10 ms.

## Going lower

The researchers measured the $^{41}$Ca abundances in a series of samples that they made using commercially available Ca with a known $^{41}$Ca abundance of $10^{-7}$ and an added dilutant. The measured abundances in those samples covered three orders of magnitude, from $4 \times 10^{-13}$ to $5 \times 10^{-16}$, and had an error of about 12%.

The lowest abundance the researchers measured was that of the dilutant itself—Ca collected from deep in a mine. They determined the dilutant's $^{41}$Ca abundance by adding known amounts of it to the commercial Ca and measuring the resulting samples with ATTA. That calibration yielded an abundance of $(8.4 \pm 3.5) \times 10^{-17}$, which agreed with the value the researchers found through ATTA measurements of the pure dilutant. And they expect to be able to reach still lower concentrations by strengthening the atom beam and improving the laser-cooling setup.

The researchers are already collaborating with other groups to explore geological applications for their device. One area of particular interest is exposure dating of glaciers. Calcium-41 is produced through the capture of cosmic-ray-induced neutrons by $^{40}$Ca, but the process happens only in rock and soil within the top few meters of Earth's surface. So if rock gets buried under a glacier, the process stops, and the $^{41}$Ca starts to decay. Measuring a newly exposed rock's $^{41}$Ca/Ca ratio should therefore reveal how long it's been since the rock was last exposed.

A problem with that logic, though, is that baseline levels of $^{41}$Ca vary considerably, so it's hard to establish the starting point from which the level declined. But that number is critical if researchers want to use the isotope for dating.

"We've been talking to experts," says Lu, "because we have this new tool, but we don't quite know what to do first." One potential starting point they've identified is collecting and measuring the $^{41}$Ca concentration in water samples from various ocean bodies to see if it's uniform. The thinking is that even if there is local variation in the concentration, the currents might even it out, and then the water could serve as a baseline in certain situations.

But that theory still needs to be tested, and future applications are still uncertain. "We're just excited that now we can measure all kinds of samples and learn about $^{41}$Ca and its distribution on Earth," says Lu. "We can now explore the world."

**Christine Middleton**

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# Russian strikes on Ukrainian nuclear plants stir talk but little action in Western nations

Even as shelling of Ukrainian facilities threatens a radiological disaster, Russia's sales of enriched uranium to the US and the EU continue.


**THE ZAPORIZHZHYA NUCLEAR POWER PLANT** has been at the front lines of fighting between Russia and Ukraine for most of the war. Located on the eastern bank of the Dnieper River in Russian-controlled Ukrainian territory, the six-reactor plant has been shelled repeatedly, and ancillary buildings have been damaged. International Atomic Energy Agency director general Rafael Grossi has been attempting to broker an agreement to shelter the facility from further attacks.

US Department of Energy officials say they are urging other countries to ignore sales pitches from Russian nuclear power plant suppliers in response to attacks on Ukrainian nuclear facilities. But the US and other Western nations have so far done little to shed their dependence on Russian nuclear fuel.

Russia supplied 28% of US low-enriched uranium (LEU) in 2021, according to the Energy Information Administration. The US also imports natural uranium from Russia, most of which originates in Kazakhstan.

US lawmakers have introduced several measures to ban uranium imports from Russia, although none have been enacted. Most recently, identical House and Senate measures introduced in February and March, respectively, would prohibit imports—with annual exceptions provided for the Russian material that the US commercial industry has contracted for through 2027.

DOE and the International Atomic Energy Agency (IAEA) both recently have warned Russia that continued attacks on Ukrainian nuclear plants and the nation's transmission grid are courting a radiological disaster. Russia is fully cognizant of that risk, says David Hoagland, who heads the Ukraine task force at DOE's National Nuclear Security Administration (NNSA). "We want the world to know that Russia knows what they are doing. They understand nuclear energy and the interconnectedness of the grid and the safe operation of the nuclear plants," Hoagland says. "If there were a nuclear accident, it wouldn't be an accident."

"The nuclear safety and security dangers are all too obvious, as is the necessity to act now to prevent an accident with potential radiological consequences to the health and the environment for people in Ukraine and beyond," IAEA director general Rafael Grossi said in a 25 March statement.

Most alarming, say Hoagland and Kathryn Huff, DOE assistant secretary for nuclear energy, are the March 2022 takeover by Russian forces of the Zaporizhzhya Nuclear Power Plant (ZNPP), the largest nuclear plant in Europe, and its continued occupation. The armed seizure of an operating civil nuclear power plant—and the combat that is continuing nearby—is unprecedented in the history of warfare, they note. No nuclear power plant has been built to operate in wartime conditions.

At the front lines of the conflict, the ZNPP is on the Russian-controlled eastern bank of the Dnieper River, with Ukrainian forces defending the opposite bank. Since its occupation, the ZNPP has been shelled repeatedly, with each side blaming the other. Strikes have damaged several buildings, including one located adjacent to the plant's spent-fuel storage facility. The last of the site's six reactors, which had supplied around 20% of Ukraine's prewar electricity, was shut down last September, and the reactors have sustained no direct damage to date. But continuous power is required to cool the shut-down reactor cores and to maintain the spent fuel that's stored on-site in pools of water.

Deliberate attacks on Ukraine's electricity transmission system have caused the ZNPP to lose off-site power six times and be forced to resort to emergency generators, Hoagland notes. The loss of a backup power line on 1 March has left the ZNPP with a tenuous single-line connection to the power grid.

Meeting with Ukrainian president Volodymyr Zelensky on 27 March, Grossi said the situation at the ZNPP "is not getting any better," due to the ongoing fighting in the vicinity. Grossi visited the plant two days later in a largely unsuccessful attempt to broker an agreement between the warring parties to protect the plant. And in early April, he traveled to Kaliningrad, Russia, to continue his efforts in meetings with Russian officials. IAEA staff have been stationed at the ZNPP since September to monitor the situation at the plant, assess equipment and other needs, provide technical support and advice, and report to the IAEA headquarters.

Russia's deliberate assaults on Ukraine's electrical grid caused all nine operating reactors at Ukraine's three other nuclear power plants to shut down simultaneously last November. The NNSA has been supplying the plants with emergency diesel generators and fuel and is offering consulting services to plant operators. Such US assistance is unavailable to the ZNPP.

Russian missile strikes over the past year have damaged buildings storing civilian radiological sources that contain cesium-133 and cobalt-60, according to DOE. The sources were not breached; had they been, they could have spewed highly radioactive material to the surroundings, adding further distress to the local population. Russian forces were fully aware of those facilities' locations, even if they hadn't been deliberately targeting them, says Hoagland.

Huff warns that radiological disasters precipitated by Russia's attacks would set back nuclear power globally at a time when expansion is critical to helping mitigate climate change. "The public needs to have confidence in nuclear facilities," she says.

## Holding Russia accountable

Not only is Russia's nuclear enterprise the source for nearly half the world's enriched uranium, but it is by far the world's largest exporter of nuclear power plants. As of mid 2022, the state-owned company Rosatom had 17 reactors under construction in other countries, according to *The World Nuclear Industry Status Report 2022*. Rosatom claims 34 reactors in total are "at various implementation stages" in other nations and says its foreign orders are valued at $140 billion. Companies from only two other nations, France and South Korea, are currently constructing reactors outside their borders.

As of mid-February, Rosatom had exported just over $1 billion of nuclear-energy-related goods and materials since the start of the war, according to the Royal United Services Institute for Defence and Security Studies.

Hoagland says the "reckless and irresponsible actions" in Ukraine display to the world Russia's lack of regard for safety. It follows that potential buyers of Russian reactors should have no faith in the safety of those systems, he says.

The US has been cajoling other nations that are considering potential nuclear partnerships with Russia to abandon them, says Huff. "Isolating Russia in this marketplace economically for its bad behavior is critical because when you partner on nuclear reactor technology, you're engaged with them on their fuel supply, operations training, and technology upgrades for decades on decades."


**CYLINDERS OF URANIUM HEXAFLUORIDE** are processed at Urenco USA's enrichment plant in Eunice, New Mexico. The sole US commercial uranium enrichment facility, it provides about one-third of the nuclear fuel used by domestic nuclear power plants.

## Western dependence

Even as the US and the European Union (EU) have imposed full or partial embargoes on Russian fossil-fuel imports, nuclear fuel from Russia has continued to flow to the West. DOE's position is that restrictions on Russian imports should be coupled to new investments in US nuclear fuel facilities, says Huff.

The nuclear fuel cycle has multiple stages. Mined ores are first processed into triuranium octoxide ($U_3O_8$), known as yellowcake. Conversion plants chemically transform that to uranium hexafluoride ($UF_6$), which is gasified and then fed into centrifuges for enrichment from the naturally occurring 0.7% $^{235}U$ to the 4.5–5% LEU that fuels all US and most EU commercial reactors.

The capital-intensive enrichment stage is the main impediment to Western uranium independence. The US gets the rest of its enriched product from the European consortium Urenco, which operates three enrichment plants in Europe and one in New Mexico, and from the single plant operated by Orano in France. Urenco's US plant supplies about one-third of the domestic annual consumption on average.

"Conversion and enrichment services from trusted sources are insufficient to replace current US imports from Russia," Huff told the Senate Committee on Energy and Natural Resources on 9 March. "This strategic vulnerability is unsustainable."

A DOE analysis shows that the production of LEU will be 14% short of Western world requirements in 2024. The gap then widens to a projected average of 26% per year from 2025 to 2030. DOE says it hopes to incentivize the US domestic uranium supply chain to expand new enrichment capacity through competitively awarded public–private partnerships. Yet Congress has appropriated no funding for that. And regardless of the availability of funds, enrichment capacity will take years to build out.

Paul Lorskulsint, chief nuclear officer at Urenco USA, says the West has enough excess LEU to replace all Russian imports until 2028, when new enrichment capacity is scheduled to come on line. Japan, for example, has a stockpile resulting from contracts it negotiated prior to the Fukushima Daiichi nuclear disaster, he says. And some utilities have offered to share some of their surplus LEU if needed.

"If we decided as an industry that we wanted to end Russian imports, we could, through some creative means, cover that and be comfortable that we wouldn't have nuclear plant shutdowns because of a lack of enriched uranium," Lorskulsint says. "It would take some creativity and a lot of collaboration."

DOE says the global surplus, which it calls the strategic inventory, includes some of its own stockpiled LEU. Joseph Dominguez is president and CEO of

| Country of enrichment | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|
| China | W | W | W | W | W |
| France | W | 0 | W | W | W |
| Germany | 437 | 1 444 | 1 238 | 1 175 | 1 825 |
| Netherlands | 1 183 | 2 864 | 1 367 | 1 885 | 1 583 |
| Russia | 2 912 | 3 473 | 3 087 | 3 220 | 3 953 |
| United Kingdom | 1 525 | 1 544 | 1 262 | 1 218 | 2 366 |
| Europe | W | W | W | W | W |
| Other | W | W | W | W | W |
| Foreign total | 7 305 | 10 034 | 7 992 | 10 012 | 11 481 |
| United States | 5 572 | 4 979 | 5 289 | 4 132 | 2 736 |
| Total | 12 877 | 15 013 | 13 281 | 14 144 | 14 217 |
| Average price per SWU (US$) | 125.43 | 115.42 | 109.54 | 99.51 | 99.54 |

W = Data withheld to avoid disclosure of individual company data.
Totals may not equal sum of components because of independent rounding. Average prices are not adjusted for inflation.
Source: US Energy Information Administration, Form EIA-858, Uranium Marketing Annual Survey (2017–21).

**LOW-ENRICHED URANIUM** imports from Russia, expressed in separative work units (SWUs), the standard measure of the effort required to separate $^{235}$U and $^{238}$U during the enrichment process, totaled 28% of US demand in 2021, the latest figures available. The Department of Energy expects Russian imports to decline somewhat this year but increase again after 2024.

Constellation Energy, which owns and operates 21 nuclear reactors in the US. He told the Senate Energy Committee at the 9 March hearing that the company has secured enough nuclear fuel inventory and future supply contracts to meet its needs through 2028, even if its existing contracted Russian fuel supply was disrupted.

Urenco USA has been licensed by the Nuclear Regulatory Commission to produce up to twice its current capacity of LEU, and by 2028 it will have expanded enough that it could cover US imports from Russia, says Lorskulsint. Centrifuge manufacturing has been dormant for years, however, and Urenco and Orano haven't been replacing centrifuges as they wear out or break. Lorskulsint says the mothballed centrifuge assembly facility in New Mexico is now reopening, and manufacturing should resume early in 2025. Jessica Sondgeroth, deputy editor of *Nuclear Intelligence Weekly*, cautions that centrifuge operations can't be resumed overnight. A "learning curve" to building centrifuges includes training and clearing employees to work on the sensitive technology.

## Overfeeding could help

Frank von Hippel, a retired Princeton University physicist, says the West could quit Russian imports relatively quickly without new enrichment capacity. He calculates that independence would require 4900 tons more natural uranium per year, which could easily be obtained from the mining capacity that Canada's Cameco plans to reopen next year.

"You can get more low-enriched uranium out of a given amount of enrichment capacity if you increase the natural uranium feed and you don't work as hard at extracting the last bit of uranium-235," von Hippel says. Known as overfeeding, the process he describes leaves behind depleted uranium tailings with a higher $^{235}$U content compared with standard enrichment feeds. Those tailings can be stored to feed centrifuges when uranium prices are high.

With excess capacity because of market conditions, enrichers in recent years have been underfeeding—spinning their centrifuges longer and extracting more $^{235}$U from a given amount of $UF_6$. Lorskulsint says that Urenco USA recently ended underfeeding. Assuming that the other Urenco plants have done the same, he says, their combined output would increase by enough to offset about 40% of Russian imports to the US and the EU. Sondgeroth says the degree to which overfeeding could supplant Russian imports depends on the demand for non-Russian LEU from elsewhere in the world, how quickly centrifuge manufacturing resumes, and adequate supplies of $UF_6$.

DOE says a combination of new enrichment capacity, the elimination of underfeeding at existing enrichment plants, and drawdowns from the strategic inventory are all needed to make up the shortfall in the event of complete disruption of Russian LEU supplies to the West.

Conversion is a second potential choke point in the fuel cycle. Cameco's Ontario facility was the sole North American conversion plant until last month, when ConverDyn reopened a facility in Metropolis, Illinois, that was closed in 2017. Von Hippel says the two plants should provide enough $UF_6$ feed to cover Russian imports. Doug True, a senior vice president with the Nuclear Energy Institute, notes that overfeeding would exacerbate any shortfall in conversion capacity.

The prospects for EU independence from Russia are clouded by the 19 Russian-made VVER-440 reactors operating in eastern EU countries. Non-Russian-made fuel assemblies for those do not currently exist, although Westinghouse is close to producing substitutes. "That makes it virtually impossible for Europe to implement sanctions," Sondgeroth says. A partial EU ban with the 19 exceptions could cause Russia to retaliate by halting shipments to those reactors, she adds.

## An inconvenience?

Edwin Lyman, director of nuclear power safety at the Union of Concerned Scientists, says the US nuclear industry has made little effort to lower its dependence on Russian LEU. "Industry came out of the gates saying no, we can't do it. I didn't see any kind of effort on the part of the US industry to get together and say let's see how we can do this."

If Constellation could do without Russian uranium, "the question is why didn't they just do it?" says Lyman. "They don't want any perturbation of their Russian supply that could inconvenience them or raise costs. I find that kind of outrageous." A Constellation spokesperson says the Russian supply contracts were negotiated before the Ukraine invasion, and none have been made since then.

The US nuclear industry has long urged the federal government to subsidize new domestic enrichment capacity, arguing that all the world's enrichment plants are essentially government-owned enterprises. The options seem limited, however. Centrus Energy, the remnants of the once federally owned enrichment enterprise, will this year begin producing under DOE contract a relatively tiny quantity of high-assay, low-enriched uranium, a specialty product needed for advanced reactors that's enriched up to as much as 19.75% in $^{235}$U. But Centrus has built just 16 centrifuges. A commercial enrichment plant has thousands.

In his Senate testimony, Constellation's Dominguez plugged laser enrichment technology in development by North Carolina–based Global Laser Enrichment. Part-owned by Cameco, GLE is preparing a commercial-scale pilot demonstration of technology developed in Australia. With DOE providing timely and modest cost-share support, Dominguez said, GLE could accelerate to 2028 the commercialization of its technology at a proposed site in Paducah, Kentucky.

**David Kramer**

# Hybrid scientific conferences: An ongoing experiment

Duplicating or replacing serendipitous encounters in virtual environments is a challenge.

"I've seen you on Zoom, but we've never met." Mark Neubauer, a high-energy physicist at the University of Illinois at Urbana-Champaign, has heard such comments repeatedly since in-person scientific conferences began making a comeback. In 2020, when COVID-19 was declared a pandemic, Neubauer, like most researchers, started spending a lot of time on Zoom for conferences and other activities. He organized a May 2021 workshop on the future of meetings (a summary is available at https://arxiv.org/abs/2106.15783).

By late 2021, many conferences were offered in hybrid formats, with some people participating in person and others logging in from afar. Before the pandemic, remote participation in conferences was often frowned on, Neubauer says. But now "the genie is out of the bottle" for remote participation in meetings, which can have the advantage of accessibility and sustainability. Hybrid formats are here to stay, he says, even as "there is a lot of pressure to get back to how we held meetings prepandemic."

The purposes of scientific conferences include sharing knowledge, providing visibility for early-career scientists, and maintaining and extending networks. Hybrid options could improve some traditional conferences, which may not always deliver what scientists want from them. "Sessions are held back-to-back, and there is little time for discussion," says Astrid Eichhorn, a University of Southern Denmark professor whose research is in quantum gravity. And, she adds, often conference goers sit in a presentation checking their phones and working rather than paying attention to the talk. "Overall, we do not have the ideal format yet."

## "Conferences need to change"

Julia Marks Peterson says that until recently, she "only knew online conferences." She began her PhD studies at Oregon State University in 2020, during the lockdown phase of the pandemic. Last October she went to an ice-core science conference in Crans-Montana, Switzerland, with about 500 attendees. "When I went to my first in-person conference, I realized what I had missed out on," she says. "I hadn't realized how productive a conference could be." The informal feeling of the gathering gave her confidence to approach leaders in her field. Besides forming connections with people, Marks Peterson says she was more likely to attend sessions that did not sound relevant to her own research than she would have been online. "When it's all in the same place, why not?"

Marks Peterson also appreciates the hybrid aspect of conferences. Last December, for example, she couldn't attend the fall meeting of the American Geophysical Union because she was doing fieldwork in Antarctica. So she prerecorded a talk, which was presented as part of an otherwise live session. "It was a nice way for me to get my work out there," she says.

"And I got feedback on the questions. The pandemic has helped us to be more flexible." And now that she's been to an in-person meeting, she adds, "I realize how valuable the networking aspect is—especially for early-career researchers."

The option to attend a conference remotely eases participation for people with travel constraints because of schedules, health, money, visa restrictions, or other reasons. Not having to pay for travel especially benefits scientists in low-income countries and graduate students and postdocs. The remote option also means presenters and attendees can pop in briefly to a meeting they would not have traveled to.

And online meetings have a lower carbon footprint. Eichhorn points to a May 2022 report by the European Federation of Academies of Sciences and Humanities, where she is active on its committee for climate sustainability, that says virtual meetings create just 2% to 6% the greenhouse gas emissions created by in-person meetings. (The federation's report is available at https://doi.org/10.26356/climate-sust-acad.)

"Conferences need to change, and they need to always be hybrid," says Andrea Armani, a University of Southern California materials science professor who has organized in-person and virtual conferences. A major focus of the efforts to reimagine scientific meetings is finding ways to facilitate networking and person-to-person engagement in virtual environments. "It's very important to be inclusive of all scientists at all career stages," she says.

## Hybrid options

"We are learning that some things work well in hybrid format, and others do not," says Jen Ives, director of meetings for the American Meteorological Society. "We will pursue the things that work well." At its annual meeting in Denver last January, the society offered Zoom rooms centered on scientific or other themes. But uptake was spotty, Ives says, as were informal interactions between people who were on-site and online. The meeting, which was attended by around 6000 people in person and 1000 online, featured both virtual and in-person poster sessions. But not all of the live posters were uploaded digitally, and for remote presenters in a virtual room, she says, "if no one stops by, the lack of interest is amplified, whereas a physical venue may still feel full." Virtual posters and networking need to be reworked, says Ives. "If we are not successful, we will probably drop them."

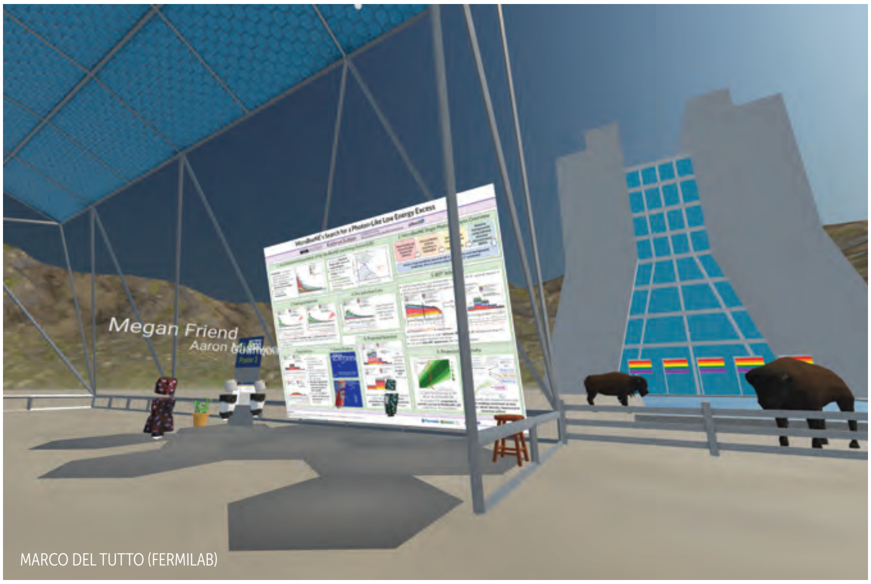

APS

**CONFERENCE GOERS GET TOGETHER** at the American Physical Society's 2023 March Meeting in Las Vegas, Nevada. Attendance reached a record high.

This year, the American Physical Society (APS) held separate in-person and remote components of its major meetings. That followed the abrupt cancellation of the 2020 APS March Meeting (see "APS cancels March Meeting due to coronavirus concerns," Physics Today online, 2 March 2020), a fully remote event in 2021, and a hybrid format in 2022. "We learned that it was difficult for presenters to have their talks ready to upload ahead of time," says Hunter Clemens, APS's director of meetings. The intention was to be able to play them at in-person sessions or on demand for virtual audiences, he explains. But the in-person crowd didn't want to watch prerecorded talks when they knew they could catch them later online, he says. "They wanted to see live talks, ask questions, and network."

APS "can't afford to live stream 75 concurrent sessions" from the in-person meeting, Clemens says. A few high-profile talks were live streamed; the rest were captured and later uploaded. He notes that the cost of running the large APS meetings "increases significantly" from the remote portions. The required internet bandwidth plus the labor to run audio and video technology add up, he says, such that the cost per participant this year was slightly higher for the March Meeting's remote component than for the in-person one.

"The in-person meeting was a home run. There was incredible buzz," says Clemens. A record 12 567 people attended this year's in-person APS March Meeting in Las Vegas, Nevada. Two weeks later, a crowd of 2293 logged into the remote meeting; nearly half of those had also attended in person. About 900 people presented virtually, he says. Some attendees gathered to watch and present talks and




MARCO DEL TUTTO (FERMILAB)

**VIRTUAL REALITY** is one way to connect, as in this poster session from the Neutrino 2020 conference. But enthusiasm for such approaches is fading as conferences resume in person.

posters at regional hubs in Brazil, India, Jordan, Rwanda, and South Africa.

"We can never re-create online the same networking experience that people have in person. We shouldn't expect it to be the same," says Clemens. Still, the remote attendees also reported having a better experience in the fully remote format than last year in the simultaneous hybrid mode. APS is assessing the meeting costs and analyzing participant surveys, but Clemens says that the society is likely to stick with separate remote and in-person meetings.

Remote participation in meetings generally was enthusiastic at first, says Kevin Marvel, executive officer of the American Astronomical Society (AAS). People "who would never have shown up in Wisconsin" for AAS's 2020 June conference attended from far-flung countries. But people are now "less willing to sit in remote meetings modeled on in-person meetings." Marvel notes that AAS has tried to foster interactions using the virtual reality platform gather.town, virtual chat rooms, and Slack channels. Everything failed, he says. "It's impossible to duplicate the interactions that take place outside of the official program."

Another twist, Marvel says, is that many remote participants want to attend for free. But while they don't use the exhibition halls, go to the registration desks, eat the doughnuts, or need the people who run around changing signs in front of lecture rooms, "you have to provide a different type of infrastructure for digital meetings."

Despite the challenges, Marvel says that "a fully virtual meeting can be fantastically successful—everyone is on the same field." That's true for in-person meetings too, but not for hybrid, which can feel like they have "two classes of attendees." AAS sees "a future where at least one of its two major annual meetings is fully virtual," he says. "We want to have a big impact on reducing our carbon footprint. And we don't want to lose the spontaneous interactions that people value in person."

## Digital first

"If you care about diversity and inclusion, meetings should be remote or hybrid. In person should only be used when it has value," says Vanessa Moss, head of science operations at Australia's ASKAP radio telescope and lead of the Future of Meetings group. "If you ask people what they miss about in-person conferences, no one mentions listening to talks. What they miss is the social interactions and the unstructured stuff that is harder to do in Zoom."

Moss and the Future of Meetings group don't claim to have all the answers. But a "digital-first" approach will work better than trying to retrofit traditional meetings with a remote component, she says. For example, a remote meeting may work better stretched out over more days than its in-person precedent. And grouping scientific sessions into blocks of a couple of hours and building in breaks can combat computer fatigue and accommodate participants in different time zones.

Moss recommends that funding slated for physical travel be redirected to improve the digital conference experience. For example, money for conference travel could go instead to better headsets or internet. As for online networking, she says it's easiest when participants share a specific goal, such as discussing methods to improve remote meetings, sustainability in science, or a narrow scientific topic. Advances in technology will help with networking, too, she says. "Virtual reality will get better. There are some very creative things that can be done virtually that we are just scratching the surface of."

Some meetings with a digital-first approach were getting started even before the pandemic. The first Photonics Online Meetup took place in January 2020. The motivations were to meet with colleagues without creating a large carbon footprint and in an accessible form that reduced the burden of participation on people with families, says Rachel Grange, one of the organizers and a professor at ETH Zürich in Switzerland. Some 1100 people participated, with many of them gathering in local hubs of 5–80 people. They presented posters via Twitter. The organizers bought a software license to permit 1000 people online. "It was cheap, but not free, to organize," and it was free for participants, Grange says. "Online is a way to share knowledge, but for networking, you need to be on-site."

"Most online conferences are not that great," says Shaun Hotchkiss, a theoretical cosmologist who is based in Auckland, New Zealand. With a handful of colleagues, he launched Cosmology from Home. The online conference emerged prepandemic, he says, from the idea that "we have all these tools. We must be able to use them better. Let's build from the ground up." (See the interview with Hotchkiss at https://physicstoday.org/hotchkiss, in which he tells about his move from research to starting a business to help researchers share their work through online meetings and other means.)


**SCIENTISTS ATTEND** a small astronomy conference on fast x-ray transients hosted at Radboud University in Nijmegen, the Netherlands, in November 2022. The remote attendees were from Chile, Israel, and the UK. (Courtesy of Peter Jonker.)

The first rule is to design online events such that nothing is passive, says Hotchkiss. "There is no boring sitting around and passively staring at a screen, unable to interact." Even when people are engaged by a 45-minute talk, he adds, by the end they are tired. Cosmology from Home is run like a flipped classroom: Talks are uploaded to YouTube, people watch on their own time and then, when they meet, "they jump straight into real discussions." The annual conference is run over a two-week period, with scheduled interaction time usually capped at six hours a day in two blocks of time that are chosen to best work for people participating from different time zones. Attendance has ranged from 200 to 350 in the three events to date.

Hotchkiss's second rule is that discussions need to be managed. "Otherwise, they can be a disaster," he says. Even in person, he adds, the more assertive, confident people tend to dominate discussion, and that can be amplified online. "We have a well-thought-out structure. If you want to say something on the current topic, you put up a predetermined symbol, and for new topics, you put up a hand."

In the social arena, Hotchkiss and his team have tried to match people up with mentors, and they've introduced games. He doesn't have data on the mentoring, but the games and other social events, which have 10–40% uptake, are "clearly very valuable to those who do come."

## Reimagining conferences

Many questions remain as to what works best for meetings. Are hubs a good idea? Should hybrid be simultaneous? Does meeting size play a role? Can networking and serendipitous conversations be reproduced in online formats? Armani, one of the Photonics Online Meetup founding organizers, favors hubs: "We are trying to encourage networking at the local scale, including with industry. Most students want jobs locally," she says. Moss likes the reduced carbon footprint that hubs offer but worries that they "reinforce boundaries and insularity."

As far as networking, agreement is widespread that it's better in person than online. But, says Neubauer, "somehow technology should make it seamless for virtual and in-person people to interact. I'm talking futuristically—maybe in 10 or 20 years."

Even in its current forms, remote conference attendance offers benefits for lowering carbon footprints and raising accessibility. Ezequiel Treister, who heads a group in galaxy evolution at the Pontifical Catholic University of Chile, used to fly 10 to 12 times a year to attend conferences and administrative meetings. He's pared that down to 3 or 4 times a year. Telescope allocation and other board meetings work well online, he says. His students and postdocs now attend more meetings with the online option. But if they are presenting important work, he says, "I still send them in person."

"The way we look at meetings for now is that it's an experiment," says APS's Clemens. "We are trying to get it right."

**Toni Feder** PT

# The CLOUD DYNAMICS of convective storm systems

Caroline Muller and Sophie Abramian

**Through a combination of idealized simulations and real-world data, researchers are uncovering how internal feedbacks and large-scale motions influence cloud dynamics.**

People are delighted by clouds and have been ever since first looking up at the sky. They have fascinating structures, which help observers to visualize atmospheric motion. Convective clouds form when air rises. Convection here refers to the movement of air within which clouds are embedded, as shown in figure 1a. Air can rise as a result of the warming of Earth's surface during the day or as it moves over mountains and other topographical features.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The air's upward movement carries near-surface water vapor, whose large concentration at low altitudes decreases rapidly with height in the atmosphere. Through a process known as adiabatic expansion, the rising moist air cools as the pressure drops at higher altitude. When the moist air is cold enough, its water vapor starts to form liquid or ice condensates, depending on temperature. The tiny, suspended condensates—typically a few tens of microns in diameter—form clouds, which unlike water vapor are visible to our eyes.

At the mature stage of cloud formation, the rising air reaches its equilibrium level—the altitude where its density matches that of the environment—and the cloudy air is no longer buoyant (figure 1b). For dense, deep clouds, the equilibrium level can be as high as the tropopause, an altitude of around 10–15 km.

Once the air stops rising, it spreads horizontally at the top of the cloud and forms what's called an anvil cloud, shown in figure 1c. The condensed droplets grow in the cloud through microphysical processes, and when large enough, they eventually start to precipitate and fall toward the ground. As they do so, they may partially evaporate, notably below the cloud base. The concomitant latent cooling leads to a cold air mass, known as a cold pool, that descends below the cloud and spreads horizontally at the surface. The downward motion counteracts the upward motion that started the convective storm, thereby ending the cloud life cycle. The whole process for a single cloud typically lasts a few hours and spans a horizontal scale of roughly one to a few kilometers.

Clouds can also form spectacular multicloud structures, several of which are shown in figure 2. At scales of hundreds of kilometers—the so-called mesoscale—organized convection can take the form of squall lines or mesoscale convective complexes. The most famous example is probably the tropical cyclone. At its center lies a relatively quiet eye, surrounded by a cloudy wall of rotating winds, which are among the strongest on the planet.

Mesoscale organized systems like the ones shown in figure 2 lead to extreme weather and to changes in large-scale properties, notably cloud cover and water-vapor distribution. Although the physical processes that cause mesoscale organization are still poorly understood, the science is improving because of significant advances in the past decade. The breakthroughs were made possible by the increased capability of computer simulations and by many idealized and theoretical investigations. Notably, much progress has been made on a mode of convective organization called self-aggregation.

## Self-aggregation by internal feedbacks

Self-aggregation refers to the spectacular ability of deep clouds to spontaneously cluster in space, despite perfectly homogeneous boundary conditions in idealized numerical simulations[1] (see figure 3). The phenomenon occurs when sea-surface temperature is constant, with neither large-scale forcing nor land–sea contrasts, and with reentrant boundary conditions—a cloud that exits the domain on one side reenters on the other side.

The clouds' spontaneous organization via internal feedbacks appears to be related to the interaction of clouds with their near environment. Researchers have put forward four feedback mechanisms to explain self-aggregation: radiative processes, entrainment at the edge of clouds, cold pools, and waves.[2]

All the aggregation feedbacks work in a similar fashion: They favor the formation of clouds in regions near clouds and disfavor formation in regions devoid of them. Both actions are positive feedbacks because they reinforce an existing cloud distribution. More clouds form where there are more clouds, and fewer form where there are fewer. That reinforcement leads to a spatial separation between cloudy, moist regions and noncloudy, dry ones.

In radiative feedback, dry regions are associated with strong radiative cooling to space because of their relatively small amount of atmospheric water vapor. It is similar to a local greenhouse effect, in that water vapor acts as a greenhouse gas—less water vapor means fewer greenhouse gases and thus cooling. That cooling of the air triggers it to subside and flow in a diverging pattern near Earth's surface. Because most water vapor is located there, the relatively dry subsiding air from above

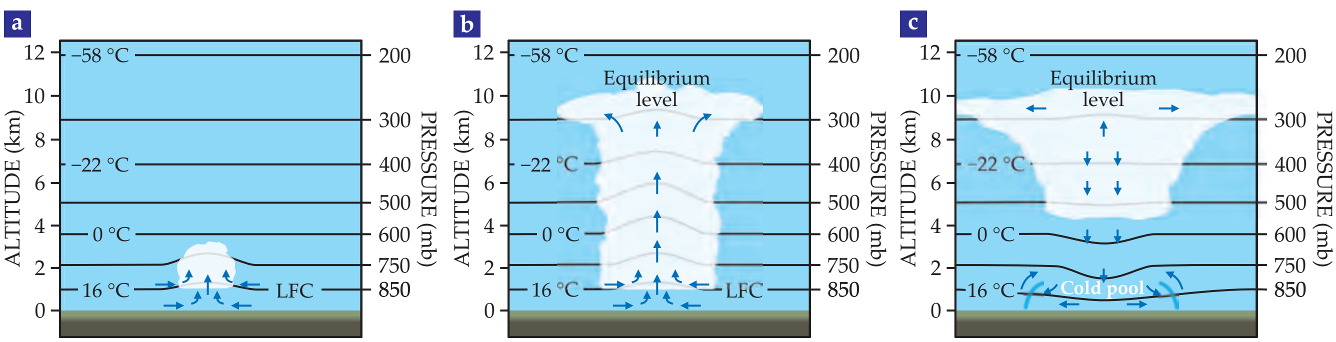


**FIGURE 1. CONVECTIVE-CLOUD LIFE CYCLE.** During a storm's developing stage **(a)**, air starts rising, and when it reaches its level of free convection (LFC), it becomes buoyant. **(b)** It keeps rising until, at the cloud's mature stage, it reaches the equilibrium level, where its density matches that of the surrounding air. **(c)** The upper-level air then spreads horizontally, forming what's known as an anvil cloud. Liquid and ice droplets grow through microphysical processes and begin to fall toward the ground. In the dissipating stage, the partial evaporation of the precipitating condensates produces a mass of cooler air and generates a downdraft that spreads it horizontally at the surface. (Adapted from the COMET website at http://meted.ucar.edu of the University Corporation for Atmospheric Research, sponsored in part through cooperative agreement(s) with the National Oceanic and Atmospheric Administration, US Department of Commerce. ©1997–2023 UCAR.)

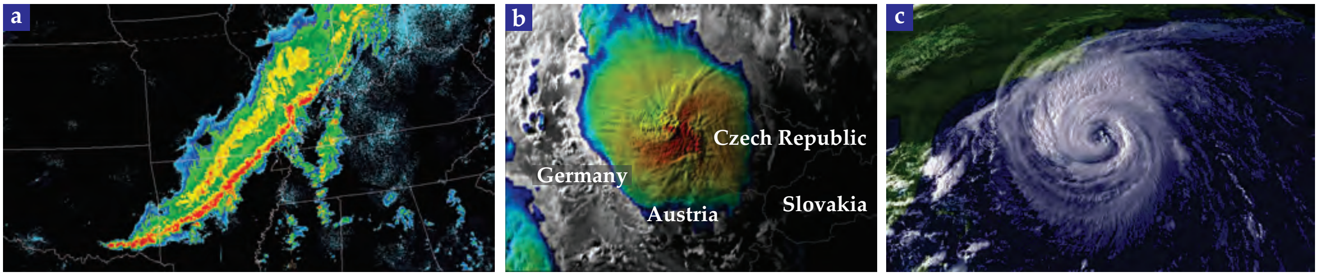


**FIGURE 2. MESOSCALE CONVECTIVE SYSTEMS** are storms in the atmosphere that can span hundreds of kilometers. Some examples include **(a)** squall lines, which are a type of elongated multicloud structure; **(b)** a circular multicloud structure; and **(c)** a tropical cyclone, composed of a rotating multicloud structure. (Panel a courtesy of Nolan Atkins; panel b © EUMETSAT 2011; panel c courtesy of the World Meteorological Organization.)

replaces the relatively moist near-surface air, drying that part of the atmosphere further. The drier air is less buoyant and thus less receptive to convection and cloud formation.[3,4]

With entrainment feedback, as air rises and water vapor condenses to form a cloud, air viscosity causes the rising air to drag surrounding air with it. The edge of the cloud becomes highly turbulent and leads to the entrainment and the mixing of environmental air with the cloudy air. Mixing at the edge can significantly reduce cloud buoyancy if the entrained air is dry. Indeed, dry-air mixing will lead to the evaporation of some of the cloud droplets, and the concomitant latent cooling reduces the cloud buoyancy. Conversely, if the environmental air is moist, which would happen if a cloud formed near a recently formed one, the upward motion will not be arrested, and it'll form more easily. That possibility favors the clustering of clouds in the moistest region.[5]

In cold-pool feedback, as cold pools spread at the surface below a precipitating cloud, they raise the surrounding warmer air at the edges. The mechanically induced upward motion encourages the formation of new clouds near the edge of cold pools. And by facilitating new clouds in the vicinity of existing ones, cold pools thus reinforce the clustering of clouds in space.[6]

In wave feedback, convection triggers internal gravity waves that propagate in stratified media.[7] (For more on internal gravity waves, see the article by Callum Shakespeare, Physics Today, June 2019, page 34.) Suppose that the atmosphere is a two-layer fluid: The denser, bottom layer of air ranges from the ground to the bases of the clouds at an altitude of about 1 km, and the lighter layer above spans from the clouds' bases to their tops at an altitude of about 10 km. In that simplified case, internal waves become interfacial waves that propagate between the two layers, similar to surface waves between air and water when a rock is thrown in a pond. Interfacial waves between the two layers are triggered by convection and propagate away from the clouds. The waves can form standing wavepackets that separate convectively active areas from inactive ones.[8]

Because of the idealized settings in which self-aggregation is investigated, researchers are still debating its relevance to the real world. Ending that debate will require more observations, either from satellites or *in situ* measurements. With recent improvements to the fundamental understanding of the physical processes involved in self-aggregation, researchers should be positioned to identify each feedback in observations and determine to what extent each dominates in the real atmosphere.

## Squall lines formed by wind shear

The difficulty in studying realistic settings from observations is that in addition to internal feedbacks, the interaction of clouds with the atmosphere's large-scale flow can contribute to organizing convection. An important example of such an interaction occurs in squall lines, known to emerge in the presence

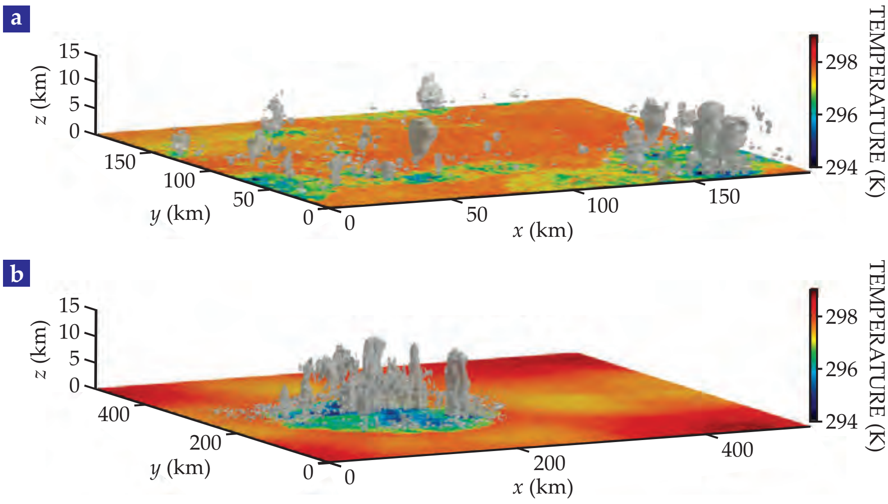


**FIGURE 3. IDEALIZED NUMERICAL SIMULATIONS.** In the absence of feedback mechanisms, **(a)** simulated clouds appear disorganized in space. **(b)** Under the influence of those mechanisms, however, clouds can self-aggregate into a coherent convective structure, and that behavior increases with domain size and temperature. Self-aggregation is associated with a large-scale drying of the atmosphere and enhanced large-scale outgoing radiative cooling to space. Based on observations of relative humidity, researchers have learned that the middle troposphere is consistent with modeled self-aggregation and is on average drier for an atmosphere in which the same amount of precipitation is concentrated into a small number of convective clusters. (Adapted from ref. 1.)

> “Observing convective organization and the relevant physical processes is challenging.”

of vertical wind shear—that is, when wind at the surface moves at a different speed than wind at altitude. In addition, large-scale variations can be induced by atmospheric circulations in the tropics. (For more on tropical circulation, see the article by Thomas Birner, Sean Davis, and Dian Seidel, Physics Today, December 2014, page 38.)

The theoretical explanation for the development of squall lines came from a foundational paper published 35 years ago.[9] It describes how wind shear can interact with the cold pool, which in this case plays a key role in maintaining the storm. The interaction is based on three main principles, shown schematically in figure 4.

First, wind shear blocks the spread of the cold pool from where it originates. Second, the cold pool acts as a ramp that lifts the warm and moist air. Finally, wind shear and the cold pool together produce a vorticity dipole—the two counterrotating wind profiles, often indicated with a + sign and a – sign.

The vorticity dipole supports upward motion between the wind profiles, which accelerate the upward motion and promote deep vertical convection. The edge of the cold pool then becomes an optimal spot for deep convective updrafts that lead to cloud formation, precipitation, and squall lines. In other words, the storm precipitation feeds the cold pool, which maintains the conditions that favor the storm updraft and subsequent precipitation. The series of interactions allows squall lines to last as long as 24 hours and to travel for thousands of kilometers.

Intuitively, one would expect the coupling between the wind shear and the cold pool to depend on the shear intensity. When it’s too weak, as illustrated in figure 5a, there’s no particular interaction and therefore no organization of the deep clouds. When the shear increases, however, a squall line tends to develop perpendicular to the imposed wind, as seen in figure 5b, which corresponds to a horizontal wind variation of about 10 m/s over the 1 km layer closest to Earth’s surface. Beyond wind speeds of 10 m/s, squall lines are oriented at an angle less than 90 degrees to the wind direction, as shown in figure 5c.

Many researchers have studied the angle of orientation of squall lines. A recent numerical simulation analysis,[10] for example, validated a decades-old hypothesis[11] that suggested that the orientation of squall lines reduces incoming wind shear and restores the equilibrium between wind shear and cold-pool spreading. Indeed, subsequent findings have indicated that cold-pool intensity is largely insensitive to wind shear, and the optimal value of shear is the one that matches the strength of cold-pool spreading. In other words, the orientation of the squall line preserves the organization of convection even in the presence of a strong shear greater than the optimal value.

Wind shears with intensities up to the optimal value make squall lines more organized and, therefore, can drive their intensification. Recent climate-model simulations, for example, highlight that over the Sahel region in north-central Africa changing wind shear is the main reason for the enhancement of squall lines under warming conditions.[12] That case illustrates how wind shear adds a critical contribution to the intricate

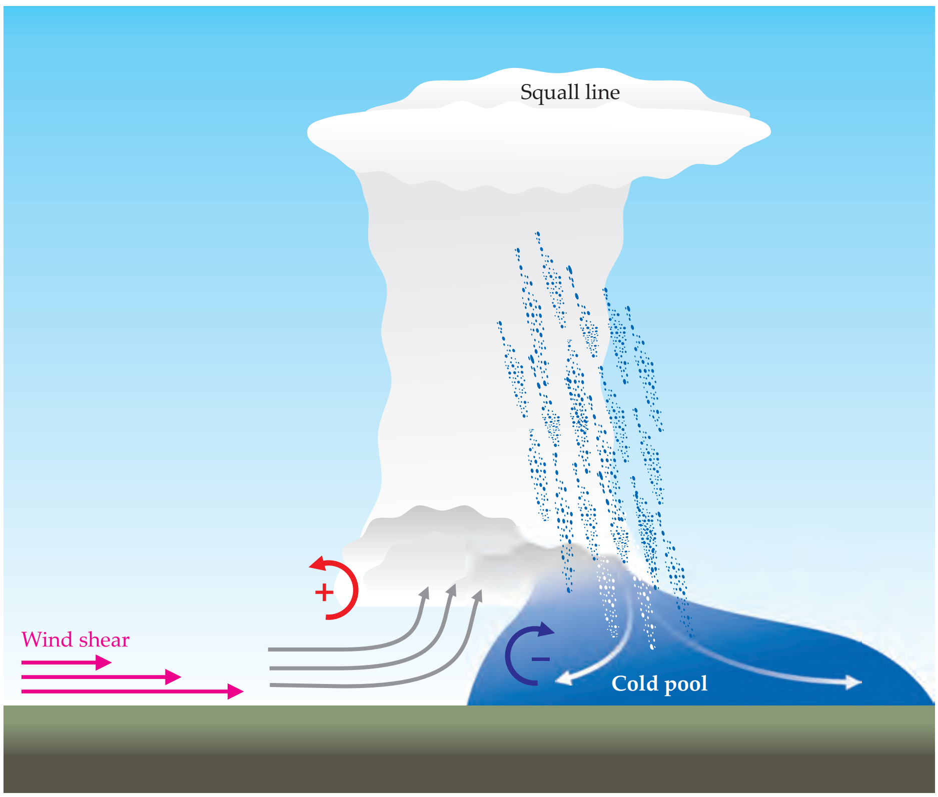


**FIGURE 4. SEVERAL INTERACTIONS** lead to the formation of a squall line of clouds. Rain and its subsequent evaporation fuel the rise of a mass of cold air that spreads below a cloud. Incoming wind (gray arrows) blocks the spreading of the cold pool, which in turn acts as a ramp for raising moist warm air. The vertical variation of wind strength (pink arrows) induces a positive vorticity (red plus sign). That twisting motion interacts with the negative vorticity found in the cold pool (blue minus sign), which favors storm drafts and other upward motion that promotes the formation of squall lines in the atmosphere.

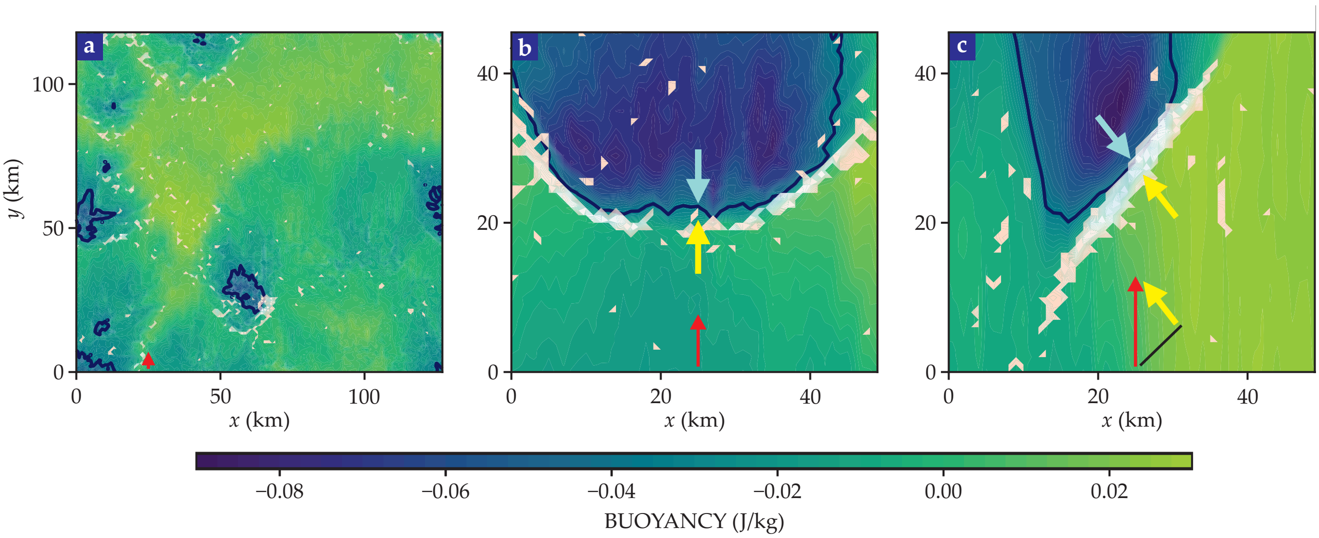


**FIGURE 5. WIND SHEAR** influences the orientation of tropical squall lines. In each of the three simulation cases, the color denotes the buoyancy field, which is proportional to the atmosphere's anomalous temperature relative to the climatological average. The cloud locations are shown in white. **(a)** When no shear is imposed, no organization of a squall line is observed. **(b)** For a horizontal wind speed $U = 10$ m/s (red arrow), a squall line of clouds develops perpendicular to the wind direction, and the projected shear (yellow arrow) is optimal because it balances the force from the spreading of the atmospheric cold pool (blue arrow). **(c)** For $U = 20$ m/s, which corresponds to greater than the optimal shear, the squall line is oriented at an acute angle to the wind direction. In that case, the squall line's orientation reduces the projected shear so as to restore the force balance with the cold pool. (Adapted from ref. 10.)

relationship between climate change and the degree of deep-convection organization.

## The road ahead

Researchers don't know the extent to which internal feedbacks organize clouds in the real atmosphere compared with large-scale forcings, such as wind shear and land–ocean contrasts. The response of clouds to global warming is one of the largest uncertainties in current predictions of climate change from models (see the article by Tapio Schneider, Nadir Jeevanjee, and Robert Socolow, Physics Today, June 2021, page 44). Given the dependence of cloud cover on convective organization, how convection changes with climate change is of major importance. All the aforementioned idealized studies can help address those uncertainties in observations and shed new light into the physical processes at stake in the atmosphere. That combination of idealized studies with analysis of real-world data will help researchers determine how cloud organization may change with global warming.

Observing convective organization and the relevant physical processes is challenging. For instance, assessing the radiative feedback requires sensitive measurements of radiative cooling rates close to the surface, which are difficult to obtain from satellite measurements.[13] The recent international observational campaign EUREC$^4$A provided invaluable *in situ* data of vertically resolved radiative cooling rates.[14] Those data helped researchers develop a theoretical basis for what dictates low-level cooling rates,[15] notably their close relationship with water-vapor variations.

A global climatology of cold pools is also missing, as they are equally challenging to observe from satellites. Recent work using synthetic-aperture radar and machine learning to obtain images shows some promise.[16] The European Space Agency's new Earth Explorer mission, Harmony, will provide fine-resolution measurements of near-surface winds.[17] Those observations will undoubtedly contribute to improved measurements and understanding of cold-pool properties.

A recent study attributed the latest observed trend of precipitation extremes to changes in convective organization.[18] Accurate predictions of the hydrological cycle, therefore, will require researchers to better understand convective organization and how it will change with warming. The theoretical work discussed in this article, increased and improved observational data, and new methodologies that include machine-learning approaches have tremendously increased the scientific basis to answer that important question. All the promising avenues make it an exciting time for cloud research.

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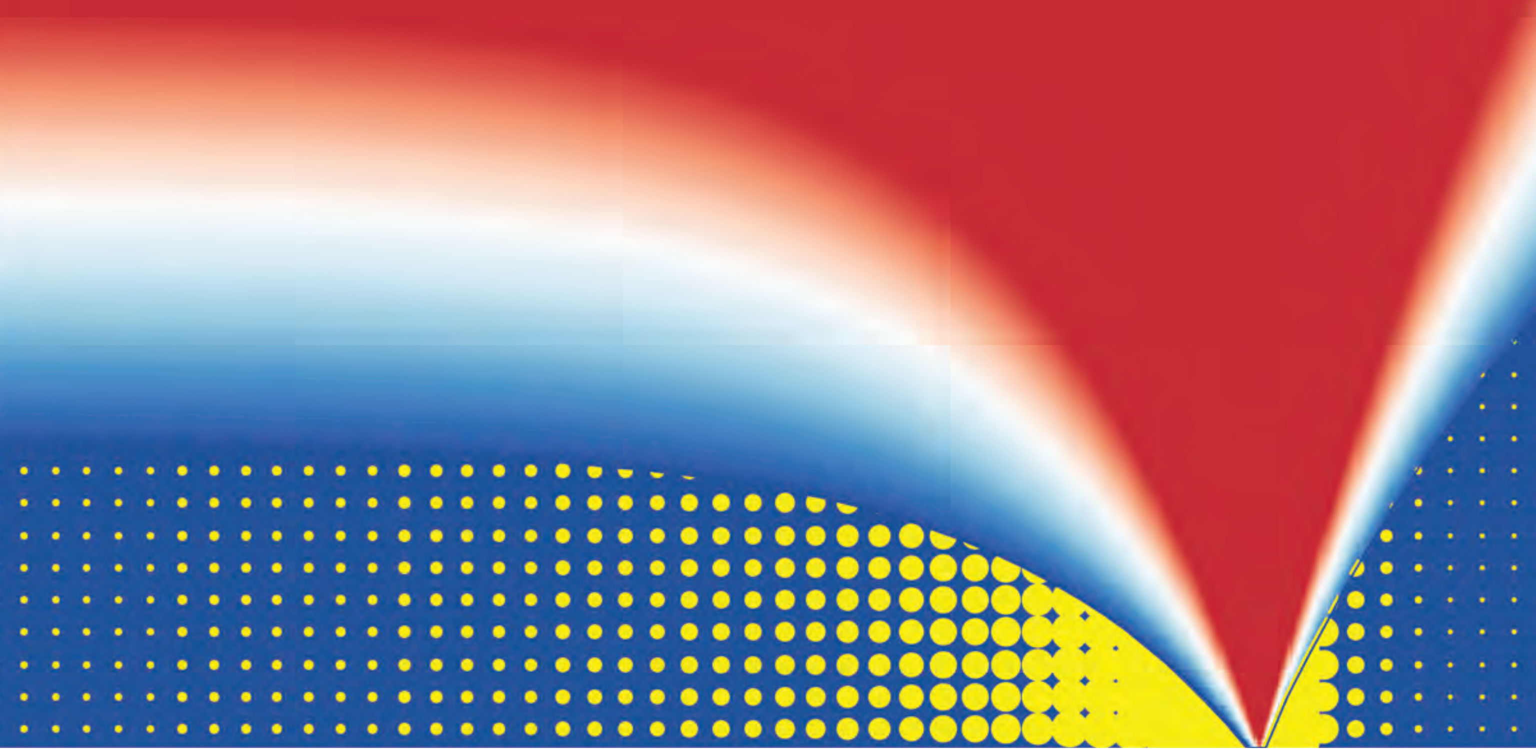
# IRON-BASED SUPERCONDUCTORS: TEENAGE, COMPLEX, CHALLENGING

Qimiao Si and Nigel E. Hussey

Fifteen years after the surprising discovery of superconductivity in iron-based materials, researchers are beginning to impart some of their newfound wisdom on a slew of emerging superconductors that display similar traits.

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The annual meeting of the American Physical Society in March 2008 was especially memorable for condensed-matter physicists. It seemed that all anyone wanted to talk about in New Orleans was the surprising discovery, and subsequent confirmation, of high-temperature superconductivity in the iron arsenides.[1] Surprising was perhaps an understatement. After all, iron was supposed to be as toxic to superconductivity as arsenic is to humans. The superconducting transition temperature $T_c$ had reached only 26 K by the time of the March Meeting, though reports were circulating that—as with high-$T_c$ cuprates two decades earlier—the application of high pressures was pushing $T_c$ to temperatures above 40 K. The race was on.

In a matter of weeks after the meeting, substitutional studies had helped to repeatedly break the $T_c$ record, which eventually plateaued at 56 K. As a barometer of the excitement, by the end of 2010, 8 out of 10 of the most cited papers published in *Physical Review Letters* in 2008 featured arsenide superconductivity. Amid the frenzied activity, superconductivity was also being reported in a simple binary iron chalcogenide, iron selenide. Although the $T_c$ of FeSe was modest—only 8 K in the bulk—in monolayer form it went on to claim the record for all the iron-based superconductors (FeSCs), with a $T_c$ in excess of 65 K. To date, only the cuprates are known to possess a higher $T_c$ at ambient pressure. And although the maximum $T_c$ in either system has not shifted in the past decade, the field of superconductivity is now enjoying a resurgence, spurred on by the discovery of unconventional or high-temperature superconductivity in a host of new materials and extreme environments.

It is therefore an opportune moment for a status update on FeSCs. Because the early years of FeSC research were expertly surveyed in 2009 (see the article by Charles Day, Physics Today, August 2009, page 36) and again six years later (see the article by Andrey Chubukov and Peter Hirschfeld, Physics Today, June 2015, page 46), our focus here will be on developments that have come to light in the intervening years. During that period, researchers recognized the all-encompassing effect of electron correlations. And as is typical for systems in which correlation effects are important, puzzles and surprises abound.

FeSCs allow for a deeper understanding of such diverse themes as electronic nematicity (that is, orientational order), quantum criticality, orbital-selective correlations, and topological superconductivity. Thus, even though FeSCs are still in their teenage years, they are already providing profound insights into the rich physics of unconventional superconductivity.

## Some basics

Iron-based superconductors primarily comprise iron pnictides—compounds based on arsenic or another element from the pnictogen group, also known as the nitrogen group, of the periodic table—and iron chalcogenides containing selenium, tellurium, or sulfur. A broad spectrum of structural types exists among those superconductors (see box 1).[2] The simplest structure occurs in FeSe, in which individual FeSe layers stack on top of each other. The highest occupied electronic states are derived almost entirely from the fivefold 3*d* orbital states of the Fe ions. The existence of Se or As means that each unit cell comprises two Fe ions. When spin-orbit coupling (which is relatively small for 3*d*-electron-based systems) is neglected, the crystalline symmetry allows researchers to consider a simpler unit cell containing only one Fe ion per unit cell. Those Fe ions form a square lattice, which is relatively straightforward to handle theoretically.

In any crystal, atoms form a periodic arrangement in a lattice. The discrete lattice in

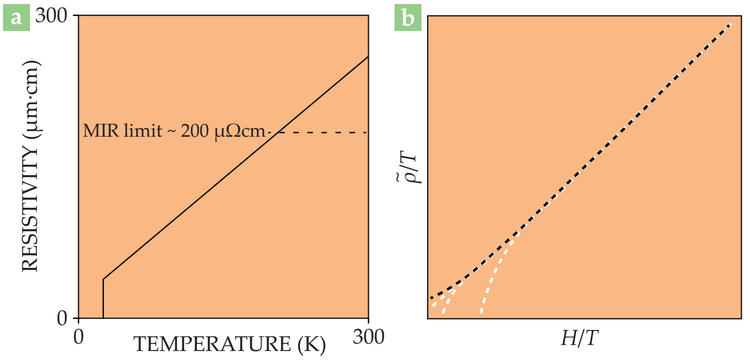



**FIGURE 1. THE ALLURE OF LINEARITY.** In a typical metal, the temperature dependence of the resistivity $\rho(T)$ is linear at intermediate temperatures but weakens and eventually vanishes at the extremes. At low temperature, $\rho(T)$ levels off because of the freezing out of the phonons, while at high temperature, $\rho(T)$ eventually saturates once the electron mean free path shrinks to the size of the lattice spacing—a threshold known as the Mott-Ioffe-Regel (MIR) limit. **(a)** By contrast, the in-plane resistivity of the iron pnictide $BaFe_2(As_{0.7}P_{0.3})_2$ shown here exhibits linearity over an extremely broad range of temperatures and magnetic fields. At high temperatures, the resistivity exceeds the MIR limit and signifies that the electron correlations are strong.[3] (Adapted from ref. 13, Kasahara et al.) **(b)** The magnetoresistance also exhibits a unique form of scaling that is clearly linked to the $T$-linear resistivity. Here, $\tilde{\rho} = \rho(H,T) - \rho(0,0)$. Such simple linear scaling implies a highly anomalous metallic state in which impurity scattering, evident in $\rho(T)$, plays no role in the evolution of the resistivity in an applied magnetic field. (Adapted from ref. 13, Hayes et al.)

real space implies, by virtue of a Fourier transform, a corresponding lattice in reciprocal (that is, wavevector) space. Condensed-matter physicists call the unit cell of that reciprocal space a Brillouin zone. Only a single Brillouin zone is needed to account for all the electronic states.

For a metal, the Pauli exclusion principle dictates that each wavevector be associated with an individual and distinct set of internal (for example, spin and orbital) quantum numbers. For a noninteracting electron system, the electrons occupy states with wavevectors that are associated with an increasing ladder of energies. The locus of wavevectors corresponding to the highest energy—the so-called Fermi energy—of occupied states forms a Fermi surface. The Brillouin zone of a square lattice is another simple square. For some iron chalcogenides in the group of highest-$T_c$ FeSCs, including monolayer FeSe, the Fermi surface also turns out to be remarkably simple, comprising only small electron pockets located at the edges of the Brillouin zone (see box 1).

## Electron correlations

When two electrons occupy either the same 3$d$ orbital or two different 3$d$ orbitals of an Fe ion, their proximity inevitably leads to a Coulomb repulsive interaction between them. The size of that repulsion quantifies the strength of electron correlations in the system, which in turn can cause the electrons to become heavier and slower. It was recognized early on that electron correlations are important to the physics of FeSCs.[2] One manifestation of strong correlations is an electrical resistivity that exhibits so-called bad-metal behavior, characterized by an anomalously short electron mean free path at room temperature,[3] as described in figure 1.

Accompanying evidence for that behavior comes from measurements of the optical conductivity and angle-resolved photoemission spectroscopy,[2] which show a significant renormalization of, among other parameters, the effective electron mass $m^*$ relative to its noninteracting counterpart $m_b$. Remarkably, in FeSCs, that renormalization can even be orbital specific, with a mass enhancement $m^*/m_b$ that varies strongly from one orbital to another. In the Fe(Te, Se) series, $m^*/m_b$ in one of its 3$d$ orbitals reaches almost 10 times that for the other 3$d$ orbitals.[4] These observations further explicate the notion that electron correlations are strong in the FeSCs and motivate a new understanding about the nature of the superconducting pairing.

Theoretical treatments of the electron correlations in models that contain multiple 3$d$ orbitals anticipated that orbital selectivity. One theoretical approach considers the system to be in the proximity of an orbital-selective Mott phase, where electrons within specific orbitals are localized on their respective lattice sites, while others remain itinerant, depending on the

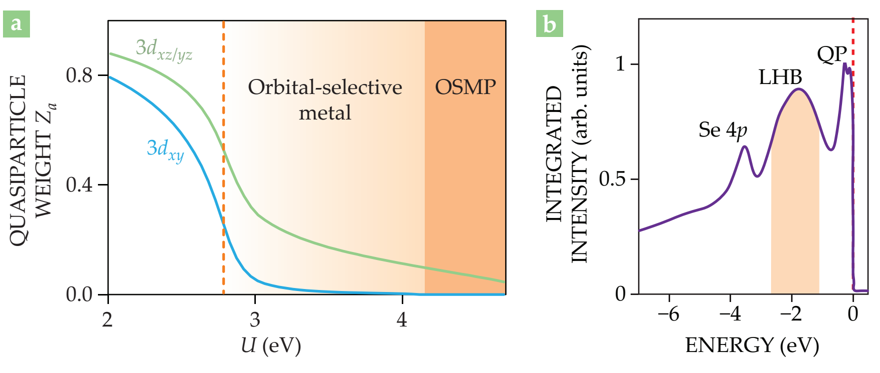



**FIGURE 2. ORBITAL-SELECTIVE CORRELATIONS** among electrons. In a simple metal, conduction electrons are essentially free of interactions and readily propagate across the entire system like waves. But in iron-based superconductors, electrostatic repulsion between electrons primarily drives their superconductivity. The correlated electrons act as if only a fraction of them, $Z$, propagate freely. **(a)** That quasiparticle weight $Z_a$ is orbital dependent. It's plotted for orbitals $a = 3d_{xy}$ and $3d_{xz/yz}$ as a function of the on-site intra-orbital Coulomb repulsion $U$. Over an extended interaction range, the quasiparticle weight of the electrons in the $3d_{xy}$ orbitals is much lower than those of the other orbitals. That regime is anchored by an orbital-selective Mott phase (OSMP), in which the $3d_{xy}$ electrons are fully localized while the other orbitals have a nonzero quasiparticle (metallic) weight. (Adapted from ref. 5, Yu et al.) **(b)** In addition to noninteracting 4$p$ states from selenium atoms and a quasiparticle (QP) peak near the Fermi energy, notice the lower Hubbard band (LHB) peak associated with the excitations between atomic energy levels split by the Coulomb repulsion. (Adapted from ref. 7.)

relative strength of the (unscreened) Coulomb repulsion (see figure 2a).[5] Another approach proposes that the system is a so-called Hund's metal,[6] with localized spin excitations but fully itinerant charge and orbital excitations.

Because the dominant Coulomb repulsion is local, the electron dynamics are best captured in terms of short-range hopping between adjacent atomic sites rather than the usual metallic, wavelike propagation across the whole sample. Excitations between atomic energy levels split by the Coulomb repulsion can create an additional peak in the excitation spectrum. Observations of that additional "lower Hubbard band" peak, illustrated in figure 2b,[4,7] also provide direct evidence that the local Coulomb repulsion is large. At the same time, the propensity for Fermi-surface nesting—whereby large sections of the Fermi surface are linked through a single wavevector—enhances correlation effects by influencing a large fraction of the electronic states.[8]

## Electronic order and quantum criticality

Classical phase transitions in matter take place when the temperature is changed, as exemplified by ice melting or water evaporating. Quantum phase transitions, by contrast, occur at zero temperature and are induced by a change in the extent to which the Heisenberg uncertainty principle is manifest upon the variation of a nonthermal control parameter. Quantum criticality develops when the transition is continuous, and it controls the physics in a larger parameter regime at nonzero temperatures. (See the article by Subir Sachdev and Bernhard Keimer, Physics Today, February 2011, page 29.)

In the phase diagram of the iron pnictides, superconductivity adjoins an antiferromagnetically ordered phase in which the adjacent spins are anti-aligned along a specific direction.[2] By tuning a system appropriately, either through chemical substitution or by applying pressure, the phase transition to the magnetic state at the Néel temperature is suppressed to ever lower temperatures. Though superconductivity invariably intervenes, experimental signatures of mass renormalization imply that the magnetic phase terminates at a quantum critical point (QCP), where quantum fluctuations destroy the magnetic order, even at zero temperature (see box 2).[9]

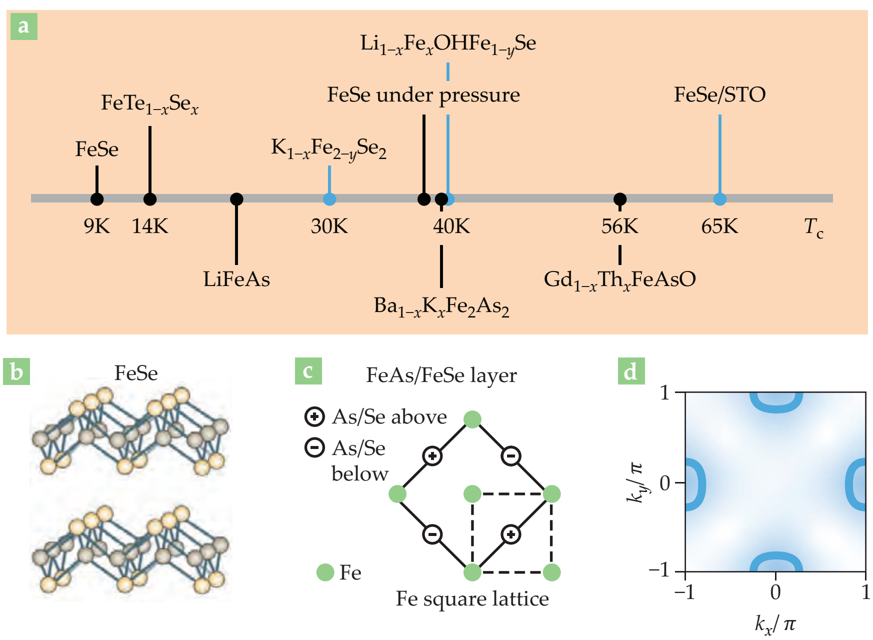
Earlier transport and thermodynamic measurements on isovalently substituted $BaFe_2(As_{1-x}P_x)_2$ provided strong evidence for mass renormalization due to the interaction of the

## Box 1. Iron-based superconductors—some basics

The various iron-based superconductor (FeSC) family members and their maximal $T_c$ values are listed in panel a. The highest critical transition temperature $T_c$ appears in monolayer iron selenide deposited on a $SrTiO_3$ substrate (FeSe/STO). The accepted record value of $T_c$, which is based on the onset of the Meissner effect, is 65 K, though transport evidence for $T_c$ above 100 K has also been reported.

All FeSCs have the same structural motif, a single layer of FeSe/FeTe or FeAs/FeP. (For an illustration of the structure of bulk FeSe, which corresponds to direct stacking of FeSe layers, see panel b.) The primitive unit cell of a single FeAs/FeSe layer is shown in panel c, with two Fe ions from an Fe layer, one Se or As ion located above the Fe layer, and one below. When spin-orbit coupling is neglected, the Brillouin zone can be unfolded to a square in reciprocal ($k$) space, shown in panel d. The unfolded Brillouin zone corresponds to the square lattice of Fe ions illustrated in panel c.

Strictly speaking, one needs to use the two-Fe unit cell and its associated Brillouin zone, which is half of what is shown in panel d. While the notation is rigorous, it is also somewhat cumbersome. Usually, it is more convenient to adopt the single-Fe unit cell and its associated Brillouin zone. Correspondingly, microscopic theoretical studies typically involve multiorbital models on a square lattice with both on-site Hubbard (direct Coulombic) and Hund's (spin-exchange) interactions.




The electronic states near the Fermi energy are dominated by the 3$d$ orbitals of the Fe ions. Thus, for most purposes, theoretical models of FeSCs retain only the 3$d$ states, with the $p$ orbitals of Se/As ions (or their variants, Te/P ions) projected out. The multiplicity of the 3$d$ orbitals near the Fermi energy is reflected in the multiple Fermi sheets. Most FeSCs have hole Fermi pockets near the center of the one-Fe Brillouin zone and electron pockets at the edges. The hole and electron Fermi pockets have roughly the same size, which enhances the phase space for interpocket electron interactions; they are called "nested." A single-layer FeSe/STO has only electron Fermi pockets near the edges of the Brillouin zone, as shown in panel d. The same is true in most members of the bulk iron chalcogenides with relatively high $T_c$, including the alkaline iron selenides, where $T_c$ reaches about 30 K, and the lithium-intercalated iron selenides (Li,Fe)OHFeSe, whose $T_c$ exceeds 40 K. Those members are marked in blue in panel a.

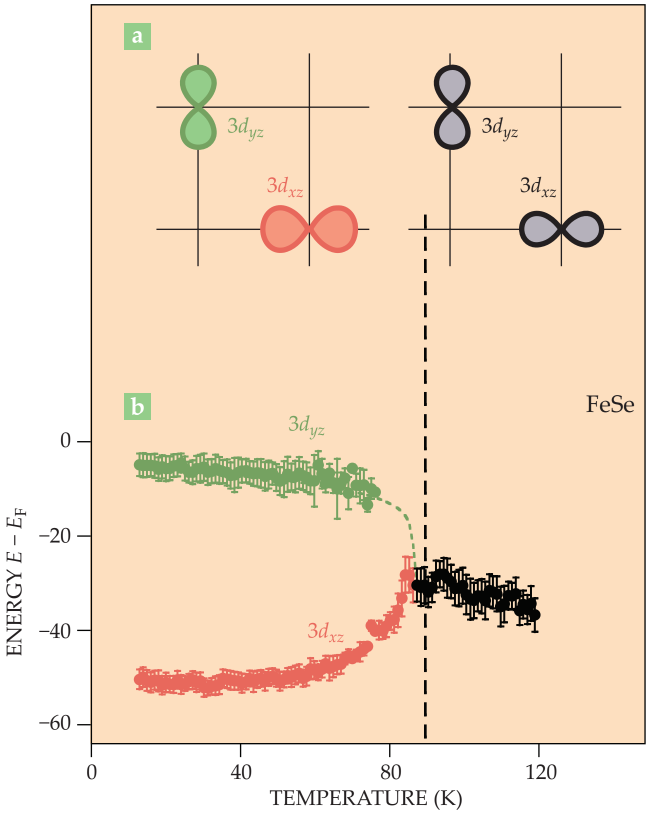


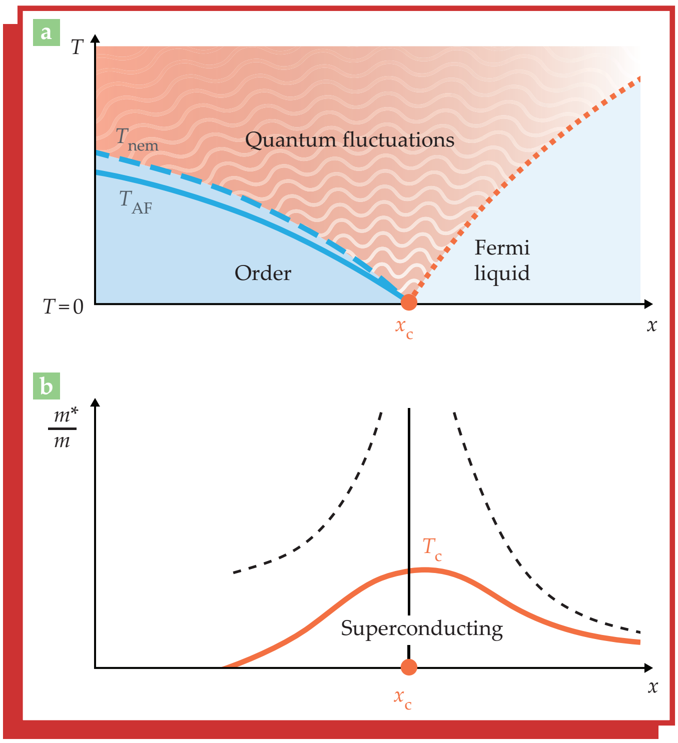

**FIGURE 3. NEMATICITY** in iron selenide. **(a)** The breaking of the orbital degeneracy, shown schematically from right to left, is a proxy for the electronic nematic transition across a structural phase transition (vertical dashed line). The constituent ions of a crystal are arranged according to a geometric lattice, which provides a periodic potential for mobile electrons. The crystalline symmetry of FeSe dictates that its $3d_{xz}$ and $3d_{yz}$ orbitals (marked by different colors) can be transformed into each other by a 90° rotation in its tetragonal plane. That is indeed what happens when $T > T_S$, the structural transition temperature. Upon FeSe's cooling below $T_S$, however, the symmetry is broken through the formation of an electronic nematic and is manifest as an inequivalence between the electronic bands associated with the $3d_{xz}$ and $3d_{yz}$ orbitals. **(b)** The $3d_{xz}$ and $3d_{yz}$ bands obtained from angle-resolved photoemission-spectroscopy measurements on detwinned FeSe show degenerate bands that are split as the temperature is lowered through the nematic transition. (Adapted from ref. 17, Yi et al.)

itinerant carriers with quantum critical fluctuations of some underlying order parameter.[9]

In addition to magnetic order, the iron pnictides also possess nematic order that spontaneously breaks the symmetry between the $x$ and $y$ spatial directions, setting in at or around the tetragonal-to-orthorhombic structural transition temperature $T_S$. Figure 3 illustrates the emergence of nematic order in FeSe. The nematic fluctuations occur over a wide energy range—about 50 meV, which is sizable compared with the roughly 200 meV scale of magnetic fluctuations.[10] From a theoretical perspective, nematic fluctuations enhance any pairing interaction that is present and thus could play a key role in increasing the critical temperature, even if the pairing itself is primarily driven by quantum fluctuations in other channels, such as spin.[11]

In many cases, the nematicity and magnetism appear to be strongly intertwined, as discussed in box 2. More recently, however, researchers have gone in search of signatures of pure

## Box 2. Quantum criticality in iron pnictides—where all the players come together




Quantum criticality has been extensively studied in the iron pnictides. An early theoretical analysis by Jianhui Dai and coauthors[9] led to the proposal that isoelectronic phosphorus-for-arsenic substitution yields a quantum critical point, shown in panel a at a concentration $x = x_c$. There, the antiferromagnetic (AF) and nematic (nem) orders vanish at the same time. Electronic nematicity describes the development of orientational symmetry breaking in the electronic phase and can be pictured by analogy with the anisotropy seen in the cosmic microwave background. As a result, both the magnetic and nematic degrees of freedom play a central role in creating critical quantum fluctuations (panel a) and in causing the effective carrier mass to diverge (panel b).

Researchers have now observed the concurrent quantum phase transitions in the P-substituted pnictides CeFeAsO and $BaFe_2As_2$. And in the $BaFe_2(As_{1-x}P_x)_2$ (and $FeSe_{1-x}S_x$) series, they demonstrated quantum criticality in multiple ways. Those include the extended $T$-linearity of the electrical resistivity inside the quantum critical fan (shown in panel a and on page 34 as the red zone) and an effective mass that diverges as the quantum critical point is approached from the paramagnetic side when the concentration exceeds $x_c$ (as indicated by the dashed black line in panel b and the intensity of yellow dots shown on page 34).[9] In the vicinity of the quantum critical point, the superconducting $T_c$ is maximized (red solid curve in panel b). Thus, $BaFe_2(As_{1-x}P_x)_2$ provides a textbook example of superconductivity driven by the same critical quantum fluctuations that are responsible for the emergence of anomalous transport properties.

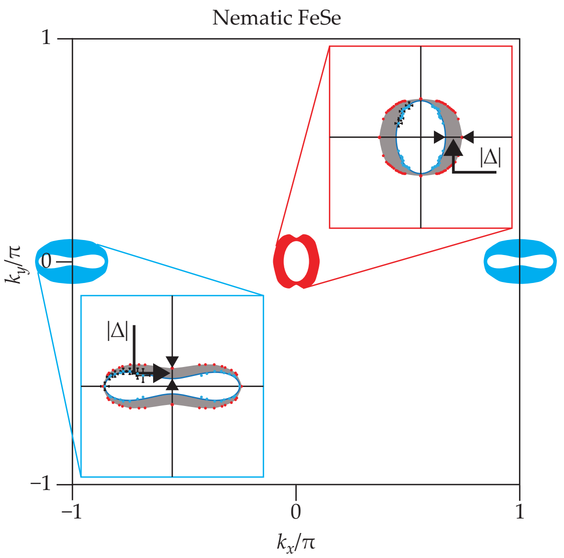



**FIGURE 4. SUPERCONDUCTING PAIRING** from orbital-selective correlations. The variation of the superconducting gap magnitude |Δ| is shown on the hole Fermi pocket at the center (red, and top inset) and on the electron Fermi pocket at the side edges (blue, and bottom inset) of the Brillouin zone in iron selenide, as determined from scanning-tunneling-microscopy measurements. In a conventional phonon-mediated superconductor, the superconducting gap is essentially isotropic—that is, of the same magnitude over the entire Fermi surface. But in FeSe, the superconducting gap almost vanishes for specific momenta. Not only does such strong anisotropy hint at a nonphonon pairing mechanism, but it also illustrates how the different orbitals that contribute electronic states at the Fermi level can have very different pairing strengths. (Adapted from ref. 14.)

nematic quantum criticality. In nonmagnetic FeSe, nematic order emerges at $T_S$, below which its normal- and superconducting-state properties both exhibit marked twofold anisotropy. That ordering temperature can be suppressed either through the application of high pressures or via chemical substitution on the chalcogenide site.

With increasing pressure, the critical nematic fluctuations in FeSe are quenched, presumably because of the emergence of long-range magnetic order before the nematic phase terminates. As mentioned earlier, $T_c$ grows more than fourfold up to 40 K with increasing pressure, in tandem with the strengthening magnetic interactions. In sulfur-substituted FeSe, nematicity vanishes at a critical S concentration $x_c$, at which point the nematic susceptibility, as deduced from elastoresistivity measurements, also diverges.[12] Since no magnetic order develops at any point at ambient pressure across the substitution series, the divergence hints at a pure nematic QCP in $FeSe_{1-x}S_x$.

One of the key experimental signatures of quantum criticality is an electrical resistivity displaying a marked linear temperature dependence down to low temperatures—well below the typical temperature scales associated with electron–phonon scattering, an example of which is shown in figure 1. Such behavior may also be linked with the bad-metal transport seen at high temperatures. The $T$-linear resistivity seen at ambient pressure in $FeSe_{1-x}S_x$ has thus been attributed to the emergent critical nematic fluctuations,[12] although residual spin fluctuations believed to be responsible for the $T$-linear resistivity seen in $BaFe_2(As_{1-x}P_x)_2$ have not been completely ruled out.

In addition to that $T$-linear resistivity, magnetotransport studies on iron-based superconductors have uncovered a startling new feature of quantum-critical transport, namely a crossover to linear-in-field magnetoresistance in systems close to the QCP.[13] The particular scaling form of the magnetoresistance, shown in figure 1b, suggests an intimate, but as yet unresolved, connection to the $T$-linear resistivity at zero field.

## Unconventional superconductivity

In the iron pnictides, the proximity of the superconducting phase to the static magnetic order suggests that the quantum fluctuations associated with the antiferromagnetic spin-exchange interactions are involved in the pairing mechanism. The same principle may apply to the iron chalcogenides. In the part of the phase diagram where superconductivity develops, the nature of the long-range electronic order differs from that seen in the iron pnictides, yet antiferromagnetic fluctuations are still prevalent. Although a smoking gun for nematic-fluctuation-assisted superconductivity remains elusive, superconductivity often emerges in FeSCs that exhibit quantum-critical nematic fluctuations.

In a conventional superconductor, the pairing function, or gap, is essentially isotropic in reciprocal space. For some of the pnictide superconductors, the Fermi surface comprises both electron pockets at the Brillouin-zone boundary and hole pockets at the zone center. Measurements largely support the notion that the pairing function actually changes sign across the electron and hole pockets while maintaining a fully gapped single-particle excitation spectrum, as predicted in a variety of theoretical studies.[2]

But phase-sensitive measurements for the sign change remain difficult to interpret when other pairing channels are close in energy. For the highest-$T_c$ group of iron chalcogenides, in which the Fermi surface contains only the electron pockets, researchers have reached similar conclusions regarding the pairing states and pairing amplitude. They suggest that the details of the Fermi surface are not as crucial as the effect of electron correlations.

The advent of orbital-selective correlations in the normal state naturally raises the question of its implications for the pairing amplitude, symmetry, and structure in the superconducting state. Indeed, such orbital-selective pairing has been visualized, in spectacular fashion, via tunneling measurements performed on the nematic FeSe (see figure 4).[14] The gap anisotropy can be understood in terms of a dominant anisotropic pairing amplitude (with a gap that becomes very small at specific locations on the Fermi surface), once the variation of the orbital weight on the Fermi surface is taken into account.[15] We note that photoemission measurements have yet to reach a consensus on the orbital dependence of the pairing amplitude in FeSe.

## New horizons

Space restrictions inevitably prevent us from covering the whole gamut of exciting physics that is emerging from research into iron-based superconductors, such as the proximity of their superconducting state to Bose–Einstein condensation or the prospects for observing topological superconductivity at elevated temperatures. (With regard to the latter, the role of quantum critical fluctuations in enhancing the transition temperature points to an interesting and potentially profitable route to expand the domain of topological superconductivity.) Rather, in this final section, we consider the major impact that FeSCs are having in our efforts to understand a variety of other disparate families of unconventional superconductors.

Chief among these efforts is the guiding principle—so aptly demonstrated by the $BaFe_2(As_{1-x}P_x)_2$ series—that superconductivity is enhanced near a QCP. Those developments have solidified the idea that quantum critical fluctuations promote unconventional superconductivity and have led to the notion that orbital multiplicity allows for new types of Cooper pairing.

In that regard, developments in FeSCs have influenced investigations into other multiorbital superconductors. Although $Sr_2RuO_4$ has long been championed as a chiral spin-triplet superconductor, recent experiments suggest that it is a spin-singlet superconductor with an unusual pairing function (see Physics Today, September 2021, page 14); the ideas being put forward for candidate pairing functions parallel those for FeSCs to some extent.

Another multiorbital superconductor, $CeCu_2Si_2$—the very first unconventional superconductor ever discovered—has long been thought to be nodeless. Recent experiments down to lower temperatures, however, have provided compelling evidence that the gap does not close anywhere on the Fermi surface, even though it is strongly anisotropic. The leading idea to resolve the conundrum invokes a multiorbital pairing state that is analogous to what has been proposed for the iron chalcogenides.[16] Multiorbital physics is now being actively investigated in a host of more recently discovered superconductors, including nickel-based compounds that represent a close structural cousin to the high-$T_c$ cuprates—the exotic, heavy-fermion compound uranium telluride and the vanadium-based kagome metals.

Not only does nematicity provide a boon for tuning and probing unconventional superconductivity using uniaxial strain measurements, it also has encouraged the community to consider new pathways to improve superconducting performance. The essential argument is the following: Although the electron–phonon interaction acts on the entire Fermi surface, it is inherently weak. By contrast, antiferromagnetic interactions tend to be much stronger, but they only influence a restricted region in momentum space. In principle, nematicity offers the best of both worlds—strong interactions acting on the entire Fermi sea.

The challenge then is to harness those interactions either on their own or in conjunction with another pairing instability. At the same time, the success of engineered structures based on monolayer FeSe in raising $T_c$ has provided an added incentive to achieve superconductivity in the purely two-dimensional limit. That frontier has enjoyed remarkable recent success with the discovery of superconductivity in monolayer tungsten telluride and twisted bilayer graphene, to name just two compounds.

One might even argue that the above effort has motivated other recent global attempts to realize superconductivity under extreme conditions, such as ultrahigh pressures for near-room-temperature superconductivity in the hydrides, or the realms of ultralow temperatures, where superconductivity is driven by quantum criticality in $YbRh_2Si_2$.

Given this rich vein of commonality, the time seems ripe for the development of a conceptual framework that unifies our understanding of such disparate material families of unconventional superconductors, with the precocious pnictides firmly at the helm. Ultimately, scientists would like to know how to achieve superconductivity with even higher transition temperatures at ambient conditions. Is there a design principle for boosting superconductivity? Our considerations in this article suggest the need for two central ingredients that cooperate with each other. One is for the entire Fermi surface to participate in promoting superconductivity. The other is to maximize the strength of the effective interactions that drive the superconductivity.

The band of unconventional superconductors to which FeSCs belong has the characteristic property that all electronic states are on the verge of localization and thus experience strong coupling. Compared with good metals, they also host stronger interactions that favor superconductivity. We envision that tuning the balance between interaction strength and localization is precisely the tool required to optimize superconductivity.

*We thank Anna Böhmer, Lei Chen, Amalia Coldea, Pengcheng Dai, Ian Fisher, Frederic Hardy, Christoph Meingast, Matthew D. Watson, Ming Yi, Rong Yu, and Jian-Xin Zhu for their input. The work has been supported in part by the Theoretical Condensed Matter Physics program under the Department of Energy's Basic Energy Sciences program and by the European Union's Horizon 2020 research and innovation program, funded by the European Research Council.*

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# PHYSICS TODAY TURNS 75


FREDDIE PAGANI

**Richard Fitzgerald** is the editor-in-chief of Physics Today. He has been with the magazine for nearly 25 years, joining shortly after the magazine celebrated its 50th anniversary.

PHYSICS TODAY 75 YEARS

Richard J. Fitzgerald

**Even as the physical sciences have advanced and transformed, many of the community's needs and concerns have persisted.**

"Physics Today is for the physicist, to inform him in comfortable, everyday language, of what goes on and why and who goes where. But it is also for the chemist, the biologist, and the engineer, to tell them of the science towards which they are driven by so many of their investigations; it is for the student, the teacher, the lawyer, the doctor, and all who are curious about physics; it is for administrative officials who deal with research; it is for editors and writers whose profession puts them midway between what is done and how it should be reported; it is for you, whatever reason brought you to this page."

David Katcher, Physics Today's first editor, wrote those words in May 1948 as part of his editorial introducing a new magazine. In those postwar days, concerns were growing that physics was becoming too specialized, too fractionated, and that the prominence and funding that flowed from the field's wartime successes were accelerating the process. There was a call within the American Institute of Physics and its five member societies—the American Physical Society, the Optical Society of America (now Optica), the Acoustical Society of America, the Society of Rheology, and the American Association of Physics Teachers—for a unifying influence to counter those forces. Thus was Physics Today born.

In the intervening years, physics—and the physical sciences more generally—has experienced staggering degrees of progress and change. Yet as we mark the magazine's 75th anniversary this month, Katcher's description still holds true.

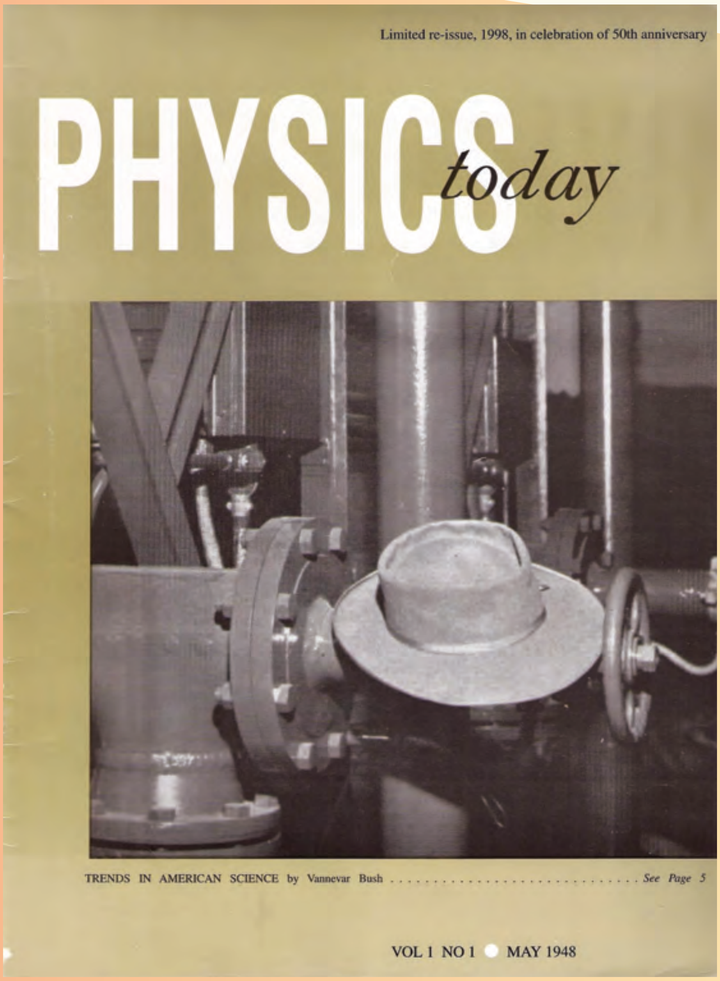
**The mission of PHYSICS TODAY** is to be a unifying influence for the diverse areas of physics and the physics-related sciences. It does that by providing authoritative, engaging coverage of physical science research and its applications without regard to disciplinary boundaries; by reporting on the often complex interactions of the physical sciences with each other and with other spheres of human endeavor; and by offering a forum for the exchange of ideas within the scientific community. With authoritative features, full news coverage and analysis, and fresh perspectives on technological advances and groundbreaking research, PHYSICS TODAY informs readers about science and its role in society.

The next several pages offer various lenses through which to appreciate how things have—and haven't—changed over the past 75 years.

As much as PHYSICS TODAY is about the physics, it is also about physicists. We strive to be a reminder of our commonalities as scientists, of the many interconnections among the varied disciplines, and of our shared priorities and concerns. Many of those concerns were extant at PHYSICS TODAY's debut, including research funding, public perceptions of science, the field's (and its practitioners') relationships with and responsibilities to society, the future of our planet, and how to prepare the next generation of scientist-citizens.

One part of Katcher's description above is notably out of date, though. PHYSICS TODAY has evolved into more than a magazine and can be found well beyond the printed page. We have a website, email newsletters, social media, and webinars, and we'll continue to seek out and engage with our audiences wherever they may be.

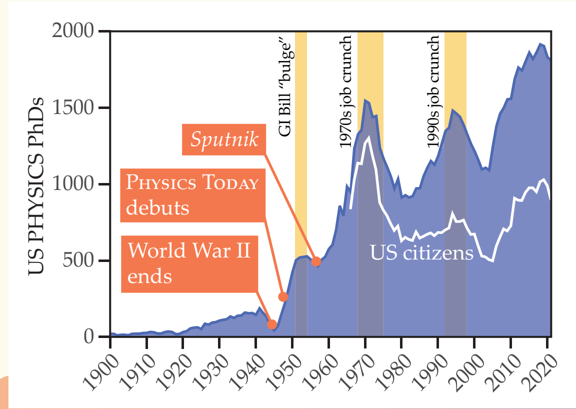
We know that you, our readers, are busy yet curious, scientifically savvy yet unacquainted with the terminology and context of subfields too far from your own. With content that we hope you find appealing, accessible, and informative, PHYSICS TODAY documents and reflects on the physics endeavor and its evolution, and it celebrates the diversity of the science and of the scientists.



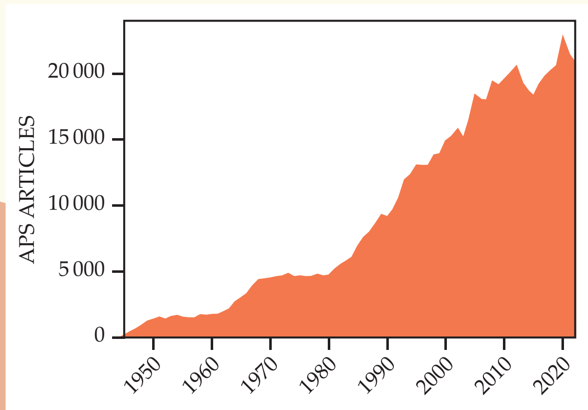

**THE FIRST ISSUE**, May 1948 (reissued in 1998).

# Growth

In its first year, Physics Today went to some 7000 readers. That initial audience comprised the members of the five scientific societies that then belonged to the American Institute of Physics. Not only are those societies each much larger today, but there now are five more societies in the AIP federation—the American Crystallographic Association; the American Astronomical Society; the American Association of Physicists in Medicine; AVS: Science & Technology of Materials, Interfaces, and Processing; and the American Meteorological Society—bringing the magazine's readership to more than 100 000.




**GROWTH IN THE PHYSICS COMMUNITY**, as measured by the number of physics PhDs conferred annually in the US. (Courtesy of the AIP Statistical Research Center, including data from the American Council on Education [1900–19] and National Academy of Sciences [1920–61].)




**GROWTH IN PUBLICATIONS**, as reflected in the annual number of journal articles published by the American Physical Society. (Data courtesy of Crossref.)

Beyond the growth in the physics community, other metrics of the physical-sciences endeavor, including the number of journal articles, the number of prizes, and the level of government funding, are also sharply higher than they were 75 years ago. Public trust in science, though, is eroding. Those ups and downs remain a core part of our news coverage. And they attest to the continuing need to unite the field's various disciplines and strengthen its engagement with broader society.



As interdisciplinary research has flourished and new fields of inquiry have emerged, Physics Today has striven to stay abreast of the expanding scope of the physical sciences. That may mean we report on some topics less often, but covering the full gamut of the physical sciences is an essential part of our mission to be a unifying influence. The difference in the words—and the densities—in these two word clouds, drawn from the titles of our published pieces in 1948 and in 2022, illustrate the diversification of the field and shifts within it.

# Changing times, needs, and tools

Feature articles have always been at the core of Physics Today. The departments rounding out each issue have evolved to reflect shifts in our audience's needs and information sources. When the community was smaller and communications speeds slower, meeting calendars, previews, and reports each had their day, as did news of job changes, honors, and awards. Other departments merged, split, or were renamed. Of the current lineup, some debuted rather recently; others go back to our very first year (see at right).

It will come as no surprise that the most dramatic shift has been the explosive growth of the internet. Content can now be published online as fast as it can be typed. But along with that capability has come ever-increasing competition for readers' attention. In 2000 Physics Today's website just posted manually produced HTML versions of each month's magazine. Today it features a steady stream of online content that complements and supplements what appears in print.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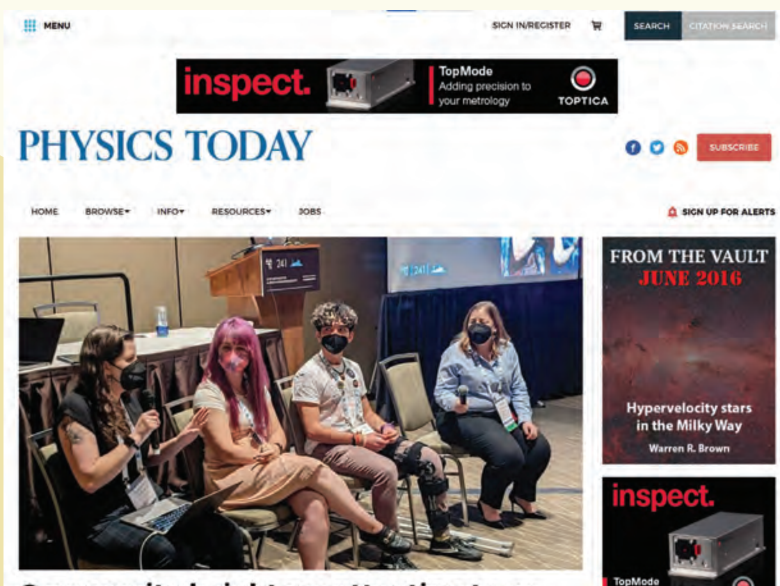
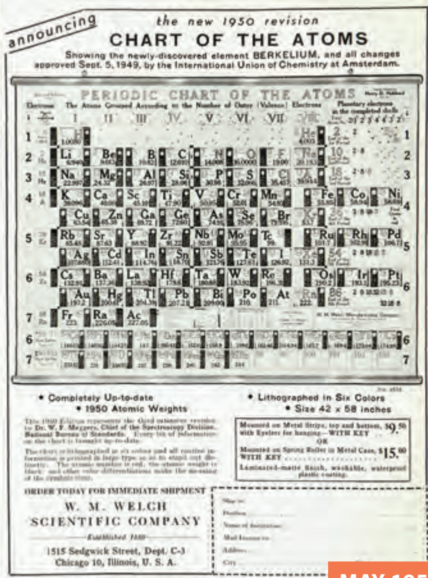



**The Physics Today website**, in September 2000 and in April 2023.

# Ads

Articles, news stories, and other editorial material aren't the only content that informs readers about what's going on in the community. So, too, do the advertisements. Ads from book publishers proliferated in the first decade and have been around ever since. The earliest issues also featured ads for surplus military optics from Edmund Salvage Corp (later Edmund Scientific) and for US savings bonds.

Ads depict not only the instrumentation and technology trends but also the job market and the field's demographics. As the Cold War and space race heated up, for example, ads for the defense and aerospace industries burgeoned. The January 1968 issue, flush with ads, ran 192 pages long. For the first several decades, most recruitment ads assumed that candidates were male and almost all the scientists depicted in them were white. As part of Physics Today's 70th anniversary commemoration, former senior editor Melinda Baldwin surveyed the ups and downs of the physics job market as told through the magazine's display and classified ads (see "Physics Today ads track employment boom and bust," Physics Today online, 7 May 2018).

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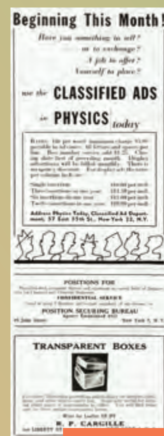


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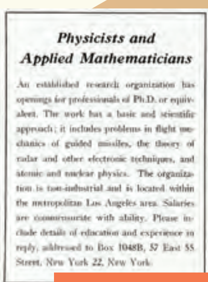



OCTOBER 1948


FEBRUARY 1980


OCTOBER 1992


APRIL 1980

PHYSICS TODAY 75 YEARS

# Special issues

PHYSICS TODAY has occasionally developed all the feature articles in an issue to a specific topic. Here is a taste:

## People

- Niels Bohr (October 1963)
- A Memorial to Oppenheimer (October 1967)
- Albert Einstein 1879–1955 (March 1979)
- Richard Feynman (February 1989)
- Andrei Sakharov (August 1990)
- John Bardeen (April 1992)
- Portraits of Fermi (June 2002)
- Hans Bethe (October 2005)
- John Archibald Wheeler (April 2009)
- A Chandrasekhar Centennial (December 2010)

## Anniversaries

- Superconductivity (March 1986)
- Centennial of the Michelson–Morley Experiment (May 1987)
- *Physical Review* Centenary (October 1993)
- X Rays 100 Years Later (November 1995)
- The Ubiquitous Electron (October 1997)

## Education and careers

- Introductory Physics Education (March 1967)
- Physics for the Nonscience Major (March 1970)
- The Education of the Professional Physicist (June 1986)
- Pre-college Education (September 1991)
- Annual Careers Issues (October 2019, 2020, 2021, 2022)

## Going broad, going deep

- Instrumentation (July 1967)
- Astrophysics (March 1973)
- Liquid Crystals (May 1982)
- Fluids Out of Equilibrium (January 1984)
- Helium-3 and Helium-4 (February 1987)
- Nanoscale and Ultrafast Devices (February 1990)
- The Physics of Digital Color (December 1992)
- Physics and Biology (February 1994)
- Everyday Physics (November 1999)
- Planetary Diversity (April 2004)
- Sound Affects (December 2020)

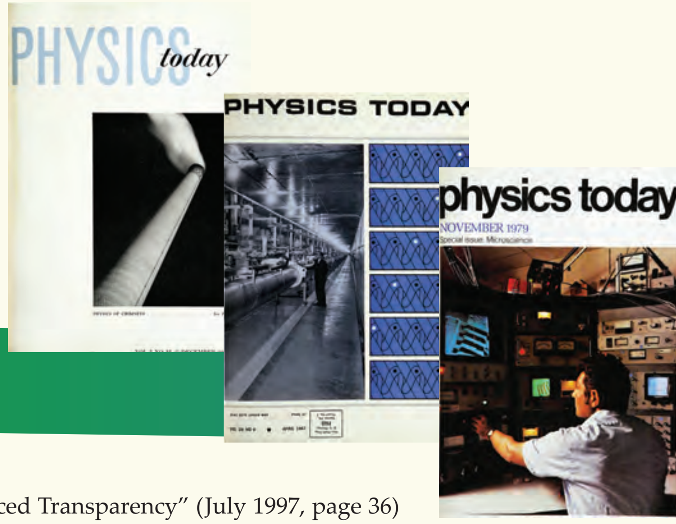
## The wider world

- Communicating Physics to the Public (November 1990)
- Physics and the Environment (November 1994)
- Radioactive Waste (June 1997)
- The Physics Community and the Wider World (March 1999)
- Physics and National Security (December 2000)
- The Energy Challenge (April 2002)

FOR MORE ON THE HISTORY OF PHYSICS TODAY, VISIT physicstoday.org/PT75th

# A valuable archive

Although Physics Today is not an archival journal, our content—and not just the feature articles—demonstrates lasting value. Our top 10 most-cited pieces (as reported by Crossref) span the years 1957–2004:

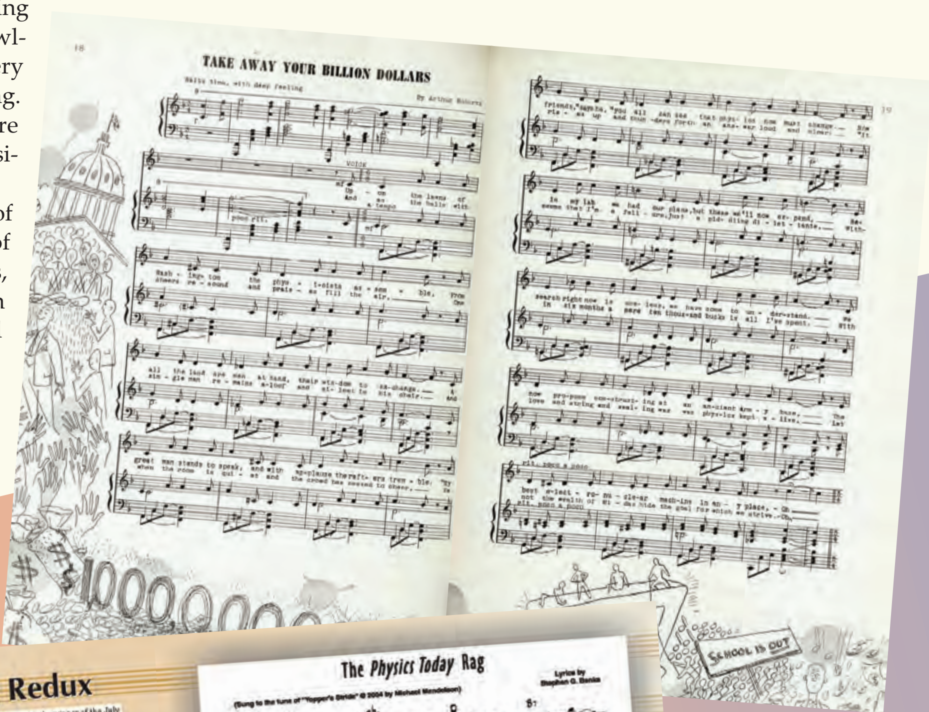



1. Stephen E. Harris, “Electromagnetically Induced Transparency” (July 1997, page 36)
2. Frank S. Bates and Glenn H. Fredrickson, “Block Copolymers—Designer Soft Materials” (February 1999, page 32)
3. Victor Twersky, review of *Light Scattering by Small Particles* by Hendrik C. Van de Hulst (December 1957, page 28)
4. Wojciech H. Zurek, “Decoherence and the Transition from Quantum to Classical” (October 1991, page 36)
5. Kevin Noone, review of *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change* by John H. Seinfeld and Spyros N. Pandis (October 1998, page 88)
6. George Weiss, review of *The Logic of Scientific Discovery* by Karl R. Popper (November 1959, page 53)
7. Cees Dekker, “Carbon Nanotubes as Molecular Quantum Wires” (May 1999, page 22)
8. George W. Crabtree, Mildred S. Dresselhaus, and Michelle V. Buchanan, “The Hydrogen Economy” (December 2004, page 39)
9. William P. Reinhardt, review of *Stochastic Processes in Physics and Chemistry* by Nicolaas G. Van Kampen (February 1983, page 78)
10. Orlando Auciello, James F. Scott, and Ramamoorthy Ramesh, “The Physics of Ferroelectric Memories” (July 1998, page 22)

# The joy of physics

Although physics can be challenging and obscure, the quest for knowledge and the process of discovery can also be thrilling and inspiring. That wonder and satisfaction are worth celebrating—by both physicists and the public.

During the 2005 World Year of Physics, honoring the centennial of Albert Einstein's annus mirabilis, we embraced that celebration with gusto. Straying from our usual content mix, we also featured literature by Alan Lightman and John Updike, a contemplation on life's meaning, correspondence and a speech by Einstein, and more.





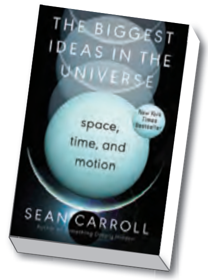
We ran two music-themed articles as part of our World Year of Physics celebration. "A Physics Songbag" (July 2005, page 56) featured 11 songs spanning more than 80 years and announced a lyric-writing contest; the winning entry was featured in "A Physics Songbag Redux" (December 2005, page 56) along with "The *Physics Today* Rag." Music first appeared in the magazine back in November 1948 (page 17), with the song "Take Away Your Billion Dollars," by physicist and composer Arthur Roberts, in which he satirized the push toward ever-bigger machines. PT


GEORGE BICKHAM THE ELDER/WELLCOME COLLECTION/PUBLIC DOMAIN

This reprint of a 1732 line engraving of Isaac Newton by the English printmaker George Bickham the Elder features astronomical and mythological imagery and a laudatory poem.

# Popular science, with equations

**The Biggest Ideas in the Universe**
**Space, Time, and Motion**
**Sean Carroll**
Dutton, 2022. $23.00




It's easy for a popular-science book to jump into the glamorous, flashy physics of seemingly paradoxical concepts like relativity, time travel, and black holes. So it might seem odd that Sean Carroll focuses on classical motion in his latest book, *The Biggest Ideas in the Universe: Space, Time, and Motion*, the first volume of a promised trilogy based on his similarly titled YouTube series. (As he suggests, trilogies have proved to be successful.) But I'm glad Carroll starts with the old, established—a nicer word for boring—Newtonian mechanics because it presents to his audience the underlying historical developments that led to Einstein's theory of relativity. Once you appreciate $F = ma$, you gain a deeper understanding of $E = mc^2$.

Carroll's research areas span cosmology, relativity, the foundations of quantum mechanics, and philosophy of science. His 2004 textbook *Spacetime and Geometry: An Introduction to General Relativity* is greatly appreciated by graduate students in that field. He's also an admirably prolific science communicator: Along with authoring several other popular-science works, Carroll served as a consultant for the Marvel films *Avengers: Endgame* and *Thor: The Dark World*. Although I'd never read any of Carroll's popular-science books before, I'm glad I picked up the latest one, because I simply love it!

What makes *The Biggest Ideas in the Universe* different from other similar titles is how much Carroll wants readers to understand physics. At the risk of sounding curmudgeonly, I think the current era of podcasts is doing science a disservice by watering down a bit too much the mathematics behind many of the biggest ideas in physics. (Yes, I know Carroll has a podcast too!) Even the physics majors in my classes today are sometimes of the mindset that if they just get the basic concepts, they can understand topics as challenging as quantum mechanics. We academics face a similar difficulty when we want to communicate our science to the public: Can we do it without the math? The overarching view is that we must not show the complicated equations behind our results lest we scare our audience.

Carroll is aware that you need to understand the math to truly comprehend the physics that underpins our greatest brainchildren. He diligently explains the concept of infinitesimal changes, for example, so that readers understand why Isaac Newton had to (co)invent calculus to explain planetary orbits. Over the course of the book, readers go from learning how to take a derivative to gaining an appreciation of the metric tensor that describes spacetime. That is also the path from Newtonian gravity to Einstein's theory of general relativity. Along the way, readers also learn how to take the shortest path between two points, which can have both physical consequences on a plane flight and metaphorical implications in life.

I don't want to make it sound like *The Biggest Ideas in the Universe* is solely a book about math, because it isn't. But it's just so refreshing to read a popular-science book that doesn't hide the math. Instead of shying away from the nitty-gritty calculations that led to the biggest leaps in our physical understanding of the universe, Carroll leans on the beauty of the math to show readers why it's an integral part of the physics we do. And he does so in a remarkably unpretentious manner: At one point, he explains that guessing is a respectable path to a breakthrough. (My students don't believe me when I tell them that sometimes you just need to guess the solution. Of course, physical intuition helps.)

*The Biggest Ideas in the Universe* reminds me of popular mathematics books that I read in high school when I was deciding between a career in physics or mathematics. (I settled on theoretical physics, which uses a lot of math!) I'm sure Carroll's book will inspire many math-inclined students to pursue science, and I'm looking forward to the next two volumes. I recommend it to all students who are interested in physics so that they can get an idea of what it's like to work in science. If it gets translated into Turkish, I would love to give it to my family so that I can finally explain to them what I actually do at work.

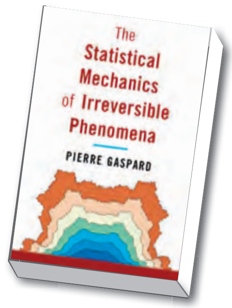
**Seyda Ipek**
*Carleton University*
*Ottawa, Ontario, Canada*


ELISHA WHITTELSEY COLLECTION/ELISHA WHITTELSEY FUND/1959/PUBLIC DOMAIN

One famous source of fluctuations—both financial and emotional—is the stock market, as illustrated in this 1799 etching by the English caricaturist Thomas Rowlandson, who based it on a drawing by the caricaturist George Moutard Woodward.

# The power of fluctuation relations

**The Statistical Mechanics of Irreversible Phenomena**
**Pierre Gaspard**
Cambridge U. Press, 2022. $99.99




During his long career, Pierre Gaspard has made a name for himself as a leader in the field of nonlinear dynamics: His highly cited 1998 book *Chaos, Scattering and Statistical Mechanics* is a classic, and he heads the unit that studies complex systems and statistical physics at the Free University of Brussels in Belgium.

Nearly 25 years after the publication of his first book, Gaspard has written a follow-up, *The Statistical Mechanics of Irreversible Phenomena*. An advanced-level textbook, it presents an overview of a broad range of nonequilibrium phenomena, including traditional subjects—such as Langevin dynamics, chemical reactions, and the kinetic theory of rarefied gases—and more novel topics like transport in open quantum systems and the motion of active particles and molecular motors.

Such a huge amount of material could easily fill several volumes. But Gaspard's clear, concise writing presents all the important ideas and their theoretical formalism in only 15 neat chapters and six appendices. For example, the first three chapters, which cover thermodynamics, statistical mechanics, and hydrodynamics, not only lay out those fundamental theories and settle on notation conventions but also include discussions of research areas where developments have been made in the past few decades, including fluctuations, nonequilibrium steady states, ergodicity, and coarse graining.

Those chapters set the stage nicely for the main part of the book, which reviews a huge body of work on fluctuation relations and irreversibility. Fluctuation relations establish a connection between forward and reverse processes that have different initial conditions. The time asymmetry from their varying initial conditions allows us to better understand irreversible processes. Because fluctuation relations can be used to describe many different phenomena and systems, they are the book's central leitmotif and act as a helpful guide for readers. They're also fascinating to examine.

Gaspard is an expert in the study of fluctuation relations, and he proclaims toward the beginning of the book that one of his goals is to demonstrate that they provide a unifying framework with which to describe nonequilibrium systems that are fully nonlinear. But some readers might question if he succeeds in that aim. He is correct when he claims that the theory of fluctuation relations is no longer restricted to the linear regime when systems are close to equilibrium.

Depending on the reader's background, that assertion may evoke associations with the groundbreaking 1962 monograph by S. R. de Groot and P. Mazur, *Non-Equilibrium Thermodynamics*, which provided the field with a complete description of linear, nonequilibrium thermodynamic systems. Despite significant effort, however, researchers do not generally agree upon a theory that provides a complete description of nonequilibrium systems that are fully nonlinear—and I don't think that fluctuation relations will be able to furnish us with such a theory.

Having said that, the book does demonstrate the broad applicability and success of fluctuation relations. After all, the nonlinear regime of nonequilibrium processes is such a huge, diverse, and enormously complicated field in which general principles are extremely hard to find. Even if they aren't a fully unifying framework, fluctuation relations are an astonishingly broad principle.

Moreover, Gaspard's mastery of the impressive range of fields he discusses makes the book stand out. The chapter on fluctuating chemohydrodynamics—the theory that combines fluctuating hydrodynamics with diffusion–reaction processes—is a case in point. Although not every reader will be intimately familiar with it, Gaspard conveys the ideas and theory of fluctuating chemohydrodynamics clearly by providing a detailed description of fluctuation relations for diodes and transistors. Using that approach, he seamlessly covers how fluctuations relate to topics as varied as surface reactions, ion transportation, and Brownian particles in fluids.

*The Statistical Mechanics of Irreversible Phenomena* convincingly demonstrates that fluctuation relations allow us to study nonequilibrium systems beyond the linear irreversible regime. A comprehensive and self-contained overview of a considerable amount of recent progress in the field, it is one of the best sources available to learn about the state of the art in nonlinear dynamics. I have no doubt that graduate students and researchers will enjoy reading it.

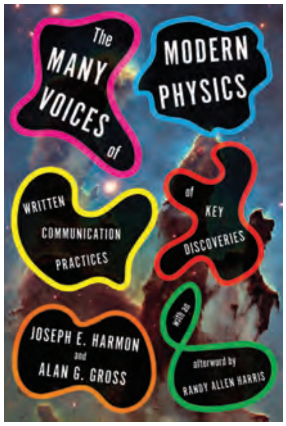
**Patrick Ilg**
*University of Reading*
*Reading, UK*

# NEW BOOKS & MEDIA

## The Many Voices of Modern Physics

### Written Communication Practices of Key Discoveries

**Joseph E. Harmon and Alan G. Gross**
U. Pittsburgh Press, 2023. $65.00




Since 2007 Joseph Harmon, a science writer, and Alan Gross, a scholar of scientific rhetoric, have coauthored a series of books on the methods and practices of scientific communication, both past and present. Their latest volume, *The Many Voices of Modern Physics*, presents a history of physics rhetoric since 1900. Using an extensive set of written and graphical examples from such authors as Albert Einstein, Richard Feynman, and Steven Weinberg, the two authors illustrate how visuals, thought experiments, and analogies have been used to advance arguments in physics. Sadly, Gross died suddenly in 2020, so this will be his and Harmon's last book together. It is a fitting capstone to their joint scholarly project. —RD


## Great Mysteries of Physics

**Miriam Frankel, host**
The Conversation, 2023–

As the title suggests, this new podcast delves into larger philosophical questions in physics. Hosted by Miriam Frankel, a science editor at the Conversation, *Great Mysteries of Physics* covers such topics as the existence of time, the multiverse theory, and why physics can't explain consciousness. The second episode is a highlight: Based on interviews Frankel conducted with the physicists Fred Adams and Paul Davies, it explores the nature of fundamental constants like the speed of light. Although some researchers have argued that the constants have been fine-tuned to allow for life to exist, Adams suggests that the universe might be more conducive to life if the constants had different values. The podcast is supported by the Foundational Questions Institute. —RD

## What's Gotten into You

### The Story of Your Body's Atoms, from the Big Bang Through Last Night's Dinner

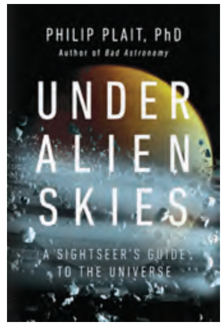
**Dan Levitt**
Harper, 2023. $32.00


What are we made of? That's the question that prompted the science and history documentarian Dan Levitt to write *What's Gotten into You*, in which he recounts the epic journey of the atoms that make up the human body. In some 400 pages, Levitt covers the Big Bang, the evolution of the universe, and four centuries of scientific investigations into the origin of life and the lives of the scientists who conducted them. Yet, Levitt writes, for all we've learned, some mysteries remain, such as how our consciousness arises from a conglomeration of molecules and cells. —CC

## Under Alien Skies

### A Sightseer's Guide to the Universe

**Philip Plait**
W. W. Norton, 2023. $30.00




What would it be like to travel to the Moon, Mars, Saturn, and beyond? In *Under Alien Skies*, the astronomer Philip Plait takes the reader on such a journey—starting in our solar system and continuing on to other cosmic objects, such as exoplanets, nebulae, and even black holes. Each chapter centers on a destination, such as Pluto, and Plait sets the scene by writing a few introductory paragraphs that place the reader in a space suit or spaceship, looking out. He then proceeds to describe the alien environment's terrain, atmosphere, gravity, and other physical details. Plait's engaging narrative brings to life the data that have been collected by Earth- and space-based telescopes. —CC

## Creativity for Scientists and Engineers

### A Practical Guide

**Dennis Sherwood**
IOP, 2022. $50.00


Ingenuity or creativity is typically thought to be an innate or unteachable quality. Some people are creative; others aren't. That's not true, according to Dennis Sherwood, who completed a PhD in biology at the University of California, San Diego, in the 1970s before embarking on a long career in consulting. In this new book, Sherwood first defines the word "creativity." He cites the author and journalist Arthur Koestler, who argued in 1964 that the act of creation "uncovers, selects, re-shuffles, combines, synthesizes already existing facts, ideas, faculties, skills." Sherwood then presents his own six-step recursive process that he argues will help anyone develop great ideas. Even if it won't be a magic bullet for all creative problems, it's nonetheless an illuminating look at the creative process. —RD PT

# NEW PRODUCTS

# Focus on lasers, imaging, microscopy, and nanoscience

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

**Andreas Mandelis**


## Single-frequency CW laser at 320 nm

Hübner Photonics has announced a new UV wavelength on the Cobolt 05-01 series laser platform. The Cobolt Zydeco 320 is a CW diode-pumped laser operating at a wavelength of 320 nm. It delivers an optical output power of 20 mW and has a spectral full-width-at-half-maximum linewidth of less than 1 MHz. The linearly–vertically polarized laser has a beam divergence at full angle of less than 0.8 mrad, wavelength stability of up to 1 pm, a polarization ratio of above 100:1, and a beam symmetry at aperture of greater than 0.90:1. It produces a beam diameter at aperture of 700 ± 50 μm with a power stability of 2%. The laser has an rms noise of 0.5%, beam pointing stability of 5 μrad/°C, and peak-to-peak noise of 5% in the range of 20 Hz to 20 MHz. The Cobolt Zydeco 320 is suitable for standalone laboratory use and for OEM integration in instruments for demanding applications that include fluorescence microscopy, flow cytometry, DNA sequencing, Raman spectroscopy, interferometry, holography, and particle analysis. ***Hübner Photonics Inc****, 2635 N 1st St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

## Erbium-glass microchip lasers

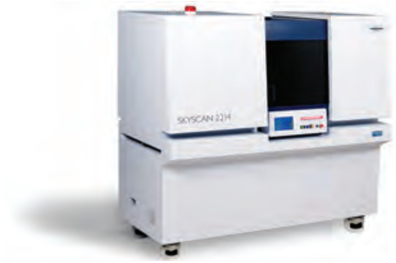
The FRLD-1535-xxxμJ-Q-BEyy series of laser modules from Frankfurt Laser are integrated 1535 nm high-energy erbium-glass microchip lasers with a photodetector and a beam expander up to 40×. The series is specified to deliver high peak power of 5 μJ–1 J at 1535 nm, with a divergence angle of less than 0.3 mrad. The wide operating temperature range is from −40 °C to 65 °C. With dimensions of approximately 78–83 mm × 32 mm × 20 mm, the lasers are very compact. Their high repetition rate, small full-width-at-half-maximum pulse, high reliability, and small size make them suitable for laser ranging, laser remote sensing, and lidar. ***Frankfurt Laser Company****, An den 30 Morgen 13, D-61381 Friedrichsdorf, Germany, https://frlaserco.com*

## Laser-pulse-characterization software

New software from APE uses the SPIDER algorithm (spectral phase interferometry for direct electric-field reconstruction) to provide precise measurement and analysis of ultrashort laser pulses down to the few-cycle (FC) regime. The Spider family is designed for phase-resolved ultrafast pulse measurements and is suitable for use in ultrafast laser development and research. The FC Spider version offers a precision tool for the complete characterization of ultrashort laser pulses with just a few electric-field cycles with a pulse width of less than 5 fs. For less-broadband pulses, Spider combined with a grating-based stretcher is the best choice for IR-wavelength pulse characterization between 15 fs and 500 fs at a central wavelength of about 0.8 μm or 1 μm. Key features of the software now include a full automatic mode, error checks, and command-driven handling in addition to established tools such as electric-field plots, peak-power calculation, phase-difference measurement, and spectral phase analysis up to fourth order. The software is backward compatible. ***APE GmbH****, Plauener Strasse 163–165, Haus N, 13053 Berlin, Germany, www.ape-berlin.de*

## High-power single-frequency laser


Redesigned with new and improved hardware, NKT Photonics' single-frequency Koheras Boostik HP laser combines ultralow frequency and intensity noise, narrow linewidth, and high power. It is highly versatile and suitable for a wide range of applications, including quantum computing, quantum metrology and sensing, fundamental physics research, development of time and frequency standards, atomic trapping and cooling, and laser interferometry. The laser is alignment- and maintenance-free, reliable, and robust enough for use in demanding industrial settings and in space. The Boostik HP features up to 15 W output power at 1 μm or 1.5 μm, wide wavelength tuning, and excellent beam quality that enables efficient frequency conversion. Improved communication lets users control the amplifier via the NKTP Control software on the laser. A state-of-the-art fiber-delivery system handles high power, preserves the low-noise laser properties, and delivers single-mode light at all wavelengths. ***NKT Photonics Inc****, 23 Drydock Ave, Boston, MA 02210, www.nktphotonics.com*

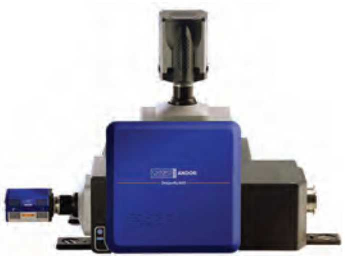


## Nanoscale 3D x-ray microscope

Bruker has released a CMOS edition of its SkyScan 2214, a multiscale x-ray microscope based on nanocomputed tomography. With the CMOS edition, the platform incorporates the latest scientific CMOS detector technology and offers cutting-edge x-ray imaging at high resolution, according to the company. The CMOS edition retains the modular design of earlier SkyScan 2214 versions. It accommodates up to four detectors and allows a wide variety of sample types and sizes to be scanned in one instrument. The design encompasses a 6 MP flat panel and three optimized 15/16 MP sCMOS detectors. They provide a wide field of view for true 3D resolution down to the 500 nm range. The Skyscan 2214 CMOS edition is suitable for academic and industrial research in materials sciences, such as in the development of lightweight high-strength composite materials and energy-storage devices like fuel cells, and in the life sciences, such as for preclinical imaging and the study of plant and animal biology. ***Bruker Corporation****, 40 Manning Rd, Billerica, MA 01821, www.bruker.com*

## Cryogenic-plasma FIB microscope

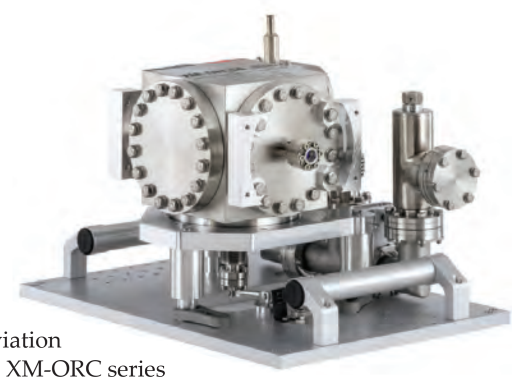
Thermo Fisher Scientific designed its Arctis Cryo-PFIB (cryogenic-plasma focused ion beam) automated microscope to advance cryo-electron tomography (cryo-ET) research. Able to perform at higher resolutions than other microscopies, cryo-ET is used to study how proteins and other molecules operate together in a cellular context. The Arctis Cryo-PFIB helps users address the time-consuming, complex process of preparing optimal samples for analysis by structural biology. According to the company, compared with other commercially available solutions, it speeds up reproducible production of high-quality samples with consistent thickness while minimizing sample contamination. Users performing cryo-ET will benefit from integrated correlative light and electron microscopy for quick targeting of the area of biological interest, PFIB technology for rapid removal of large sample volumes, automation to simplify sample preparation and enable remote operation, and connectivity in the workflow that simplifies transferring samples to the Thermo Scientific Krios or Glacios cryo-transmission electron microscopes. ***Thermo Fisher Scientific Inc****, 168 Third Ave, Waltham, MA 02451, www.thermofisher.com*



## Confocal microscope

Oxford Instruments Andor has presented a new flagship product in its confocal microscopy portfolio. Dragonfly 600 introduces three groundbreaking features: a new total internal reflection fluorescence (TIRF) modality, Borealis TIRF; a high-power laser engine; and a uniquely designed 3D superresolution module that retains parfocality across all imaging modes. Combined with innovative software, those technical advancements enable Dragonfly to deliver results with nanometer precision and thus to excel at single-molecule localization microscopy. The new product is 10 times as fast as point-scanner confocals. It images very deeply into thick organisms, and live specimens can be imaged for days without phototoxicity or photobleaching. According to the company, cancer and neuroscience research are among the fields that will benefit from the highly flexible system. ***Andor Technology Ltd****, 7 Millennium Way, Springvale Business Park, Belfast BT12 7AL, UK, https://andor.oxinst.com*

## Optical reference cavities for stabilized lasers



Menlo Systems and Thorlabs have jointly brought to market a co-branded line of high-finesse Fabry–Perot optical reference cavities housed in a stainless-steel vacuum chamber. The XM-ORC series comprises a 12.1-cm-long cylindrical ultralow-expansion glass spacer that incorporates cavity mirrors with high-reflectivity crystalline (xtal stable) coatings on fused silica substrates. Designed to provide high laser stability, the XM-ORC series includes all necessary hardware to stabilize the cavity at its zero crossing of the thermal-expansion coefficient, which is near room temperature. The optical reference cavities are offered with finesse values of greater than 300 000 for operation at 1550 nm or 1397 nm and greater than 100 000 for operation at 1064 nm. Other wavelengths are available upon request. With a thermal-noise Allan-deviation limit of as low as $1.6 \times 10^{-16}$ and a low linear-drift rate of about 150 mHz/s, the XM-ORC series is an optimal reference for cavity-stabilized lasers. It is suitable for select applications in high-resolution spectroscopy, quantum computing, optical clocks, cooling and trapping of atoms and ions, and low-noise microwave generation. ***Menlo Systems Inc****, 56 Sparta Ave, Newton, NJ 07860, www.menlosystems.com*

## Microlens for SPAD array cameras


Photon Force has launched a microlens option for its single-photon avalanche diode (SPAD) array PF32 camera range. The microlenses increase by a factor of 10 the image sensor's effective fill factor—the ratio of the actual sensitive area of a pixel to the total area of each element of an array. In many arrays, much of the area of each element is occupied by support circuitry for each pixel, which reduces the active sensitive area. A microlens—one is needed for each pixel—concentrates more of the incident light onto the sensitive area of the pixel, thereby enhancing the sensitivity of the camera for time-resolved measurements. The option especially benefits low-light applications such as imaging through scattering media and fluorescence microscopy. The PF32 time-resolved photon-counting camera range includes powerful features such as ultrahigh-speed digital readout, picosecond timing resolution, and low power consumption. ***Photon Force Ltd***, *Murchison House, 10 Max Born Crescent, Edinburgh, Scotland, EH9 3BF UK, www.photon-force.com*

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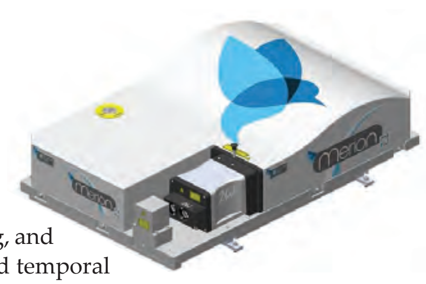
## Compact high-power diode-pumped laser



The Merion MW HP is the latest addition to Lumibird's family of high-power diode-pumped Nd:YAG (neodymium-doped yttrium aluminum garnet) lasers for laboratory and industrial applications. Leveraging the technology developed for the company's Merion MW series, configured with an oscillator and amplifier combination, the lasers can reach up to 100 W at 1064 nm. Use of the platform Lumibird developed for its Q-smart HE series provides versatility while minimizing the footprint. The Merion MW HP features plug-and-play harmonic modules, automatic phase matching, and detachable cables and coolant lines. The optical specifications deliver high spatial and temporal beam qualities. A single longitudinal mode option is offered with a narrow linewidth of 0.005 $cm^{-1}$. ***Lumibird***, *2 Rue Paul Sabatier, 22300 Lannion, France, www.lumibird.com*

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## Nanoscale 4D scanning TEM


Tescan's Tensor 4D scanning transmission electron microscope (4D-STEM) addresses the needs of users working in multimodal—morphological, chemical, and structural—nanocharacterization applications. Integrating 4D-STEM capabilities onto legacy TEM columns, it synchronizes scanning of the electron beam with diffraction imaging. That synchronization is achieved through the use of a hybrid-pixel direct electron detector, electron-beam precession, energy-dispersive-spectroscopy acquisition, beam blanking, and near-real-time analysis and processing of 4D-STEM data. For materials science and semiconductor R&D and failure analysis, the Tensor 4D-STEM provides high-contrast, high-resolution 2D and 3D characterization of functional engineered materials at the nanoscale. It can be applied to thin films for R&D and failure analysis of logic, memory, and storage devices and can help determine the crystallographic structure of submicron natural or synthetic particles that are too small to be characterized using micro-x-ray diffraction techniques. ***Tescan Orsay Holding AS***, *Libušina tř 21, 623 00 Brno-Kohoutovice, Czech Republic, www.tescan.com*

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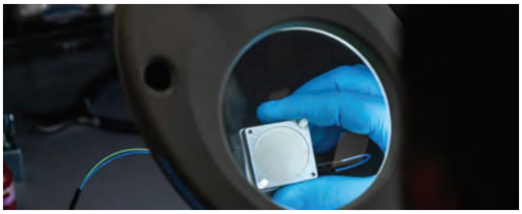
## High-resolution holotomography microscope

According to Tomocube, its holotomography (HT) platform HT-X1 is the first holotomography microscope to utilize incoherent light. Instead of a laser light source, the HT-X1 uses a conventional single-beam LED to illuminate the sample with various beam patterns specifically designed to retrieve the refractive index and capture a sequence of holograms from different positions. The unique single-beam technique simplifies the imaging process by eliminating the need for background calibration and allowing imaging in confluent samples without an increase in light intensity. It provides high mechanical stability, and because it is less sensitive to speckle noise, it delivers high-contrast imaging with a lateral resolution of 156 nm. The all-in-one system offers label-free, true 3D time-lapse live-cell imaging for higher-throughput and automated screening applications. ***Tomocube Inc***, *4th Flr, 155, Sinseong-ro, Yuseong-gu, Daejeon 34109, South Korea, www.tomocube.com*

## Shortwave IR cameras

With the introduction of new sensors from Sony, Allied Vision has expanded the spectral range of its GigE Vision Alvium G1 camera series. The Alvium G1-130 VSWIR and Alvium G1-030 VSWIR cameras feature Sony's SenSWIR IMX990 and IMX991 InGaAs-based shortwave IR (SWIR) sensors, respectively. The SenSWIR sensors do not require thermoelectric cooling. The resolutions of the IMX991's video graphics array and the IMX990's superextended graphics array enable users to capture images with high quantum efficiency in the visible and SWIR regions with a single camera. The architecture of the InGaAs digital sensors allows pixel sizes of only 5 μm; because of their copper-to-copper interconnects, they have high image homogeneity. The small pixel size facilitates SWIR applications that require high resolution and precision, such as semiconductor inspection and quality inspection of optics for laser-based measurement systems. ***Allied Vision***, *Taschenweg 2a, 07646 Stadtroda, Germany, www.alliedvision.com*



## Nanoscale metrology for demanding environments

Queensgate now offers its NanoCeramic NanoSensor series for nanoscale metrology in demanding environments such as ultrahigh vacuum, high radiation, and extreme temperatures of 80 K to 423 K. The NanoCeramic series is based on the principle of capacitance micrometry: Two gold-coated sensor plates—a target and a probe—form a parallel-plate capacitor; the spacing of the plates is measured using an electronic controller. A glass ceramic glaze protects the sensor faces and prevents accidental shorting between the plates. The series offers measurement ranges from 20 μm to 1250 μm with frequency responses up to 20 kHz, capabilities that make it suitable for vibration monitoring and detecting noise in precision instrumentation. They ensure linearity down to 0.05% and measurement resolution as low as 7 pm (rms) in a non-self-heating assembly. Selected designs are suitable for ultrahigh-vacuum operation down to $10^{-9}$ torr. Housing materials include Invar, stainless steel, and aluminum as appropriate for specific uses, among which are long-term space missions, synchrotron light sources, and materials science applications. ***Queensgate Instruments***, *3-4 Fielding Industrial Estate, Wilbraham Rd, Fulbourn, Cambridge CB21 5ET, UK, www.nanopositioning.com* PT

# OBITUARIES

## Karl Alexander Müller


Karl Alexander Müller

AIP ESVA/W. F. MEGGERS GALLERY OF NOBEL LAUREATES COLLECTION

Karl Alexander Müller, synonymous with his pioneering work in structural phase transformations, ferroelectricity, and superconductivity in oxides, peacefully passed away on 9 January 2023 in Zollikerberg, Switzerland. He was an IBM fellow, a professor of physics at the University of Zurich, and a corecipient of the 1987 Nobel Prize in Physics.

Alex was born on 20 April 1927 in Basel, Switzerland. After the early death of his mother, he attended a boarding school in Schiers in the Swiss Alps, where he became an enthusiastic radio hobbyist and skier. He studied physics at ETH Zürich. There Alex was strongly influenced by Wolfgang Pauli and his lectures and developed a lifelong admiration for him.

For his PhD thesis, Alex built an apparatus for measuring the resonance of paramagnetic impurities in crystals and determined the resonance of the iron-doped single-crystal strontium titanate (STO). That work became a true landmark in Alex's scientific life. With the first detection of a structural phase transition in STO from cubic to tetragonal around 100 K, he established electron paramagnetic resonance (EPR) as an important local tool for studying impurities in solids.

STO served as a model substance for many perovskites, but for Alex, the beauty and simplicity of the crystal structure became his mandala—a spiritual, empowering, and inspiring symbol.

After getting his PhD, Alex started in 1959 at the Battelle Memorial Institute in Geneva as head of the magnetic resonance group. In view of his scientific reputation, the IBM Zurich Research Laboratory in Rüschlikon offered him the position of a research staff member in 1963, and eight years later he was promoted to lead the physics department. His focus was on STO and related perovskites regarding their dielectric, polar, and structural properties. He received the most attention for his discovery of quantum paraelectricity, where the polar instability in STO is suppressed by quantum fluctuations.

Alex's early interest in the Jahn–Teller (JT) effect became important for the later search for superconductivity in oxides. Using EPR, he demonstrated both the static and the dynamic JT effect of impurities with orbitally degenerate ground states in perovskites. A decisive step happened in 1978 when Alex left the IBM Zurich lab for a sabbatical at the IBM Thomas J. Watson Research Center in Yorktown Heights, New York. As an IBM fellow, he had the freedom to decide independently about his further research areas. For the first time, he became intensely involved in superconductivity—another milestone on the way to the Nobel Prize.

Back in Zurich, Alex, inspired by the prediction of Harry Thomas of the existence of JT polarons in semiconductors, considered the importance of oxides for superconductivity and applied the concept to conducting oxides with JT centers. Alex asked one of us (J. Georg Bednorz) to join him in the project and was, as he later confessed, very surprised by the spontaneous acceptance. Georg had previously worked with Gerd Binnig on superconductivity in STO and was disappointed that Gerd ended the project in 1982.

Indeed, that was a venturous enterprise with an uncertain outcome—but it took only three years to achieve the breakthrough in 1986 with the discovery of the lanthanum barium copper oxide, or La-Ba-Cu-O, system. At the 1987 American Physical Society March Meeting—later called the Woodstock of Physics—in New York, the discovery was already peaking tremendous interest and was being covered by the *New York Times*. Both Georg and Alex were awarded the Nobel Prize in Physics in October of that year for their discovery of superconductivity in ceramic materials.

In the following years, Alex continued his activities in superconductivity to demonstrate that the JT polarons were the source of the electron pairing in oxides, when the generally believed assumption was that the source was of a purely electronic origin. The ceramic character of those oxides strongly supported his conviction that inhomogeneity is essential to high-temperature superconductivity, and he questioned the assumption that the pair wavefunction has a $d$-wave order parameter. Instead, Alex postulated that two order parameters, $s + d$, are necessary to understand experiments that are incompatible with a single $d$-wave order parameter. To demonstrate the importance of the lattice for the pairing mechanism, he initiated a project on isotope effects. Numerous unexpected isotope effects on characteristic superconducting properties were discovered, which supported Alex's idea of the JT polarons and unconventionally strong local electron–lattice interactions as the driving force for high-temperature superconductivity.

Alex was an inspiring teacher who encouraged young scientists to follow their own ideas in research. He participated regularly in university life and frequently attended seminars at the physics institute of the University of Zurich. In his private life, Alex was a devoted husband, father, and grandfather who shared not only his musical interests but also many travel memories with his wife, Ingeborg.

We will deeply miss him, not only as an ingenious scientist but also as a great friend who always supported us both in scientific endeavors and with respect to our private welfare.

**J. Georg Bednorz**
*IBM Research*
*Rüschlikon, Switzerland*
**Annette Bussmann-Holder**
*Max Planck Institute for*
*Solid State Research*
*Stuttgart, Germany*
**Hugo Keller**
*University of Zurich*
*Zurich, Switzerland*

# Roger H. Stuewer

Roger H. Stuewer, a giant in the history of physics and an emeritus professor of history of science at the University of Minnesota, died on 29 July 2022 in his home in New Brighton, Minnesota.

Roger was born on 12 September 1934 in Bonduel, Wisconsin. In 1952 he began his undergraduate studies at the University of Wisconsin–Madison. After a stint in the US Army, stationed mostly in Munich, he resumed his undergraduate work in 1956, eventually majoring in physics education.

After teaching high school for a year, Roger used the one year of academic education he had left under the GI Bill to study physics in Vienna in 1959. A few months after he married Helga von Schmeidel in April 1960, they moved to Tiffin, Ohio, where Roger had been hired as a physics instructor at Heidelberg College. In 1962 they and their two children moved to Madison so that Roger could pursue graduate studies at the University of Wisconsin. He earned his PhD in 1968 with a double major in history of science, with Erwin Hiebert, and physics, with Heinz Barschall. His dissertation would form the basis for his first book, *The Compton Effect: Turning Point in Physics* (1975), which became a classic in the field.

To show how the job market had changed since he first started applying, Roger loved telling how even before he had his PhD in hand, he received 35 offers! He accepted a position as a historian of science at the University of Minnesota, with a joint appointment in the center for philosophy of science and the school of physics and astronomy. That planted the seed for what in 1972 would become the program in history of science and technology, with historians embedded in science and engineering departments. Roger served as its director until 1989. He became emeritus professor in 2000. One of us (Shapiro) succeeded him as the program's director, and the other (Janssen) as its historian of modern physics. The original program lasted until 2007, when it merged with the program in history of medicine.

In 1977 Roger organized a symposium in Minnesota on nuclear physics in the 1930s that attracted many of the pioneers

JOHN D. NORTON

Roger H. Stuewer

from that time. He edited its proceedings, *Nuclear Physics in Retrospect*, which came out in 1979. It was the first of many publications that established Roger as the world's leading authority on the early history of nuclear physics. He synthesized much of that work for a broader audience in his last book, *The Age of Innocence: Nuclear Physics Between the First and Second World Wars* (2018).

As a historian of modern physics, Roger was ahead of the curve in several respects. First, long before it became the norm, he made extensive use of archival sources. Second, at a time when the field was dominated by the history of theory, he focused on experiment. Third, he paid close attention to institutional settings.

Roger was a great ambassador for the history of physics. He was a much sought after speaker at both physics and history of science conferences. He lectured to captivated audiences as a visiting professor in Vienna in 1989 and in Amsterdam in 1998. Wherever he went, he made many lifelong friends in both the physics and the history and philosophy of science communities.

Throughout his career, Roger took on leadership roles in organizations focusing on history of physics and physics teaching. He served two terms, for instance, as chair of the executive committee of the American Physical Society Forum on History of Physics, and he was a member of the Advisory Committee on History of Physics of the American Institute of Physics (publisher of PHYSICS TODAY) for 15 years. From 1978 to 2015, he was the resource-letters editor of the *American Journal of Physics*. During those 37 years, he published a record 183 resource letters. In 1999, together with John Rigden, he started a new journal, *Physics in Perspective*, which he edited until 2013. During his tenure, many of the articles' acknowledgments mentioned his meticulous copyediting.

In 1997 Roger helped Lee Gohlike in founding the Seven Pines Symposium, which for 25 years has brought together scientists and historians and philosophers of science in a charming inn outside Stillwater, Minnesota, to discuss problems at the intersections of those fields.

Roger was also instrumental in establishing the American Physical Society's Abraham Pais Prize for History of Physics in 2005. He was awarded the prize in 2013 for "his pioneering historical studies of the photon concept and nuclear physics, and for his leadership in bringing physicists into writing the history of physics by helping to organize and develop supporting institutions and publications."

Of the many honors Roger received, the Pais Prize and the Distinguished Alumni Award from the University of Wisconsin–Madison's department of physics meant the most to him. Both underscore Roger's deep commitment to bridging the worlds of physics and history and philosophy of science.

**Michel Janssen**
**Alan E. Shapiro**
*University of Minnesota Twin Cities*
*Minneapolis* PT

**Nathan Gabor** is a professor of physics, **Jed Kistner-Morris** is a graduate student, and **Benjamin Stewart** is an assistant project scientist, all with the Quantum Materials Optoelectronics Lab at the University of California, Riverside.

# Nature's search for a quiet place

**Nathaniel M. Gabor, Jed Kistner-Morris, and Benjamin W. Stewart**

The predominance of green terrestrial plants stems from chlorophyll's absorbance wavelengths. Those spectral selections ensure consistent energy harvesting and avoid photo-oxidative stress.

A patch of green grass is full of life and likely to host fungi, bacteria, and insects. Temperature, wind, and sunlight fluctuate constantly. Every biological system—including the food chain and the hardware of DNA replication—is fraught with noise. Given that context, how do living systems establish themselves and work so well?

Take photosynthesis, for example. In certain light conditions, 99 out of 100 photons that enter a plant's light-harvesting antenna complex excite a chlorophyll electron and make its energy chemically available. That efficiency is possible because of the configuration, or spatial arrangement, of photosynthetic antenna arrays, which consist of pairs of chlorophyll pigments that have been tuned to absorb photons in narrow frequency windows. To help explain the principle that regulates the selection of those frequencies, let's consider the difficulty of photosynthesis in light of that faced by networks in general.

## Goldilocks

For a network that experiences rapidly changing environmental conditions and internal fluctuations, what is the best way to achieve just the right flow of energy? The process of converting noisy inputs to quiet outputs has relevance in nearly every practical application of network design, including multicomponent, large-scale energy grids and auditory and visual stimuli in neural networks.

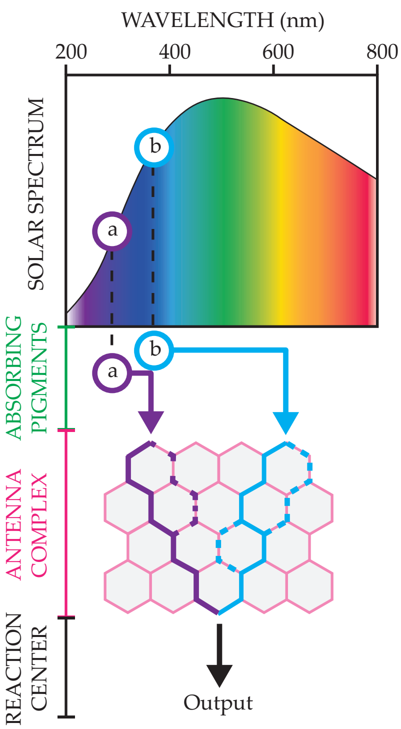



**FIGURE 1. IN PHOTOSYNTHESIS,** solar energy is absorbed by an antenna complex that consists of chlorophyll pairs—pigments a and b. Their arrangement attenuates the effects of environmental fluctuations and reduces noise in a plant cell's energy-conversion network. Optimally, a chlorophyll pair situates itself on the steepest slope of the solar spectrum, where the two inputs have similar wavelengths but different energy-absorption rates. Tuned to that part of the spectrum, the inputs deliver consistent output power.

The issue is especially acute for networks composed of delicate quantum states. What's more, when a network fails to manage the over- or underflow of energy or information, the results can be disastrous. Uncontrolled surges can trigger blackouts in the energy grid; likewise, too much input through our five senses may lead to sensory overload in the brain. In plants, such overloads lead to photo-oxidative stress. For the photosynthetic network to avoid that outcome, it must be optimized for a consistent flow of energy.

To make sense of how photosynthesis achieves that Goldilocks state, the three of us and our colleagues in the lab started with a straightforward intuition—namely, that there must be a relationship between the visible spectrum and the biological apparatus that harvests the Sun's energy. We sought to characterize that relationship using a minimalist model. A famous example of such a model is the parable of Daisyworld, proposed in 1983 by Andrew Watson and James Lovelock to explain biofeedback's role in global temperature stability.

## Daisyworld

Daisyworld is an imaginary planet with just two daisy species, one black and the other white. At first, the planet is too cold to support much life. But the black daisies start bucking that trend by absorbing most of the light that falls on them and gradually heating up the planet. In turn, the white daisies thrive. But they also reflect light, which reverses the planet's heating trend. As the temperature continues to fluctuate, each daisy species keeps the effect of the other in check. Over time, their combined effects stabilize the planet's temperature. Watson and Lovelock's model illustrates how a simple system can render an environment more consistent and more favorable to life.

Even so, large, homeostatic systems, such as Earth's atmosphere, experience a variety of fluctuations. How, then, do plants tune their photosynthetic antenna arrays to account for such changes? Earlier, we noted that networks should optimize for consistent power delivery rather than for maximum power. Photosynthetic networks accomplish the task by diversifying their inputs. They tune pairs of pigments to parts of the solar spectrum that yield similar wavelengths but different power levels. For each pigment pair, those wavelength selections result in one low-power input and one high-power input.

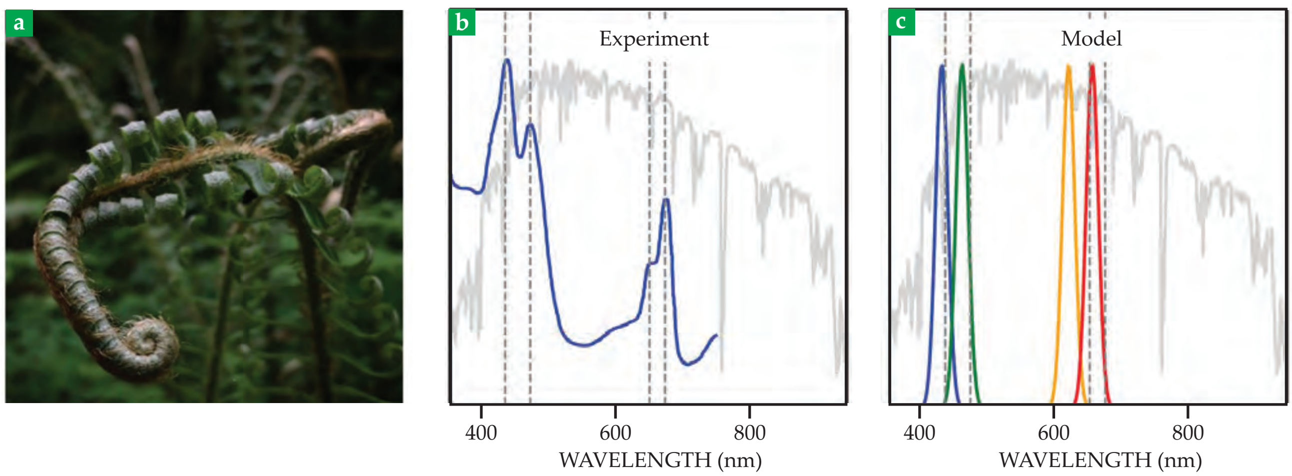



**FIGURE 2. A FERN** sunbathes **(a)**. Its experimentally observed absorption spectrum **(b)** is shown in gray, superimposed with peaks (blue) that mark the wavelengths at which chlorophyll pairs in terrestrial plants absorb light. Against the same solar power spectrum (gray), dashed lines mark the spectral frequencies to which the plants' antenna complexes are tuned. **(c)** Colored lines represent our model's predicted peaks. They closely match the frequencies at which plants absorb light. (Adapted from T. B. Arp et al., *Science* **368**, 1490, 2020.)

To understand the principle at work, let's turn to our own minimalist model, shown in figure 1, which describes a simple, light-energy-harvesting antenna complex. It is a network in which two inputs are directly coupled to a singular output. Energy enters the network from input channels (chlorophyll pair a and b) that correspond to light absorption through different pigments. Each channel is defined by the wavelength and rate at which it absorbs. The overall absorption rate is determined by the external light spectrum—that is, the intensity of available light at the two wavelengths.

Although many pathways exist in the network, all of them lead to a single output channel that represents an electron excitation. With multiple inputs and only one output, the network is inherently noisy. External noise comes from rapid fluctuations in incident light, whereas internal noise arises from structural dynamics and mismatches between different input rates. The result is a noisy output that fluctuates between underpowered, optimal, and overpowered states. The underpowered state is metabolically insufficient. The overpowered state risks cell damage from photo-oxidative stress.

How then should the two inputs be arranged so that the output spends most of its time at the optimal state? If two input channels are identical—effectively becoming a single channel—the antenna minimizes internal noise since there is no mismatch between different input rates. Unfortunately, committing to a single frequency would make the system highly sensitive to external noise. If the external light conditions suddenly change, the absorber is stuck, left with too much or too little power. Conversely, if the two channels differ strongly in both absorption rate and wavelength, internal noise dominates. Although the system is robust to external variations, it would suffer from a large mismatch between the two very different inputs.

Optimum output occurs when the two channels are balanced—that is, when we tune the two inputs to similar wavelengths but different absorption rates. When we examine the spectrum of available light, we find a means of achieving a Goldilocks solution. To get just the right amount of energy flowing out of the antenna complex, the absorbance peaks of the pair of pigments should be located in a region of the spectrum that has the steepest slope. That approach yields similar input wavelengths relative to different absorption rates, which smooths the power delivery.

## Pairs in quiet places

With surprising consistency, we have found that numerous phototrophic organisms exhibit those exact absorption characteristics: pairs of pigments situated on the steepest slopes of the light spectrum (see figure 2). Indeed, our research group predicted—accurately, it turns out—the absorption profile of green plants, purple bacteria, and green sulfur bacteria, among other organisms. Those organisms depart from our single-pair model in that many have two pairs of chlorophyll receivers, one for each slope of the solar spectrum's peak in power.

Because the absorption parameters of those organisms determine their color—terrestrial plants absorb in the blue and red and therefore reflect green light—one can predict how the organisms would appear in a given light environment. Most plants on Earth are green because they abhor the noise in the high-power portion of the light spectrum.

As a result of that abhorrence, plants have made evolutionary selections that are fundamental to life as we know it. By tuning their chlorophyll pairs to receive at frequencies just below the solar spectrum's irradiance peak, plants have nestled themselves into some of nature's relatively quiet places. Our research has isolated the general design principles behind that trend. And future solar-energy-harvesting grids can benefit from those principles.

## Additional resources


► T. Nesti, A. Zocca, B. Zwart, "Emergent failures and cascades in power grids: A statistical physics perspective," *Phys. Rev. Lett.* **120**, 258301 (2018).

► I. Kanitscheider, R. Coen-Cagli, A. Pouget, "Origin of information-limiting noise correlations," *Proc. Natl. Acad. Sci. USA* **112**, E6973 (2015).

► T. B. Arp et al., "Quieting a noisy antenna reproduces photosynthetic light-harvesting spectra," *Science* **368**, 1490 (2020).

► A. J. Watson, J. E. Lovelock, "Biological homeostasis of the global environment: The parable of Daisyworld," *Tellus B: Chem. Phys. Meteorol.* **35**, 284 (1983).


PT

## A smart bandage

Watches that track a wearer's heart rate and other biomedical data are becoming increasingly common and even prescribed by doctors in some cases. Researchers are expanding the data that can be measured by wearable devices (see Physics Today, September 2022, page 17). As a step in that direction, Wei Gao of Caltech and his colleagues have developed a wireless, electronic bandage, shown here on a gloved hand. Not only can the bioelectronic device measure a patient's metabolic and inflammatory response to a wound, it can also apply anti-inflammatory and antimicrobial treatments and electrically stimulate the site for tissue regeneration.

The durable yet highly elastic bandage is attached to a flexible printed circuit board that directs six embedded sensors. To study the therapeutic benefit of the bandage in a living organism, the researchers examined groups of diabetic rats, some of whom had infected wounds. Over a period of 14 days, the rats with smart bandages healed more quickly and effectively than the control groups. Although more studies are needed before human trials can begin, the researchers suspect the bandage could be particularly beneficial for patients with diabetic ulcers, burns, ulcerations, and other nonhealing wounds. (E. S. Sani et al., *Sci. Adv.* **9**, eadf7388, 2023; image courtesy of Caltech.) —AL

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