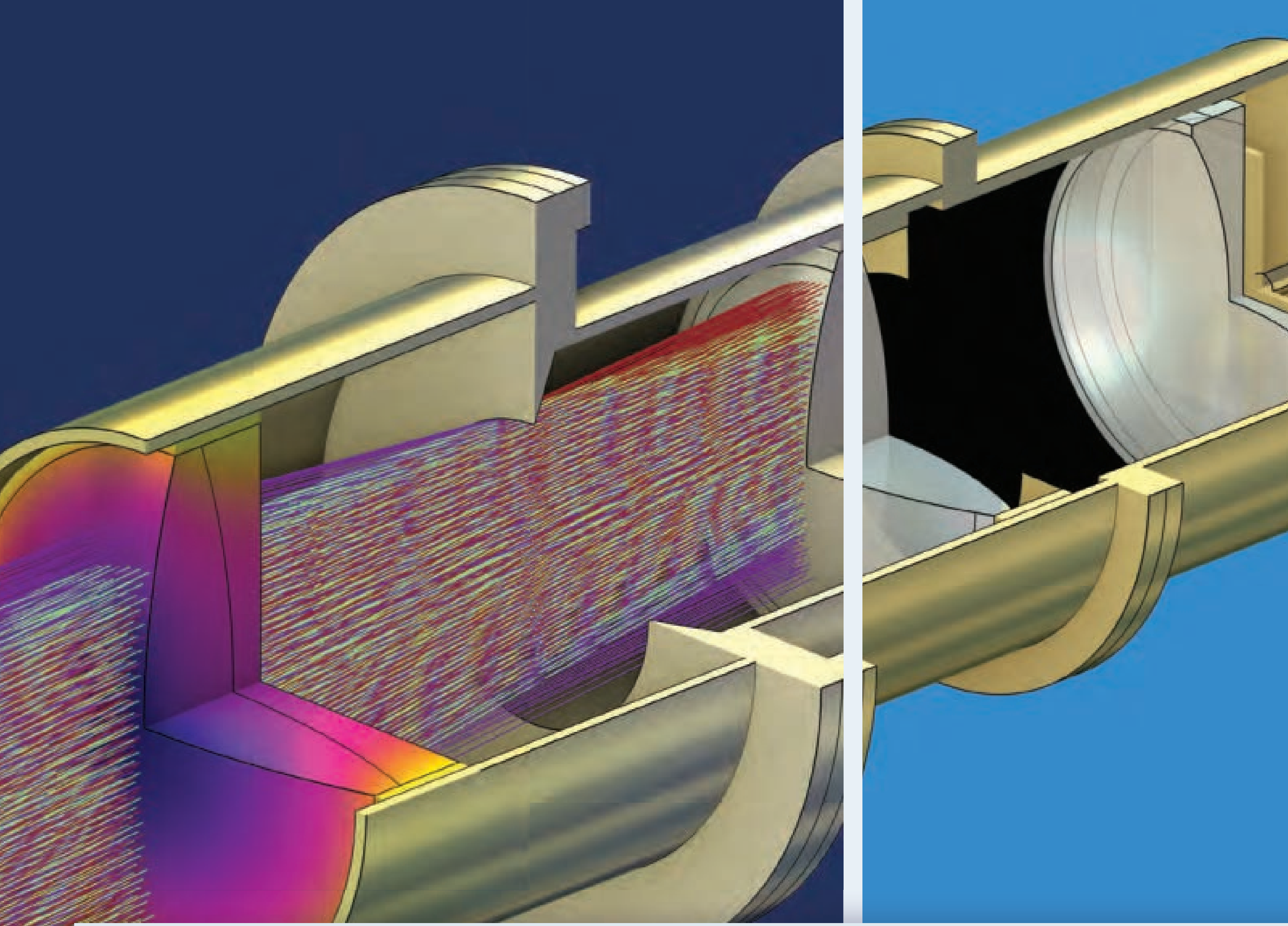

# PHYSICS TODAY

April 2024 • volume 77, number 4
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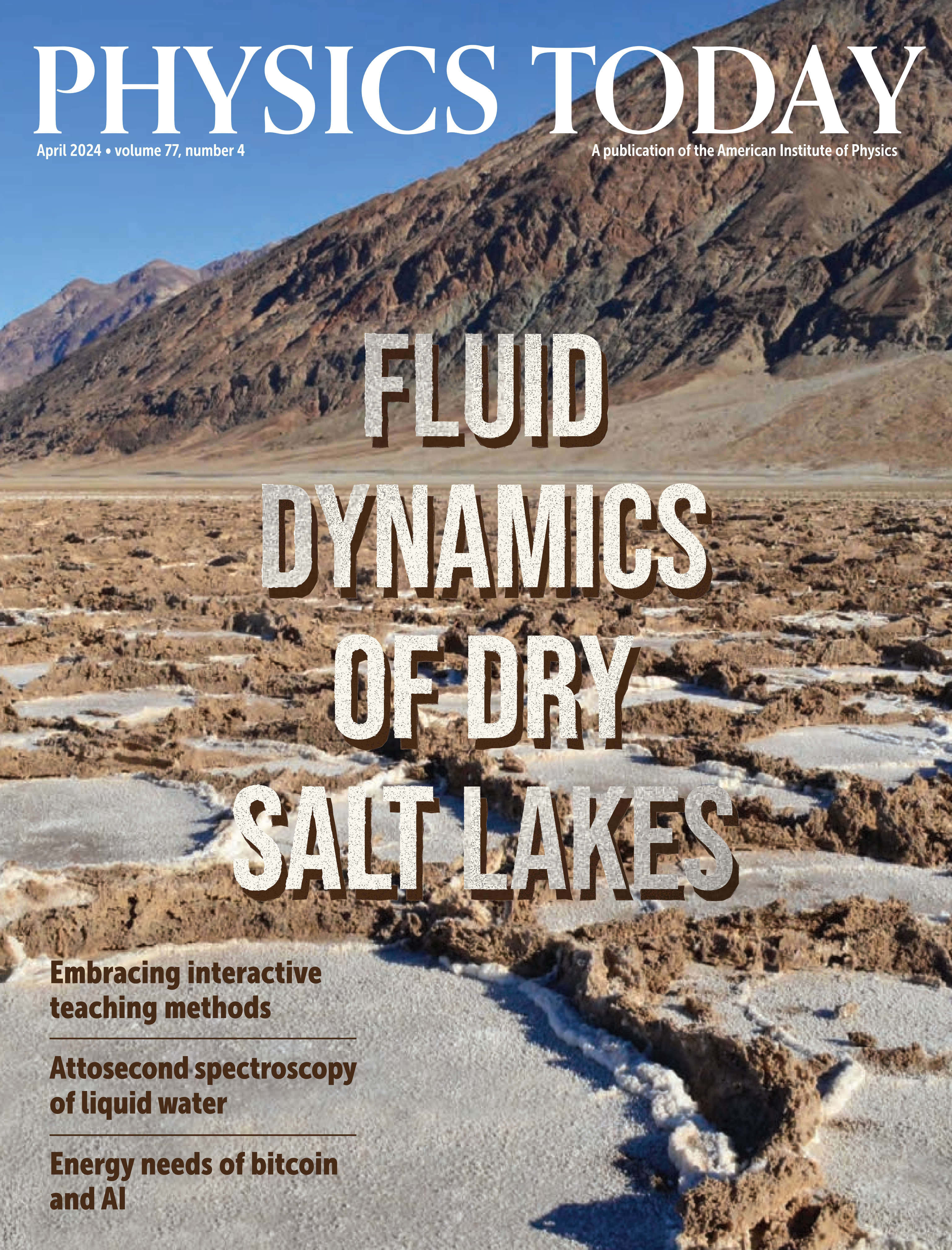

# FLUID DYNAMICS OF DRY SALT LAKES

Embracing interactive teaching methods

Attosecond spectroscopy of liquid water

Energy needs of bitcoin and AI

AIP

**NASA came to me twofold: once as a child in my dreams and then once as an adult to realize my actual academic achievements.**

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> **I call myself a nerd-entrepreneur. I think it’s a natural evolution that comes from a revolution.**

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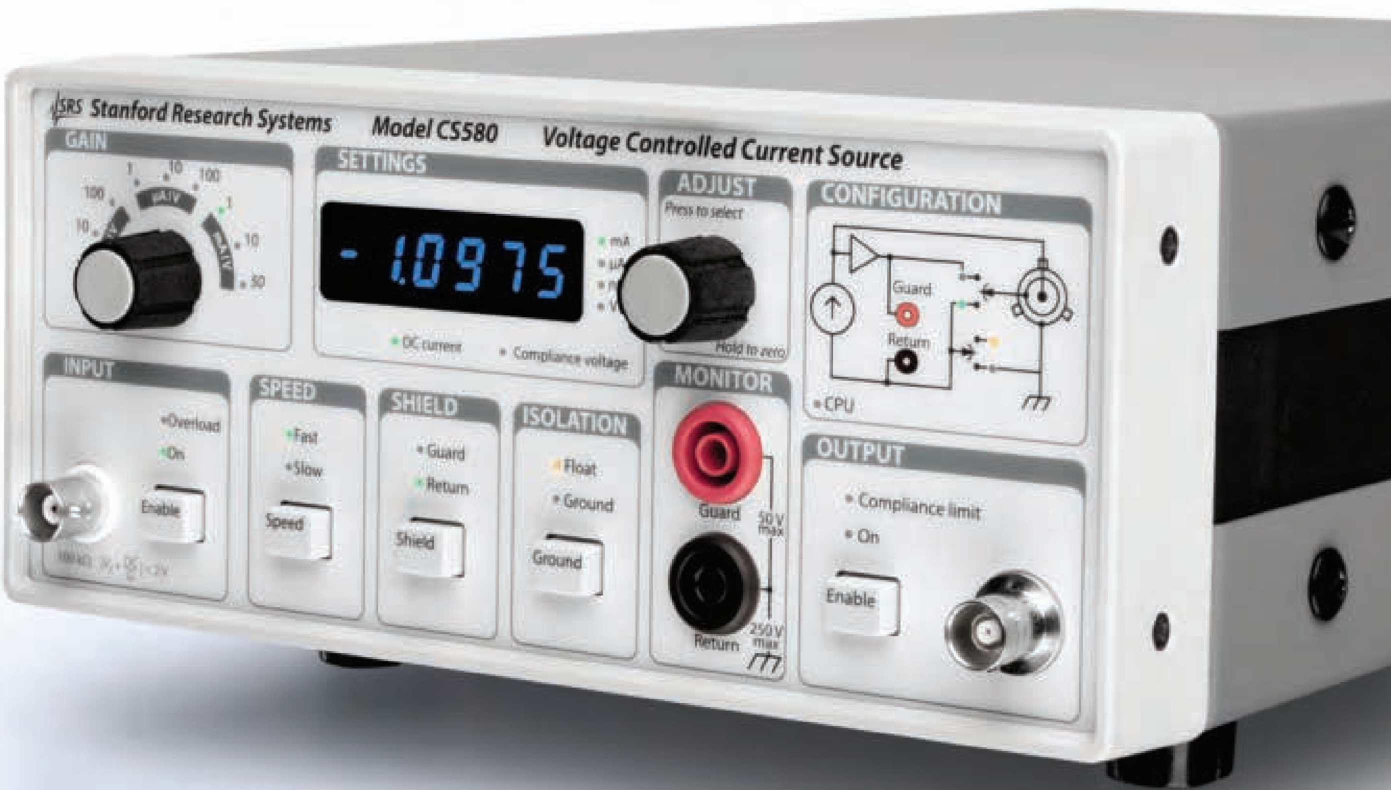


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# PHYSICS TODAY

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## FEATURES

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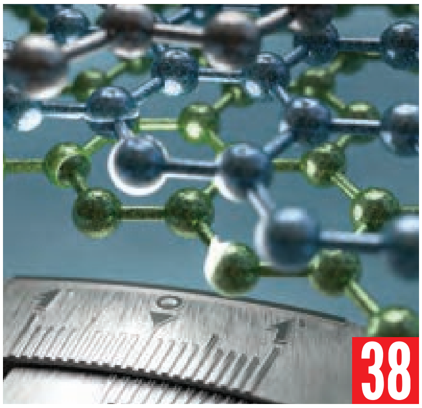

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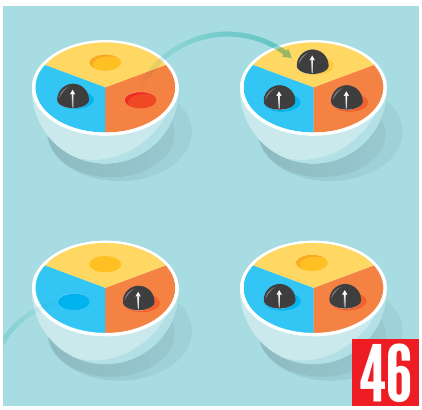
SPECIAL FOCUS ON STRONGLY CORRELATED MATERIALS





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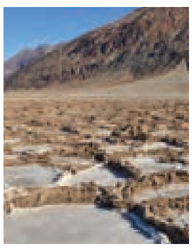

**ON THE COVER:** Death Valley's Badwater Basin is the lowest point in North America. Where there was once an ancient lake, water now flows underground in porous soil. As water evaporates, it leaves behind salt and other minerals, which slowly accumulate. Instead of producing a flat crust on the surface, the minerals develop a network of narrow ridges that form polygons a few meters in diameter, as shown in the image. To learn about the convective fluid dynamics that produce the polygons, turn to the Quick Study by Cédric Beaume, Lucas Goehring, and Jana Lasser on **page 62**. (Photo courtesy of Lucas Goehring and Jana Lasser.)

## Recently on PHYSICS TODAY ONLINE

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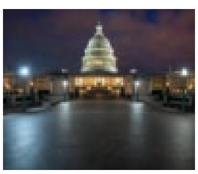

ARCHITECT OF THE CAPITOL

### US science funding

NASA, NIST, and other science agencies received overall budget cuts in the 2024 funding legislation signed by President Biden in March. Now attention shifts to the fiscal year 2025 budget. The president's proposal being considered by Congress requests more money for many of those same agencies.

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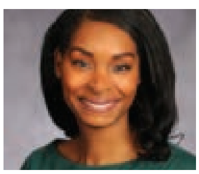
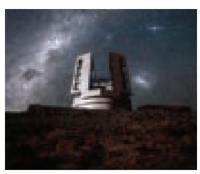


IDAHO NATIONAL LABORATORY

### J'Tia Hart

Before becoming the director of nuclear nonproliferation at Idaho National Laboratory, J'Tia Hart advised other countries on export controls, briefed the secretary of energy on nuclear security, and more. She talks to Physics Today about her career path and her numerous outreach and advocacy efforts.

***physicstoday.org/Apr2024b***



GMTO CORPORATION

### Giant telescopes

The NSF board recently set a funding cap for construction of the Thirty Meter and Giant Magellan Telescopes, a decision that implies NSF is unlikely to fund both observatories. Mitch Ambrose lays out the implications and describes the balancing act the agency faces in funding multiple high-priority projects.

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## DEPARTMENTS






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**It was a such a random event that led me to finding medical physics. But I believe that it was just my path and that everything fell into place at the right time.**

Julianne Pollard-Larkin

Watch her story

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# FROM THE EDITOR

## The march of change

Richard F. Fitzgerald

I've been at PHYSICS TODAY for 25 1/2 years. When I joined the staff, the PHYSICS TODAY website—indeed, the Web as we know it today—was in its infancy. Google was newly incorporated. Webpages were static. "Physics Today" meant PHYSICS TODAY the magazine, its sole incarnation.

The world of publishing has changed radically since then. Many of us are omnivorous consumers of content, and content can now be found in vastly more places—and in vastly more forms. PHYSICS TODAY has certainly evolved, too, especially in the digital space, with online-only content, webinars, and more.

The mission of PHYSICS TODAY, though, remains the same: to be a unifying influence across the many subdisciplines in the physical sciences. If you receive the magazine, chances are you belong to at least one of the 10 professional societies that are part of the American Institute of Physics federation. Those societies span a rich variety of fields: physics, astronomy, optics, medical physics, acoustics, meteorology, and more. Our challenge is to provide diverse content that is informative and engaging to most people across most fields most of the time. Only by doing that can we live up to our mission to be a unifying influence.

Last year marked PHYSICS TODAY's 75th anniversary. That milestone prompted not only a look back at where we came from but also a look forward to where we are going. Audience feedback and much deep introspection have led us to evolve how we approach our mission and, in particular, how we can better satisfy your curiosity and better cover the breadth and richness of the physical-sciences enterprise. Some of the resulting changes are already showing.

As I wrote in last December's issue, obituaries are now only online, where they are available in a single, readily findable place. Many individuals' contributions and life stories certainly have been worthy of a place in our pages, but with our capacity to run only a small number of obituaries each month, the decision of who received one of those places became increasingly difficult to make in an equitable way. Our website provides a better, fairer option for honoring community members no longer with us, and anyone is welcome to submit a remembrance online. Our books department, too, has been unable to keep pace with the many noteworthy books being published—at least in a way that adequately captures the ever-increasing range of subjects they cover. We've thus made the difficult decision to discontinue our books department after this issue.

Those changes, however, enable us to meet what is by far the most common request we've received from reader surveys: providing more coverage about advances in fields outside one's own—that is, across the full gamut of research areas. After all, part of what unites us as a community is our curiosity and sense of wonder. So starting this month (page 17), in each issue of the magazine we are including highlights of the short research news updates, selected by our editors, that we have recently published online. They'll run in the back of the Search and Discovery department, where they will follow stories of research advances deemed by subject-matter experts as significant enough to warrant more in-depth coverage. By serving up a broader collection of what's important and what's interesting, we hope that you'll regularly find items that you find informative and that you can share with others, be they scientists, science enthusiasts, policymakers, or members of the public.

Another integral part of what unites us is our shared experience of being a scientist and of being co-inheritors of a rich, fascinating scientific heritage. Over the course of 2024, you'll start seeing more reporting not just of new science but also of scientists. Science doesn't progress in a vacuum; it can't—and shouldn't—be separated from the people who conduct it. Other changes are also in the works for this year.

The forefront of science is continually advancing; PHYSICS TODAY will be too. We always welcome your input and feedback, whether on reader surveys, at conferences, or sent to us at pteditors@aip.org or on our website, www.physicstoday.org.

# More on nuclear treaties

Hannah Pell's article titled "'Peaceful' nuclear explosives?" (Physics Today, November 2023, page 34) is informative about the US Atomic Energy Commission's Project Plowshare, which sought to make use of nuclear explosions in applications such as gas stimulation and the creation of canals and harbors.

Pell reports that the Soviet Union was carrying out a similar program. She also makes note of the 1963 Limited Test Ban Treaty, which prohibited nations from conducting nuclear explosions in the atmosphere, underwater, and in outer space—but not underground, unless the explosion would create radioactive debris outside the territorial limits of the state conducting it.

Later arms-control agreements were also related to nuclear explosions for peaceful purposes. In particular, the US–Soviet Threshold Test Ban Treaty, signed in 1974 and ratified in 1990, prohibited underground nuclear weapons tests that would yield more than the equivalent of 150 kilotons of TNT. The Peaceful Nuclear Explosions Treaty, signed in 1976 and ratified in 1990, included the same stipulation for all individual nuclear explosions.

The Comprehensive Nuclear-Test-Ban Treaty, which opened for signatures in 1996 and has not yet come into force, calls for the prohibition of all nuclear explosions, regardless of yield or stated purpose. It now has 187 signatories, 177 of whom have ratified the treaty and become parties to it. The treaty provides for review conferences that "take into account any new scientific and technological developments" relevant to it. Such conferences would consider, at the


A meeting on the Comprehensive Nuclear-Test-Ban Treaty at the United Nations Headquarters in New York City in 2016. (Courtesy of the US State Department/public domain.)

> “‘Peaceful’ nuclear explosions seem unlikely to have a future on our planet.”

request of any nation, allowing underground nuclear explosions to be conducted for peaceful purposes. If a consensus is reached to allow such explosions, the treaty says, the conference should then recommend an amendment “that shall preclude any military benefits of such nuclear explosions.”

But the preclusion of military benefits seems impossible, and the requirement for consensus among the parties seems to be a substantial obstacle for amendment. “Peaceful” nuclear explosions seem unlikely to have a future on our planet.

**Pierce Corden**
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Something not mentioned in Hannah Pell’s article “‘Peaceful’ nuclear explosives?” (Physics Today, November 2023, page 34) is that the work of Project Plowshare and its Soviet counterpart became an issue during the negotiations over the Nuclear Non-Proliferation Treaty (NPT), which entered into force in 1970.

Concerned about getting left out of an important technology, non-nuclear-weapons countries insisted that the treaty guarantee them access to the benefits of peaceful nuclear-explosion applications—and indeed, the NPT’s Article V covers that point. But the lines between peaceful and nonpeaceful explosions are blurry, as evidenced, for example, by India saying that its 1974 nuclear test was a peaceful explosion.

Although Article V hasn’t been removed from the treaty in an official manner, it has been in essence. As stated by the National Security Archive’s William Burr, Article V “has been virtually a dead letter because of the basic U.S. government policy that explosive devices were the same as nuclear weapons and involved the same risks to public health and safety.”[1]

That brings me to a vital point regarding the motivation for Project Plowshare. In 1964 I was in a group of young scientists who received a briefing on it from the director of the Livermore branch of the University of California Radiation Laboratory (now Lawrence Livermore National Laboratory). He confided that the real reason for Plowshare was not economics. Rather, it was that it offered an opportunity for the public to become acquainted with nuclear explosives and more comfortable with their effects—so that in wartime, the president could more easily release nuclear weapons for use in battle.

## Reference

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**Victor Gilinsky**
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*Santa Monica, California*

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### Little quarks

Little bitty quarks
whirling inside the proton
we can’t set you free

**Mac Mestayer**
*Spring 2021*

# Correction

**March 2024, page 38**—Project Vista was mischaracterized as being focused on strategic nuclear weapons. It was focused on tactical nuclear weapons to defend Europe. PT
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# Attosecond analysis illuminates a watery mystery

With powerful x-ray free-electron lasers, researchers are making great strides in ultrafast spectroscopy—with lessons about how molecules arrange themselves at rest.

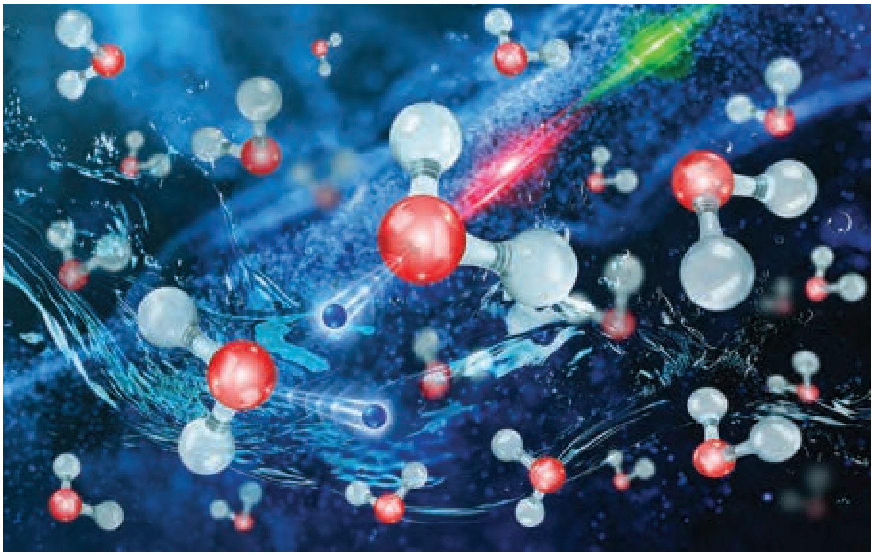

**FIGURE 1. LIQUID WATER** is pumped and probed by two closely spaced x-ray pulses, represented in this artist's depiction as red and green flashes. The first pulse kicks electrons (blue) out of some of the water molecules, and the second pulse measures the energy levels of the ionized molecules. (Courtesy of Stacy Huang.)

In the 1990 movie *Awakenings*, Robin Williams's character, based on real-life neurologist Oliver Sacks, revived patients from a catatonic state using a drug developed to treat Parkinson's disease. The parkinsonian tremors, he reasoned, if accelerated to the extreme, would appear not as a tremor at all but as immobility. Although the film simplifies the neurological principles, he was right, and the drug worked.

Now, working at SLAC's Linac Coherent Light Source (LCLS), researchers led by Linda Young, Robin Santra, and Xiaosong Li are making a similar connection between fast motion and complete stillness. They set out to develop an experimental capability at the cutting edge of ultrafast science: a pump–probe experiment in which a sample is excited with one x-ray pulse and probed with another, all in less than a femtosecond. And yet, when they applied their technique to liquid water, as illustrated in figure 1, their results had more to say about water's equilibrium structure than about its subfemtosecond dynamics.[1]

## Laser power

The push to observe matter on faster and faster time scales has been the subject of multiple Nobel Prizes. In 1999 Ahmed Zewail was honored for his work in femtosecond spectroscopy, which for the first time could measure the real-time motions of atomic nuclei, including the making and breaking of chemical bonds (see Physics Today, December 1999, page 19). Two dozen years later, Pierre Agostini, Anne L'Huillier, and Ferenc Krausz were recognized for bringing the attosecond regime—the next unit of time shorter than femtoseconds and the natural time scale of the motion of electrons—under experimental control (see Physics Today, December 2023, page 13).

Last year's Nobel focused on one facet of attosecond research: the discovery that attosecond-scale light pulses could be made and characterized with ordinary tabletop lasers. Tabletop attosecond experiments have allowed the measurement of quantities previously thought to be unmeasurable, such as the time scale of the photoelectric effect. But pump–probe experiments with two attosecond-scale pulses have remained largely out of reach to the tabletop approach.

The problem is that the efficiency of tabletop attosecond pulse generation, although higher than one might naively expect, is still extremely low, so the pulses are dim. And pump–probe spectroscopy is a nonlinear technique: To produce a signal, an individual atom or molecule must interact with a photon from the pump pulse and one from the probe pulse. The output, therefore, depends on the product of the pulse intensities, and with weak pulses, it doesn't leave much to see.

But x-ray free-electron lasers (XFELs), such as the LCLS, have also entered the attosecond game. An XFEL wouldn't fit on a tabletop—the LCLS, for example, is more than 3 km long—and only a handful of them are in operation around the world. But their extraordinarily intense x-ray beams, a billion or more times as bright as synchrotron sources, make them ideal for many applications. (See the article by Phil Bucksbaum and Nora Berrah, Physics Today, July 2015, page 26.)

An XFEL's x rays don't naturally come out in attosecond-scale bursts. The electron bunches, which pass through magnetic undulators to produce radiation, are typically a few femtoseconds long. But there's a phenomenon called microbunching instability, which speeds up some electrons in a bunch and slows down others, that temporarily transforms a continuous electron bunch into a train of shorter microbunches. It was a major technical challenge to figure out how to control and exploit microbunching to produce attosecond-scale XFEL pulses.[2] But once the first attosecond pulses were achieved, pulse pairs weren't far behind.[3]

## Twin peaks

Attosecond pump–probe spectroscopy captures how the electrons in an atom, molecule, or material respond in the first instants after being struck by an x ray. Young and her postdoc Shuai Li, who led the experimental team on the new research, had hoped (and still do hope) to use the technique to study the mechanisms of radiation damage in aqueous chemical systems. So for their first experimental target, they chose liquid water. And they happened upon a completely different implication of their measurements.

Water, after all, is a strange substance. Among its many anomalous properties, liquid water can take two structurally distinct forms: a high-density liquid and a low-density liquid. It's only in a deeply supercooled regime with the sinister-sounding name "no-man's-land" that the liquids exist as separate phases. (See "Fast x-ray scattering reveals water's two liquid phases," Physics Today online, 19 November 2020.) But the distinct structures were thought to leave an imprint on water's room-temperature properties too.

That speculation was fueled by water's x-ray emission spectrum. As shown schematically in figure 2a, x-ray emission spectroscopy kicks an electron out of a low-energy core orbital and measures the energies of the photons emitted as electrons from other orbitals tumble down to fill the hole. Each valence orbital—marked as $1b_2$, $3a_1$, and $1b_1$ in the figure—should yield photons of a characteristic energy, albeit with some broadening of the spectral peaks to reflect how molecules in a liquid interact randomly with their neighbors.

As figure 2b shows, though, the $1b_1$ peak isn't just broadened; it's split in two. That's not what one would expect from a homogeneous liquid. One explanation, then, is that water isn't really a homogeneous liquid, but rather an amalgamation of globs of molecules with two distinct liquid structures—perhaps the same structures as the low-density and high-density phases of no-man's-land.[4]

But that's not the only possible origin of the split peak. Another is that x-ray emission spectroscopy is measuring something other than water's equilibrium structure. That possibility is easily overlooked, because emission spectroscopy in general isn't designed to study dynamical processes. But the lifetime of inner-shell holes in oxygen is about 4 fs, which is plenty of time for atoms—especially the lightweight hydrogen atoms—to move around. It's entirely possible that water molecules, once ionized, could quickly distort their structures in ways that affect the x-ray emission spectrum.

Attosecond pump–probe spectroscopy can resolve the ambiguity. As shown in figure 2a, it accesses the same energy transitions as x-ray emission spectroscopy, but in reverse: The first pulse removes an electron from a valence orbital—$1b_2$, $3a_1$, or $1b_1$—and the second pulse excites a core electron into the vacancy. The researchers measure the energies of the photons absorbed out of the second pulse. Their spectrum, shown in figure 2b, contains a single unsplit $1b_1$ peak.

The delay between the pump and probe pulses was a mere 700 attoseconds, which isn't enough time for atoms to move. Even so, says Santra, "it was not totally obvious that the observed signal would be confined to the attosecond

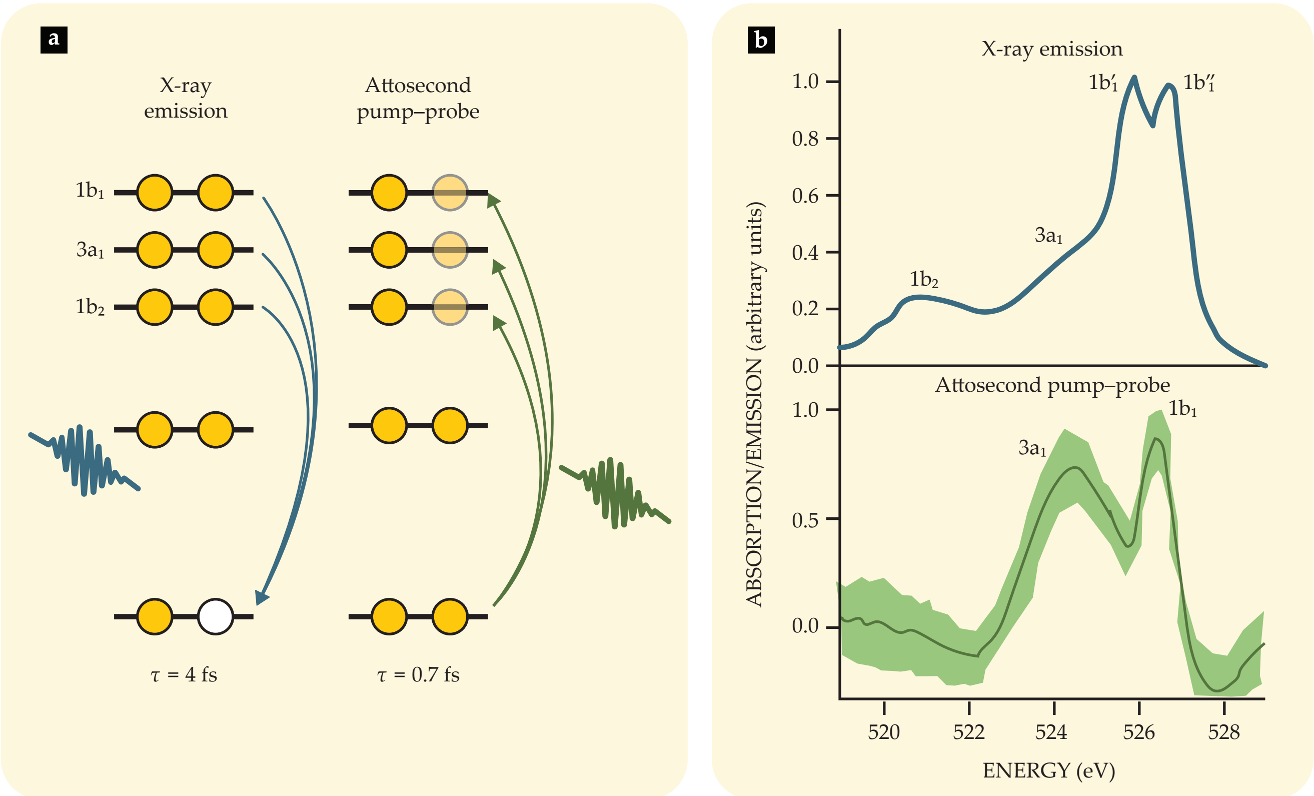


**FIGURE 2. TWO SPECTROSCOPIC TECHNIQUES (a)** measure the same energy transitions in water, but in reverse order. The big difference between them is the time scale $\tau$ of the measurement: X-ray emission spectroscopy gives hydrogen atoms enough time to move around, whereas attosecond pump–probe spectroscopy does not. **(b)** So when the $1b_1$ peak is split in two in the x-ray emission spectrum but not in the attosecond pump–probe spectrum, the implication is that the splitting is due to hydrogen-atom dynamics, not the result of an inhomogeneous structure of liquid water. (Adapted from ref. 1.)

time scale." The probe pulse doesn't merely excite electrons; rather, it creates oscillating superpositions of quantum states that send electromagnetic ripples throughout the liquid. The consequence is that the pump–probe spectrum could be just as affected by hydrogen-atom dynamics as the x-ray emission spectrum is. It took months of theoretical work by Santra, his postdoc Swarnendu Bhattacharyya, Li, and his student Lixin Lu to show that it wasn't: The ultrafast experiment was a true measurement of what water looks like at rest.

Importantly, the result has nothing to do with the existence of two liquid-water phases in no-man's-land. And it's still possible that room-temperature water is a mix of high-density and low-density globs. "The evidence for a liquid–liquid phase transition is still sound, as far as we can tell," says Young. "What we've demonstrated is that if there are two structural motifs, their impact on the x-ray emission spectrum is much smaller than the impact of hydrogen-atom motion."

### Room to run

Water is far from the only substance whose x-ray emission spectrum might have been misinterpreted. Whereas inner-shell holes in oxygen have lifetimes of 4 fs, those in carbon and nitrogen persist for even longer. Just about all organic molecules, including proteins and DNA, could have x-ray emission spectra slow enough to be muddied by hydrogen dynamics. "But with attosecond methodology, we can outrun the undesirable hydrogen motion," says Young.

Outrunning all of it could take some time, however. The LCLS, currently the only XFEL equipped for attosecond pump–probe spectroscopy, is already oversubscribed by a factor of five: For every experiment granted beam time, four others get turned away. But as more of the world's XFELs develop attosecond capabilities, the burden could be eased.

**Johanna Miller**

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2. S. Huang et al., *Phys. Rev. Lett.* **119**, 154801 (2017); J. Duris et al., *Nat. Photon.* **14**, 30 (2020).
3. Z. Guo et al., https://arxiv.org/abs/2401.15250.
4. A. Nilsson, L. G. M. Pettersson, *Nat. Commun.* **6**, 8998 (2015).


# Highly charged uranium tests the limits of quantum electrodynamics

Technical advances and clever correction schemes separated signals of quantum effects in heavy atoms from the noise.

When it comes to the most tested and precise scientific theories, quantum electrodynamics (QED) ranks at or near the top of the list. The theory of light–matter interactions has predicted, for example, the value of the electron's magnetic dipole moment to 12 significant figures, and observations published last year are in agreement.[1] That's equivalent to measuring the distance from New York City to Los Angeles to a precision better than the width of a human hair.[2] Yet despite QED's superlative predictions, the theory is more readily validated in light atoms than in heavy atoms.

For low-mass atoms, perturbation theory can precisely predict QED effects, such as a slight change in the transition energy of an electron that's decaying from an excited atomic orbital to a low-energy orbital. But in a high-mass atom, relativistic and QED effects cannot be well approximated as small disturbances to the system. That's because such effects scale with $Z\alpha$—where $Z$ is the atomic number and $\alpha \approx 1/137$ is the fine structure constant. One can use nonperturbative methods to predict QED effects, and that's been done for heavy atoms, such as uranium.[3] The problem is that the methods have yielded different calculations and aren't as precise as perturbative approaches.

Previous efforts from 2009 to observe the transition energy of highly ionized uranium with x-ray spectroscopy weren't precise enough to distinguish one calculation of QED effects in uranium from another.[4] Since then, advances have been made in predicting QED effects in heavy atomic systems and improving the experimental instrumentation. A team of 34 researchers, led by Martino Trassinelli of the CNRS in Paris and Robert Loetzsch of Germany's Friedrich Schiller University Jena, now present transition-energy measurements in highly ionized uranium, and they're precise enough to distinguish small QED effects in high-mass systems.[5]

### Uranium that comes around

Willis Lamb and Robert Retherford helped jump-start the field of QED with a 1947 experiment. They observed an unexpected energy difference—what became known as the Lamb shift—between the two lowest excited orbitals of the hydrogen atom, levels that existing predictions said should have the same energy. In response, researchers developed theoretical techniques to accurately account for the Lamb shift, which is a QED effect caused by the electron interacting with virtual photons.

Shortly after the discovery in the lightest atom, many began to wonder: How would the effects of QED change the behavior of an electron bound to uranium or another heavy element? Validations of QED over the past several decades have mostly been done in light atoms, but an experiment in highly ionized uranium could test for quantum effects in previously untested parameter space.

By the late 2000s, after decades of work, some theorists used nonperturbative methods to precisely calculate QED effects in heavy atoms with strong electric fields.[4] The advance set a challenging and motivational target for experimentalists: If x-ray spectroscopy measurements of an electron's transition energy are precise enough, then QED effects in highly ionized uranium are observable.

Measuring a transition energy in a massive system like uranium demands a facility with a storage ring that can produce and hold a lot of ions. For experiments that test QED effects in heavy systems, the only place capable of meeting those requirements is the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany. (The Heavy Ion Research Facility in Lanzhou, China, does offer similar capabilities, but the intensity of its ion beam isn't high enough to generate the necessary precision.)

At GSI, Trassinelli, Loetzsch, and colleagues ionized neutral uranium atoms and then sent the beam through a series of further ionization steps that accelerate it to near-relativistic speeds. More and more electrons are stripped from the nucleus until all that's left is hydrogen-like uranium, $U^{91+}$, with a single electron. Once decelerated and cooled to their ground state, the hydrogen-like uranium ions circulate in a vacuum in GSI's experimental storage ring, as shown in figure 1. Along the ring is a chamber where they interact with a jet of molecular nitrogen, and each one captures an electron to form excited helium-like uranium ions, $U^{90+}$, with two electrons.

A pair of x-ray spectrometers are positioned perpendicular to the gas-jet chamber to record the energy of photons emitted when one of the electrons decays from an excited 2*p* atomic orbital to a lower-energy 2*s* orbital. Out of all the possible transitions to measure that are sensitive to QED effects, that intrashell transition lies at an easily detectable energy. It has a 30% chance of occurring, and in the experiment, a spectrometer measures about one photon every three minutes.

In 2009 Trassinelli and his collaborators taking measurements at GSI had a single spectrometer and just three days of beam time to collect the observations.[4] The few hundred photons they observed weren't enough to get the precision they were after. Another challenge was the large measurement error caused by the spectrometer's imprecise viewing angle. For an accurate observation, the angle must be known to about a hundredth of a degree or better, but the uncertainty was about 0.4°. And the relativistic Doppler shift of the photon source and receiver added to the uncertainty, as shown in figure 2.

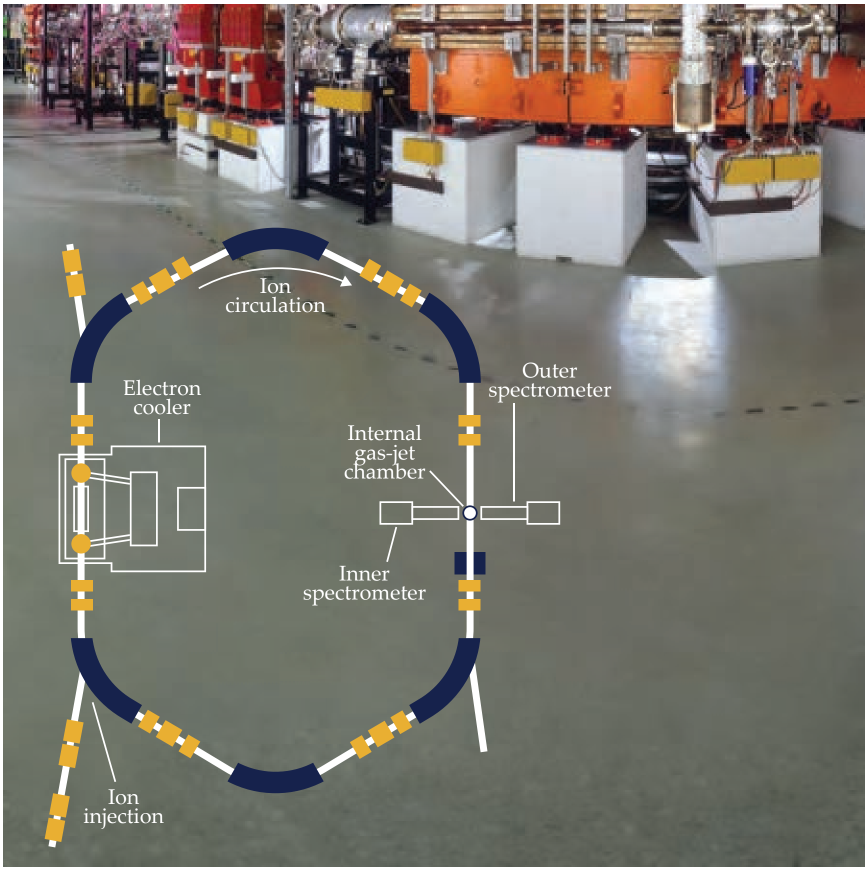



**FIGURE 1. THE EXPERIMENTAL STORAGE RING** at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany. Large, curved dipole magnets (blue in the schematic) steer highly ionized uranium in a vacuum around the ring, and other magnets (yellow) refocus the ion beam. On interacting with nitrogen at the gas-jet target, the uranium can take on different charge states, such as $U^{90+}$, with two electrons. A pair of x-ray spectrometers measures an atomic transition that incorporates quantum electrodynamical effects in the highly charged system. (Photo courtesy of A. Zschau, GSI/FAIR; schematic adapted from ref. 5.)

## Lowering uncertainties

Although the 2009 measurements did agree with predictions, the large experimental uncertainty meant that researchers couldn't evaluate whether one theoretical approach was more accurate than another. Of that work, Trassinelli says, "it was a plan B sort of experiment, and we were a little bit frustrated." So he and some colleagues began designing an improved experiment, and by the time the new measurements were taken in 2021, the team had made several changes to the design.

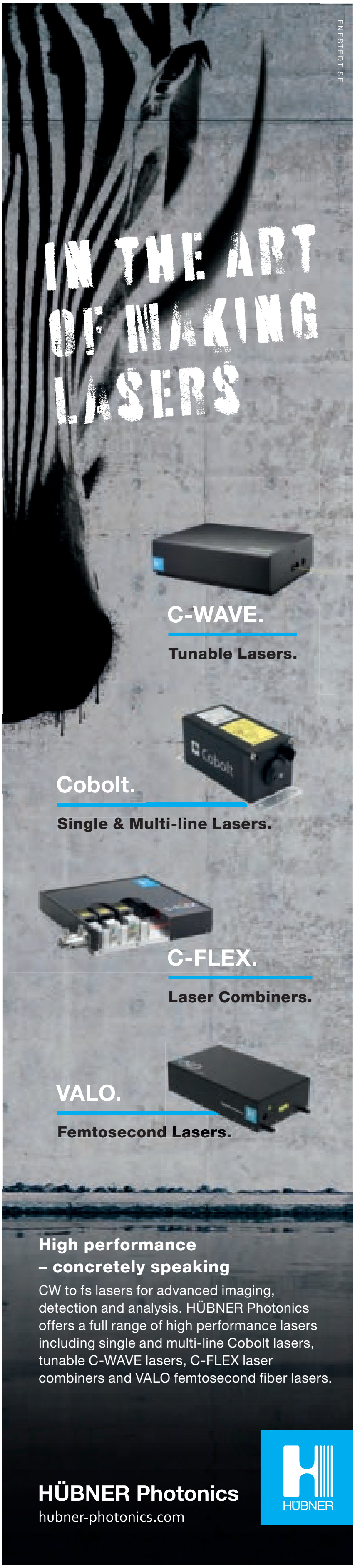
The researchers added a second spectrometer to collect more measurements. They also incorporated into the spectrometers high-quality curved germanium crystals. Loetzsch determined that they reflected incoming x-ray photons much more homogeneously than what was used in 2009.

Another improvement came in the form of a novel correction for the Doppler shift. In the storage ring, the team circulated the helium-like uranium, which, through electron capture in the gas-jet chamber, generated lithium-like and beryllium-like uranium. The spectral data from those charge states could then serve as additional reference lines for the Doppler-shift correction.

By improving the correction method and incorporating some previous spectral results, the researchers predicted that the precision of the spectrometer's viewing angle could reach a resolution of 0.011°. In addition, GSI also improved the beam's control system and upgraded its facilities in the intervening time (see PHYSICS TODAY, November 2015, page 22).

## A hyperfine result

Loetzsch says that "the biggest challenge was getting beam time." The facility's upgrades made beam time an even more scarce resource than usual. So when the researchers finally got two weeks at GSI to collect observations, years after their initial request, they worked 24/7 with usually two people at a time controlling the experiment. After someone else's experiment was canceled, the team got a third week to collect data. "The big question was if we could accumulate enough photons in the amount of time we had,"



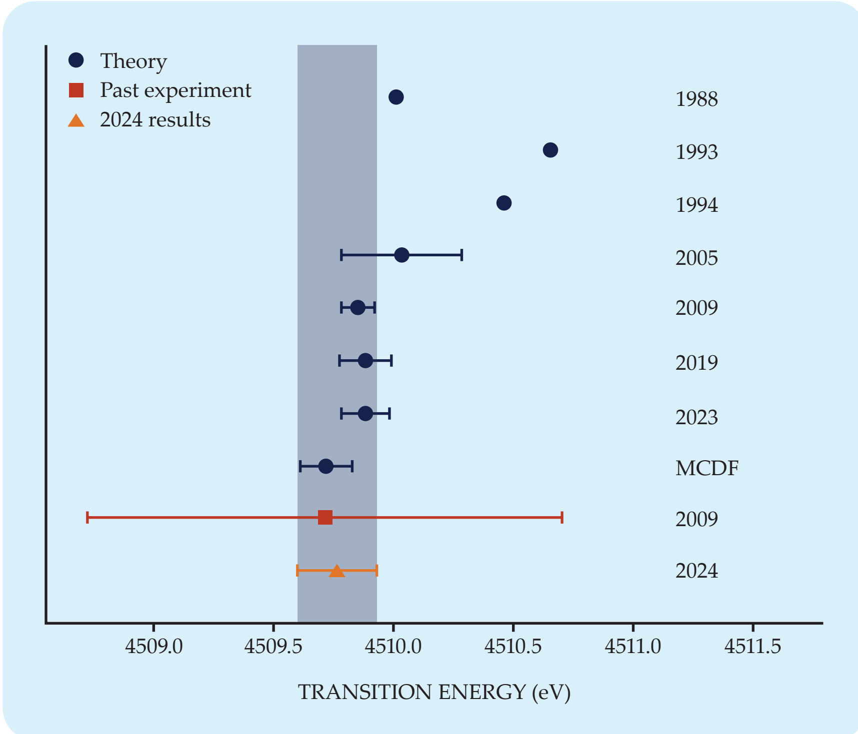




**FIGURE 2. THE TRANSITION ENERGY** of an electron decaying from the 2*p* atomic orbital to the 2*s* orbital was measured in 90-fold ionized uranium, a helium-like system with two electrons. A new measurement[5] is the most precise to date for a heavy atomic system and agrees with the latest quantum electrodynamical predictions based on multi-configuration Dirac–Fock (MCDF) calculations and a new method published last year.[6] The gray band shows the uncertainty of the new measurement. (Adapted from ref. 5.)

says Loetzsch. "So we were happy when we saw the first photons on the computer screen."

After Loetzsch and colleagues collected the data and accounted for the Doppler shift and other known factors, they reported a transition energy of 4509.763 ± 0.166 eV, which, as figure 2 illustrates, is consistent with and almost as precise as recent theoretical predictions. The largest quantum effect on the transition energy is the so-called one-loop QED contribution, arising from an electron's interactions with virtual particles. A second, weaker two-loop contribution can come from local fluctuations of the electromagnetic field.

The new detailed measurements are already improving QED calculations. A few months ago, Aleksei Malyshev of St Petersburg State University and colleagues used the results to help calculate the transition energies for ionized uranium with one electron up to four electrons.[6] With measurements of four highly charged states, they compare predictions that include various QED effects, including electron–electron effects and nucleus-size contributions.

Upgrades to the experimental storage ring and the spectrometers could lead to about an order-of-magnitude improvement in the measurement's precision. Increasingly precise transition-energy measurements may show evidence of higher-order QED effects, whose energy signatures are just a fraction of the one-loop and two-loop effects that have already been measured. The researchers aren't sure yet whether the higher-order effects are observable in uranium or other heavy atoms.

**Alex Lopatka**

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## Pandemics in Roman Empire correlate with sudden climate changes

A new temperature and precipitation proxy record shows that periods of rapid cooling align with the civilization's three worst disease outbreaks.

**GERARD VERSTEEGH AND KARIN ZONNEVELD**, coauthors of the new study on climate change and pandemics, process a sediment core from the Gulf of Taranto. (Courtesy of Karin Zonneveld.)

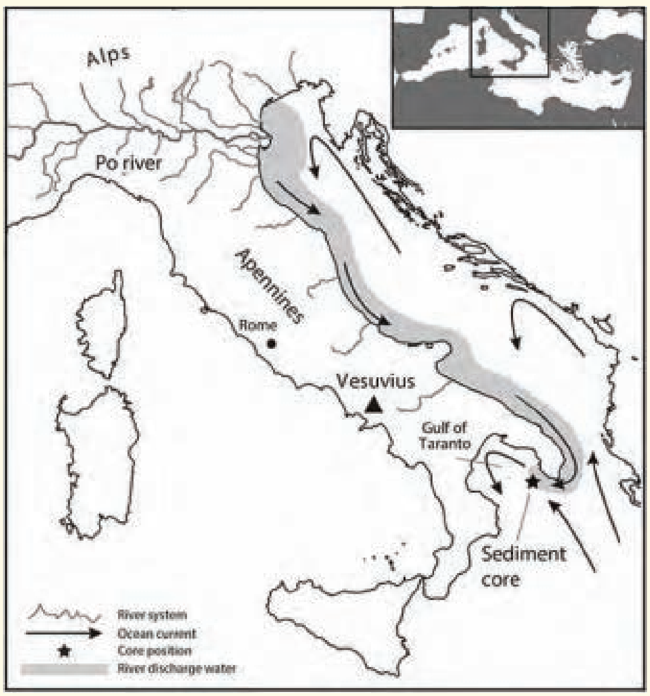
Plankton living in the Mediterranean Sea some 2000 years ago have helped researchers to uncover a correlation between climate change and the spread of disease in ancient Roman Italy and into the early Middle Ages.

Using a sediment core recovered from the Gulf of Taranto, in the arch of Italy's boot, Karin Zonneveld of the University of Bremen in Germany and colleagues reconstructed the regional climate from 200 BCE to 600 CE. The sediment record reveals that periods of rapid cooling and drying in the heart of the Roman Empire align with documented major disease outbreaks, the researchers report in a new study.

The core's plankton fossils are from dinoflagellate cysts, also known as dinocysts. Dinoflagellates bloom in late summer and early fall, with thousands of species that thrive under varying surface temperatures and nutrient levels. By comparing the ratios of dinocyst species that flourish in warmer waters with those that flourish in cooler waters, researchers can precisely estimate historical temperatures. Dinocysts also respond to the water's changing nutrient levels, which are controlled by precipitation. Rain and snowfall over the Italian Peninsula are channeled by rivers into the Adriatic Sea, where currents carry the nutrient-enhanced water southward around Italy's heel and into the gulf.

The core was recovered from a location with a rather high deposition rate, with 1 cm of sediment deposited roughly every 10 years (compared with about 1 cm/1000 yr in the open Mediterranean Sea). That high deposition rate translates into the most detailed record to date of the regional climate at that time—with changes discernible down to a three-year resolution. The new data fill a gap in knowledge that other climate proxies were unable to. Tree-ring records for the area don't go back far enough in time, pollen records are tainted by human agriculture, and cave stalactites don't have a fine-enough temporal resolution. Ash and glass shards from nearby volcanic eruptions, combined with lead and carbon isotope dating, were used to constrain the ages of sediments in the core.

The researchers found that after a few hundred years of a warm, wet, stable climate known as the Roman Climate Optimum, a sharp downward temperature trend began around 130 CE and continued well past the arrival of the Antonine Plague in 165 CE. Temperatures never returned to the warmth or




**A MAP OF ITALY** shows the site where the sediment core was recovered from the Gulf of Taranto and the direction of offshore currents that carry river discharge southward along the eastern coast and into the gulf. (Adapted from K. A. F. Zonneveld et al., *Sci. Adv.* **10**, eadk1033, 2024.)

stability of the early Roman Empire. The Plague of Cyprian hit around 251 CE amid another rapid temperature decline that lasted half a century. The first plague pandemic arrived in roughly 541 CE, when temperatures were near the lowest measured over the entire record.

"This is a wake-up call," says Zonneveld, who studies marine microfossils. She says climate change affects biodiversity and the migration of species—and of germs. Although the study doesn't attribute a causal relationship between climate change and pandemics, the researchers note that climate impacts on agriculture and regional ecosystems could cause perturbations that trigger or exacerbate disease outbreaks. The results highlight the value of studying the complex relationship between climate change and infectious disease. (K. A. F. Zonneveld et al., *Sci. Adv.* **10**, eadk1033, 2024.)

**Laura Fattaruso**

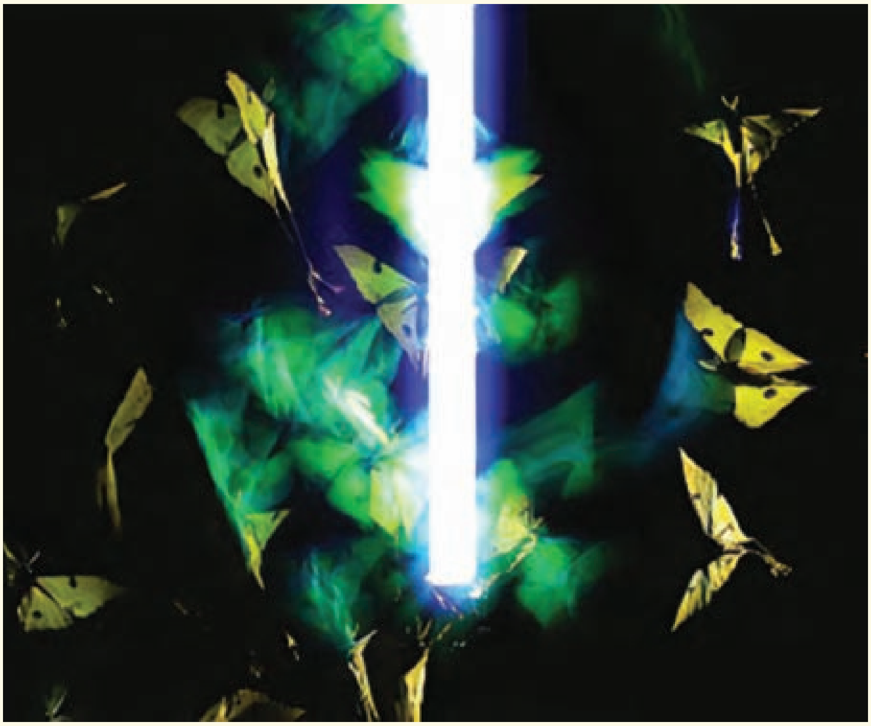
# Why insects orbit light at night

Mistaking artificial light for the sky, insects become entrapped while circling it. High-speed camera footage captures the behavior in action.

As soon as human beings started making campfires at night, they noticed that flies, moths, butterflies, and other insects were attracted to the glow. Indeed, records of finding them trapped in the orbit of such artificially produced lights go back to the Roman Empire. Some biologists wondered whether the insects might be confusing the artificial light with the Moon, which some insects use for navigation. Others proposed that insects are instead attracted to its heat. But the kinematic data needed to test predictions are exceedingly rare. Tracking the positions of small, fast-moving insects in low light is technically difficult.

Flying insects need a reliable way to determine their orientation in midair. As the brightest part of the visual field, the sky serves that function—to indicate which way is up. The presence of artificial point light sources can mislead or confuse an insect's sense of orientation. Dragonflies, butterflies, and other large flying insects can leverage their passive stability to stay upright. But the smaller size of most insects makes their lives more turbulent. Their Reynolds number—the ratio of the inertial and viscous forces they experience—is lower. So they must rely on visual cues to remain oriented in a gravitational field.

Two postdoctoral researchers—Sam Fabian from Imperial College London and Yash Sondhi from the University of Florida in Gainesville—and three colleagues have now taken high-resolution video footage of the trajectories of 10 taxonomic orders of insects in the presence of two artificial light sources. A UV LED bulb or tube light first attracted the insects' attention. IR light was then used to photograph their motion without influencing them. That work was done in different locations: first in a controlled laboratory environment in London and subsequently in the wild during trips to Costa Rica.



**MULTIPLE EXPOSURES TRACK** an African moon moth as it flies around a UV tube light at a laboratory at Imperial College London. (Courtesy of Sam Fabian.)

In the laboratory, the researchers attached reflective markers to the insects' bodies and tracked their positions and orientations using eight motion-capture cameras. That footage and stereo videography taken in the field at rates up to 500 frames per second revealed that the flying insects rarely head directly toward a light source but, rather, fly orthogonal to it. They tilt their backs toward the brightest area they perceive, which can cause an asymmetry in the distribution of the forces on them.

Known as the dorsal-light response, the behavior normally keeps the insects aligned with the horizon. But a point light source disrupts that cue and prompts insects to turn their backs on what they mistake as the sky. The result is a circular orbit in which they're subsequently trapped, as shown in the figure. One of the most concise pieces of evidence revealing that the insects are confused, according to Fabian, is that they flip upside down while flying directly over the light. "That behavior is not explained by any other theory," he says.

Despite the ubiquity of the behavior among insects, there are exceptions. Some species, such as vinegar flies and oleander hawk moths, appear less affected by UV light. Why some species are more sensitive than others remains an open question that the researchers plan to address. (S. T. Fabian et al., *Nat. Commun.* **15**, 689, 2024.)

**R. Mark Wilson**

# What makes blueberries blue?

A new study reveals how the berries and some other waxy fruits look blue despite a lack of blue pigment.

**RIPENING BLUEBERRIES.** (Photo by ChiemSeherin/Pixabay.)

Blueberries are blue despite the dark red pigments in their skin. The same is true of other blue fruits like some plums, grapes, and juniper berries. Their color was strongly suspected to be a result of the structure of their waxy outer layer, which may play a role in holding in moisture and protecting the fruit. A research team led by Heather Whitney and Rox Middleton at the University of Bristol in the UK has investigated those waxy blue fruits to find out how they produce the color we see.

To begin, the researchers removed the wax of a blueberry to find how deep the blue goes. Removal of the outermost wax layer removed the brilliant blue color, leaving a very dark blue. But rubbing off the entire waxy covering showed that the underlying outermost skin cells are dark red. In fact, using microscopy, the only pigment found in the berry was observed to be red. That indicated that the blue color occurs in the outermost layer of the waxy covering.

The researchers used a scanning electron microscope to examine the morphology of the outermost layer of different blue fruits. Studying 14 fruit species, they found wax structures that they classified into four types of shape. The first type exhibits rings, the second rods, the third slabs, and the fourth tubes. The exception is the blueberry wax, which was classified differently than all the other species measured. Despite the different shapes of the crystals, they all produced a similar optical-reflectance spectrum. While other examples of both structural and pigmentary color show a clear reflectance peak corresponding with the dominant visual color, the bloom fruits studied by Middleton and colleagues have no peak in the spectrum, which continuously decreases with increasing wavelength. The fruit surfaces reflect the least light around 700 nm, the wavelength reflected by the underlying red pigment in the skin. Instead, the light is scattered from the random structure of the nanocrystals. Because shorter wave-

**WHEN THE OUTER LAYER** of wax coating is removed, a blueberry appears dark blue. When the entire coating is peeled off, the redder skin of the fruit is apparent. (Adapted from R. Middleton et al., *Sci. Adv.* **10**, eadk4219, 2024.)

lengths are scattered more, to our eyes the dominant color is blue.

To further confirm that the structure is the primary reason we see those fruits as blue, the researchers dissolved the fruit's wax using chloroform. When suspended in the solution, the wax was transparent in the visible wavelength range. After evaporating the chloroform around the dried wax, the wax crystals self-assembled into a structure similar to that of their natural state. The wax looked blue.

Color appearance without the corresponding pigment isn't unknown to science. Rainbows stretching across the sky or seen shimmering on a CD create colors by reflecting light as it interacts with structures. (For more on color due to structure, see the article by Ross McPhedran and Andrew Parker, Physics Today, June 2015, page 32.) The structural color of bloom fruits may also be advantageous by attracting the birds that eat them. The spectral signature allows the vibrant color to be seen in both UV and blue visual channels. (R. Middleton et al., *Sci. Adv.* **10**, eadk4219, 2024.)

**Jennifer Sieben**

## Geologic evidence that volcanic lightning promotes life on Earth

Large quantities of fixed nitrogen found in ash and pyroclastic deposits confirm suspicions about a likely source of life's earliest building blocks.

Every protein molecule in every cell in your body contains nitrogen, but the abundant $N_2$ molecules in the atmosphere are useless to you. The triple bonds that hold them together are just too strong. Atmospheric nitrogen is made available to organisms by breaking apart that $N_2$ and bonding the free nitrogen with oxygen or hydrogen—a process known as fixation. Nitrogen fixing can be accomplished in a few ways, including biotic processing by bacteria and algae, high-energy industrial-fertilizer production, and lightning strikes.

Without fertilizer factories, algae, or bacteria around to provide the fixed nitrogen for life on Earth, its emergence would have required abiotic nitrogen fixation. Lightning has been the leading candidate for the source of that process. Lab experiments and theoretical models have suggested that volcanic lightning in particular could have played a vital role because ash and gas plumes promote the highest rates of lightning strike. Yet, until now, no significant quantities of abiotically fixed nitrogen have been found in the geologic record or from present-day eruptions.

Adeline Aroskay and Erwan Martin of Sorbonne University and their colleagues were looking in volcanic deposits for sulfates, which contribute to eruption-related climate change. They turned to rocks in arid environments in Turkey and Peru, where the soluble sulfate molecules would be preserved and not flushed away by water over time. Alongside the sulfur and chlorine compounds that they expected to find, they discovered a surprisingly high concentration of nitrates, a fixed form of nitrogen.

Looking at the stable isotopes of oxygen in the nitrates, the researchers found that they contained high concentrations of oxygen-17—as much as 17 parts per thousand—that would require contributions from ozone, which is rich in $^{17}O$. The researchers concluded that the nitrates in the volcanic deposits must have been formed in the atmosphere. "We found natural samples in which we have the end product of this process," says Martin.

**VOLCANIC LIGHTNING**, like that seen in the ash plume of an eruption in Iceland in 2010, may be a significant source of abiotically fixed nitrogen. (Courtesy of Terje Sørgjerd/CC BY-SA 3.0 DEED.)

Using the nitrate concentrations in their samples and estimates of the volcanic deposit volume, they calculate that as much as $282 \times 10^9$ kg of nitrogen were deposited in one eruption. That's on the same order of magnitude as what is produced for industrial fertilizer in a year. But volcanic events large and explosive enough to fix so much nitrogen are rare—occurring perhaps once every 100 000 years—as are the arid conditions necessary to preserve the highly soluble nitrates. So it's not surprising that they hadn't been found in volcanic deposits before. (A. Aroskay et al., *Proc. Natl. Acad. Sci. USA* **121**, e2309131121, 2024.)

**Laura Fattaruso**

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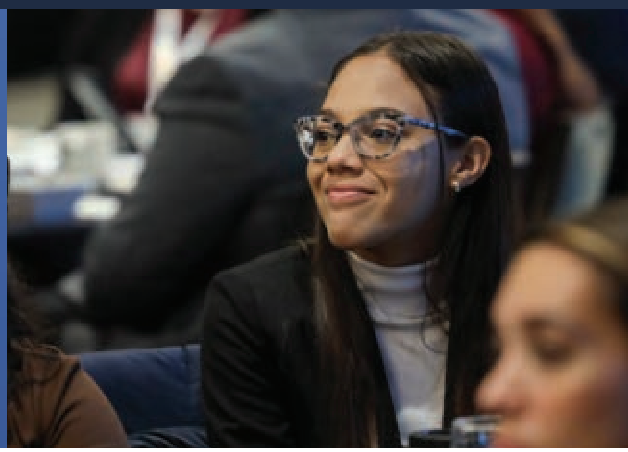

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# State anti-DEI laws sow uncertainty in public colleges and universities

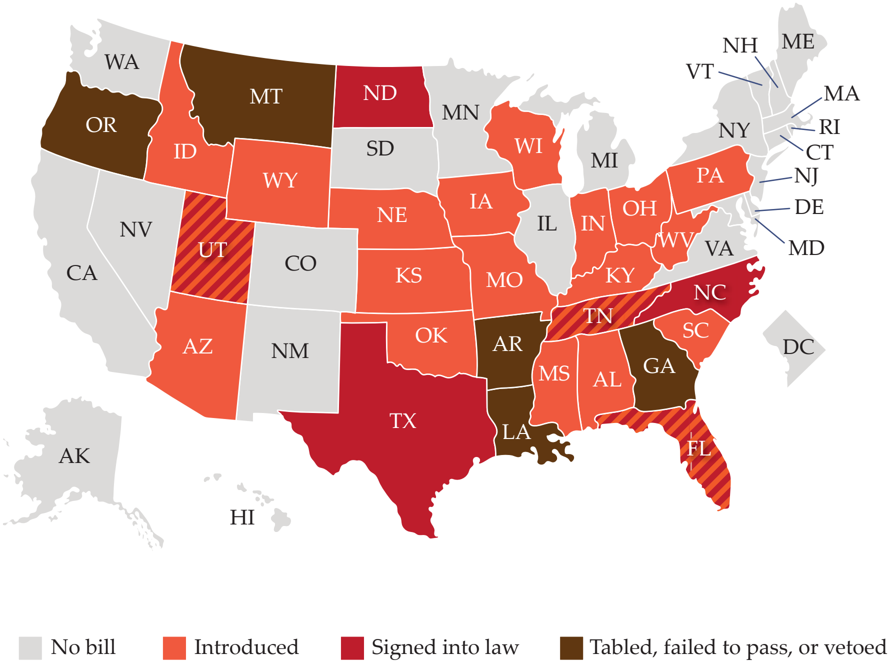
Inclusivity efforts are thwarted as faculty and institutions navigate new laws with unclear penalties.

Last July a law in Florida went into effect that banned many diversity, equity, and inclusion (DEI) activities in the state's public institutions of higher education. On 1 January, a similar law began in Texas, and this summer one kicks in for Utah. Additional legislation along the same lines in both those and many other states exists or is in the works. The new laws have academic communities scrambling to figure out how they can continue to legally support students and faculty from underrepresented groups.

Among the constraints the new laws impose are bans on campus DEI offices. Such offices have traditionally offered DEI training, facilitated community conversations, and the like. Spending state money for DEI activities, mandating DEI training, and requiring DEI statements from job candidates are also banned by many of the laws. Some also ban using federal money for campus DEI activities. Generally, classroom teaching, research, and student clubs and activities are exempt from the DEI bans.

The existing and proposed laws create tension with ongoing efforts to increase diversity in academia. The American Physical Society (APS) statement on diversity in physics, for example, says that the society "recognizes that the health of the physics discipline is best served by addressing the equally important goals of improving access to opportunities in physics to the betterment of all people, while also engaging the vast intellectual potential that resides in groups underrepresented in physics."

The laws are sending a chill across campuses, with uncertainty about what is legal and what the consequences are for individuals or institutions that overstep.




**MORE THAN HALF THE STATES** have introduced legislation that limits activities related to diversity, equity, and inclusion at institutions of higher education. (Map based on the DEI Legislation Tracker, *Chronicle of Higher Education*, 11 March 2024.)

## Playing it safe

On 1 March the University of Florida announced that to comply with state regulations on prohibited expenditures, it has eliminated DEI positions. A university spokesperson said that 13 full-time positions were cut and 15 faculty members lost their DEI-related administrative responsibilities.

Chris Kelso, a physics professor at the University of North Florida (UNF), was part of a committee that focused on improving DEI across the College of Arts and Sciences. The committee was suspended last year after Florida's anti-DEI law passed, he says. "The chair was concerned that we couldn't have that kind of a committee. The efforts of the last three to four years will likely have to be scrapped." UNF is also phasing out its interfaith, intercultural, LGBTQ, and women's centers, he adds. "It's hard to know where the line is."

At a rural public university in Texas, a professor who requested anonymity was uncertain whether they were allowed to promote the Conference for Undergraduate Women and Gender Minorities in Physics on their website. Since the conference was open to everyone, says the professor, they did advertise it. "We can't promote things that don't apply to all students. We can say we promote activities for 'underserved' students, but not for 'underrepresented' students."

One typical prohibition of anti-DEI laws is to bar requiring a DEI statement from job applicants. "We now say we are looking for a candidate who is 'interested in creating a sense of belonging,' " says the Texas professor. "We are tweaking language everywhere to play it safe."

Around the country, university DEI offices have changed their names to the likes of "office of student success" or "office of student engagement." Several of those offices did not respond to questions on whether and how their activities have changed.

At the University of Central Florida (UCF), says physics professor Talat Rahman, "any committee that had 'diversity and inclusion' in its title was renamed." Florida universities had for years been emphasizing diversity and inclusion, she says. "A lot of efforts are in place at UCF; that is how we got the [federal] status of 'minority serving institution.'" The laws are trying to undo progress made in the past decade, she adds. "Our department has changed for the better for everyone, not just minorities."

Rahman says she will "proudly" continue her work on DEI activities, including the APS Bridge Program, which since 2013 has been offering an alternate path to graduate school. (See "A bridge between undergraduate and doctoral degrees," by Ted Hodapp and Kathryne Woodle, Physics Today, February 2017, page 50, and Physics Today, April 2019, page 22.) Rahman adds, though, that "we can be more inclusive," an approach that is in keeping with the scope of anti-DEI laws. "I am sensitive to first-generation college goers," she says. "We should be cognizant of white Americans who don't have access." She notes that anyone can apply to the Bridge Program.

Some departments or schools have put on hold prizes given to marginalized students, because they are unsure whether the awards are legal. Or they have changed the description to include students who have overcome barriers. That's also part of how many universities have pivoted with their admissions processes since the Supreme Court struck down affirmative action in higher education last June.

Academics are also questioning whether anti-DEI laws will negatively affect their applications to funding agencies, which often require a DEI statement. An NSF spokesperson wrote in an email to Physics Today that external factors such as state DEI laws are not considered in the evaluation of proposals. The agency, she wrote, "will continue to emphasize the importance of the broader impacts criteria in the merit review process and . . . is committed to continuing supporting programs and activities that broaden participation in STEM for the benefit of the Nation."


**RAMÓN BARTHELEMY**, a physicist at the University of Utah, is running for a seat in the state house, motivated in part to combat legislation that targets diversity, equity, and inclusion activities. (Courtesy of Ramón Barthelemy.)

Before Florida's anti-DEI law took effect, Kelso submitted a grant proposal to the US Department of Energy, which required a plan for promoting inclusive and equitable research (PIER). "I obtained funding," he says, "but it wasn't clear if UNF would take the money since my PIER plan may be in violation of state law." His proposal specifies that students who are hired on his grant participate in the APS Inclusion, Diversity, and Equity Alliance. APS-IDEA was started in 2018 to connect physics faculty and students at different institutions so that they could advance DEI in their home contexts. The program, says Kelso, "has been a very large benefit to our students. It's helped us to create a community for historically excluded students."

Ramón Barthelemy, whose physics education research at the University of Utah focuses on LGBTQ and other marginalized groups, expects grants to continue. "Universities find ways to let money flow in," he says.

Although research and teaching are supposedly unaffected by the new laws, professors worry about students reporting on comments that they make in class. "That could lead to a reprimand, or worse," says Barthelemy. He also notes that even though Utah's anti-DEI legislation is not yet law, a university announcement about his project, "Queering STEM Education," avoided the word "queer" in the public-facing abstract.

And anti-DEI laws may contribute to brain drain. UCF has openings in every department, says Rahman. In physics, four of five recent departures were because of the "political situation" in Florida, she says. “You can’t trace it all to the anti-DEI legislation, but that plays a role.” The legislation will also make it harder to recruit both faculty and students, she and others say.

Maria Ong is a senior research scientist who studies the culture of physics at TERC, a STEM education R&D nonprofit in Cambridge, Massachusetts. Women and people of color already face “roadblock after roadblock” when they pursue physics careers, she says. “My fear is that with these new pieces of legislation, individuals will opt out early in their education and careers, and physics will be the worse for it.”

### External programs

Although independent DEI programs don’t require state funding, physicists and their departments in states with anti-DEI legislation are reconsidering whether they can legally participate. Rahman says her department chair said they would pull out of APS-IDEA. “I said no, and the department chair said I have to do it on my own time,” she says. At least one Texas physics department withdrew its application to join APS-IDEA because of that state’s new law.

Erika Brown, the APS-IDEA program lead, notes that institutions are still interpreting the new legislation. “Ambiguity makes it unclear for some folks whether participation might be construed in a way that negatively impacts them,” she says, adding that the consequences are “serious sounding.”

The TEAM-UP Together initiative, launched in 2022 by the American Institute of Physics (publisher of Physics Today) and partners, aims to double the number of African American physics bachelor’s recipients by 2030. It grants money to students and to de-

ASHAUNI LENNOX/AAPT

# Scientific progress and preservation clash in demolition of Curie building

A compromise involves relocating the historic structure.

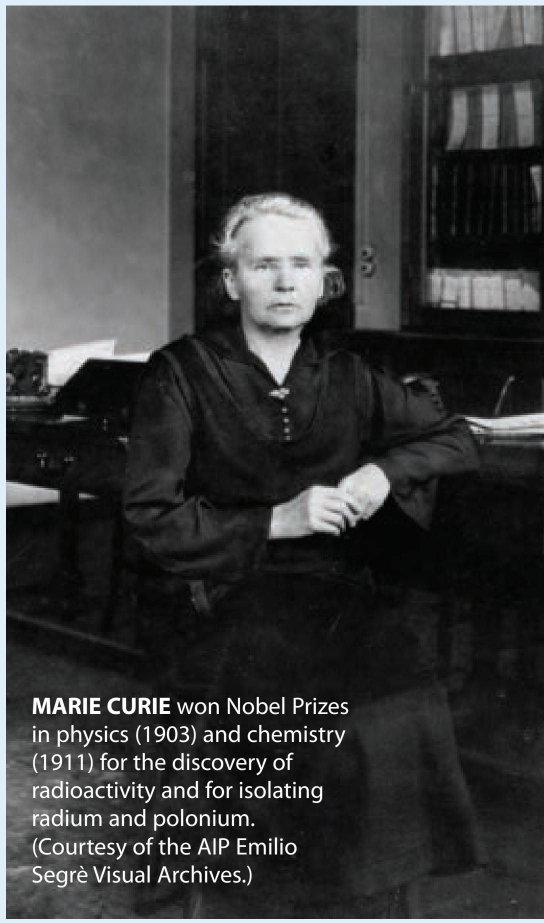
The Pavillon des Sources in Paris, where Marie Curie prepared and stored radioactive samples, is set to be removed to make way for a building that will house offices and laboratories for cancer research.

The plan was originally approved by the city of Paris in March 2023. At least two petitions were circulated worldwide in favor of preserving the building in honor of Curie—a two-time Nobel Prize recipient and possibly France’s most prominent physicist as well as the world’s most famous female scientist.

In response to opposition, the demolition plan was delayed and revised: Instead of razing the Pavillon des Sources, the building will be taken apart brick by brick and rebuilt nearby as an expansion to the Curie Museum. The solution was put forward by the Curie Institute—a nonprofit foundation created by Marie Curie that focuses on cancer research, teaching, and treatment—which announced it in a press release on 31 January.

Taking apart and rebuilding the Pavillon des Sources adds €5 million ($5.4 million) to the €13 million cost of the new building, according to the Curie Institute press office. The new building is supposed to be completed by 2026, the office says. It did not provide a date or exact site for the reassembly of the Pavillon des Sources. Many observers doubt it will really happen. “It’s a decision that will not be fulfilled,” says a Curie Institute scientist who requested anonymity because of the topic’s controversy.

Completed in 1914, the Pavillon des Sources and two companion buildings were erected for Curie partly because people were “making pilgrimages to meet her, and she worked in disgraceful labs,” says Laura Dawes, a science histo-


**MARIE CURIE** won Nobel Prizes in physics (1903) and chemistry (1911) for the discovery of radioactivity and for isolating radium and polonium. (Courtesy of the AIP Emilio Segrè Visual Archives.)

**JOYCE PALMER-FORTUNE** and Gary Felder mark the recognition of Smith College's physics department by SEA Change, a program that aims to advance diversity, equity, and inclusion in higher education. State anti-DEI laws are causing some departments to reevaluate how to frame their applications for SEA Change recognition.

partments (see PHYSICS TODAY, February 2020, page 20). "Any department working toward our goals can apply for funding in our program," says project manager Arlene Modeste Knowles. "The question is whether departments in some states would be able to participate in a program that is geared toward African American students." The initiative is "keeping a close watch on anti-DEI laws," she says. "We want to make sure we don't put stakeholders in jeopardy."

SEA Change, a program headed by the American Association for the Advancement of Science, recognizes departments for working toward and achieving diverse and inclusive environments. In preparing its recent application to the program, one physics and astronomy department sought legal advice to preemptively avoid falling afoul of potential future anti-DEI laws. "We didn't want to plan this and not be able to carry it out," says a professor who was involved in the application process.

Many physicists wonder whether TEAM-UP and other programs will adjust to serve all students as a way to help participants comply with state anti-DEI laws. Many of the programs are already open to everyone. But, says Kelso, "we are trying to center the voices of marginalized people. If you say you are doing something for everyone, it waters down the effort."

**Toni Feder**

rian at the Australian National University who started one of the petitions to save the Pavillon des Sources. Meanwhile, fancy new radium institutes were being set up in London, Vienna, Warsaw, and elsewhere, says Dawes. The labs and buildings where Curie had earlier discovered radium and polonium no longer exist, she adds.

To one side of the Pavillon des Sources is the Pavillon Curie, where Curie and others conducted experiments with radioactivity and which now houses physics offices and laboratories and the Curie Museum. On the other side is the Pavillon Pasteur, where cancer patients were treated with radium; it now houses biology offices and laboratories.

The layout of the three buildings reflects the flow of activity, says Dawes, with the central Pavillon des Sources originally supplying radioactive sources for both experiments and cancer treatment. "From a heritage point of view, to maintain the integrity of the site, all three buildings need to be kept intact and in their spatial relationship with each other," she says.

The new, five-story building will house a chemical biology and cancer project. The research direction "fits in perfectly with Marie Curie's scientific heritage," the press release says, and "will increase our knowledge of how tumors function, exploit identified vulnerabilities and develop new therapeutic strategies."

**Toni Feder**

INSTITUT CURIE

**THE PAVILLON DES SOURCES** in Paris is slated to be taken apart brick by brick and reassembled nearby. Radioactive samples were prepared and stored in it, part of an ensemble of three buildings where Marie Curie worked from 1914 until her death in 1934. A five-story structure dedicated to cancer research to be built in its stead will extend partly atop one of the neighboring structures.

# Code changes could drastically reduce bitcoin's enormous electricity requirements

As the value of bitcoin soars to record levels, the environmental impacts of cryptocurrency mining are attracting scrutiny from governments.

Power-hungry bitcoin miners in the US won a victory of sorts last month when the Energy Information Administration (EIA) agreed to soften its demand for the industry to detail its electricity consumption. But the controversy over bitcoin's surging energy demand and carbon footprint worldwide is unlikely to go away.

The EIA estimated in February that cryptocurrency mining accounts for anywhere from 0.6% to 2.3% of US electricity consumption. Bitcoin is by far the largest of the world's more than 10 000 cryptocurrencies, accounting for around half the total market. To create new bitcoins, mining companies must solve cryptographic puzzles that require vast computational resources. The rapid growth in electricity demand from bitcoin mining has drawn the attention of the Biden administration, some members of Congress, and grid planners concerned about its impact on electricity cost, reliability, and emissions. As PHYSICS TODAY went to press, bitcoin was trading at an all-time high price of around $73 000. Bitcoin mining—and its energy consumption—rises in parallel with the price.

A federal judge in Texas on 1 March issued an order under which the EIA agreed to abort its survey of cryptocurrency miners, destroy information it had gathered, and follow a more deliberate process before reissuing its request. Texas bitcoin miners had objected to the "contrived and self-inflicted urgency" of the EIA's demand, which the agency had made on an emergency basis. An association of bitcoin miners complained in the lawsuit that the information sought was proprietary and could allow competitors to reverse engineer companies' operations. The EIA agreed to follow the regular procedures of the Paperwork Reduction Act, which includes opportunities for public comment.

## Bitcoin capital

With an estimated current mining capacity of 2.7 GW, Texas is the "bitcoin mining capital of the world," boasts the nonprofit Texas Blockchain Council, which filed suit against the EIA in February. It was joined in the complaint by Riot Platforms, which operates what it says is the largest bitcoin mining plant in North America, with a capacity of 700 MW. A second facility under construction will have a capacity of 1 GW when completed, the company says. For reference, a typical commercial nuclear reactor produces about 1 GW of power.

The bitcoin miners say they reduce their electricity demand and help prevent blackouts by curtailing their operations during peak load periods in exchange for payments from utilities. And when market prices are higher than their revenues from bitcoin mining, the companies can sell back the power that they have purchased under long-term contracts.

Worldwide, bitcoin mining used more energy in 2020–21 than all but 26 countries, according to an October 2023 report by an academic arm of the United Nations. It emitted carbon dioxide equivalent to burning 38 billion kg of coal.

Because of the decentralized nature of bitcoin, no one knows the exact number of mining farms in the world. Estimates of the electricity used in bitcoin mining vary. Both the UN report and the EIA cited figures from the Cambridge Centre for Alternative Finance (CCAF), which in early March estimated current annualized consumption at 163 TWh, or 0.63% of the world's total. Digiconomist, another widely cited index created by Alex de Vries, a PhD candidate at the Free University of Amsterdam School of Business and Economics, estimated annualized bitcoin consumption at 146 TWh, comparable to the energy consumption of Ukraine. It has put electricity use from the mining of gold, which is often compared with bitcoin as a financial asset, at 132 TWh.

Bitcoin miners say their energy efficiency is steadily increasing and their total energy usage and carbon footprint are puny relative to global electricity consumption and carbon emissions. In a report summarizing operations for the first half of 2023, the Bitcoin Mining Council (BMC), a 57-member association purporting to represent 43% of the global industry, says the entire global mining network (including non-BMC members) would consume 0.21% of global energy production in 2023.

A 400% rise in bitcoin price from 2020 to 2021 was followed by a 140% surge in the worldwide bitcoin mining electricity


**RIOT PLATFORMS'S** bitcoin mining facility in Rockdale, Texas. With an installed capacity of 700 MW, it is the largest bitcoin mining farm in North America. The company, which produced 6626 bitcoins in 2023, is constructing a larger farm in the state that will have a capacity of 1 GW.

use, according to the UN report. Energy usage then plunged by more than two-thirds from mid 2022 to January 2023 when the price bottomed out at $15 000 from its previous record high, according to Digiconomist. Electricity usage has climbed steadily upward since then as bitcoin's value has surged.

In bitcoin's energy-intensive validation process, known as proof of work, huge numbers of servers incorporating application-specific integrated circuits (ASICs) compete to add to the blockchain, the currency's publicly distributed ledger. Miners completing a new block are currently rewarded with 6.25 new bitcoins. As the mining network has grown over time, the computing power necessary to create new blocks has increased, since the code automatically adjusts the difficulty to keep the time required for completion of a block steady at around 10 minutes.

Conversely, the difficulty was adjusted downward when China's ASICs farms, which had accounted for three-quarters of the world's mining in 2021, largely shut down in response to a late 2021 government ban on cryptocurrency mining. The US is now the world's largest bitcoin mining nation, according to the CCAF, with around 37% of the world's capacity.

The CCAF estimates that when using a typical grid-supplied mix of renewable, nuclear, and fossil-fuel power, bitcoin mining is responsible for 87 million tons of greenhouse gas emissions annually.

The efficiency of ASICs has improved dramatically since they were introduced in 2013. The improvements mainly resulted from miniaturization of the chips, which at a process size around 5 nm currently aren't likely to get any smaller, says Alexander Neumüller, who leads research on the climate impacts of digital assets for the CCAF.

Environmental groups, including Greenpeace and the Environmental Working Group, last year urged bitcoin to change its code to a far lower energy-intensive process called proof of stake. Ethereum, the second-largest cryptocurrency, switched in 2022 to proof of stake, where large holders of the cryptocurrency offer some of their own holdings as collateral to validate new blocks and transactions in exchange for a chance to receive rewards. That change lowered the Ethereum network's energy consumption by 99.9%, to an annualized 7.5 GWh, according to the CCAF.

But large holders of bitcoin have opposed change. The BMC says the energy is required in order to provide network security and tie the cryptocurrency's value to the physical world.

The BMC claims that 60% of the energy consumed by the global bitcoin mining industry is supplied from sustainable, non-

# Will AI's growth create an explosion of energy consumption?

Further improvements in hardware and software efficiencies may counteract an expected surge in demand for electricity needed to power the new large language models.

When OpenAI's ChatGPT was introduced in November 2022, it quickly captured the public's imagination, surpassing 100 million active users within two months. Since then, analysts have been issuing eye-popping projections for the growth of generative artificial intelligence (AI). Bloomberg Intelligence in March forecast a \$1.3 trillion market by 2032, from a market size of \$40 billion in 2022—a compounded annual growth rate of 43%.

It's been widely reported that new AI models are power hungry and that they will add to the consumption of electricity by data centers. But no consensus has emerged as to the size that jump will be.

The data-center builder Schneider Electric's 2023 white paper *The AI Disruption: Challenges and Guidance for Data Center Design* estimated that AI workloads accounted for 8% of the estimated 54 GW of electricity used by data centers last year. Schneider expects that share to rise to 15–20% by 2028, when data-center demand is forecast to reach over 90 GW. Of total AI usage, 20% is currently used for the training of models, with the rest going to inference—the individual instances with which the the model is tasked. The ratio is expected to evolve to 15:85 by 2028.

Since the introduction over the past year and a half of ChatGPT and other so-called large language models (LLMs), such as Microsoft's Copilot and Google's Bard, some researchers have issued—and news outlets have reported—predictions of skyrocketing electricity demand. One such forecaster was Alex de Vries, a data analyst and PhD candidate at the Free University of Amsterdam School of Business and Economics. He says that global electricity demand for AI could grow larger than the entire consumption of Argentina by 2027. "With AI, the whole principle is that bigger is better," de Vries says. "Bigger models are more robust and perform better. But they require more computational resources and more power."

## Overblown forecasts?

In a 2023 commentary in *Joule*, de Vries pointed to estimates by Alphabet chairman John Hennessy that the cost of Google searches might increase by a factor of 10 if an LLM were used in every interaction. (See the figure.) That isn't likely to happen in the near term, he acknowledges. For starters, it would require the prompt delivery of more than 500 000 high-end servers, at a cost to Google of around \$500 billion.

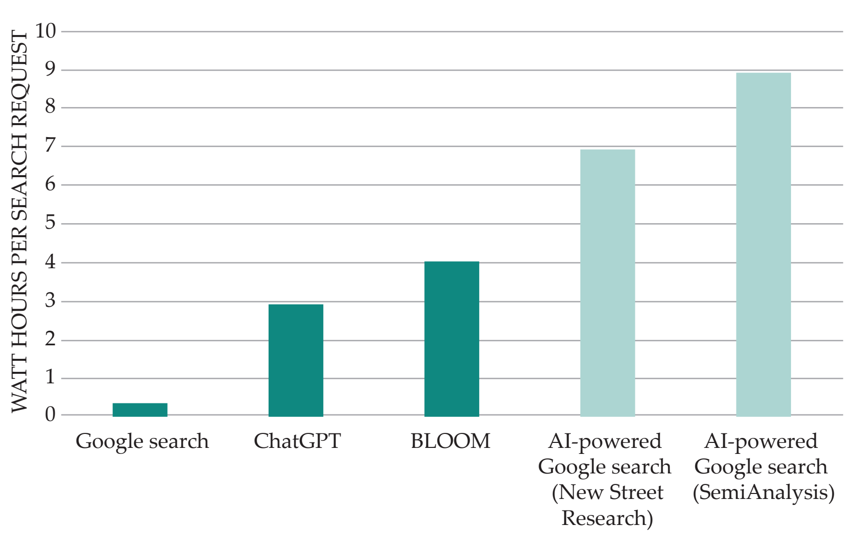
Yet past forecasts of exponential increases in electricity consumption from other transformative developments in IT have proven wildly inaccurate, says Daniel Castro, who authored a January white paper on AI energy use for the Information Technology and Innovation Foundation (ITIF) in Washington, DC. He points to a French think tank's widely reported estimate in 2019 that the carbon footprint of streaming Netflix for 30 minutes is equivalent to driving a car 6.4 km. The correct comparison is 9–91 m, which the think tank later acknowledged. The Center for AI and Digital Policy said in 2022 that "AI-enabled systems require exponentially rising computing power . . . despite overwhelming evidence showing that the assertion was misleading and overblown," the ITIF report states.

Vast efficiency improvements in data-center operations have occurred as centers have proliferated. One widely cited 2020 study by Eric Masanet and colleagues, between 2010 and 2018, states that compute instances at data centers surged by a factor of more than five and storage capacity by a factor of 25, while total energy use rose just 6%.

But de Vries and others argue that AI will grow so rapidly that it will overwhelm any further increases in efficiency that can be wrung out of computing hardware, which they say is already reaching the limits of Moore's law for chip feature sizes. "There's a fear of missing out," says Roberto Verdecchia, an assistant professor at the University of Florence in Italy. "There is a race to make a better model, and a new model comes out every other day. There isn't time to improve energy efficiency."

## Developer awareness

A 2023 report by Google and Boston Consulting Group notes that AI model design is an evolving field, and new releases and versions consistently demonstrate improved energy efficiency while maintaining performance. Improvements in software and algorithmic optimization are likely to significantly enhance efficiency and decrease computational requirements, the report says. For example, 18 months after the release of GPT-3, the AI model used by ChatGPT, Google pro-




**GOOGLE SEARCHES** would require more than 10 times the electricity if artificial-intelligence functionality were added, according to two different analyses. (Adapted from A. de Vries, *Joule* **7**, 2191, 2023.)

duced an LLM nearly seven times as large. That model, GLaM, outperformed GPT-3 and required one-third the energy to train, according to the ITIF report.

A spokesperson for OpenAI says the company recognizes that training large models can be energy intensive and that it's "constantly working to improve efficiencies." The company gives "considerable thought about the best use of our computing power and support efforts with our partners to meet their sustainability goals," she says.

OpenAI's model-training runs, while individually very energy intensive, often enable customers to skip having to train their own models from scratch, the spokesperson says. "We also believe that large language models can be helpful in accelerating scientific collaboration and discovery of climate solutions."

Microsoft, which introduced its LLM chatbot Copilot (formerly known as Bing Chat) in 2023, is investing in R&D to better measure the energy usage and carbon intensity of AI and find ways to make large models more efficient to train and use, a spokesperson says.

There are practical limits to the size and improvements that can be made to LLMs—and hence limits on their energy consumption. Neil Thompson, director of the FutureTech research project at MIT's Computer Science and Artificial Intelligence Lab, says that halving the errors produced by LLMs requires 1.9 million times the amount of computing.

Jonathan Koomey, who is part of a team of researchers preparing a congressionally mandated report on electricity use in data centers, says that the surge of interest and investment in AI recalls previous IT hype cycles, such as the dot-com craze and the overbuilding of fiber-optic networks in the 1990s. "There are real uses that will come out of AI, but I'm very skeptical that this will be a thing that takes over the whole economy." He says that he isn't sure that AI would improve the accuracy of Google searches. "If you can automate the testing of accuracy, great. But the world is messy and full of bad actors trying to cause trouble, and there are gray areas and ambiguities. You may never be able to solve the accuracy problem."

ITIF's Castro foresees "plenty of places where people will try and fail to use AI or they'll do it because of the novelty where there's no value." Developers, he says, are looking for ways to create smaller models that are just as effective. Caching answers to frequently asked prompts instead of generating entirely new responses for each instance is an example, he says.

**David Kramer**


KITTI SUWANEKKASIT/SHUTTERSTOCK.COM

**AS BITCOIN'S PRICE** reaches record levels, the cryptocurrency is expected to attract more power-hungry mining operations.

$CO_2$-emitting sources—more green energy than is used by almost any other industry sector. The UN report and the CCAF both estimate that about 38% of bitcoin mining's energy in 2021–22 came from clean sources. A July report from Greenpeace identified a similar proportion, while noting that some coal-fired plants that had been slated to close were kept open or even reopened to fill demand from bitcoin mining. The fraction of green power has likely fallen since China's largely hydroelectric-powered miners mostly disappeared, says CCAF's Neumüller.

A 2022 report by the Sierra Club and Earthjustice accused some companies of "greenwashing" by locating their plants in proximity to wind or solar farms. Unless a company has a power purchase agreement or a direct connection to a renewable supplier, the proportion of renewables they use will be the same as that of the grid from which they draw. Apart from a few publicly traded bitcoin mining companies, few self-report their energy consumption source, Neumüller says.

When bitcoin was launched in 2009, the maximum supply was set at 21 million to keep the currency scarce and prevent inflation. Bitcoins currently number around 19 million. The reward for mining a block is set to periodically halve to reduce the rate at which new bitcoins can be minted. A halving is set for this year.

**David Kramer** PT

# EMBRACING INTERACTIVE TEACHING METHODS

STEPHANIE CHASTEEN, EDWARD PRATHER, AND RACHEL SCHERR

JASON KEISLING

**Stephanie Chasteen** runs Chasteen Educational Consulting. She worked on the New Faculty Workshop (NFW) programs as an evaluator from 2015 to 2022 and then on the Faculty Teaching Institute (FTI) as colead designer with **Edward Prather**. In 2006 Prather began leading the NFW, and he has been coleading the FTI with Chasteen since its inception in 2022. He is also an astronomy professor at the University of Arizona in Tucson. In 2020 **Rachel Scherr**, an assistant professor of physics at the University of Washington Bothell, was an NFW facilitator from 2020 to 2022 and in 2022 became the newest FTI colead designer.

## New physics and astronomy faculty are excited about active teaching, but they still need support to implement the ideas in their classes.

If you teach, you may remember your first time in front of a classroom. You were probably nervous, wondering whether you had planned a good lesson and the students would like both it and you. You may have been excited to light up a set of fresh faces with your favorite topics or demonstrations. Whether that first day was yesterday or 20 years ago, you probably thought deeply about what to teach and how best to convey it to your students. But teaching physics now is not the same as it was 20 years ago.

Lecturing has been the predominant mode of instruction since the birth of universities, but those norms have changed. Modern physics classes often use methods that more actively engage learners. For example, to give students the opportunity to work through the meaning of physical ideas, an instructor might ask them to predict the outcome of a demonstration and talk through their reasoning with a neighbor, all before doing the demonstration itself.

Such beneficial teaching changes are largely due to the efforts of physics and astronomy education research (PAER) and the professional societies that have helped spread PAER-inspired instructional strategies and curricula. In addition to improving student education, the increased use of active learning in the classroom has also created a need for faculty to develop their knowledge and skills. The three of us and a collaborative team of PAER experts over several decades have been putting together professional development workshops for college faculty, which have helped to drive the increased use of active teaching and learning in higher education.

Luckily for today's new (and not so new) faculty, we know how to teach physics and astronomy more effectively than we used to. A broad set of research has demonstrated the value of active learning and interactive engagement—educational techniques that go beyond lectures.

## Education research to the rescue

Active learning can narrow achievement gaps. For example, a meta-analysis of 225 studies found that students in traditional lecture classes were 1.5 times more likely to fail than students in active-learning classes.[1] The researchers also found that student learning, as measured by conceptual assessments, increased by half of a standard deviation in active-learning classes, and those results held across all STEM disciplines and all class sizes. Another meta-analysis of 15 studies found that a high use of active learning significantly reduced gaps between students from underrepresented and overrepresented groups (as determined by using race, ethnicity, and socioeconomic status as a proxy for underrepresentation). Active learning also reduced gaps in examination scores by 33% and in passing rates by 45%.[2]


**FACULTY TEACHING INSTITUTE WORKSHOP PARTICIPANTS** share their hopes and plans for teaching improvement over the next year. The look-forward exercise occurs on the final day. Check-ins with the participants will continue over the next year to support implementation of their plans.

A wellspring of results from PAER has informed our understanding of effective teaching and learning of physics and astronomy since the 1980s.[3] That work has also given rise to many PAER-informed instructional methods and curricula that can be used to teach physics concepts and skills: tutorials, ranking tasks, tasks inspired by physics education research, peer instruction, interactive lecture demonstrations, and investigative science learning environments. Details about those and other teaching methods can be found at PhysPort (https://www.physport.org).

In addition to improved comprehension, increased engagement in the classroom has also been shown to increase equity in physics. For example, Joshua Von Korff and coauthors reviewed the results of two common force-and-motion conceptual assessments taken between 1995 and 2014. They found that across 72 studies covering 600 classes, active-learning methods were significantly more likely to show high learning gains than lecture-based ones.[4] Moreover, those results held across two-year colleges, liberal arts colleges, research universities, and different class sizes. Active learning also led to greater learning for students at varying levels of incoming preparation, measured by either SAT scores or precourse conceptual-understanding assessments.

How can physics faculty get up to speed on implementing active-learning techniques? Most new physics faculty need explicit instruction on how to teach effectively. Some have never seen active learning in practice. Creating a productive class, especially an active-learning one, is not trivial. We also know that many student populations, such as first-generation students and historically underrepresented groups, too often leave STEM because of the negative experiences they have in their introductory classes.[5] To intentionally design college physics and astronomy classes that maximize student learning and promote a sense of belonging, we need professional development experiences that can help physics faculty evolve their teaching.

## The New Faculty Workshop

Our professional societies have long sought to support faculty as effective teachers to help the physics and astronomy disciplines thrive. Since 1996 the flagship program to introduce new physics faculty to research-based teaching has been the annual Workshop for New Physics and Astronomy Faculty, affectionately known as the New Faculty Workshop, or the NFW. Three societies—the American Association of Physics Teachers, the American Physical Society, and the American Astronomical Society—partnered to offer the four-day workshop.

From 1996 through 2022, the NFW introduced participants to the primary findings of PAER and various PAER-based instructional materials and strategies. PAER curriculum developers and researchers presented sessions on their instructional methods at each NFW. The workshop's primary goal was to reach a significant fraction of the physics and astronomy tenure-track faculty, thus broadening the use and uptake of PAER techniques.

The NFW boasts 2900 alumni from 85% of all physics-degree-granting institutions and about 40% of physics and astronomy new faculty hires in the US. The endorsement of the NFW—and the current Faculty Teaching Institute—by professional societies conveys that our physics community encourages thinking about teaching as a scholarly activity and promotes the use of active-learning techniques. The explicit focus on physics and astronomy teaching ensures that we provide applicable advice and examples that respond to the needs of physics and astronomy teachers, which increases the likelihood that they bring innovations to their classes.

The goal of the early NFW events was to persuade faculty to try active learning in their classroom. When community leaders first developed the NFW, PAER was a relatively new field. Academia changes slowly because of the decentralized nature of higher learning and because new scholarship takes a long time to establish and gain broad credibility. Therefore, more physics faculty were unfamiliar with or skeptical of research-based teaching approaches. Part of the job of the NFW was to establish the value and credibility of PAER-developed instructional strategies and materials, including the benefits to students.


**ACTIVE LEARNING AT WORK.** Physics and astronomy educators collaborate on a small-group activity during the June 2023 Faculty Teaching Institute workshop. They then consider how they can use the same technique with their students.

To achieve that goal, organizers arranged the NFW as a series of approximately 25 presentations, each led by an expert in a particular instructional method. The presenters spent significant time sharing evidence of improved student learning, explaining how their instructional methods intellectually engaged students and improved their learning, and modeling best practices for use in the classroom. The featured methods had well-established instructor materials and clear guidelines on implementation. Because the presentations were standalone, the parade of presenters gave participants a broad view of key developments in physics teaching.

“Active learning reduced gaps in examination scores by 33% and in passing rates by 45%.”

The workshops were eye-opening for many faculty, a majority of whom then experimented with the methods in their classes. Participants reported increased knowledge of and motivation to use active learning.[6,7]

One year after the workshop, almost all participants surveyed across multiple years reported using more active learning than before the workshop, and 87% said they used at least one published PAER technique. Additionally, 96% reported changing their teaching after the NFW and attributed at least some of that to their workshop attendance.[6] Even more compelling, a large regression study found that attendance at the NFW was the best predictor of whether a faculty member would try a published PAER teaching practice.[8] Thus the NFW has been crucial in setting teaching norms and establishing a common knowledge base among physics faculty.

The NFW did have shortcomings, however, and attendance didn’t necessarily lead to long-term use of its promoted strategies.[8] Alumni often reported feeling unable to use the strategies well.[7] And, troublingly, some participants reported feeling disempowered by the NFW, as though the organizers were explicitly telling them how to teach.[9] We’ve since realized that trying to persuade faculty to use active learning isn’t what they actually need. Professional development must be faculty centered, attending to and informed by educators’ existing knowledge and interests.

## Today’s faculty are different

New physics faculty are coming into the profession with markedly different beliefs and experiences than 20 years ago, and we realized that the NFW was no longer well aligned with the needs and expectations of that population. Evaluation results from 442 participants who attended a workshop between 2015 and 2018 showed that only 18% were unaware of the teaching methods presented in the NFW, and 80% had already tried at least one PAER teaching technique.[7] Such increased awareness holds true beyond the NFW: A 2019 survey of new and experienced physics faculty found that 87% reported using at least one published PAER technique, and most spend at least 30% of class time on active learning.[10]

## Box 1. FTI long-term goals

As a result of our Faculty Teaching Institute workshops, physics and astronomy faculty will

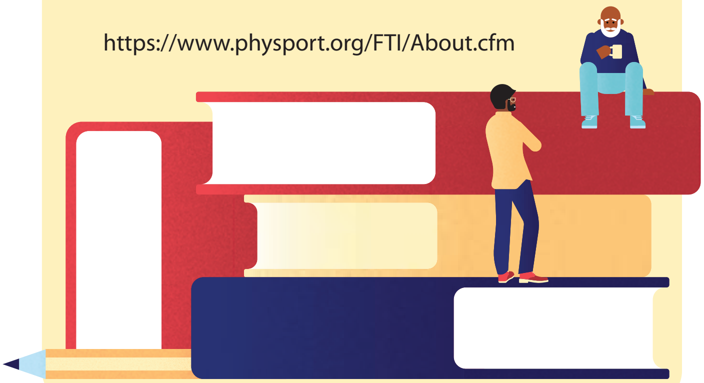
1. Value and use **student-centered and reflective practices**, and consider excellent teaching and learning to be a shared responsibility within departments.

2. Demonstrate awareness and practices that support **diversity, equity, and inclusion**, with particular attention to marginalized groups.

3. Connect to a **supportive disciplinary community** that is engaged in helping and empowering one another to evolve their approach to student-centered teaching as lifelong learners.

4. Be empowered to **navigate a fulfilling academic career**, achieving a rewarding balance among teaching, service, and research commitments.

https://www.physport.org/FTI/About.cfm



New physics and astronomy faculty today have come of age in a different culture of teaching. Research-based instructional strategies are a more accepted part of the academic lexicon than they used to be. Terms like "physics education research," "active learning," and "learner-centered instruction" are no longer unfamiliar to faculty. The favorable climate for using learner-centered teaching has helped new faculty take up—and continue to use—PAER teaching techniques. In the past, 30% of faculty who tried published PAER methods stopped using them; now only 5% stop.[10]

In light of that, it's no longer appropriate to view new faculty as skeptical novices. They aren't starting from scratch. They have existing experiences and beliefs that can be built on in a professional development learning environment—just like the one we are teaching them to create for their physics classes. As one faculty participant told us on a postworkshop survey, "We get it, we want it, so GIVE IT TO US."

## How do we teach teachers?

What faculty need is to engage in experiences that help them develop their confidence and skills as educators. While new physics faculty are generally eager to use active learning, they are still in the first few years of their career. As such, they have little experience with what it takes to create an efficient and effective class. Professional development workshops are one tool for faculty support, and we now know more about how to set up faculty for success. We know that professional development can be powerful if it is discipline specific and of sufficient duration. We also know more about how to design the workshop experience.

First, faculty need (and want) good knowledge about teaching. They need an organized mental framework to guide their teaching decisions—just as our students need an organized set of ideas about physics. Faculty also need to know that all students can learn physics; they need to understand issues of equity and inclusion in the classroom.

But people need more than motivation and knowledge to adopt a new behavior—they need to feel empowered to act. People are much more likely to take up behaviors that they choose and that they feel are achievable. Therefore, the workshop needs to help faculty cultivate a sense of ownership and autonomy over their teaching, make sense of their class outcomes, and still maintain their creative control. We need to set up new physics faculty as lifelong learners.

A key part of that is supporting faculty as reflective practitioners. All learning—academic, professional, and personal—is supported best by reflecting on one's progress and improving for the future. Faculty are learners engaged in a continuous cycle of teaching development: trying something, gathering feedback, reflecting on their experience, seeking input and knowledge, and deciding on future changes that better meet their goals and address students' needs. It is, after all, the same process as developing scientific knowledge through research. Thus helping faculty learn to perceive and respond to student learning needs, including equity issues in teaching, is a vital goal.

Another important goal is to instill faculty with a growth mindset around teaching and a willingness to learn. When educators see teaching as a continuous journey of learning and growth, they can become resilient in the face of inevitable challenges.

Additionally, new faculty are in the early stages of professional careers. Teaching support should occur in the context of the larger faculty role: It should address the whole faculty member, help them navigate common issues, connect with other faculty and professional societies, and develop resilience. Now that we are equipped with that new knowledge, we are reenvisioning physics and astronomy faculty development to better meet the current moment.

## Introducing the Faculty Teaching Institute

To meet the changing norms of the physics community, in 2022 the American Association of Physics Teachers, the American Physical Society, and the American Astronomical Society, with generous support from NSF, have engaged in a strategic redesign of the NFW that is focused on the needs of today's faculty. We have rebranded the workshop as the Physics and Astronomy Faculty Teaching Institute (FTI; www.physport.org/FTI). The new name better represents the comprehensive nature of the workshop and professional development experience while allowing room for the project to expand beyond tenure-track, early-career faculty.

The workshop experience of the FTI is collaboratively developed and led by the three of us and facilitated by a set of roughly five diverse and experienced physics and astronomy education practitioners and researchers. The team approach offers a more coherent experience than was possible in the old parade-of-presenters model. We developed the FTI around a set of design principles, which can be found at PhysPort (https://www.physport.org/FTI/About.cfm). One such principle is that "workshop delivery is respectful and participant-centered." The FTI instruction emphasizes that learners, including faculty, construct their knowledge based on their existing needs.

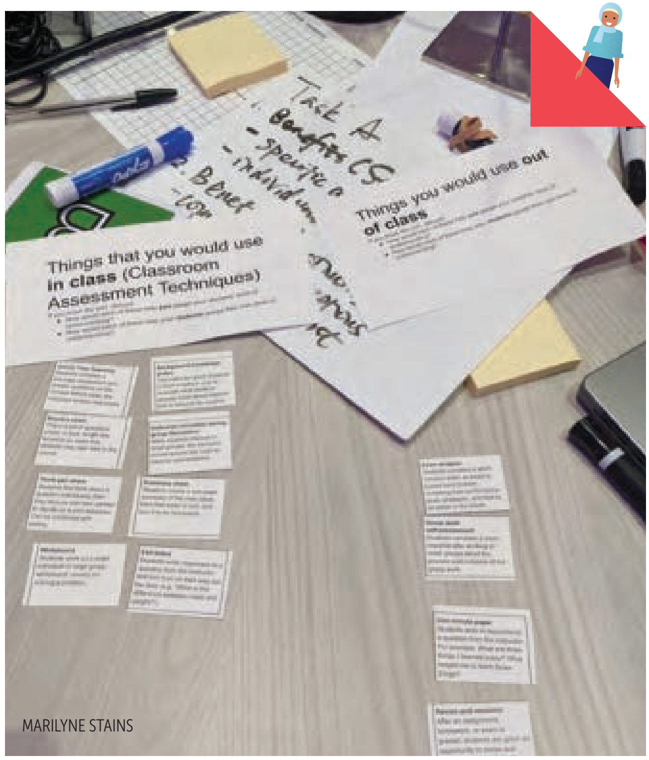
In the current design, the FTI offers a four-day, coherent interactive workshop focused on learner-centered education in an equity, diversity, and inclusion framework. Rather than persuading faculty to use student-centered instruction, the FTI aims to build faculty's agency to make their own well-informed teaching changes. It does that by providing them with a firm grounding in the principles of teaching and learning, engaging them in transformative experiences that offer deep insight into real-world student experiences, and encouraging reflection on their teaching. The FTI's long-term goals for physics and astronomy faculty are summarized in box 1.

Participants at the FTI are introduced to a wide array of effective teaching methods and assessment. That coherent "big tent" approach is a significant shift away from the previous model of featuring siloed sessions narrowly focused on specific PAER methods. Those specific methods, however, still appear as exemplars of generalized strategies.

The FTI also offers extensive postworkshop opportunities, including a newsletter, virtual office hours, and a yearlong faculty learning community.

Being a faculty member involves more than just teaching. The FTI aims to discuss how teaching is evaluated, how the tenure process works, what learning to prioritize, and how faculty members identify themselves. For example, we urge participants not to overprepare for teaching and to say no to requests that don't meet their career goals. The FTI workshop treats faculty as people with multiple responsibilities rather than focusing on teaching as yet another task to do perfectly. As our collaborator Laurie McNeil urges our faculty, they should "do their very goodest."

To help faculty engage all of their students, the FTI addresses equity and inclusion throughout the workshop. Faculty begin by reflecting on how their identities and lived experiences shape their teaching interactions. Those reflections are greatly enriched by the diversity of the FTI participants. Students with a wide range of lived experiences engage in courses differently, so specific teaching practices and structures can be used to support them. The workshop helps faculty adjust their teaching for students at risk of feeling disconnected and educates them on historic harms from schooling or science that students may have experienced.




MARILYNE STAINS

**DIFFERENT ASSESSMENT TECHNIQUES** to evaluate student progress can be used inside or outside the classroom. Faculty are challenged to sort the techniques (displayed on pieces of paper) by where best to use them.

The workshop content is tied together through a set of principles of teaching and learning that aid faculty in selecting thoughtful strategies and using them well. Those principles give a shorthand for understanding why different teaching techniques are effective and help educators make informed choices for their classroom. The principles, along with some example prompts, are presented in box 2.

"Research-based instructional strategies are a more accepted part of the academic lexicon than they used to be."

To further support faculty adaptation, the FTI offers multiple options for achieving any particular goal, such as supporting students' sense of belonging. The workshop emphasizes practical tips and dedicates time for working in small collaborative groups, engaging in deep discussions, journaling, and developing a sense of community with their fellow participants. Those discussions and writings culminate in each participant developing a concrete action plan to guide their learner-centered teaching experiment over the next year. Participants are regularly reminded of their action plan during the subsequent year and supported in achieving it through postworkshop engagement opportunities that are organized by the FTI.

## Our hopes for physics faculty

Overall, we intend for the FTI to support participants in becoming

## Box 2. Principles of teaching and learning

### Prior knowledge and motivations

Connect to students' prior knowledge and motivations to leverage their powerful ideas and interests and support them throughout any struggles.

"What do you think of when I say 'force'?"

### Active engagement

Use active engagement so that students make meaningful connections, because they were the ones to make sense of the material themselves.

"What do you think will happen when . . . ?"

### Social interaction

Use social interaction so that students can verbalize their thinking and coach one another.

"Turn to your neighbor and discuss."

### Feedback and reflection

Provide opportunities for feedback and reflection so that students can adjust their learning.

"Let's do a quick poll . . . "

### Inclusive and supportive classrooms

Use inclusive classroom strategies and create a supportive and welcoming climate to strengthen learning for students from all backgrounds.

"I'd like to hear from at least three students . . . "

### Scaffolding

Start simple and provide early support so that students can build skills and concepts. Then gradually step back and provide less structure.

"I've set up the problem. Now what is the next step?"

Adapted from references 11 and 12.

thoughtful, effective teachers who feel empowered to select and use techniques to create learner-centered classrooms and have a fulfilling teaching career. The redesigned workshop was offered twice in 2023 with positive results. Postworkshop evaluations showed that participants reported gains in knowledge, skill, and motivation to use student-centered practices, and 92% would recommend the workshop to a colleague.

Participants appreciated the practical and relevant content, the deliberate modeling of the teaching techniques, and the extensive collection of resources. As one participant shared, "I thought it was a great experience . . . . It was helpful to see what others were doing and to feel like I was part of a larger community who had the same struggles as me." Another said, "I knew there were better ways to teach before the FTI, so [I] had good motivation but little idea on where to start. The FTI provided that, and gives me much more confidence that I can improve my teaching using the tools provided."

Participants also appreciated the use of action planning, and all intended to carry out their action plan. "I appreciated having plenty of time to work on [my action plan] each day, which encouraged me to take it more seriously," one participant said. "I think there was sufficient time and structure to make use of it, and I appreciated how the facilitators emphasized keeping plans small and manageable."

As reflective teachers ourselves, we also learned many ways to better attend to the needs of our new faculty learners, such as improving pacing, ensuring that journal prompts are meaningful, and carefully building the action plan throughout the workshop.

Teaching physics and astronomy matters. It matters for us, for our students, and for our institutions. It has ramifications beyond what we directly influence. That is partly why new professors are nervous: They are educating the next generation about how physicists and astronomers think about the world. The FTI and the professional societies that support us are committed to helping all physics and astronomy teachers flourish. We want faculty members to experience the joy of being a great teacher and reaching students. Our hope is that by equipping them with foundational knowledge, skills, and mindsets, they will be empowered to go back to their home institutions and create effective and inclusive classrooms that are welcoming and intellectually stimulating.

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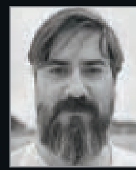
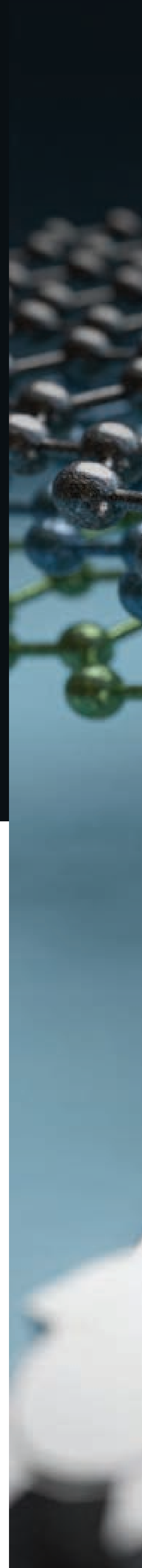


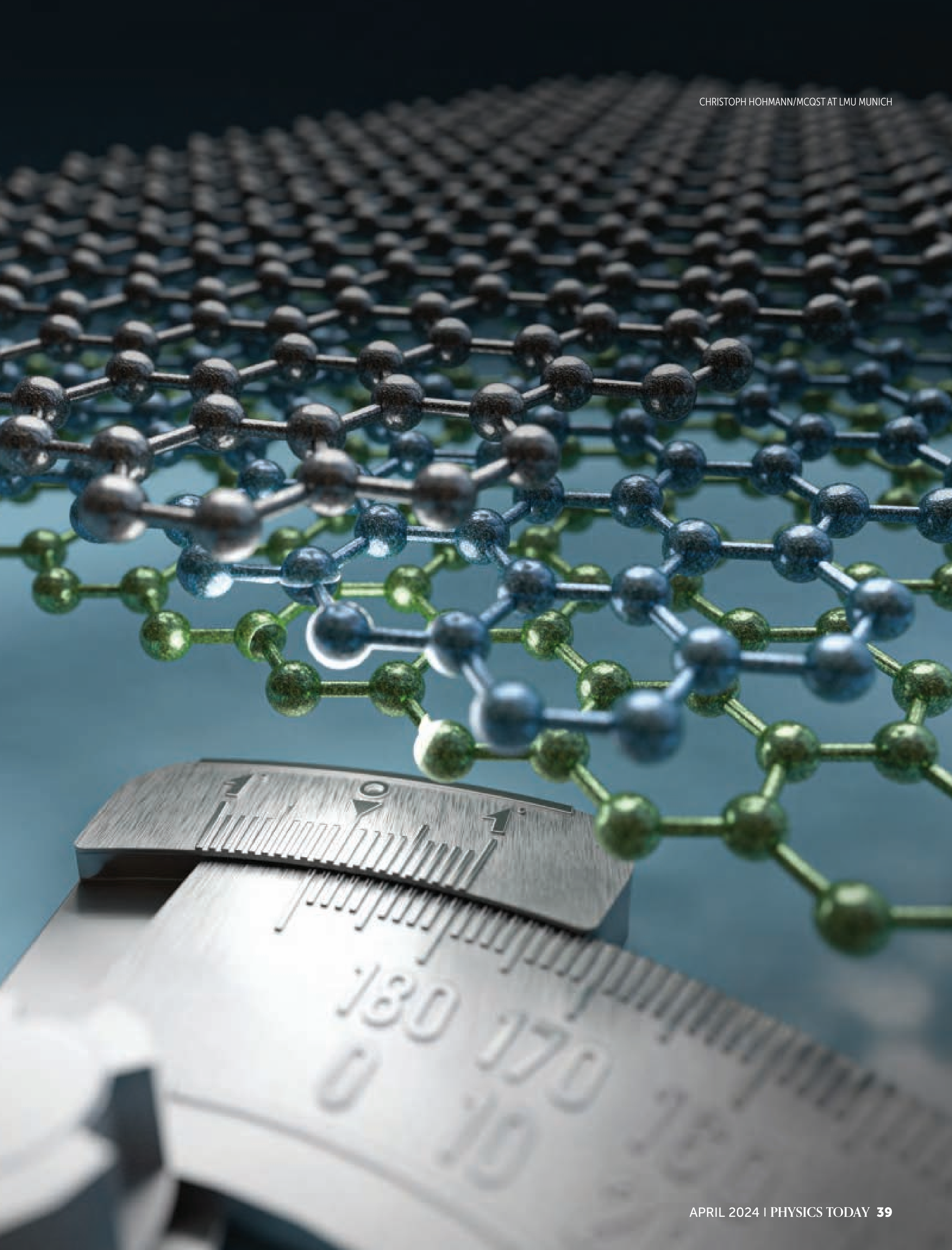
# Twisted bilayer graphene's gallery of phases

B. Andrei Bernevig and Dmitri K. Efetov

**The simultaneous occurrence of exotic phases, and the ability to easily tune them, has positioned magic-angle twisted bilayer graphene as one of the richest materials platforms in condensed-matter physics.**

A simple twist between two sheets of carbon crystals has taken the condensed-matter-physics community by storm. The discovery of superconductivity and other phenomena in that system, announced in 2018, has revealed an array of new options to also realize interacting topology, magnetism, and other many-body states of matter, in an entirely novel and simple way. Now, six years after that initial revelation, researchers are still trying to grasp the full details of its complex phase diagram. Since the universal principles that give rise to those phases can be transferred to other 2D materials, big discoveries continue to happen almost every month.



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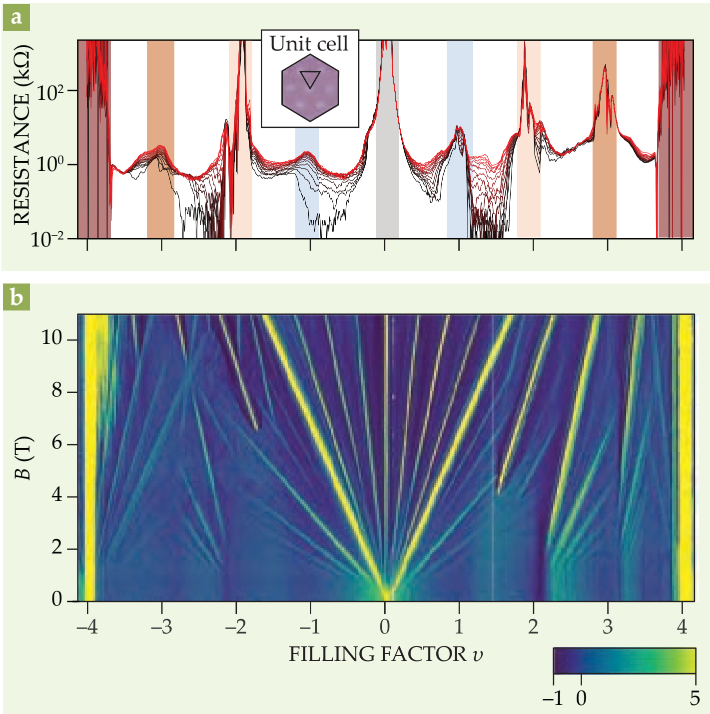



**FIGURE 1. EMERGENT STATES** of magic-angle twisted bilayer graphene. **(a)** Correlated insulator states, characterized by peaks in the resistance, are found at almost all integer values of the filling factor *v*. Integer filling factor *v* is the number of excess electrons (positive) or holes (negative) in each unit cell of a moiré lattice. Lines ranging from black to red correspond to increasing values of the applied magnetic field. (Adapted from ref. 4.) **(b)** The yellow streaks in this plot of inverse electron compressibility map the rich sequence of topological Chern-insulator states with quantized Hall conductance that appear when a perpendicular magnetic field *B* is applied. (Adapted from ref. 8.)

Traditionally, the electronic properties of a material are the result of its atomic composition and the arrangement of its atoms. So-called strongly correlated materials are one of the richest and yet least understood material classes. Their electrons do not behave as individual particles but are highly entangled with one another. Such compounds include, for example, heavy-fermion systems and cuprate high-temperature superconductors that exhibit a rich phase diagram governed by a mysterious interplay between magnetic and superconducting phases, in which current flows without resistance. Typically, strongly correlated materials are complex, multicomponent systems that often contain large atoms with *f*- and *d*-shell electrons. (See the article by Antoine Georges and Gabriel Kotliar on page 46.) In search of novel physical effects, scientists have been striving to synthesize crystals with evermore complex structures and compositions.

The observation of strongly correlated electrons and multiple many-body ground states in magic-angle twisted bilayer graphene (MATBG) devices shocked and excited the physics community.[1–3] The surprise lies in the fact that it was achieved by an entirely novel and previously unthinkable approach and in the unlikeliest of materials. In stark contrast to traditional strongly correlated systems, MATBG consists entirely of light and simple carbon atoms, and its building blocks, the single-layer graphene sheets, show no signs of strongly correlated electron effects. Those properties can, however, be turned on by a conceptually simple trick—stacking two graphene sheets, one on top of another, and twisting them. Just like when a combination lock is opened by turning to the right sequence of symbols, strong electronic correlations are unlocked when the twist angle between the layers is set to a well-defined value, 1.1°, the so-called magic angle. (See box 1.)

## 2D materials and moiré superlattice

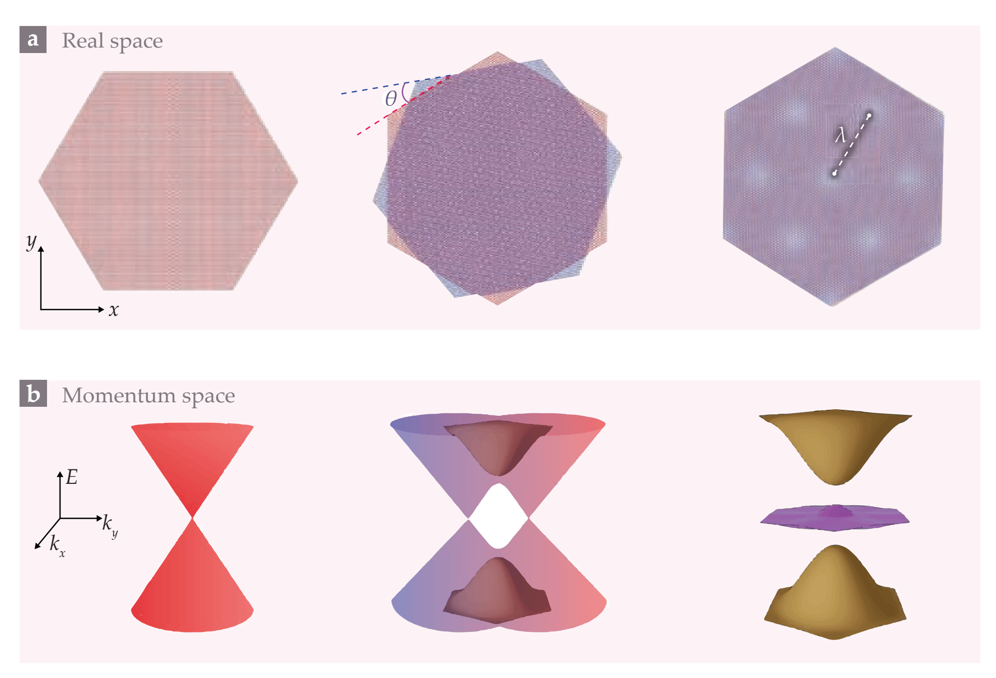
The fabrication of MATBG was enabled by a breakthrough in the engineering of structures composed of vertically assembled 2D van der Waals materials, a large class of materials that consists of weakly coupled sheets. For example, the van der Waals material graphite, called graphene when separated out as single layer, consists of carbon atoms arranged on an atomically thin hexagonal lattice. Because of the weak coupling between the layers, it's possible not only to extract 2D layers from bulk van der Waals crystals but also to assemble them one on top of another using a simple colamination technique, thus creating vertical van der Waals heterostructures.

In more-traditional techniques, crystals are typically grown by epitaxy of individual atoms, and the grown layers automatically lock into the crystallographic orientation of the underlying substrate. But since van der Waals heterostructures are assembled from preformed 2D crystals, it has become possible to freely choose the crystallographic orientation between the layers during the assembly process and to set a twist angle between the crystals with a precision of a tenth of a degree. When two misaligned 2D crystals are stacked one on top of another, the individual crystal lattices produce between them a type of geometric interference known as a moiré pattern.

The moiré pattern forms a periodic, triangular superlattice on top of the original graphene lattice, which, for small twist angles, forms a unit cell with a lattice constant $\lambda$ of about 10 nm, which is orders of magnitude larger than that of single-layer graphene. The enlarged unit cell in real space gives rise to a reduced unit cell in momentum space. In addition, the moiré pattern can naturally break some of the internal symmetries of the underlying 2D crystal, such as its inversion symmetry. In high-quality devices, where the electron mean free path is bigger than the lattice constant $\lambda$, the moiré superlattice can strongly affect the electronic wavefunctions and lead to a strongly altered electronic band structure.

When scientists started to theoretically investigate the effect of the moiré pattern of two twisted graphene layers, they found that for a set of well-defined twist angles—the magic angles—the effect of the electronic coupling between the layers becomes extremely strong.[1] In particular, for the first magic angle of 1.1°, the electrons slow down dramatically and condense into extremely flat energy bands, which have a bandwidth of only about 10 meV. Further, scientists have realized that those renormalizations possess all the necessary ingredients to turn on topology in the MATBG bands. In such topological bands, while the interior of the device behaves as an insulator, the edges of the device behave as a metal, forming

## Box 1. What makes the magic angle magical




Graphene is a single 2D layer of hexagonally arranged carbon atoms, as shown in real space in panel a. Much of the fascination with the material arises from the fact that in special places in momentum space, the valence and conduction bands meet at one point, and the energy varies linearly with momentum. In the immediate vicinity of those points—the so-called valleys—the band structure thus has the shape of two cones, called Dirac cones, seen in panel b.

When one graphene sheet is stacked on top of another at a twist angle $\theta$, a geometric interference pattern between the individual lattices emerges. Known as the moiré pattern, it takes the form of a triangular superlattice.

For large $\theta$, the separation of the Dirac cones of the individual lattices in momentum space is large, and the two graphene layers are almost decoupled and only weakly affected by the moiré pattern.

When $\theta$ is small, however, the Dirac cones in the individual layers strongly overlap and begin to hybridize. For a twist angle close to the magic angle of 1.1°, the Dirac cones flatten and converge to zero energy. That results in the occurrence of ultraflat bands with a bandwidth of only about 10 meV. Because all the electrons in those bands have almost the same energy, the density of states is extremely large and peaks in the centers of the moiré lattice sites. That produces the topological flat bands, induced by the moiré superpotential, observed in magic-angle twisted bilayer graphene.

states similar to the quantum Hall effect, in which the electrons can only move along the device edges.

## Tunable topological flat bands

The resulting topological flat bands are the key starting point to understand the rich phenomenology of MATBG. The electrons' lack of kinetic energy makes the electron–electron Coulomb interactions the dominant contribution to the system energy. Since all electrons in the flat bands have almost the same energy, their density of states is also extremely large, which in turn further increases the electronic interactions and favors the formation of strongly correlated phases. The combination of topology and strong electron interactions represents a long-sought blend of properties that enables the formation of entirely new electronic phases.

As a result of the strong electronic interactions, MATBG exhibits many complex quantum phases that are not present in a single layer of graphene, including correlated insulators,[2,4] superconductors,[3–5] and a so-called strange-metal phase.[6] Additionally, as described below, the inherent topological property of the flat bands gives rise to orbital magnets[4,7] and Chern-insulator states.[8,9] Incredibly, all those phases can coexist in a single device, and they can be tuned into one another by a set of external experimental knobs, a capability that is not possible in other strongly correlated systems. One such tuning knob is the voltage applied to an electrostatic-gate electrode that is placed underneath each device. It acts as a capacitor plate that can charge the MATBG sheet and allows for direct, clean, and reproducible control of the electron density in the device. (See Physics Today, January 2020, page 18.)

One emergent property of MATBG that can be directly observed through the manipulation with the electrostatic gate is a strong electron-density dependence of the resistance, as shown in figure 1a. When the moiré lattice sites are fully occupied by an integer number of electrons or holes, known as integer filling factors, and no free lattice positions remain, resistance can jump by orders of magnitude, while remaining low at electron densities that fall between those values. In the absence of an applied magnetic field, the resistance entirely vanishes in some regions, indicative of superconducting behavior.

Highly resistive regions at integer filling factors are interpreted as correlated insulators. Since the cost in Coulomb energy that each electron has to pay by tunneling to an already-occupied lattice site is much higher than its kinetic energy, the electrons localize on the moiré lattice sites and induce interaction-driven energy gaps that give rise to insulating states. Because of the Pauli exclusion principle, each energy state can be occupied by two electrons with spin-up and spin-down. In addition to the spin quantum number, electrons in MATBG have quantum numbers defined by the sublattice (×2) and valley (×2), totaling

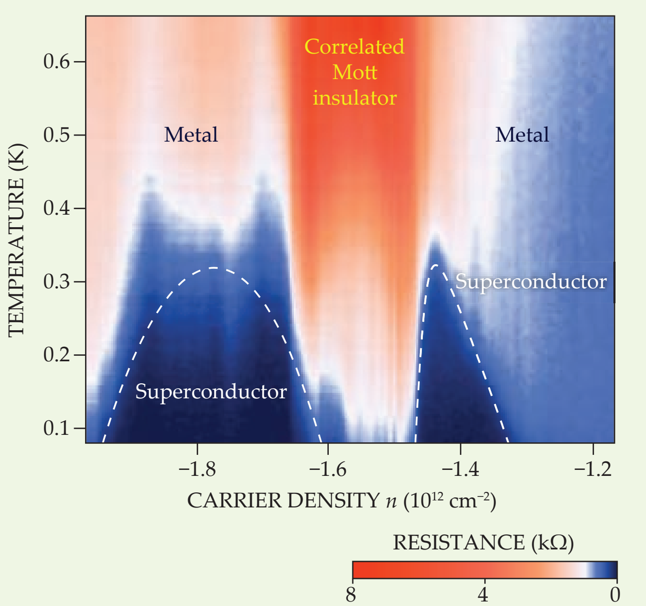



**FIGURE 2. A PHASE DIAGRAM** of magic-angle twisted bilayer graphene. Dome-shaped superconducting regions appear in close proximity to correlated Mott insulator states. (Adapted from ref. 3.)

an overall eight electrons per energy state. The interaction-induced energy gaps naturally polarize the energy bands with respect to those quantum numbers and produce a cascade of phase transitions, forming complex many-body ground states with broken spin, sublattice, and valley symmetries.

To understand in detail the possible low-energy many-body states in MATBG, one must also consider the inherent nontrivial topological properties of the energy bands. The abundance of low-lying topological states becomes visible when a perpendicular magnetic field $B$ is applied. As shown in figure 1b, MATBG exhibits a robust sequence of Chern-insulator states of quantized Hall conductance with Chern numbers $C$ of ±1, ±2, ±3, and ±4 (proportional to the slopes of the strongest yellow lines) nucleating from filling factors $\nu$ of ±3, ±2, ±1, and 0, respectively.[8] The Chern numbers indicate the number of topological edge states, each of which contributes to the conductance $e^2/h$, where $e$ is the electric charge and $h$ is Planck's constant; the sign of the Chern numbers reflects its propagation direction.

More-complex Chern insulators with fractional Chern numbers have also been discovered.[9] And at odd-integer filling factors, specifically when $\nu$ is 1 or 3, MATBG has exhibited the quantum anomalous Hall effect—quantized conductivity in the absence of a magnetic field.[7] Those zero-field Chern-insulator states have insulating magnetic bulk and metallic topological edge states that arise from circular currents rather than from spin symmetry breaking, hence they form an orbital magnet.

## Superconductivity and quantum geometry

As shown in figure 2, upon slight doping away from (most of) the correlated insulators at integer filling factors in MATBG, the resistance drops to zero, and extended dome-shaped superconducting regions appear with a critical temperature $T_c$ of roughly 0.1–0.3 K (and up to 5 K in other experiments)—and of yet-unknown mechanism.[3] Such behavior initially sparked direct comparisons to unconventional superconductors, like cuprates and heavy-fermion materials, in which superconductivity also appears upon doping localized, correlated insulating states. Such superconductors are widely believed to have a purely electronic coupling mechanism. That picture contrasts strongly with that of conventional superconductors, which are well-described by the Bardeen-Cooper-Schrieffer (BCS) theory, which states that electrons form bound pairs because of an attractive electron–phonon interaction.

One of the key attributes of the superconducting phase in MATBG is its unprecedentedly low electron density, which is only about $10^{11}$ cm$^{-2}$. Another is the very high ratio—roughly 0.1—of its critical temperature $T_c$ to its Fermi temperature $T_F$, which is the Fermi energy divided by Boltzmann's constant. That ratio is comparable to only that of unconventional superconductors. The unconventional nature of the superconducting phase in MATBG is further supported by the fact that the size of the superconducting electron pairs is similar to the spacing between moiré lattice sites, which suggests that the system lies close to the crossover between a BCS-like state and a Bose–Einstein condensate.[3]

It still cannot be ruled out that MATBG superconductivity could also arise from a simple BCS mechanism, where the electron–phonon coupling could be strongly enhanced by the immense density of states in the flat bands. Initial experimental studies based on scanning tunneling microscopy[10] and thermal-conductivity measurements have spurred researchers to propose a nodal superconducting pairing symmetry: The superconducting energy gap vanishes in certain crystallographic directions. That behavior contrasts with the uniform pairing usually found in a conventional BCS-like superconductor, but could still arise from electron-phonon pairing or bands with topological properties.

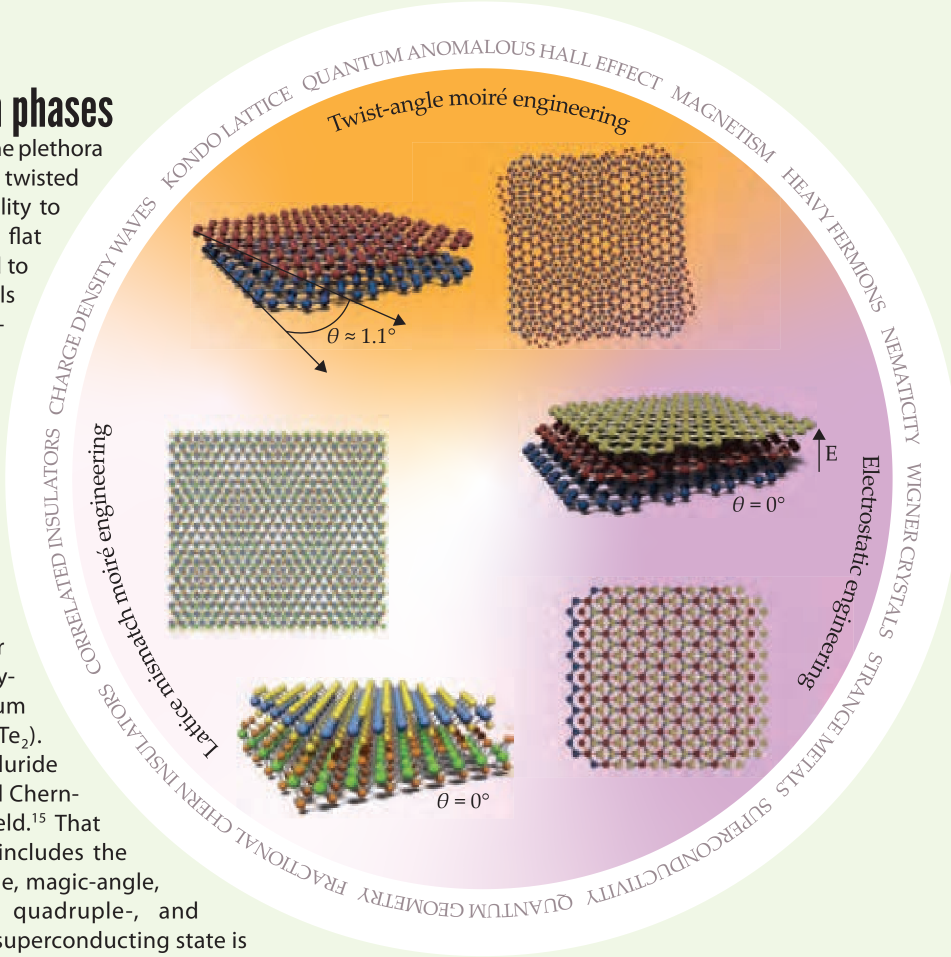
Meanwhile researchers have also recognized an entirely novel aspect of superconductivity in MATBG. Previous research has shown that superconductivity is hindered in a conventional localized flat band, but it can be made possible through the so-called quantum geometry and the topology of the band structure.[11] It arises from the overlap of the orbital wavefunctions, which facilitates movement of interacting particles even when noninteracting particles would usually be localized. The flat-band dispersion and quantum geometry together hence guarantee a lower bound for superfluid weight in MATBG even if the bands were exactly flat.

## Strange metals

Another exotic phase in MATBG is the metallic phase that exists between the integer filling factors. It is markedly different than the metallic phases observed in standard metals, which are typically well described by a Fermi-liquid theory in which the electrons behave as noninteracting quasiparticles. In contrast, the metallic phase in MATBG shows features similar to the ones observed in other strongly correlated materials, such as cuprates and heavy fermions, where a strange-metal phase is observed.

The key attribute of such a phase is that its low-temperature resistivity scales linearly with temperature, which is in stark contrast to the quadratic dependence observed in normal met-

# Box 2. Emergent quantum phases




The main principle that gives rise to the plethora of quantum phases in magic-angle twisted bilayer graphene (MATBG) is the ability to engineer topologically nontrivial flat bands. That ability can be transferred to a much larger set of van der Waals materials, which has led to the discovery of an even bigger multitude of exotic ground states. Graphene-based systems, however, remain the only ones to show a robust superconducting phase.

Similar to MATBG, twist-angle engineering can be used to create moiré-induced flat bands in various twisted layers of sheet-like materials, such as monolayer-on-bilayer graphene, bilayer-on-bilayer graphene, tungsten diselenide bilayers ($t$-$WSe_2/WSe_2$), and molybdenum ditelluride bilayers ($t$-$MoTe_2/MoTe_2$). Twisted bilayer molybdenum ditelluride has been shown to have a fractional Chern-insulator state in zero magnetic field.[15] That class of twist-angle materials also includes the alternating multilayers—for example, magic-angle, mirror-symmetrical twisted tri-, quadruple-, and quintuple-layer graphene—whose superconducting state is believed to have a spin-triplet pairing.

It is also possible to create moiré flat bands without any twisting of the layers. One such way is by stacking and aligning layers of different materials, which produces a moiré lattice because of the mismatch between the different crystal species. Those stacked systems include graphene sheets on hexagonal boron nitride substrates, bilayers of $WSe_2/WSe_2$, and $MoTe_2/WSe_2$, in which a Kondo lattice state was observed that shows highly localized and magnetically ordered heavy fermions on the moiré lattice sites,[16] similar to MATBG.

Van der Waals engineering further allows alteration of materials properties by, for example, inducing strong spin–orbit coupling through the introduction of heavy element layers, such as $WSe_2$.[17] It is also possible to introduce close-by metallic layers, which can be used as electrostatic gates and as screening layers,[5] which reduce the Coulomb interaction. Additionally, it is possible to tune the band structure by applying strong out-of-plane electric fields. In some moiré-free stacked bi- and trilayer graphene sheets, that dramatically flattens the bands and induces strong interactions and superconductivity.[18] The absence of the moiré superpotential and critical temperatures that are two orders of magnitude lower than MATBG, however, could mean that the nature of those states is distinct from its moiré counterparts.

als. Electrons in the strange-metal phase also have an extremely high electron-scattering rate, with an upper limit dictated by the Heisenberg uncertainty principle. Such a strange-metal phase is often found close to a quantum critical point in the vicinity of magnetically driven zero-temperature phase transitions (see the article by Subir Sachdev and Bernhard Keimer, Physics Today, February 2011, page 29).

In MATBG, the characteristic Planckian-limited linear-in-temperature resistivity was found down to the extremely low temperature of 40 mK and over a range of filling factors.[3,6,12] At elevated temperatures, a linear-in-temperature resistivity would not be too surprising, as one is also found in noncorrelated single-layer graphene devices above 10 K, where it is a result of conventional electron–phonon interactions.

The persistence of the linear scaling down to millikelvin temperatures in MATBG, however, makes a similar scenario quite unlikely, as phonons at such low temperatures are effectively frozen out. That behavior points rather to the existence of a quantum critical point and the prevalence of strong electron–electron interactions. An understanding of how electrons interact with each other in the strange-metal phase can likely shed light on the origin of all the other low-temperature phases, because the strange-metal phase acts as their "parent phase." In particular, the superconducting phase directly nucleates from the strange-metal phase.

## A heavy-fermion picture

The striking similarities between the phenomenology of MATBG and other strongly correlated systems have found a solid theoretical foundation, and the physics of the MATBG

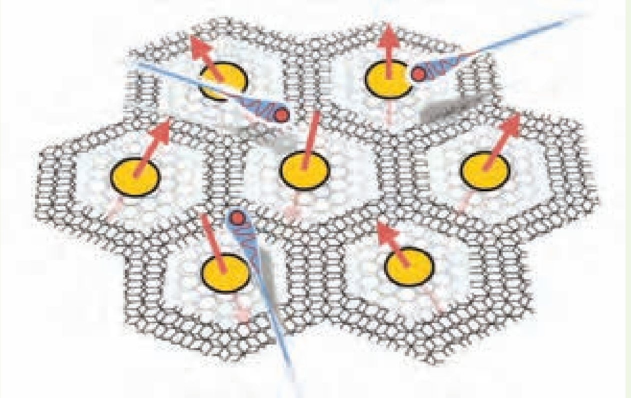


**FIGURE 3. IN A TOPOLOGICAL HEAVY-FERMION MODEL** of magic-angle twisted bilayer graphene, electrons can have light or heavy effective masses. Heavy fermions (yellow dots) remain localized in the moiré lattice, while light fermions (red dots with blue tails) move freely though the crystal lattice. (From ref. 14.)

low-energy manifold of states can be understood through several approaches. Two initial complementary strategies have been proposed to provide a theoretical basis for understanding the strongly correlated and topological MATBG bands. One is to construct extended Hubbard models in which the symmetries are represented nonlocally in real space. The other is to adopt a full momentum-space formalism, which hides the local nature of the interactions. Neither of the approaches, however, could easily explain the presence of two carrier types with local and itinerant moments.

Recently it has become possible to write down a fully symmetric model with a simple real-space picture that remarkably and elegantly explains the ground states of MATBG and their topologies.[13] The interacting MATBG can be reformulated as an effective topological heavy-fermion system consisting of local *f* orbitals and delocalized topological conduction bands (*c*). As illustrated in figure 3, the *f* electrons are so localized that they have a kinetic energy of only about 0.1 meV, but they have a strong on-site Coulomb repulsion, computed to be about 60 meV. The *c* electrons, however, carry the symmetry anomaly and have unbounded kinetic energies. The actual flat bands emerge from a hybridization between the *f* and *c* bands, and several types of interactions also couple the *f* and *c* electrons. With that understanding, scientists can explain the coexistence of quantum-dot-like behavior and superconductivity: They come from two different types of carriers (*f* and *c*).

## Challenges and opportunities

The simultaneous occurrence of all those phases and the ability to modulate between them by simply applying a voltage have positioned MATBG as one of the richest and most tunable materials platforms in condensed-matter physics. MATBG also established the novel concept of twisting of materials as a simple but extremely powerful technique to dramatically alter materials properties and to induce strong electron correlations and topology in a large variety of systems. (For more on the engineering of other van der Waals materials, see box 2.) Those innovations have been achieved in a highly controllable, albeit detail-sensitive, system environment, and currently the community is struggling to grasp the full details of the MATBG's colorful phase diagram.

The complex quantum phases of MATBG create both an unprecedented opportunity to crack the mysteries of strong-coupling superconductivity and unprecedented challenges in understanding the myriad phases of the system. A plethora of different possible ground states arise from the combination of broken-symmetry phases and crystallographic symmetry operations, intertwined with nuances in twist angle, dielectric environment, strain, disorder, and other material properties. The details of the experimental findings finely depend on the competition between all the different orders that are closely adjacent to each other, which results in different phase diagrams for different samples. The ultimate challenge is to find a unified formalism that both explains all the possible phases and points out universal features of the problem.

Meanwhile, each year researchers discover more and more novel 2D flat-band platforms with seemingly similar many-body phases. Among those discoveries have been the transition-metal-dichalcogenide moirés and the crystalline nonmoiré graphene multilayers. The many material platforms enabled by van der Waals materials and their degree of controllability allow for significant progress in the coming years.

The intriguing link between MATBG and heavy-fermion physics offers a bridge between two formerly disjointed communities. The machinery of heavy fermions—including dynamical mean-field theory—can now be applied to the physics of MATBG. Van der Waals moiré materials also provide an avenue for controllable tests of heavy-fermion physics and possibly their quantum critical points, in ways that the doping of 3D crystals cannot. The interplay between topology, interaction, heavy fermions, and superconductivity is a fundamental strength of MATBG research, which promises to provide an exceptional range of discoveries in the future.

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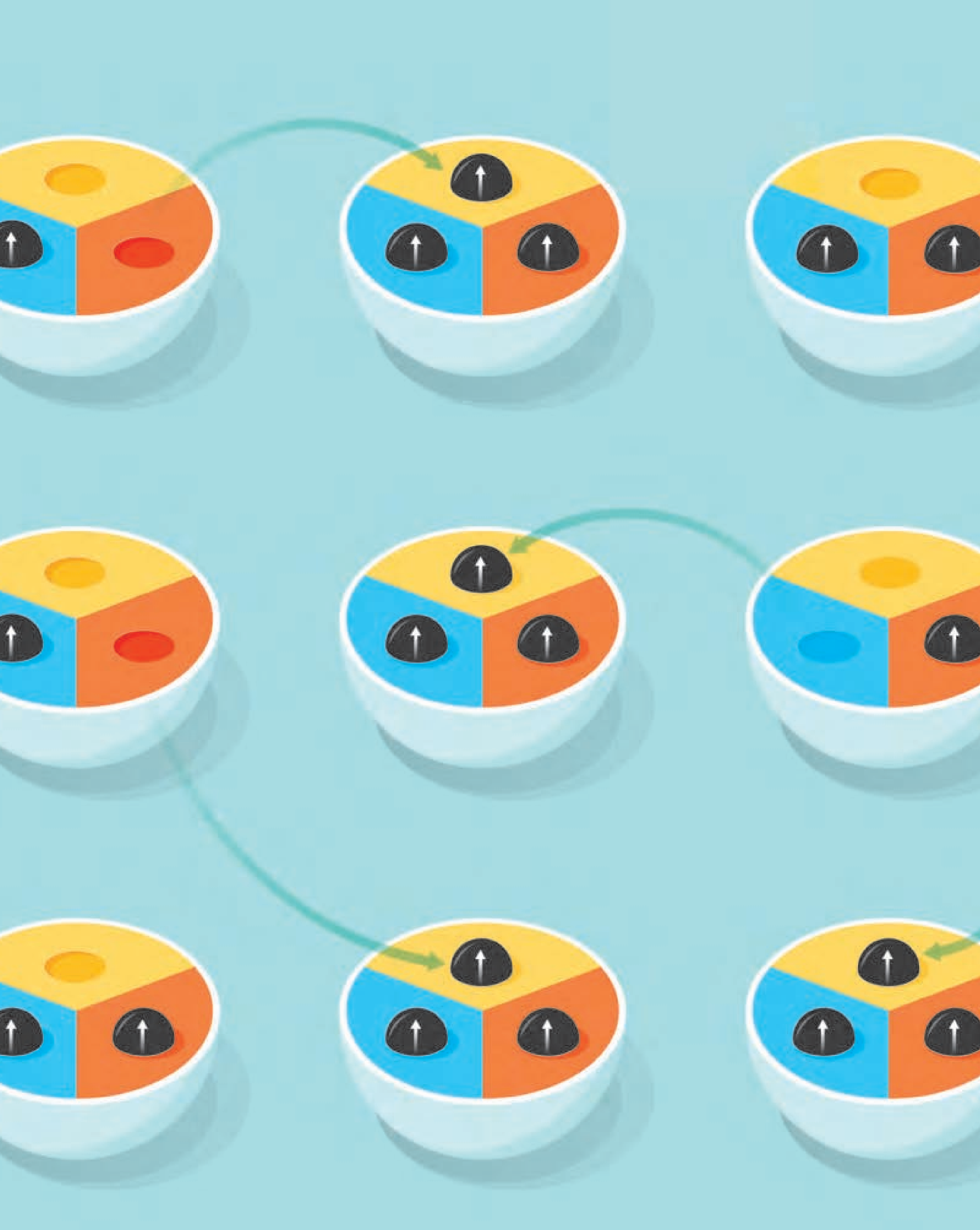


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# The Hund-metal path to strong electronic correlations

Antoine Georges and Gabriel Kotliar

**A new type of metal has taken the scientific community by surprise. Classic concepts from atomic physics—the electrons' orbitals and spin alignment—are key to understanding it.**

Electrons in solids can behave independently from one another or as collective team players, whose interactions result in emergent cooperative phenomena such as magnetism, metal–insulator transitions, and unconventional superconductivity, to name a few. That team behavior happens in so-called strongly correlated materials that raise fundamental science questions, offer promising technological applications, and have given birth to a whole subfield of condensed-matter physics.

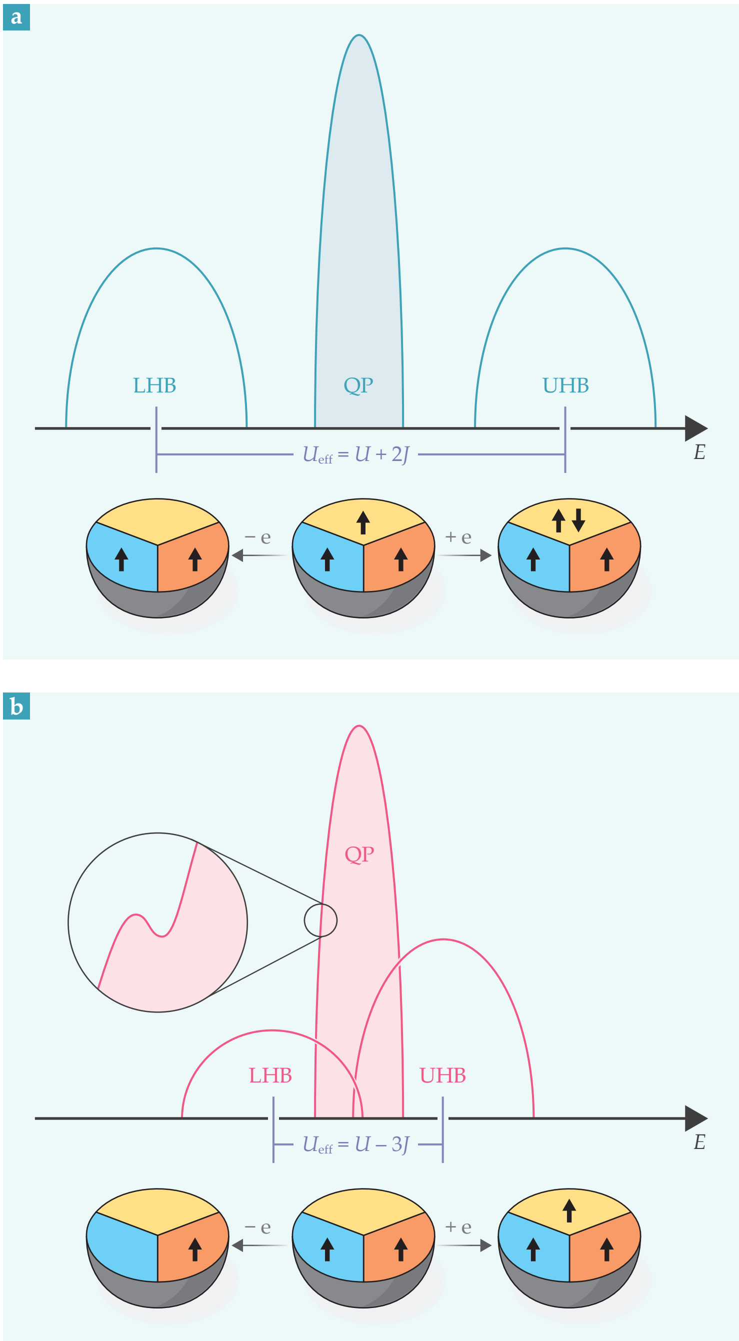


**FIGURE 1. EXCITATIONS** in three-orbital systems with **(a)** three electrons (a half-filled shell) in the ground state and **(b)** two electrons. Each electron is in a different orbital with parallel spins (bottom panels), in accordance with Hund's rules. Removing or adding an electron produces a lower Hubbard band (LHB) and an upper Hubbard band (UHB) in the total density of states, plotted in the upper panels as a function of excitation energy *E*. The LHB and UHB are separated by an energy $U_{eff}$, the effective Coulomb interaction, which depends on the repulsion *U* for electrons in the same orbital and on the Hund coupling *J*, the energy change from aligning electron spins. For metals, the spectrum also contains low-energy quasiparticle (QP) excitations. When the Hund coupling is large, those excitations can overlap the Hubbard bands for non-half-filled shells. In such Hund metals, the QP peak has a substructure (inset).

In weakly correlated materials, such as simple metals and semiconductors, electrons reside in extended orbitals and have a large kinetic energy. One can think of their quantum state in terms of independent waves that are delocalized through the solid and have an energy spectrum organized into bands. In contrast, electrons in strongly correlated materials reside in more localized orbitals; hence it is more natural to think of their quantum states in terms of correlated particles residing near the nuclei.

Strong-correlation phenomena abound not only in materials with partially filled *d* and *f* shells, such as transition metals, rare earths, and actinides, but also in organic materials where electrons reside in molecular orbitals. The degree of correlation is usually controlled by pressure, stress, or doping. Recently, multilayers of 2D materials, such as graphene and transition-metal dichalcogenides, were turned into strongly correlated systems by twisting or misaligning the layers and applying gate voltages. (See the article by Andrei B. Bernevig and Dmitri K. Efetov on page 38.)

Different families of materials follow distinct routes to strong-correlation physics. In so-called Mott insulator systems, the Coulomb repulsion of electrons impedes their motion and blocks their kinetic energy. Materials in the heavy-fermion family have two fluids of electrons, which live rather independent lives at high temperatures: mobile electrons and localized *f* electrons that form local magnetic moments. At very low temperatures, the hybridization, or quantum mechanical mixing, between those two species of electrons becomes relevant. Then a single fluid of itinerant, albeit slowly moving, "heavy" electronic quasiparticles emerges below a characteristic scale known as the Kondo temperature.

This article focuses on a new perspective that describes a broad family of materials whose properties cannot be understood within either the Mott or the heavy-fermion paradigms. Those materials display obvious signs of strong correlations, but unlike Mott systems, they have mobile electrons; unlike simple metals, they have local moments; and unlike heavy fermions, they involve a single fluid of electrons. As we describe below, a key concept needed to understand the puzzling materials is what's known as Hund's-rule coupling—the lowering of the Coulomb repulsion that accompanies the placement of two electrons of parallel spins in different orbitals.[1]

The theory of what are now called Hund metals, a term coined in 2011,[2] was launched by two pioneering papers that applied dynamical mean-field theory to the study of the normal state of iron-based superconductors[3] (see the article by Qimiao Si and Nigel Hussey, Physics Today, May 2023, page 34) and to the celebrated three-band Hubbard–Kanamori model—a simplified Hamiltonian that captures the essence but not the specifics of strongly correlated systems.[4]

Researchers soon realized that a large, and still growing, family of compounds fits within the new paradigm.[2,5] Prominent members of that family are the ruthenium oxides, includ-

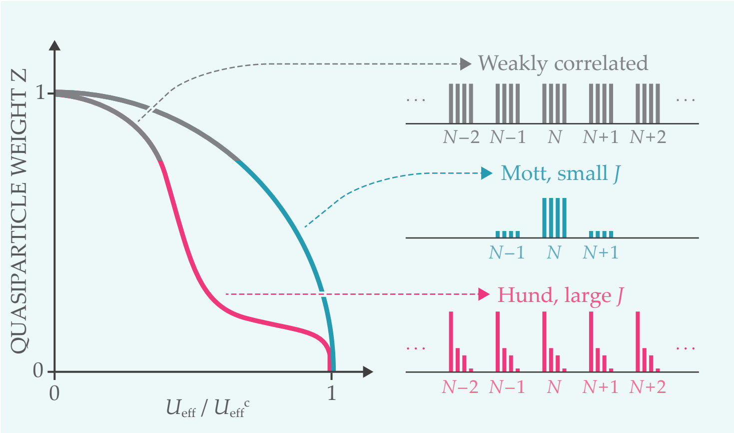


**FIGURE 2. THE QUASIPARTICLE WEIGHT *Z***—the probability that an electron removed or added to the ground state will be in a quasiparticle state—depends on $U_{eff}/U_{eff}^c$, the ratio of the effective Coulomb energy $U_{eff}$ to the critical value $U_{eff}^c$ at which the metal–insulator transition takes place. The plot compares three cases: a weakly correlated metal (gray), a strongly correlated metal close to the transition (blue), and a metal with substantial Hund coupling (pink). The Hund-metal regime has a characteristic plateau[5] of $Z$ versus $U_{eff}/U_{eff}^c$. The histograms display the probability of different atomic configurations in the ground state. In the weakly correlated metal, each atomic configuration is equally likely ($N$ refers to the number of electrons). But in the Hund-metal regime, the most likely atomic configurations are those (the prominent spikes) in which electron spins are aligned.[3]

ing the superconductor $Sr_2RuO_4$ and the antiferromagnet $Ca_2RuO_4$. Their puzzling thermodynamic and transport properties and intricate phase diagrams have been studied since the mid 1990s, but a consistent physical picture of their normal-state properties and the key role played by Hund coupling have only emerged in the past dozen years.[6]

The modern development of the Hund-metal picture now explains the odd coexistence of itinerant and localized behaviors first noticed in photoemission studies of $V_5S_8$ by Atsushi Fujimori and coworkers[7] and has shed additional light on classic experiments showing enormous variations in the Kondo scale of different magnetic atoms embedded in a metallic host.[8] In this article we present in a pedagogical fashion the insights into Hund metals that have emerged. For a more detailed exposition, see review articles and references.[9,10]

## Atomic shells

An atomic shell with orbital angular momentum $L$ has $M = 2L + 1$ orbitals corresponding to the possible values of the magnetic quantum number $L_z$. Orbital degeneracy is lifted by the crystalline environment and produces distinct subshells. Figure 1 illustrates two cases of a subshell with $M = 3$ orbitals. Figure 1a describes a model for a metal in the Mott regime, with $N = 3$ electrons in the ground state (a half-filled shell). Figure 1b describes a model Hund metal with $N = 2$ electrons, a situation relevant to $Sr_2MoO_4$ and, exchanging electrons and holes, $Sr_2RuO_4$. The electronic configuration of an atomic shell is determined by two key energy scales: the so-called Hubbard energy $U$ and the Hund coupling $J$.

When two electrons with opposite spins occupy the same orbital, they feel the largest repulsive interaction $U$, the effective Coulomb interaction screened by the solid-state environment. By contrast, if two electrons occupy different orbitals, their effective repulsion is smaller—equal to an energy $U' < U$ if they have opposite spin, and equal to $U' - J$ when they have parallel spin. The Hund coupling $J$ is the intra-atomic exchange interaction. Think of it as the energy gained by the material when its electron spins are aligned. When spherical symmetry exists, $U' \simeq U - 2J$, and the interactions in decreasing order are $U$, $U - 2J$, and $U - 3J$.

Given the magnitude of those interaction terms, the lowest-energy configuration of $N$ electrons in an atomic shell with $M$ orbitals follows these rules: If $N$ is smaller than $M$—that is, the shell is less than half filled—each electron occupies a different orbital and all have parallel spins, hence a total spin $S=N/2$. If $N = M$ (a half-filled shell), all orbitals are singly occupied, with maximal spin $S = M/2$. And if $N$ is larger than $M$, $N - M$ orbitals must be doubly occupied, while the remaining spins are aligned, hence a total spin, $S = M - N/2$. Those statements illustrate the more general rules formulated in 1925 by Friedrich Hund.[1] For a simple picture of Hund's rules, think of a bus with rows of two seats each. If possible, passengers (electrons) will typically spread out so that the seat next to them is empty.

The Hubbard energy $U$ penalizes charge imbalance. It is the main player in Mott and heavy-fermion materials. It blocks charge motion, promotes localization in Mott systems, and reduces the hybridization in heavy-fermion materials. In Hund metals, by contrast, the Hubbard repulsion is too small to localize electrons. Those materials' key parameter is $J$, which forces the electrons to adopt a collective configuration with the largest possible spin as they hop around and induces strong correlations. In a nutshell, Mott insulators, heavy-fermion compounds, and Hund metals are all correlated materials, but their electron correlations arise from constraints on charge, hybridization, and spin, respectively.

In a solid, an atomic configuration with one extra electron added to the ground state can move around. That excitation is known as the upper Hubbard band. Similarly, excitations with one less electron form the lower Hubbard band, as shown in figure 1. The bands can be viewed as atomic transitions broadened by the solid-state environment. The electron removal or addition can be measured by photoemission.

The so-called Mott gap between the lower and upper Hubbard bands is controlled by the energy cost $U_{eff} = E_0(N + 1) + E_0(N - 1) - 2E_0(N)$ required to transfer a single electron from one atom to another, where $E_0(N)$is the atomic energy when the atom has $N$ electrons. For a half-filled shell, one finds $U_{eff} = U + 2J$, and increasing the Hund coupling also increases the Mott gap. That explains why many materials with a half-filled shell are Mott insulators. But for a non-half-filled shell, $U_{eff} = U' - J \simeq U - 3J$, and the Mott gap decreases when $J$ is increased. As a result, $J$ promotes metallicity by increasing the overlap between the Hubbard bands. Those effects were pointed out early on by Dirk van der Marel

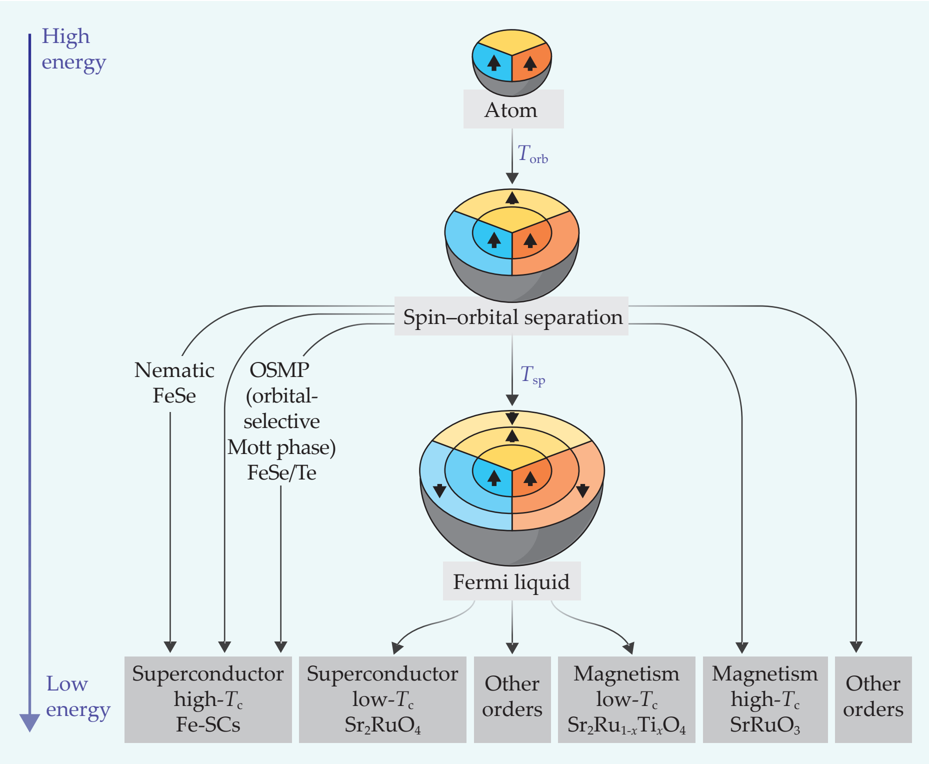


**FIGURE 3. EVOLUTION** of a material's active degrees of freedom as a function of energy. It goes from a high-energy regime (top), in which atoms fluctuate between different atomic configurations, to a low-energy regime (bottom), in which coherent quasiparticle excitations emerge. The dynamical mean-field description of the process is depicted here as an onion-like sequence of effective energy shells added to the isolated atom, pictured at top. In Hund metals, the quenching of orbital and of spin fluctuations occurs at distinct temperatures $T_{orb}$ and $T_{sp}$, respectively. Between $T_{orb}$ and $T_{sp}$, the spin–orbital separated regime, the orbitals are quenched but a higher spin ($S = 3/2$ here) remains. At low energy, the so-called Fermi-liquid regime, all orbitals and spin states are effectively filled by an equal number of electrons so that the atomic degrees of freedom no longer fluctuate. A large diversity of symmetry-breaking instabilities and long-range orders, such as superconductivity and magnetism, may emerge out of either regime.

and George Sawatzky[11] and by Fujimori and colleagues.[7]

In metals, additional excitations, called Landau quasiparticles, exist at low energy. Those quantum states are waves with a well-defined momentum that are delocalized throughout the solid. The occupied and unoccupied states are separated by a boundary in momentum space known as the Fermi surface. Interactions can strongly reduce the velocity of the quasiparticle states near the Fermi surface, which enhances the effective mass of the excitations.

The quasiparticle weight $Z$ is the probability of an electron being in a quasiparticle state when it is removed from (or added to) the ground state of the solid, as probed in photoemission. In a weakly correlated material, most of the excitations are quasiparticles, and $Z$ is close to unity (see figure 2). A small value of $Z$ thus is an indication of strong correlations. In metals close to the Mott-insulator transition, quasiparticles emerge between Hubbard bands. But in Hund metals, the quasiparticle excitations emerge from overlapping Hubbard bands, as shown in figure 1b.

## Dynamical mean-field theory

For strongly correlated materials, a serious revision of the "standard model" of solid-state physics, which focuses solely on quasiparticles, is needed. Instead of adding correlations to an electron gas, a proper description of a correlated solid begins with the many-body eigenstates (so-called atomic multiplets) of individual atoms, which constitute a sizeable part of the excitation spectra at energies up to several electron volts.

Think of a strongly correlated material as a collection of atomic many-body systems that exchange electrons. That perspective is central to dynamical mean-field theory (DMFT). For reviews, see reference 12 and the article by one of us (Kotliar) and Dieter Vollhardt, Physics Today, March 2004, page 53.

DMFT focuses on the sequence of quantum jumps between electronic configurations of the atoms as electrons hop between them. It describes that process as the emission and absorption of electrons between an atom and an effective self-consistent bath representing the rest of the solid. The theory details whether, how, and when quasiparticles then emerge at low energy. In $Sr_2RuO_4$, for example, Landau's Fermi-liquid regime—characterized by long-lived, coherent quasiparticles—is formed only below a temperature $T_{FL} \sim 25$ K, which corresponds to an energy scale of about 2 meV.

## Hund metals

Figure 2 illustrates three metallic regimes: a weakly correlated metal with $Z$ close to unity and two strongly correlated metals with a small value of $Z$—one in the Mott regime and one in the Hund-metal regime. When the Hund coupling is sizable and the shell is neither singly occupied nor half filled, the dependence of $Z$ on $U_{eff}$ exhibits a plateau. Hence an extended regime displays strong correlations while the system is not close to the Mott metal–insulator transition.

The Hund coupling is two-faced: On the one hand, it pushes the Mott transition to larger values of $U$; on the other hand, it leads to an extended, strongly correlated metallic regime by decreasing $Z$ and enhancing the quasiparticle effective mass.[5]

A useful diagnostic of the different regimes is a histogram of the relative weights associated with each atomic configuration in the ground state of a given material. It is what an observer embedded in the solid at a given atomic site would record by measuring the time that an atom spends in each atomic configuration. As depicted in figure 2, the histogram for a weakly correlated metal extends over

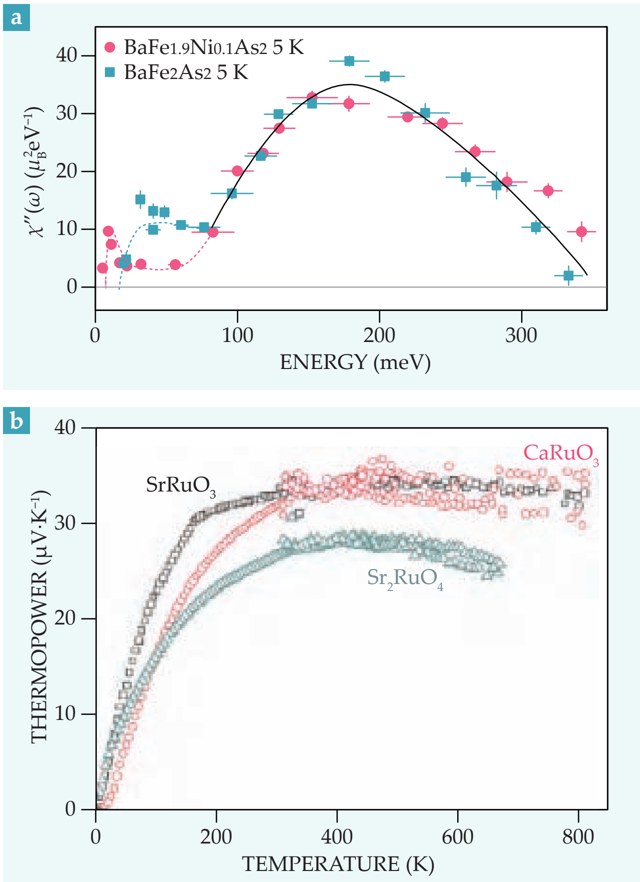


**FIGURE. 4. SIGNATURES OF HUND METALS. (a)** The energy dependence of the momentum-averaged imaginary part of the magnetic susceptibility $\chi''$ is shown for antiferromagnetic $BaFe_2As_2$ at $T = 5$ K and for 5% nickel-substituted $BaFe_2As_2$, a superconductor, at 5 K. Unlike the low-energy spectrum, the high-energy spectrum (above 80 meV) is only weakly doping dependent. (Adapted from ref. 14). **(b)** The Seebeck coefficient, or thermopower, is plotted as a function of temperature for $SrRuO_3$, $CaRuO_3$, and $Sr_2RuO_4$. The rather universal value of the plateau above 200 K is due to fluctuating spins. The orbital degrees of freedom, by contrast, do not fluctuate. (Adapted from Y. Klein et al., ref. 15.)

many charge configurations and atomic multiplets. In the Mott regime, it is concentrated on a single charge state $N$ with small contributions from $N \pm 1$. For a Hund metal, the histogram extends over many charge states, but it is dominated in each by multiplets with large spin and angular momentum, consistent with Hund's rules. Hence it provides a direct signature of "Hundness."[3]

## Go with the flow

Figure 3 illustrates the evolution of a material's active degrees of freedom as a function of energy scale, or "flow" in renormalization-group parlance, from a high-energy regime with fluctuating electron spins and orbitals associated with atomic multiplets to a low-energy regime, where the degrees of freedom reorganize into itinerant quasiparticles. DMFT describes that process as the gradual "binding" of bath electrons to specific atomic orbital and spin degrees of freedom. Powerful renormalization-group analyses by two groups—a collaboration between Ludwig-Maximilian University in Munich, Brookhaven National Laboratory, and Rutgers University and a team from the Jožef Stefan Institute in Ljubljana, Slovenia—have recently provided a theoretical understanding and numerical computation of the flow.[13]

As illustrated in figure 3, the flow involves two distinct crossover temperatures: a higher one, $T_{orb}$, at which the local orbital degrees of freedom become mobile, and a lower one, $T_{sp} = T_{FL}$, at which the spin degrees of freedom become coherent and delocalized, corresponding to the formation of a Fermi liquid. That spin–orbital separation (SOS) can lead to a distinctive feature in one-particle spectra.[13]

In the SOS regime, which is a hallmark of Hund metals, the spins are quasi-localized, or "frozen" on intermediate time scales,[4] leading to a Curie–Weiss temperature dependence $\chi \sim 1/(T + T_0)$ of the local magnetic susceptibility with a tiny value of $T_0$. In contrast, the orbital and charge degrees of freedom are itinerant and the corresponding susceptibilities are temperature independent.

## Smoking guns

Inelastic neutron scattering is an important experimental tool in the SOS regime because it directly probes the nature of the spin excitations. The frequency-dependent imaginary part of the spin susceptibility, averaged over wavevectors, is related to the density of states of spin excitations. Multiplying it by a Bose factor and integrating it over frequency gives the size of the fluctuating local moment. Figure 4a displays it for two members of the iron-based superconductor "122" family.[14]

The high-energy part of the susceptibility and the fluctuating local moment do not vary much from one family member to another or as the temperature is changed. The low-energy part, however, displays a strong temperature and material dependence: Undoped $BaFe_2As_2$, for example, undergoes a transition to a stripe phase, whereas the nickel-doped compound becomes superconducting.

Those examples illustrate the large diversity of possible long-range orders at the low-energy end of the flow shown in figure 3. The ordering can emerge in two ways—either at $T < T_{FL}$ as a low-temperature instability of the Fermi liquid because of interactions between coherent quasiparticles, or at $T > T_{FL}$ as an instability of the less-coherent Hund metal. The latter case is hard to treat with textbook many-body methods and requires a framework, such as DMFT, for its description.

An example of the low-temperature instability is seen in $Sr_2RuO_4$: It undergoes a superconducting transition at $T_c \sim 1.4$ K, well below the onset of the Fermi-liquid regime at 25 K. Above $T_{FL}$, the material enters the SOS regime. The ferromagnet $SrRuO_3$ and the nematic superconductor FeSe are examples of materials that order above $T_{FL}$.

At intermediate temperatures or energies, $Sr_2RuO_4$, $SrRuO_3$, and other members of the ruthenate family display characteristic features of Hund metals. Resonant inelastic x-ray scattering measurements performed by Hakuto Suzuki and colleagues in Bernhard Keimer's group at the Max Planck Institute for Solid-State Research in Stuttgart, Germany, in 2023 provide direct experimental evidence of the separation of energy scales associated with orbitals and spins in $Sr_2RuO_4$.

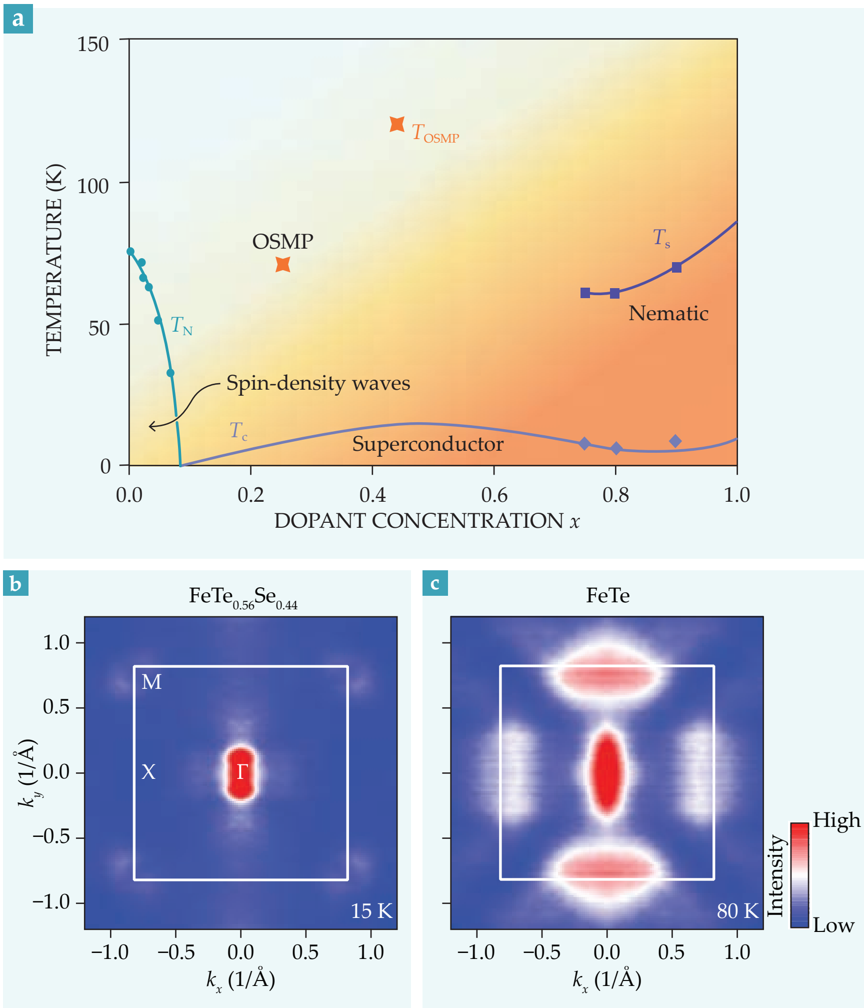


**FIGURE 5. ORBITAL-SELECTIVE** phenomenon in $FeTe_{1-x}Se_x$. **(a)** The material's phase diagram as a function of dopant concentration *x* and temperature *T*. The two orange points mark the boundary of the orbital-selective Mott phase (OSMP), in which one orbital no longer hybridizes with the others. A lighter color indicates a lower degree of quasiparticle coherence. **(b)** The Fermi surface of $FeTe_{0.56}Se_{0.44}$ in momentum space at 15 K for the correlated metallic phase. **(c)** For FeTe at 80 K in the OSMP, pockets at the Fermi surface around the X point in the Brillouin zone emerge from the dehybridization of the $d_{xy}$ orbital. Those dramatic differences, which are produced by variations in *x* or *T*, are signatures of the orbital differentiation. (Images adapted from ref. 18, courtesy of Ming Yi and Jianwei Huang.)

Evidence given by the Seebeck effect has shown that spins fluctuate in the SOS regime but orbitals do not. The effect measures the electrical potential drop when a sample is subject to a thermal gradient, and its value can be related to the entropy of fluctuating degrees of freedom in the material. The Seebeck coefficient of three ruthenates is shown in figure 4b. It increases linearly at low temperature, as expected in a Fermi-liquid metal, but at higher temperature it reaches a plateau with a value around 30 μV/K that depends only weakly on the compound.

As noted by Yannick Klein, Sylvie Hébert, and coworkers from the CRISMAT laboratory in Caen, France, and confirmed by DMFT calculations,[15] that value can only be explained by considering that the spin degrees of freedom fluctuate while the orbital ones do not. Hence spin entropy provides the only contribution to the Seebeck coefficient. Inelastic neutron scattering experiments also reveal the presence of fluctuating local moments in $Sr_2RuO_4$, as signaled by a component of the magnetic response that depends weakly on momentum. As shown by DMFT, these local spin fluctuations are associated with Hund physics.[16]

## Orbital differentiation

While the concept of Hund metals was emerging, it became clear that Hund coupling plays a key role in promoting orbital differentiation—the emergence of a large difference in the degree of correlations among otherwise similar orbitals. The phenomenon is especially relevant to iron-based superconductors.[17] Groups led by Séamus Davis and Zhi-Xu Shen observed it using different experimental probes—scanning electron microscopy and angle-resolved photoemission, respectively. Figure 5, based on experiments on $FeTe_{1-x}Se_x$ from Ming Yi's group at Rice University in Houston, Texas, illustrates the phenomenon.[18]

As the tellurium-rich end of the phase diagram is approached, the electrons residing in the $d_{xy}$ orbital become heavier and more incoherent than those in the other *d* orbitals, as predicted by DMFT calculations.[2] Eventually the system enters an orbital-selective Mott phase (OSMP), an extreme form of orbital differentiation in which the $d_{xy}$ orbital is so incoherent that its dispersion cannot be observed, while the other remaining *d* orbitals still form itinerant quasiparticle bands. The panels in figure 5 reveal a dramatic change of the Fermi surface. In the OSMP regime, hybridization of the $d_{xy}$ orbitals with other orbitals turns off, which changes the quasiparticle dispersions. In figures 5b and 5c, for example, new Fermi-surface sheets emerge around the X point of the Brillouin zone.

## Outlook

The crucial role played by the Hund coupling in inducing strong electronic correlations is relevant to many more materials than the ones discussed in this article. Hund physics may actually occur in combination or in competition with other important factors, such as the proximity of a van Hove singularity—a region of momentum space with vanishing electronic velocity—as in $Sr_2RuO_4$,[9] and the emergence of Mott physics, for example, when iron-based superconductors are brought closer to a half-filled $d^5$ shell by hole doping.[10]

In all cases, it is essential to think in terms of the dynamical fluctuations between different many-body atomic configurations to describe Hund metals. They provide some of the most beautiful illustrations of the DMFT concept. As we have argued, DMFT provides a deep understanding of strongly correlated materials by describing the flow from fluctuations between atomic configurations at high energy to emerging, coherent quasiparticles at low energy.

Along with that conceptual framework and in combination with electronic-structure methods, DMFT offers a powerful framework to calculate and predict thermodynamic, transport, and spectroscopic properties of correlated materials, starting from their structure and chemical composition. Indeed, an extraordinary number of successful comparisons between experimental studies and materials-specific calculations by groups across the world have provided evidence of the crucial role of Hund physics.

The challenges for researchers are to understand how instabilities, such as high-temperature superconductivity, emerge out of a metallic state in which a description in terms of long-lived coherent quasiparticle excitations is not applicable and also to extend computational methods to reach lower energies and address fluctuations over long length scales.

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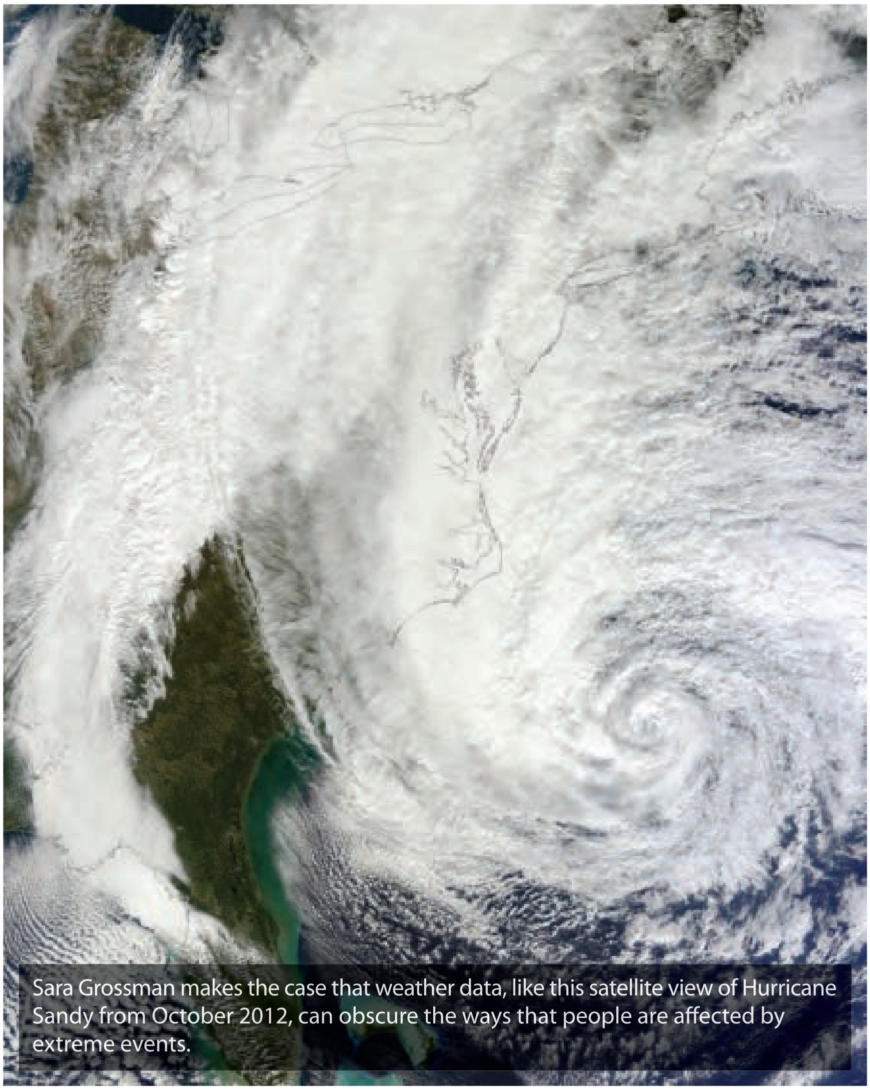


LANCE MODIS RAPID RESPONSE TEAM AT NASA GSFC

Sara Grossman makes the case that weather data, like this satellite view of Hurricane Sandy from October 2012, can obscure the ways that people are affected by extreme events.

# The sinister side of weather data

## Immeasurable Weather

### Meteorological Data and Settler Colonialism from 1820 to Hurricane Sandy

**Sara J. Grossman**

Duke U. Press, 2023. $104.95

Data are not neutral. That argument has gained currency over the last several decades as various disciplines have come to terms with the fact that knowledge is produced at unequal institutions and with unequal results. Meteorology, historically, has been no exception.

In *Immeasurable Weather: Meteorological Data and Settler Colonialism from 1820 to Hurricane Sandy,* Sarah Grossman contends that data did more than just detail precipitation or temperature during the origins of American meteorology. In a volume that covers the data-collection efforts of meteorologists—like the work of Joseph Henry organizing a nationwide system for weather measurements and the launching of the first meteorological satellites—Grossman shows that American settler colonists used weather data to distance themselves from the world around them. Data obscured human–environment relations, making environments into something to be studied and optimized, rather than understood in a network of mutual obligations with humans. Grossman, in line with the field of settler colonial studies, defines "settlers" as "white populations who historically dispossessed, or who participate in the present-day dispossessions of, Indigenous peoples from their homelands across the United States, and who participated—or whose ancestors participated—in systems of enslavement."

Environmental data helped American settler scientists form their understanding of what their "nation" and its boundaries actually were—with new weather stations sometimes driving the occupation of uncolonized regions. By positioning weather observers as objective and settlers and statistics as the only relevant frames for relating to the environment, American scientists used those data to understand their land and see Indigenous history and knowledge systems as irrelevant. Meteorology was not alone in that, but its history is utterly entangled with that of settler ideology in the 19th and 20th centuries.

It might surprise some readers that Indigenous peoples barely figure into Grossman's narrative at all. Instead, she focuses on the legacies of settler colonialism that endured long after any active conflict. The processes of violent erasure and intentional forgetting made Americans less likely to feel indebted to or responsible for the environments they seized, with catastrophic consequences. That analysis fits *Immeasurable Weather* firmly into a growing body of historical work on settler colonialism, both as one of the principal structuring forces in American history and as an ongoing phenomenon.

The book also excavates an omnipresent gender inequality built into every level of the science. As early government weather observers were sparse, the National Weather Service and its precursors in the mid 19th century relied on voluntary data collection by settlers to get more consistent observational coverage across the country. Central offices consistently and quickly gave instruments and forms to the men who volunteered as observers and ignored requests for equipment from women, even when the latter proved more reliable. Women serving as computers—cleaning and curating data in the national offices—were seen as a liability to institutional culture. At times sequestered in the basement, women were eventually entirely removed from the offices through ostensibly "meritocratic" measures. Those problems with 19th century data collection, Grossman notes, continued into the 20th century.

*Immeasurable Weather* also explores the way that notable natural disasters bring such issues to the forefront. The Dust Bowl, for example, juxtaposed two puzzles. First, how should airborne dust be quantified: as cloud, precipitation, or something else? Second, the worst-stricken counties lay far from the densest lines of official observers, which were along former railroad trunk lines and military fortifications. The most-affected settlements thus had minimal capacity to grapple with the problem, forcing US authorities to again rely on volunteer observers. Largely because settlers did not recognize that their agricultural practices helped produce dust storms, the settler imagination struggled to deal with the novel catastrophe—an apt (and concerning) historical analogue for climate catastrophe.

In her final chapter, Grossman connects the rising use of computer and satellite imagery to the long history of the settler colonial state. Satellites, she argues, have continued and amplified the abstraction and obscuring of human relationships with the environment as well as the partnership of meteorologists and the military. Satellite photography has aided in military planning and resource extraction, both inside the US and globally. But in Grossman's telling, one of satellites' most complicated effects lies in how they turn deadly storms and messy data into aesthetic creations. As images of storms spread online, they become objects of awe.

"Put another way, the messiness of environmental data (and the nation-state relation to it) seems to melt away when these images circulate as aesthetic—beautiful and terrifying—visions," Grossman writes. The culprits behind intensifying storm systems, the use of meteorological technology to maintain the nation-state, and the unequal harms of storms' destruction are all hidden by the repackaging of environmental data into mesmerizing GIFs. The flaws in settler knowledge production are only magnified in an era of anthropogenic climate change. As Grossman puts it, "The visual response to Hurricane Sandy manifests not a failure at 'imaging' better relations between the US settler state and nature but a failure to imagine any affective relation at all."

*Immeasurable Weather* is a timely addition to the study of meteorology's formative decades. Its introduction of settler colonialism as an analytical frame to the history of that field is both an interesting and valuable perspective. Perhaps the only area I might have wished to see unpacked a little more is the link between early weather observation and the military—while that has been partially explored before, it surely merits some space in an analysis about settler colonialism and its ties to weather and data. Otherwise, the book surely ought to find its way onto the shelf of anyone interested in the evolution of US meteorology, the history of settler colonialism and American nation building, or data in the history of science more generally.

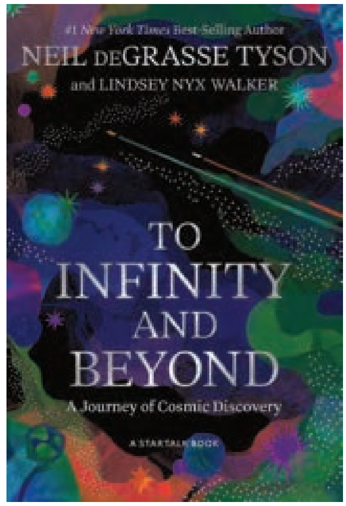
**Robert Suits**
*University of Edinburgh*
*Edinburgh, UK*

# NEW BOOKS & MEDIA

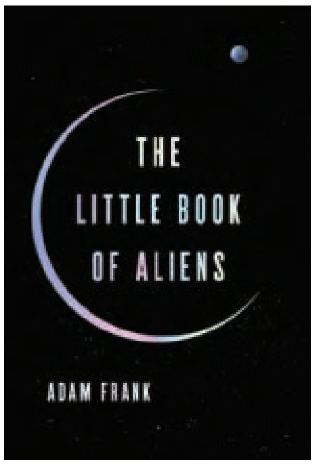
## To Infinity and Beyond

### A Journey of Cosmic Discovery

**Neil deGrasse Tyson and Lindsey Nyx Walker**
National Geographic, 2023. $30.00



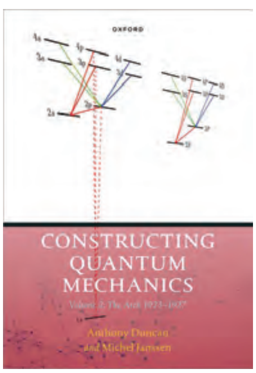

The evolution of human thought about Earth, the solar system, and the universe is the subject of this recent book by astrophysicist Neil deGrasse Tyson and *StarTalk* senior producer Lindsey Nyx Walker. As evidenced by 40 000-year-old cave paintings depicting constellations, humans have long been aware of the cosmos. In *To Infinity and Beyond*, the authors begin with the history of humans striving to understand the physical laws governing Earth, before they move on to what we've learned about other planets, stars, and galaxies. Combining science, pop culture, and humor, the book aims to educate and entertain readers. —CC




## The Little Book of Aliens

**Adam Frank**
Harper, 2023. $27.99

Do aliens exist? If so, how would we find out? Those are the types of questions that astrophysicist Adam Frank addresses in *The Little Book of Aliens*. A self-avowed nerd and sci-fi fan, Frank dives into the topic with gusto. Although humans have pondered the question of whether we're alone in the universe for millennia, the field of astrobiology—the search for life outside Earth—has only really taken off since the discovery of the first exoplanets around three decades ago. Aimed at the general reader, the book provides an overview of the current science, upcoming missions, and the importance of SETI. —CC




## Constructing Quantum Mechanics

### Volume 2; The Arch: 1923–1927

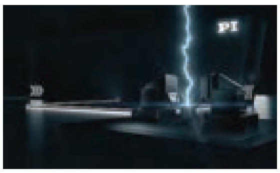
**Anthony Duncan and Michel Janssen**
Oxford U. Press, 2023. $110.00

The literature on the development of modern quantum mechanics in the 1920s is so vast that probably no work on the topic could ever be encyclopedic. But Anthony Duncan and Michel Janssen's two-volume magnum opus, *Constructing Quantum Mechanics*, comes about as close as humanly possible to comprehensiveness. The newly released second book covers the development of modern quantum mechanics in 1923–27. Duncan and Janssen carefully walk readers through the major publications by physicists such as Werner Heisenberg and Paul Dirac, explaining the methods used and attempting to reconstruct thought processes. They argue that quantum mechanics was an "arch" built on the "scaffold" of the older quantum theory, which was then cast away once the arch was completed. —RD PT

# Focus on software, data acquisition, and instrumentation

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

**Andreas Mandelis**

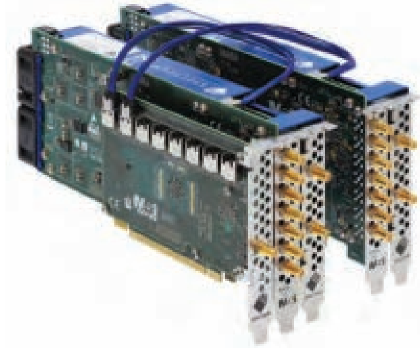



## Automated photonic alignment

PI (Physik Instrumente) says that its new PILightning search-and-alignment algorithm represents a breakthrough in optimizing the alignment of optical components. Before that process can start, an optical signal, above the noise level, must be registered in a procedure called first-light detection. PILightning, the newest functionality in PI's photonics-process-automation suite, is a first-light search method with an integrated artificial-intelligence-based real-time executive function. Replacing fine-pitch scanning with high-frequency data sampling, it significantly raises acquisition speeds. Tests have shown improvements of one order of magnitude and more in single-sided alignment applications; higher gains are achieved in double-sided first-light detection applications. PILightning has the potential to lower costs for test and assembly in industrial photonic-alignment applications, from wafer probing to final packaging. ***PI (Physik Instrumente) LP**, 16 Albert St, Auburn, MA 01501, www.pi-usa.us*

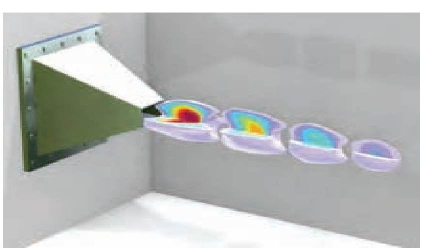
## Single- and multiaxis servo drives

Aerotech has introduced its XA4 and iXA4 PWM (pulse-width modulation) servo motor drives with options from one to four axes. The XA4 and iXA4 are part of the company's user-friendly Automation1 motion-control platform, which includes development software, controls, motor drives, and the fiber-optic HyperWire communication bus. The streamlined, economical single- and multiaxis panel-mounted servo drives include a full motion controller and input–output expansion options. They support multiple feedback-device types and include onboard memory for high-speed data capture and process control. The simplified dual-axis XA4 PWM servo drive communicates to Automation1 PC- and drive-based controller products over the HyperWire motion bus. The iXA4 PWM servo drive, which has a motion controller, eliminates the need for an industrial PC and reduces machine footprint. Users can control 12 HyperWire axes of motion and run up to nine tasks on the embedded Automation1 controller. ***Aerotech Inc**, 101 Zeta Dr, Pittsburgh, PA 15238-2811, www.aerotech.com*



## Ultrafast multichannel data acquisition

Star-Hub, a new option from Spectrum Instrumentation, offers a user-friendly way to create multichannel-data-acquisition systems with ultrafast sampling speeds of up to 10 GS/s. Star-Hub allows up to eight of the company's Peripheral Component Interconnect Express digitizers from its M5i.33xx series to be connected. Individual cards then share common clock and trigger signals, which ensures minimal phase delay and timing skew between all the channels. The Star-Hub option is installed by mounting a single piggyback module onto any of the M5i series cards in the multichannel system. Using accurately matched and shielded coax cabling, the board distributes the clock to each module and precisely synchronizes the trigger event with the system clock. Data-acquisition systems can be built with 2–16 channels at sampling rates of up to 5 GS/s or 2–8 channels at the maximum sampling rate of 10 GS/s. They can be used in a wide variety of applications, including scientific experimentation, communications, automated testing, and aerospace. ***Spectrum Instrumentation Corp**, 401 Hackensack Ave, 4th Fl, Hackensack, NJ 07601, https://spectrum-instrumentation.com*



## Modeling and simulation software

Version 6.2 of Comsol's Multiphysics software for creating physics-based models and simulation applications is now available. It adds data-driven surrogate-model functionality for efficient standalone simulation apps. Surrogate models deliver accurate simulation results much faster than the full-fledged finite-element models that they approximate and are useful for digital twins, where fast and frequent updates of simulation results are often necessary. The AC/DC module now features high-performance multiphysics solvers for the analysis of electric motors, transformers, and other electric machinery. Version 6.2 speeds up computations, providing up to 40% faster turbulent computational-fluid-dynamics simulations. A boundary element analysis for acoustics and electromagnetics can now be performed up to seven times faster. In addition to providing new modeling features, the updated software expands and enhances add-on products and improves core offerings, such as visualization and meshing. ***Comsol Inc**, 100 District Ave, Burlington, MA 01803, www.comsol.com*

## Thermal power sensor

Rohde & Schwarz has launched its R&S NRP170TWG(N) thermal power sensor for precise power-level measurements in the D band. According to the company, it is the only RF power sensor on the market that offers full traceability to national metrology institutes in the frequency range of 110–170 GHz. The sensors are suitable for general R&D for 6G mobile communications, novel subterahertz communications, sensing, and future automotive radar applications. They are fully calibrated for long-term stability and can compensate for environmental temperature influences within the specified operating range of 0 °C to +50 °C. They offer a dynamic range of −35 dBm to +20 dBm and up to 500 measurements/s. For ease of use, the sensors provide stable power readouts even at levels below −20 dBm, have no drift, and are resilient to external temperature changes and out-of-band signals such as the ones in far-IR. The devices can be easily integrated into any measurement setup with a USB or LAN connection. ***Rohde & Schwarz GmbH & Co KG***, *Mühldorfstraße 15, 81671 Munich, Germany, www.rohde-schwarz.com*

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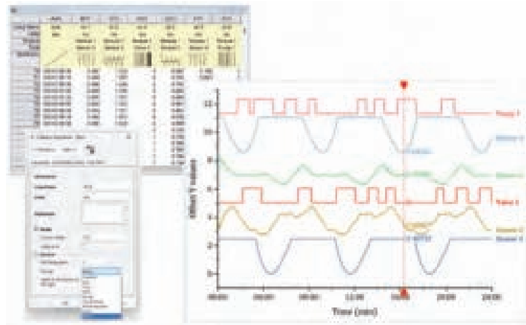
## Data analysis and graphing software



OriginLab has released Version 2024 of its Origin and OriginPro data analysis and graphing software. New features include support for dark mode, which can be set for Origin independent of Windows dark mode. Multiple built-in dark color themes and dynamic color-reversal levels for graphs in dark mode are offered, and the background color of graph pages can be customized. This version adds new ways of interactively adjusting axis scales on graphs: Users can either click on an axis and drag the axis ends or press the Z/X keys and drag layer boundaries. The sheet-based browser plot now allows for easy visualization of data across multiple worksheets in a project. A new binary-column type has been introduced for test and measurement data in graphs. New graph types—Tile Grid Map Plot and Split HeatmapPlot—have been added, and the Design of Experiments app has been updated. New apps include Statistical Process Control, Power Spectral Density, Youden Plot, and Poisson Regression. ***OriginLab Corporation***, *One Roundhouse Plaza, Ste 303, Northampton, MA 01060, www.originlab.com*

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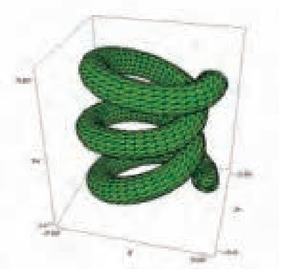

## Software for partial differential equations

New features have been added and internal improvements made in version 8 of the PDE Solutions FlexPDE multiphysics finite-element solution environment for partial differential equations. The software now offers support for OpenGL graphics, with new selectors for mesh, contour, and surface plots. Automatic reconnection for moving meshes is offered. Models that produce complex eigenvalue solutions can now be solved. Any plot can be exported in Scalable Vector Graphics format, and Periodic Map now allows variable exchange, which is helpful for exchanging vector components. A new edge distance function lets users calculate the distance along a named path. New utility functions and additional hyperbolic functions have been added and improvements made to the Transfer file format, error measure, parameter or equation summaries in debug files, and diagnostics for discontinuous Jacobians interfering with Newton convergence. ***PDE Solutions Inc***, *9408 E Holman Rd, Spokane Valley, WA 99206, www.pdesolutions.com*

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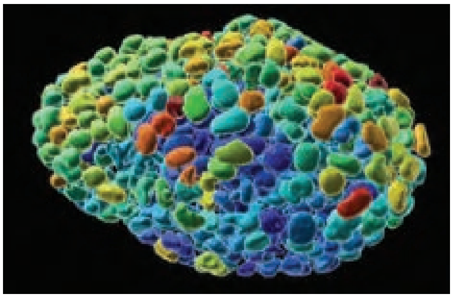
## High-bandwidth oscilloscope probes

According to Keysight, its InfiniiMax 4 series high-bandwidth oscilloscope probes are the only available probing solution with a high-impedance probe head operating at more than 50 GHz. Since it delivers bandwidths with filters up to 52 GHz Brickwall and 40 GHz Bessel–Thomson, the new instrument can perform system verification without loading the device under test. By maintaining accuracy and minimizing interference, it can accelerate design, validation, and testing in high-speed digital, semiconductor, and wafer applications. The InfiniiMax 4 series offers an innovative RCRC (double resistance–capacitance) design with a flexible PCA (probe card analyzer) head that uses its natural flexibility to take the strain off the delicate tip wires. The modular design features an amplifier with multiple access points. It bypasses the need for custom evaluation boards or interposers and enables users to debug designs faster. The InfiniiMax 4 probes are compatible with Keysight's real-time UXR-B Series oscilloscopes and the InfiniiMax III probe head. ***Keysight Technologies***, *1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

## Beryllium-window monoblock x-ray source

Spellman has unveiled its XRBe80PN300 beryllium-window monoblock x-ray source. Designed for OEM applications and running at 300 W, the integrated monoblock x-ray source powers the internal bipolar x-ray tube to 80 kV. It is available with a cone-shaped beam geometry. Proprietary emission-control circuitry provides excellent regulation of the x-ray tube current and high performance. Features such as a universal voltage input, power-factor corrected; a compact size and light weight; the ability to be mounted in any physical orientation; and a standard RS-232 digital interface simplify integration of the XRBe80PN300 into x-ray systems. Applications include nondestructive testing, thickness and plating measurement, food inspection, fill-level confirmation, and security scanning systems. ***Spellman High Voltage Electronics Corp**, 475 Wireless Blvd, Hauppauge, NY 11788, www.spellmanhv.com*



## Microscopy-image-analysis software

Oxford Instruments Andor has announced the latest version of its artificial-intelligence microscopy-image-analysis software, Imaris 10.1. AI-segmentation tools have been integrated into the main image-analysis workflows, improving ease of use and providing better, more versatile segmentation for users in life sciences applications. A native, trainable AI pixel classifier is an integral part of the Imaris 10.1 big-data-capable Surface segmentation model. It simplifies and improves segmentation and object detection in challenging fluorescent data sets and paves the way for 3D scanning electron microscopy segmentation and shape recognition. Researchers of all experience levels can use the AI pixel classifier. They can train and compute the results with the classifier on their local machine by painting the data with the efficient smart-brush tool. Training and the results preview are fast and interactive. The pixel classifier can be trained and utilized on 2D, 3D multichannel, and time-lapse data sets and used in a batch mode to analyze more samples of a similar type. ***Andor Technology Ltd**, 7 Millennium Way, Springvale Business Park, Belfast BT12 7AL, UK, https://andor.oxinst.com* PT

**Cédric Beaume** is an associate professor in applied mathematics at the University of Leeds in the UK. **Lucas Goehring** is a professor of physics at Nottingham Trent University in the UK. **Jana Lasser** is a Marie Curie fellow at Graz University of Technology in Austria.

# Hidden fluid dynamics of dry salt lakes

**Cédric Beaume, Lucas Goehring, and Jana Lasser**

A new theory reveals how polygons that decorate the surface of dry lakes are linked to phenomena at play below the ground.

Dry salt lakes are an extraordinary part of desert landscapes. Their surfaces are often covered by strikingly regular polygonal shapes bounded by narrow ridges. Familiar to millions of tourists who have visited Death Valley, shown in figure 1, or Bolivia's Salar de Uyuni—Earth's largest known natural source of lithium—these otherworldly patterns inspired the *Star Wars* planet Crait, site of the climactic battle of *The Last Jedi*. Surprisingly, the mechanism by which the polygons form has remained elusive until this past year.

However, dry lakes are not always as dry as they first appear. Instead, water flows underground in porous soil. That groundwater collects in valleys, where it resides close to the surface. Even at Badwater Basin in Death Valley, which holds records for its hot and dry climate, if you dig a few tens of centimeters into the soil, you will find water, albeit unpalatably salty. At such places, the water evaporates, and any dissolved minerals are left behind to slowly accumulate. Rather than only producing a flat crust on the lake surface, the salt instead develops into a network of narrow ridges, defining polygons that are always just a few meters across. In this Quick Study, we explain why.

**FIGURE 1. SALT POLYGONS** at Middle Basin in California's Death Valley. (Courtesy of Sarah Marino.)

## Wrinkling?

Ecologically, dry lakes are known as sources of mineral-rich dust. Although detrimental to air quality, visibility, and respiratory health, the dust is a source of nutrients for ocean ecosystems. The minerals concentrated in salt flats can also be harvested, as they are at Salar de Uyuni. Because historically most attention has been focused on the salt, researchers have tried to explain the surface patterns via mechanisms acting in the crust itself. That line of inquiry led to the idea that salt polygons are the result of a mechanical instability of the crust, akin to cracking or wrinkling (see the article by Michael Marder, Robert Deegan, and Eran Sharon, Physics Today February 2007, page 33).

Theories based on the mechanics of the crust are logical candidates for several reasons. Dry salt is hard and brittle. The ridges bordering the polygons are often broken up by cracks, as in figure 1. Some salts, like sodium sulfate, change state near room temperature, absorbing or releasing moisture while dramatically altering their size. Their swelling can generate enough stress to shatter rock. Finally, the polygonal shapes in salt crusts look somewhat like the crack patterns of columnar joints, such as those at the Giant's Causeway in Northern Ireland.

The first time any of us encountered salt polygons was in Namibia, along the Skeleton Coast. A salt seep had been built to extract salt from seawater via evaporation. Polygons were forming in a thin crust that surrounded the seep on all sides. When we were standing on the real thing, however, it was immediately clear that those polygons were not just a crack pattern.

As with other problems in elasticity, cracking and wrinkling are strongly influenced by geometry. In a flat layer such as a crust, the typical distance between features should be a few times the thickness of that layer. The scaling works well for cracks in dried mud, columnar joints, frozen soils, and crocodile snouts (see the article by one of us [Goehring] and Stephen W. Morris, PHYSICS TODAY, November 2014, page 39).

That, however, is not what we saw. In Namibia, meter-wide polygons were forming where the salt crust was thin enough to crunch underfoot. At other dry lakes, polygons appear with a similar size, despite differences in crust thickness, soil type, and salt chemistry. For example, near the Dead Sea in the Middle East, we have seen polygons growing out of a salt mush, a soft slurry lying directly on top of soaking-wet mud. There was nothing solid enough there to break, but the same pattern was apparent with the same meter-wide polygons. The discrepancy between those observations and the predictions of a purely mechanical model was a fascinating puzzle.

## Convection!

Curious for a better explanation of how salt polygons form, we sought answers in other areas of physics. Convection in a porous medium, such as wet soil, has many applications, including in sea-ice formation, metallurgy, carbon geosequestration, and the dynamics of Earth's core (see the article by Daniel Anderson, Peter Guba, and Andrew Wells, PHYSICS TODAY, February 2022, page 34). In those diverse cases, fluid flow takes the form of convection cells that can resemble the salt-crust patterns along their boundaries. Inspired, we began to look at the fluid dynamics taking place below the crust, away from sight.

In a dry salt lake, water rises to balance evaporation from the desert surface. Salts remain behind, either trapped in the crust or dissolved in near-surface water. Within the soil, the lake then becomes stratified, with saltier, denser water sitting above the fresher, lighter groundwater seeping up from below. For the conditions measured in dry salt lakes, the density-stratified situation cannot be maintained and plumes of heavy, salt-rich water develop and sink downward. We speculated that those convective plumes could provide a template for the surface patterns.

We initially predicted the size of the convection cells expected beneath a dry lake using a simple physical argument. Groundwater evaporates from salt deserts at modest rates and with surprisingly little geographical variation worldwide—at approximately 0.1 mm/day ($10^{-9}$ m/s). Salt is carried by water travelling upward at the same rate. But it also diffuses, which spreads out any salt-rich layer that develops near the surface. The diffusivity of salt in water is about $10^{-9}$ $m^2/s$. If convection strikes a balance between diffusion and fluid transport, the ratio of the two quantities gives the natural scale of the convection—about 1 m.

Digging deeper (metaphorically), we combined experiments, numerical simulations, and field studies. In the lab, we reproduced desertlike conditions in a vertical slice of wet sand. Watching from the side, we witnessed how our artificial dry lake became stratified and developed the anticipated salinity-driven convection cells. Numerical simulations then allowed us to explore convection in a wider range of environments, without having to repeatedly clean our lab of sand and salt.

The simulated pattern is illustrated in figure 2. The side faces show high-salinity plumes draining the salt that had accumulated at the surface, interspersed with areas of fresher fluid seeping upward. The size of the polygonal patterns that emerge becomes independent of most parameters after the simulation is run and confirms the simpler argument we made about evaporation rates and diffusion. In other words, detailed models of the fluid dynamics taking place inside the lake can explain why the same pattern appears with the same length scale in salt deserts around the globe—from the thin crusts on the Skeleton Coast to the massive crusts of Salar de Uyuni.

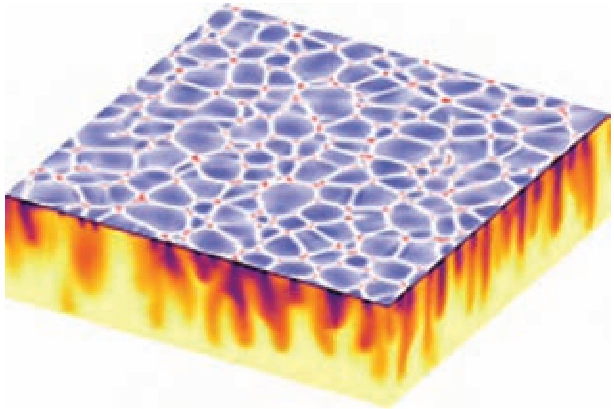


**FIGURE 2. NUMERICAL SIMULATION OF CONVECTION** in a dry salt lake. In this snapshot, groundwater salinity is shown on the sides (black: high salinity; yellow: low salinity) while the salinity flux into the surface is shown on the top face (red: positive salinity flux; blue: negative salinity flux).

Finally, a convective model can be relevant to salt polygons only if there is a direct link between the flow inside a real dry lake and its crust. So we spent weeks digging beneath the salty crust of Owens Lake, near Los Angeles, and subsequent months patiently separating the salt from thousands of soil samples. We found that the polygonal ridges consistently lay above soil with groundwater that was saltier than that collected from below the polygons' centers.

The observation compares well with our numerical simulations: Figure 2 shows that the high-salinity plumes are located under the lines of highest-salinity flux into the surface (red and white areas). Those regions, where more salt enters the simulated surface, correspond to the faster-growing salt crusts that form into the ridges found in nature. That correspondence represents the final link that connects the fluid dynamics of dry lakes to the formation of salt polygons.

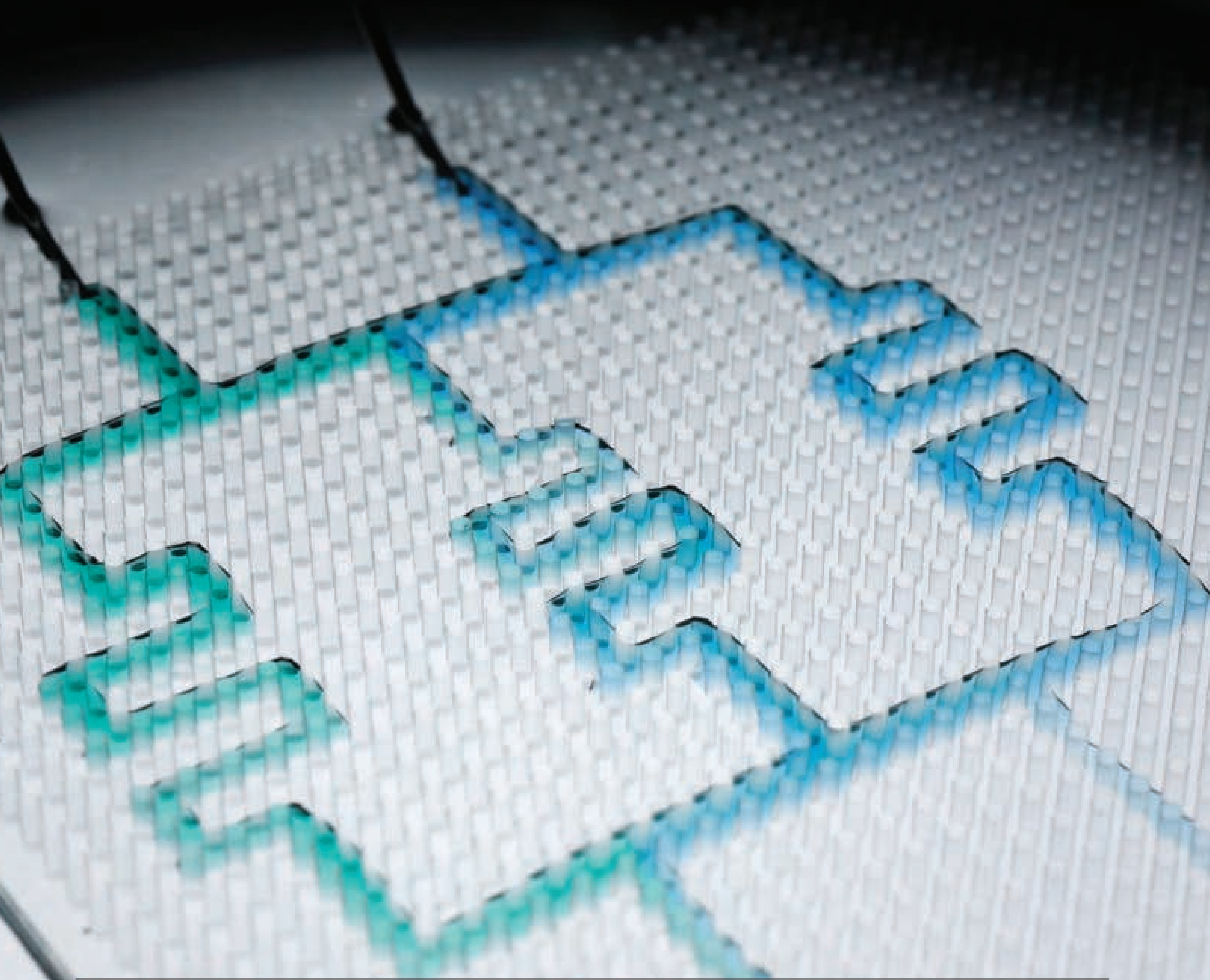
*The authors acknowledge long-standing and invaluable contributions from Marcel Ernst, Volker Karius, Joanna Nield, Matthew Threadgold, and Giles Wiggs.*

## Additional resources

▶J. Lasser et al., "Salt polygons and porous media convection," *Phys. Rev. X* **13**, 011025 (2023).

▶J. Lasser, J. M. Nield, L. Goehring, "Surface and subsurface characterisation of salt pans expressing polygonal patterns," *Earth Syst. Sci. Data* **12**, 2881 (2020).

▶J. Lasser, "Salt polygons and porous media convection," (2 April 2021), www.youtube.com/watch?v=vNJk6AdsOoI. PT



# Building with liquid blocks

Inkjet printers, microfluidic "labs on a chip," and other liquid-based devices all need to move liquids to particular places. That requires confining the fluids in appropriate channels, typically defined by solid walls or textured surfaces that, once fabricated, can't easily be modified to deliver liquids to new places. Xin Du, Zhongze Gu, and their colleagues at China's Southeast University in Nanjing have now developed an alternative. The pillared substrate shown in the photo allows for the assembly of liquid channels out of individual droplets and quick reconfiguration of the paths into any desired arrangement.

The liquid building blocks were assembled in silicone oil. When a 10 μL water droplet was pipetted onto the nonreactive plastic substrate, the surrounding hydrophobic pillars, spaced 2 mm apart, trapped it. By adding more droplets where they wanted, the researchers made an aqueous fluid-transporting channel, demonstrated in the photo by the two dyed solutions, which mix in the middle channel. They easily reconfigured the path by removing droplets with a pipette and by cutting the channel with a fluorinated paper sheet. The researchers demonstrated other possibilities of their method too, including a multiphase liquid battery. (Y. Zeng et al., *Nat. Chem. Eng.* **1**, 149, 2024; photo courtesy of Xin Du.) —AL

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