PHYSICS TODAY

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LEARNING TO SPOT GRAVITATIONAL LENSES

Squeezing accelerator beams in Japan

Earth's changing length of day

Nanoparticle force sensors

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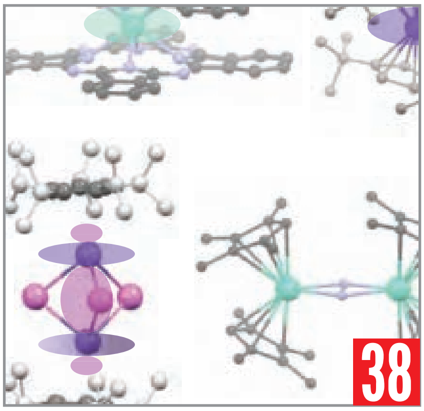

FEATURES

ON THE COVER: Einstein rings, such as the one that encircles galaxy NGC 6505, located near the center of the image, are examples of strong gravitational lensing, which occurs when light from a distant source is bent by a massive foreground object. For more on the ways astronomers learned how to identify gravitational lenses, turn to the article by Sebastian Fernandez-Mulligan on **page 30**. (Image from ESA/*Euclid*/*Euclid* Consortium/NASA; processing by J.-C. Cuillandre, G. Anselmi, T. Li.)

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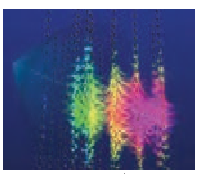

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Record-setting neutrino

Evidence of an extraordinarily energetic neutrino has been obtained by a detector array in the Mediterranean Sea. The particle, which had an order of magnitude more energy than any previously detected neutrino, likely originated near a powerful cosmic accelerator or in a collision involving an ultrahigh-energy cosmic ray.

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EMILIA DI LORENZO, ERNESTO DI MAIO

Egg-cooking physics

If you're willing to put in the time and effort, it may be worth trying a newly demonstrated method for cooking whole eggs that yields a solid white and a creamy yolk. Developed by a team of polymer engineers, the half-hour process involves transferring eggs between boiling and 30 °C water every two minutes.

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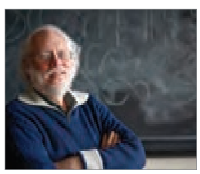

CHRISTOPHER HARTING

Peter Shor

In 1994, Peter Shor outlined one of the first algorithms that would run far faster on a quantum computer than on a conventional machine. In an interview, he discusses the genesis of his factoring algorithm and reflects on the past three decades of progress in quantum computing.

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Optically variable inks

In their article "The black powder behind battery power" (Physics Today, September 2024, page 26), Jeffrey Richards and Julie Hipp discuss how the electrodes for lithium-ion batteries are created by coating metal foils with a complex slurry of conductive compounds, electrochemically active materials, polymers, and other components. They describe how the microstructure of carbon black, the most-used conductive additive, depends on the shear applied during the coating process. That reminded me of the story behind the rise of optically variable inks (OVIs), also known as color-shifting inks.

At the end of the last century, fast advances in color printing and copying led to increased risks of counterfeit currency. To combat counterfeiting, countries began using OVIs on their money. The color of an OVI depends on the angle at which it's viewed.

A printing ink generally consists of a pigment, which determines the optical properties of the final image, dispersed in a liquid carrier and mixed with additives to facilitate drying. A final step in ink preparation is kneading the mixture to the correct viscosity. In an OVI, the pigment is formed by depositing interference layers onto a substrate and then crushing the substrate into small platelets. The delicate balance between the OVI's optical performance—which depends on the size and alignment of the platelets—and the required viscosity created through kneading has been established by trial and error.

The neutron-scattering techniques that Richards and Hipp describe would certainly reduce the trial and error today and at the same time help establish and make understood the critical parameters for the production process of OVIs.

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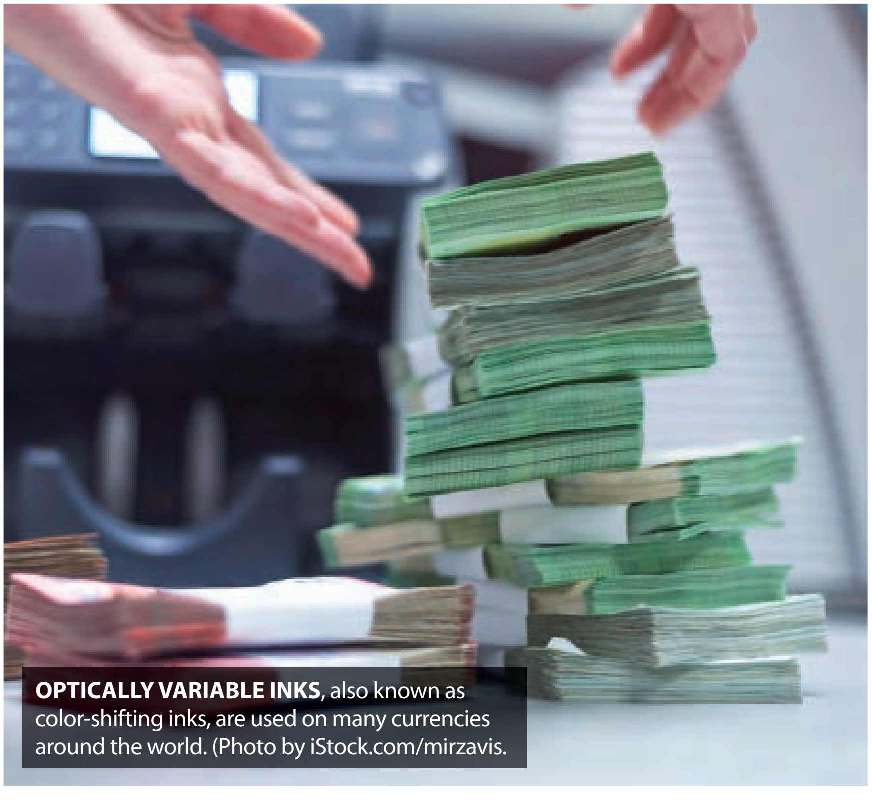

OPTICALLY VARIABLE INKS, also known as color-shifting inks, are used on many currencies around the world. (Photo by iStock.com/mirzavis.

Open access for reading or closed access for publishing?

What a marvel open access has become! Sparkling and progressive, it allows everyone access to scientific literature—provided, of course, that scientists are ready to pay dearly for the privilege of sharing their work with the world. The noble goal of disseminating knowledge widely has found an equally noble price tag that has turned many scientists' dreams of open sharing into a harsh reminder of their financial limitations.

Consider the researcher from a country with limited funding. How fortunate they are to find that their esteemed work can be shared freely—if only they can muster a few thousand dollars in fees. And those hoping for a waiver? They get the delight of navigating convoluted processes that often result in outright rejection or significant delays. And although some publishers still offer reasonable policies, others cling to a strict fee schedule and have adopted an unyielding approach that favors revenue over global accessibility.

Publishers need to cover costs, of course. But the shift from pay-for-reading to pay-for-publishing risks broadening the existing divide in scientific publishing and further isolating researchers from underfunded regions.

If open access is to benefit the entire scientific community, it surely requires measures that promote equity and transparency. May this glimmering model one day be no longer a roadblock but instead a true bridge.

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Support science diplomacy in the Middle East

I appreciated the October 2024 Q&A with Tareq Abu Hamed (page 26), the Palestinian Israeli executive director of the Arava Institute for Environmental Studies, a nongovernmental organization in southern Israel that fosters cross-border collaboration on environmental issues during political conflict. The piece is refreshing in the wake of so much negative news from the region. I have personally visited the Arava Institute and experienced the Arab–Jewish collegiality that Abu Hamed describes.

Sadly, in the Q&A, Abu Hamed says he thinks that the Arava Institute is "the only organization in the region that uses science diplomacy with students and researchers." Members of the region should work to create and support such organizations in their countries. Perhaps both the American Institute of Physics and the Arava Institute could advise, cheerlead, and uphold such efforts. I should hope that they do not let anti-Semitism, racism, political conflict, or cultural differences stand in the way.

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Support for a revamped qualifying process

I read the article "Fixing the PhD qualifying exam" by Tim DelSole and Paul Dirmeyer (Physics Today, July 2024, page 34) with great interest. I entered a PhD program in astronomy in the fall of 1993. I performed well in all my classes and passed my qualifying exams by the summer of 1995. At the time, there were no classes that taught students how to refine a research question. The expectation seemed to be that anyone good enough to do research would just know how or would be able to figure it out on their own. I left the program with a master's degree in February 1996. Had the qualifying process been as DelSole and Dirmeyer describe, I believe I would either have succeeded in doing research or have departed knowing that I had not been left to the whim of my adviser.

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Up-conversion nanoparticles measure medium-sized forces in hard-to-reach places

Squeezing the tiny crystals can dramatically change their photophysics.

Caenorhabditis elegans, illustrated in figure 1, is a well-studied worm. Since the pioneering work of biologist Sydney Brenner in 1965, it's been featured in tens of thousands of research papers and has had connections to four Nobel Prizes. In Brenner's own Nobel lecture, in 2002, he called the organism "without doubt the fourth winner of the Nobel Prize this year . . . but, of course, it will not be able to share the monetary award."

A big part of *C. elegans*'s appeal is that it occupies a useful middle ground between small and large: It's simple enough to study thoroughly but sufficiently complex to have salient features in common with humans. It's a millimeter long and comprises less than a thousand cells, but it contains differentiated organ systems, including muscle, a digestive tract, and a central nervous system. Its rudimentary brain was the first of any organism to have all its connections mapped. And in its brief two- to three-week lifespan, it experiences age-related muscle and neurological degeneration, often with striking biochemical similarity to the same phenomena in humans.

But something has been missing from the intermediate-scale measurements researchers can make: mechanical forces. Molecular tools exist for measuring the forces exerted by single proteins. And macroscale forces can be probed by piezoelectric transducers, among other technologies. Largely unmeasured is the in-between regime of forces exerted by several cells working together, whether to squeeze food through *C. elegans*'s digestive tract or to pump blood through human arteries.

Now two interdisciplinary research groups—one led by Jennifer Dionne at Stanford University[1] and the other by P. James Schuck at Columbia University[2]—have developed new force sensors for bridging that scale gap. The details of their implementations differ: Schuck's focus so far has been on dynamic range, whereas Dionne's has been on biocompatibility. But both groups used lanthanide-doped up-conversion nanoparticles (UCNPs), a versatile platform for optically probing inside living organisms. Indeed, Dionne and colleagues have already used their sensors to measure how hard *C. elegans* chomps on the bacteria it eats.

FIGURE 1. LOOKING FOR A MEAL, *Caenorhabditis elegans* slithers through a field of what, for all it can tell, are nutrient-rich bacteria. But actually, they're polystyrene spheres embedded with force-sensitive nanoparticles. Tricking the millimeter-long worm into eating the micron-size pressure gauges is the first step toward measuring the forces exerted in its pharynx—the region from the front of the worm to the back of the second bulbous structure, where *C. elegans* crushes up its food—and other parts of its digestive tract. (Image courtesy of Jason Casar.)

Up with up-conversion

UCNPs turn low-frequency light into high-frequency light. That by itself is not so unusual: Many nonlinear optical materials can do the same. One of the things that makes UCNPs so special is that their excitation wavelength, in the near-IR, is one where biological tissues are nearly transparent. Another is that they can perform the conversion efficiently even when the input light is relatively dim.

Typically, for a nonlinear optical material to convert two low-energy photons into one higher-energy one, it needs to absorb those photons at almost exactly the same time. The probability of that happening is low and scales with the

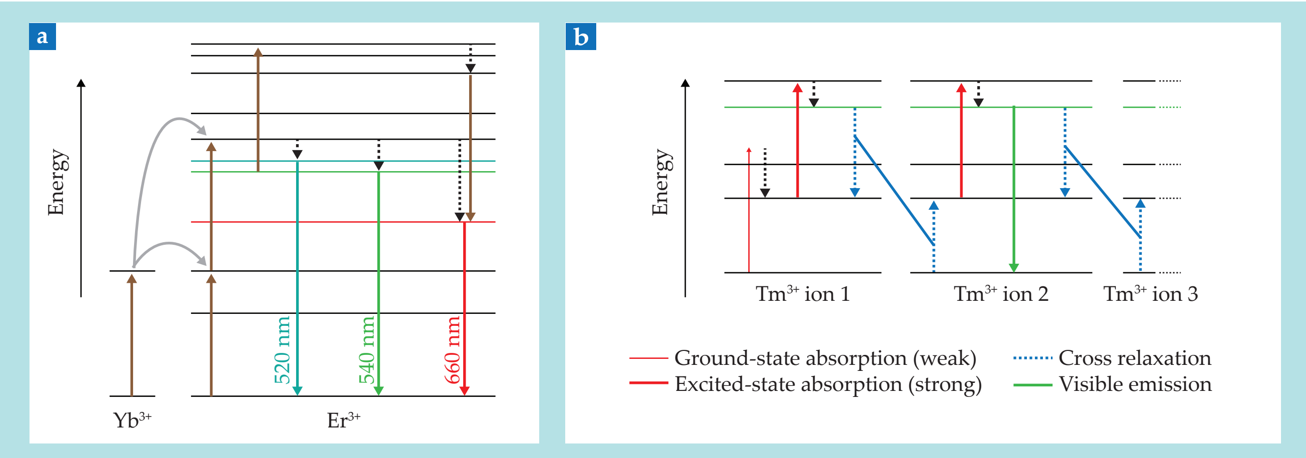

FIGURE 2. MECHANISMS OF UP-CONVERSION. (a) In a nanoparticle doped with ytterbium and erbium, Yb^{3+} ions absorb near-IR photons and transfer their energy to nearby Er^{3+} ions. Through a complicated network of photophysical pathways—sensitive to pressure, as it turns out—the Er^{3+} ions emit a combination of green and red photons. (Panel adapted from ref. 3.) **(b)** In a thulium-doped nanoparticle, one Tm^{3+} ion absorbs two photons and then shares part of its energy with a second ion. If the conditions are right for the absorption and sharing to continue—again, a pressure-sensitive matter—the excitations spread exponentially across the nanoparticle, until all the excited Tm^{3+} ions emit visible photons. (Panel adapted from ref. 4.)

square of the illumination power. That's why, for example, nonlinear operations had been considered prohibitively difficult for low-power optical computing (see Physics Today, October 2024, page 12).

But ions of the lanthanides—elements 57 through 71, usually depicted as the upper of the two rows floating below the body of the periodic table—have excited electron states with rather long lifetimes: milliseconds, rather than picoseconds. So a lanthanide ion in a crystalline matrix can absorb one photon, linger for a while in its excited state, and then catch a second photon that arrives later. It can also use its excited-state dwell time to transfer energy to another lanthanide ion with a different spectrum of excited states. From a single input wavelength, lanthanide-doped UCNPs can produce a rich and tunable array of output colors, depending on how they're designed. (For more on the design and application of UCNPs, see the article by Marco Bettinelli, Luís Carlos, and Xiaogang Liu, Physics Today, September 2015, page 38.)

What does any of that have to do with measuring forces? The mechanism of mechanosensitivity is complicated—and not always completely understood—but the key aspect of it seems to be the lanthanide–lanthanide energy transfer. Squeezing a lanthanide-doped UCNP brings its dopant ions closer together and alters the spectrum of vibrational modes that ions use to couple to one another. So a nanoparticle under pressure, both research groups reasoned, could display a significantly different pattern of optical emission than an uncompressed particle. And they were right.

Belly of the beast

Dionne and colleagues, including biologist Miriam Goodman and Dionne's student Jason Casar, used a tried-and-true UCNP formulation based on erbium and ytterbium. As sketched in figure 2a, the Yb^{3+} ions absorb near-IR light and transfer energy to Er^{3+} ions, which emit some combination of red and green photons, depending on the conditions.

Those conditions, as Dionne and colleagues showed in 2017, include mechanical force: Compressed particles emit more red, whereas uncompressed particles emit more green.[3] In the years since then, they've been working out the details in preparation for biological experiments. What other factors influence the up-conversion output, and how could they calibrate the sensors to account for those? How could they coat the particles to make them nontoxic to living organisms, and would that coating also affect the calibration? How could they get the particles into the target region of the organism to begin with?

That last part required a *C. elegans*–specific solution. The worm eats bacteria, which it recognizes by their size: Anything smaller than 200 nm gets filtered out before it reaches the digestive tract, and the nanoparticles are an order of magnitude smaller than that. So the researchers embedded the nanoparticles in micron-sized lumps of polystyrene, the same size as bacteria. And the worms ate them up.

Chain reaction

Meanwhile, Schuck and colleagues, including chemist Emory Chan, biologist Bruce Cohen, and Schuck's postdoc Natalie Fardian-Melamed, were exploring a different up-conversion mechanism, illustrated in figure 2b: the photon avalanche.[4] The name is a slight misnomer because the avalanche builds on itself inside the nanoparticle before the photons ever come out.

The researchers used nanoparticles doped only with thulium, chosen because the coupling between its ground and first excited states is especially weak when the particles are illuminated with near-IR light. The Tm^{3+} ion struggles to absorb its first photon, but once it does, it absorbs a second one easily. Moreover, once it's absorbed two quanta of energy, it can share one of them with another Tm^{3+} ion—so two dopant ions get promoted to the first excited state for the price of just one sluggish ground-state absorption.

From there, the avalanche grows—two become four, four become eight, and so on—but only if the excited ions keep absorbing and sharing photons faster than they can relax back to the ground state. Typically, the photon avalanche manifests as an extremely nonlinear dependence on the power of the excitation laser: Below a threshold brightness, there's no avalanche and little up-conversion; above it, the avalanche switches on and the particle lights up.

But what if the avalanche depends on more than just laser power? "This is a chain reaction that spreads over 30 different levels before photons come out," says Schuck. "If the particles are even slightly sensitive to anything in the environment that changes how energy is transferred, that gets raised to the 30th power. So it's potentially very sensitive."

The researchers hypothesized that the photon avalanche would be sensitive to force, but they weren't sure how sensitive until they probed the nanoparticles with an atomic force microscope (AFM), whose pointy cantilever acts like a finger to feel the contours of a surface. "Just with the AFM tip tapping on the particles, their emission changed drastically," says Schuck. "It was such a big change that we almost didn't believe it at first."

In general, tapping on the photon-avalanching particles made their emission dimmer. But when particles were carefully crafted with a Tm^{3+} concentration just below the threshold needed for a photon avalanche, mechanical force could squeeze the ions closer together, initiate the avalanche, and make the emission much brighter. Through the combination of the two phenomena, the nanoparticles respond to forces over four orders of magnitude: from hundreds of piconewtons to several micronewtons.

Powerful bite

Dionne and colleagues' work has so far focused on the high end of the force range. When they fed their polystyrene-wrapped nanoparticles to *C. elegans*, they found that the particles experienced forces of around 10 μN in the worm's pharynx, the first part of its digestive tract. That may sound like a small number, but it's equivalent to a pressure of 80 MPa—the same pressure felt by a 1 cm cube under the weight of a large male polar bear. The human bite, in contrast, exerts just over 1 MPa of pressure.

The proof-of-concept measurement shows that UCNPs work for measuring forces *in vivo*. But at the same time, as Goodman points out, "The thing we chose to measure was completely unknown. We knew that *C. elegans* gets nutrition from bacteria, but we didn't know how hard it needed to chew, and now we do."

And it's not just an isolated measurement. Like humans, *C. elegans* grows frailer with age, and the weakening muscles in its pharynx have been studied as a model for such human conditions as muscular dystrophy and cardiac disease. The goal is to screen potential drugs: If some chemical compound can restore lost function in *C. elegans*, it might do the same in humans. Previously, researchers measured electrical signals as a proxy for muscle strength, but the UCNPs make it possible to measure the muscle forces directly. "This paper is the capstone of our work in many ways," says Dionne, "but in other ways, it's just the beginning."

Schuck and colleagues also have their sights on biophysical measurements, including the force involved in embryo development. It's known that mechanical forces help to govern how tissues grow (see Physics Today, April 2007, page 20). But so far, researchers have largely been limited to inferring 3D force patterns from optical images of the cells on the surface. "They don't have great ways of looking inside," says Schuck. "But these pressure sensors can do that."

Beyond biology, Schuck is also working with roboticists to see if an array of nanoparticles could be the basis for a touch-sensitive robot fingertip. The forces would be measured optically, so Schuck envisions that the fingertips would also contain tiny LEDs to excite the nanoparticles and cameras to record their output. That is, for future robots, touch may be a second sight.

Johanna L. Miller

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Water's hydrogen bonds are seen like never before

With a new spectroscopy approach, researchers observed how charge redistributes through hydrogen bonds when water becomes acidic or basic.

Liquid water has a dynamic atomic-scale structure, which gives rise to many of the unique properties of water, such as its extraordinarily high boiling and freezing points. Water's hydrogen bonding—the interaction that attracts a hydrogen atom on one molecule to an oxygen atom on another—facilitates the transfer of a small amount of electric charge, about one-fiftieth that of a single electron, between molecules.

No two molecules have identical sets of hydrogen bonds, because each hydrogen bond affects the formation of others on the same molecule and beyond (see figure 1). The behavior yields a complex network of hydrogen bonds that are constantly forming and breaking on time scales of a millionth of a millionth of a second. Hydrogen bonds are complicated further by nuclear quantum effects (NQEs)—the position of a hydrogen atom, because of its low mass, is delocalized. Computations predict that NQEs can weaken hydrogen bonds.[1]

What is known about hydrogen bonds in liquid water comes predominantly from molecular dynamics simulations. Because the bonds carry a small amount of delocalized charge, which is transferred when the bonds are broken or formed, changes in pH could affect charge transfer in liquid water.[2] Theorists have proposed that in a cluster of three water molecules, excess protons decrease or hydroxide ions increase the amount of electronic charge that is shifted across the hydrogen-bond network. NQEs should also affect charge transfer, but that possibility has not been well observed.

The lack of experimental data on charge transfer and NQEs is caused by the structural complexity of water and

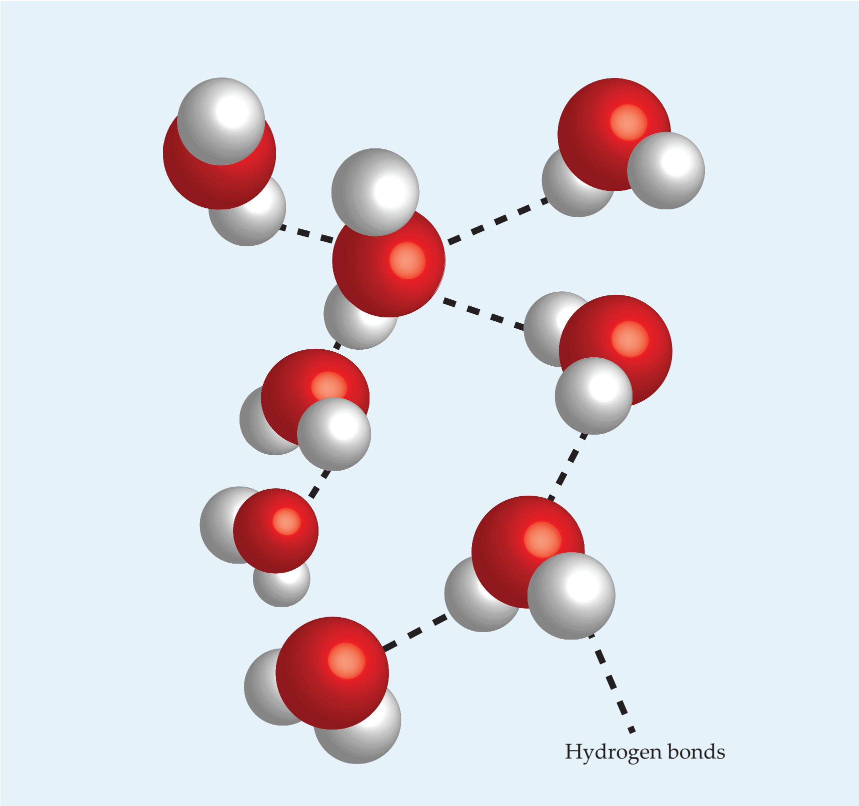

FIGURE 1. HYDROGEN BONDS (dashed lines) in water connect a hydrogen atom on one molecule and the oxygen atom of a nearby molecule. The new technique of correlated vibrational spectroscopy can directly measure the frequency of the hydrogen-bond stretch mode and probe its dependence on pH and nuclear quantum effects. Previously, hydrogen bonding could be studied in detail only with molecular dynamics simulations. (Image by Mischa Flór, EPFL.)

intrinsic limitations in the spectroscopic methods used to measure them. Now Mischa Flór and Sylvie Roke of EPFL in Switzerland and their colleagues have developed an experimental approach that directly measures hydrogen bonds' stretch mode between interacting molecules.[3] The new observations are the first of their kind and help disentangle how pH and NQEs contribute to charge transfer in water.

Hiding in plain sight

Hydrogen bonds have resonant frequencies at about 200 cm^{-1} (6 THz), a frequency that is challenging to probe with IR spectroscopy. Although Raman spectroscopy can make reliable measurements at that frequency, the spectrum is unstructured and notoriously difficult to interpret. "What are we seeing there?" says Roke. "If you can tell, you will be famous."

In a 2022 paper, Roke and colleagues reported a clue for how to focus on hydrogen bonds. They were using a near-IR femtosecond laser pulse to study water's structure, and the liquid target emitted light at the laser's second harmonic.[4] The researchers found that nonlinear spectroscopies, including frequency-doubling techniques, are sensitive probes of the transient, nonhomogeneous structure that hydrogen bonds provide liquid water over the duration of the probing laser pulse.

The remaining critical insight for how to experimentally isolate the hydrogen-bond signal came to Roke and Flór when they were discussing a 1966 theory paper that focused on nonlinear optical effects in homogeneous liquids.[5] The paper derived the relationships among the second-harmonic emissions that are expected for the four possible polarization combinations of the ingoing and outgoing light.

Flór realized that if the relationships were applied to a liquid that has a transient structure arising from hydrogen bonding, they could be used to isolate

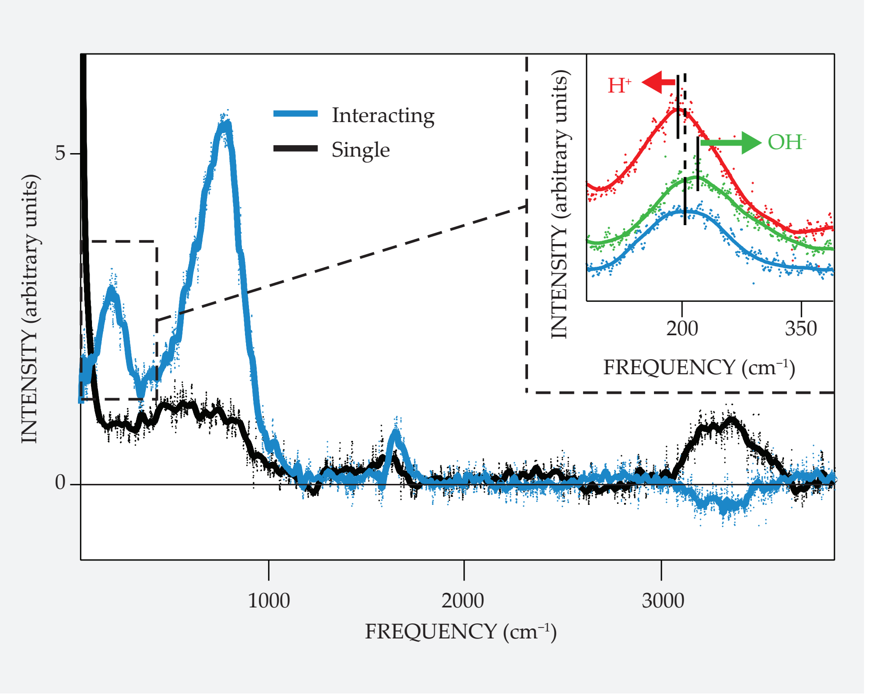

FIGURE 2. WATER'S VIBRATIONAL SPECTRUM was measured using a spectroscopy method based on hyper-Raman transitions. In hyper-Raman spectroscopy, light at frequency ω scatters at a frequency 2ω minus a vibrational mode ω_0. Using symmetry principles, researchers combined several spectra, recorded under different polarization settings, into two spectra. The black line shows vibrational modes of single water molecules, and the blue line shows interacting molecules. The blue peak at 205 cm^{-1} corresponds to the hydrogen-bond stretch mode, and the one at 600–1000 cm^{-1} to hindered rotations of water molecules. Protons (H^+) and hydroxide ions (OH^-) shift the hydrogen bond's stretch frequency; the shift indicates a change in charge redistribution through the hydrogen-bond network. (Image by Mischa Flór, EPFL.)

the intensity from only the interacting molecules. "The equations have been there for 60 years, but there was just one missing small trick that had to be done," says Flór. "And that's what we found." By measuring samples at each of the four polarization combinations, the researchers could simply obtain the signal from liquid water's hydrogen bonds.

Nonlinear spectroscopy

With the analytical approach for second-harmonic scattering in place, Roke and colleagues developed a technique they call correlated vibrational spectroscopy. With good spectral resolution and at various scattering angles, it records spectra of scattered light at low frequencies.

The spectra contain peaks at the second-harmonic frequency minus the resonant frequency of a vibrational mode. The vibrational mode comes from a nonlinear optical process called hyper-Raman scattering. Paper coauthor David Wilkins, from Queen's University Belfast in Northern Ireland, worked out the theoretical formalism to mathematically show that hyper-Raman scattering could be used to directly measure the frequency of the hydrogen-bond stretch mode.

From spectra measured for different polarization combinations, the researchers calculated one combination that contained only single-molecule interactions and one that contained only signatures of interacting molecules. As shown in figure 2, the hydrogen-bond stretch mode was visible only in the interacting-molecule spectrum, as expected.

The frequency of the hydrogen-bond stretch mode contains information about charge transfer. The bond strength, which is measured by the frequency, is linearly related to the bond's electric charge. Any shifts in the frequency, then, yield information about charge transfer.

The group's experiments on acidic and basic solutions of water found a difference in charge transfer. Compared with water with a pH of 7, highly acidic water contained 4% less electronic charge in the hydrogen-bond network, and extremely basic water contained 8% more electronic charge in the hydrogen-bond network. The results agree with quantum chemical computations of small water clusters.

In addition to considering pH, Flór, Roke, and colleagues also explored how NQEs affect the charge transfer in water's hydrogen-bonding network. They analyzed sample solutions of heavy and normal water and found that the frequency of the hydrogen-bond stretch mode in heavy water was shifted higher than that of normal water. Hydrogen, being lighter than deuterium, is much more sensitive to NQEs and is more delocalized. Those features resulted in a 10% weaker bond.

Beyond liquids

For the method's proof of concept, the researchers' main focus was on water. But other liquids—and even 2D or 3D solids—could be studied too. In one of their experiments, the researchers studied the molecular vibrations of a solution of potassium thiocyanate salt in water. As expected, the vibrational modes of the molecular ions were observed only in the single-molecule spectrum, and changes to the hydrogen-bond network were seen in the interacting-molecule spectrum.

Correlated vibrational spectroscopy, the researchers say, could help improve the understanding of how water's structure affects and promotes biochemical reactions associated with DNA and proteins. The researchers are analyzing the results from several other liquid samples to better understand the capabilities of the approach. "Every time we measured a sample, we got a whole truckload of information," says Roke. "We are still working through publishing all the other things that we measured."

Alex Lopatka

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UPDATES

Birdlike robot flies steady without a vertical tail

A pigeon-inspired design for mechanical flight uses avian-like movements to achieve autonomous, rudderless flight.

Unlike birds, most airplanes have a vertical tail. The feature works like a weather vane and prevents the aircraft from rolling and yawing, but it also adds weight, increases drag, and reduces fuel efficiency. Seeking to mimic the flight of birds, David Lentink and his colleagues at the University of Groningen in the Netherlands and Stanford University have built a rudderless flying robot that replicates the reflexive movements of the horizontally oriented tail feathers that birds use to steady themselves.

Previous studies have shown that birds move their tail feathers in four primary ways: rotation relative to the direction of flight, side-to-side deviation from a neutral position, up and down motions, and feather spreading. Lentink and his team brought the biological research into the engineering regime. They focused on the triggers that spur each of those avian reflexive movements to replicate the responses in a robot.

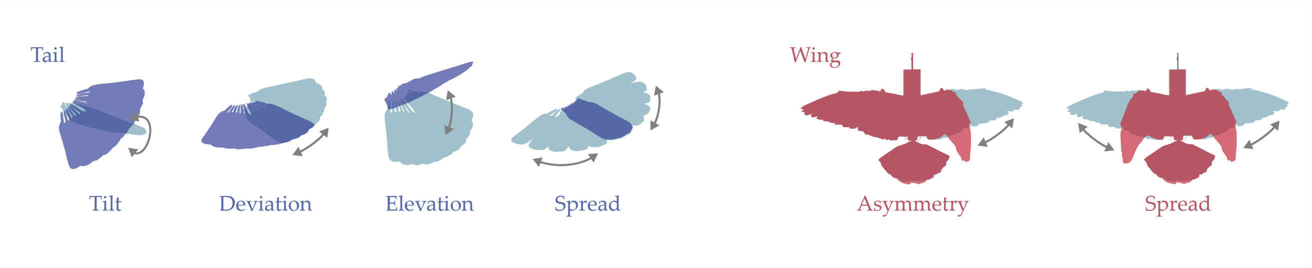
In the lab, Lentink recognized that birds respond to their environment primarily by adjusting the tilt of their tail based on how fast their yaw angle is changing. A sudden change in position—a large angular velocity vector—causes a proportionally large tail tilt to keep the bird from losing control. To make the correction work, birds couple the tail motion with asymmetric wing spread to simultaneously balance roll. Specifically, the tail of a bird will rotate to essentially become a temporary rudder. The rotation creates sideward-pointing lift in the back that forms a restoring torque to drive the yaw angle back to zero. The flight of the bird steadies, and the tail feathers return to a neutral position. "It's reorienting the lift vector in a really interesting way," Lentink says.

DESIGNED TO FLY LIKE A BIRD, PigeonBot II doesn't rely on a rudder to prevent rolling and yawing. Instead, the wings and tail can shift into multiple positions in response to turbulence. (Image courtesy of Eric Chang, Lentink Lab.)

Lentink and colleagues applied that understanding to a tethered robot called TailBot and then to PigeonBot II, a new iteration of an earlier flying robot the researchers had developed. The bird-shaped robot with real bird feathers flies autonomously, using changes in both the wings and the tail feathers to respond to position shifts and altitude changes. The wings' asymmetrical adjustments are able to counter larger-scale roll instabilities, and the tail feathers counter smaller yaw perturbations. The robot can use those same movements to adjust position and to carry out high-level commands given by the researchers, such as to fly higher or to bank left.

There is still work to be done to develop airplanes without a vertical tail. Among other challenges, experiments will need to be carried out to determine how to take the same physics principles and apply them to less flexible airplane wings. Lentink says he is confident that engineers will be up for the task. (E. Chang, D. D. Chin, D. Lentink, *Sci. Robot*. **9**, eado4535, 2024.)

Jennifer Sieben



THE TAIL AND WINGS of PigeonBot II have six controllable degrees of freedom to mimic the movements that birds do reflexively. Corresponding changes to both the wings and the tail feathers allow the robot to fly steadily without a rudder. (Image adapted from E. Chang, D. D. Chin, D. Lentink, *Sci. Robot*. **9**, eado4535, 2024.)

Baseball rubbing mud does, in fact, make balls grippier

Scientific analyses confirm long-held suspicions: Players can throw harder-to-hit pitches when the ball is covered with river sediment.

Before the first pitch of any US professional baseball game, each team's equipment manager applies mud to balls so that they're less slick and easier to grip. To keep competition fair, every team, for decades, has used one brand: Lena Blackburne Baseball Rubbing Mud. Despite efforts to develop other treatments, none offer the same consistency without damaging the baseballs or making them too difficult to hit. (See "The physics of baseball's sticky situation," Physics Today online, 8 July 2021.)

Douglas Jerolmack (University of Pennsylvania) first got interested in the mud in 2019, when a sports reporter emailed him requesting some scientific analyses. He and his group did a few simple tests over two weeks. "Then we put it on a shelf," says Jerolmack, "until Shravan [Pradeep] came along and reignited the project because of his capabilities and his interest."

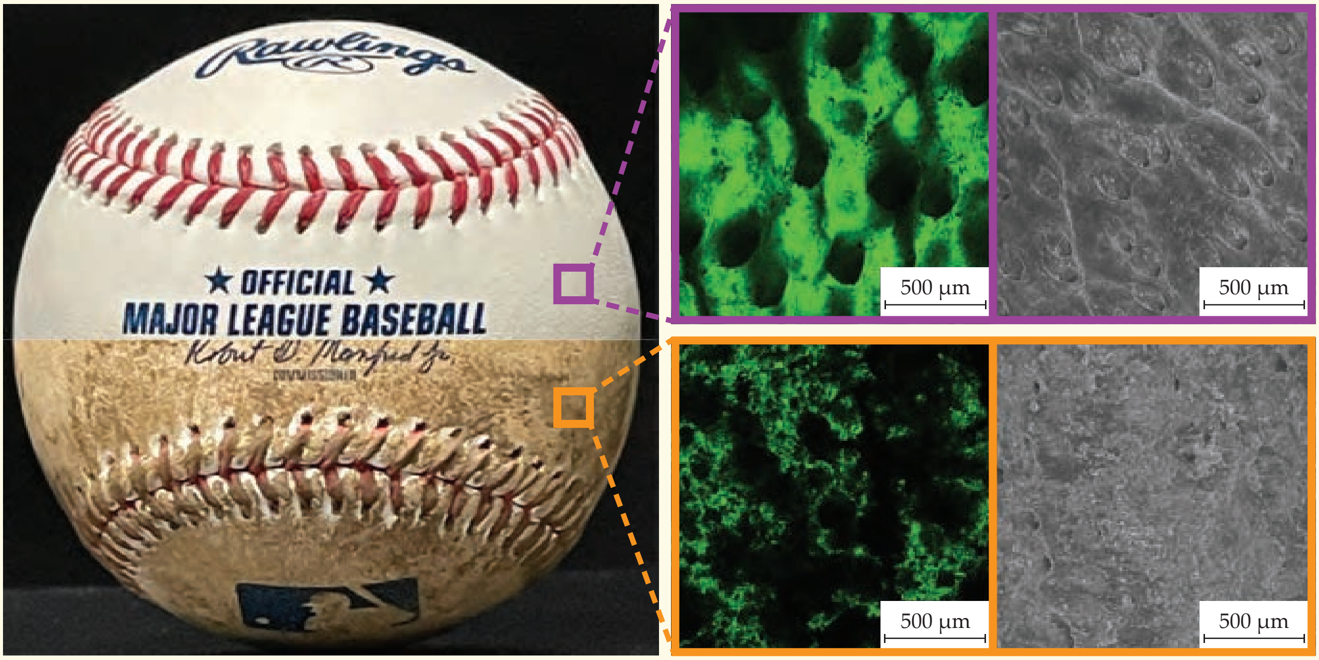
Pradeep, a postdoc who joined the group in 2021, has a background in the study of flow behaviors of dense suspensions. After imaging the mudded baseballs and designing an experimental apparatus to analyze them, Pradeep, Jerolmack, and colleagues found that the mud's specific composition and flow properties give it the ideal characteristics for increasing the friction of a baseball's surface.

X-ray spectroscopy and x-ray diffraction revealed that the mud is composed of roughly equal parts clay and a silt–sand mixture. That composition is, by and large, similar to natural muds. But the baseball mud has a weird, unnaturally sharp upper limit in grain size: Almost no grains are larger than 169 μm, which could explain why the rubbing mud feels so smooth to the touch. The flow tests show how the mud coats the ball's surface. Rubbing applies shear stresses that deform the mud so that its viscosity decreases, making it flow like a liquid. Once dry, it forms a metastable solid that's easy to grip.

The changed surface is apparent in microscale images—the researchers took the ones shown here with confocal laser scanning microscopy (green) and scanning electron microscopy (gray). A clean baseball's surface is pockmarked with holes hundreds of micrometers long and wide and dozens of micrometers deep. When the mud is applied, the holes are filled uniformly with adhesive clay aggregates and silt, while sand particles stick to the ball and create a surface with higher friction.

The mud is collected from a riverbank in New Jersey, but the exact location is a closely guarded secret, as is the processing and screening that's done before the mud is sold. From the analyses done so far, the researchers speculate that the Lena Blackburne company processes the raw material to remove the largest grains and adjusts the water content for maximum shear-thinning behavior. But the researchers won't be making their own mud anytime soon. "We know how the mud works, but we don't know why," says Jerolmack. "Earth makes complicated materials, and it would be nontrivial to mix together all the right compounds in just the right proportions." (S. Pradeep et al., *Proc. Natl. Acad. Sci. USA* **121**, e2413514121, 2024.)

Alex Lopatka



A BASEBALL'S SURFACE, when rubbed with a unique mud, is easy for players to grip. The mud's mixture of clay, silt, and sand results in a more uniform microscale surface that's free of holes and with enough adhesion to increase the surface's friction. (Image adapted from S. Pradeep et al., *Proc. Natl. Acad. Sci.* USA **121**, e2413514121, 2024.)

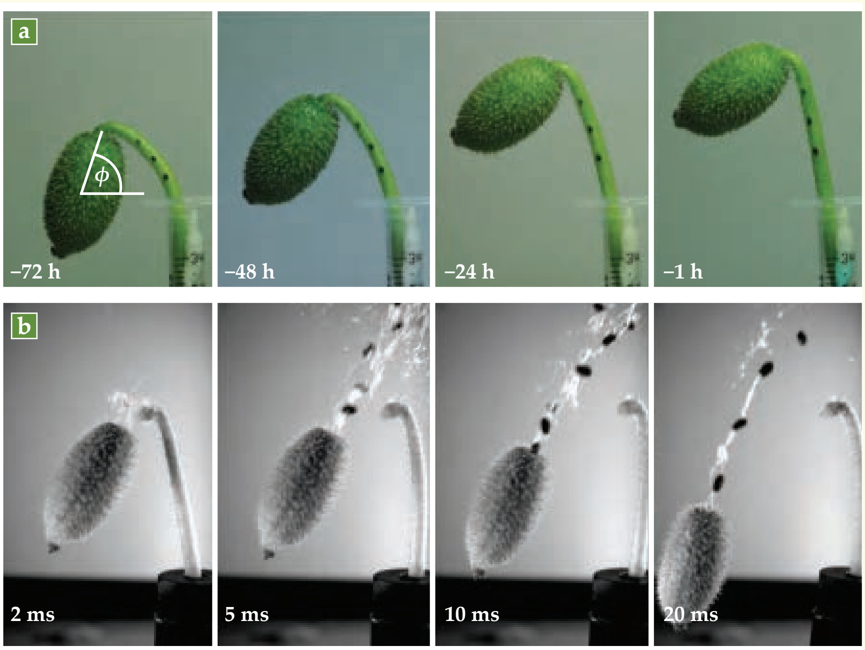
Squirting cucumber seeds go ballistic

A mechanics study reveals how the gourd uses fluid pressure and subtle shape changes in the days before ejection to maximize the dispersal of its offspring.

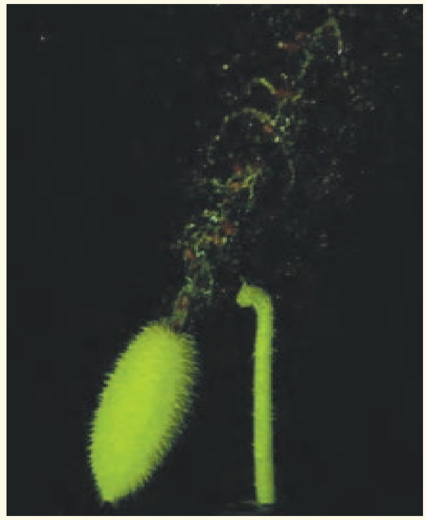
When you think of plants, you don't usually think of fast-moving objects. But some flora have evolved seed-dispersal methods that don't rely on the typical trick of hitching a ride via wind, water, or fauna. Rather, they convert stored pressure or elastic energy into kinetic energy to fling their seeds out into the world. The squirting cucumber is among the fastest of those seed-spitting plants. When ripe, the cucumber fruit falls from its stem and explosively launches a stream of fluid and seeds from the hole where it had been attached. Now, Finn Box and a set of colleagues from the University of Manchester and the University of Oxford, both in the UK, have unveiled details of how the cucumber achieves that feat.

Squirting cucumber seeds can travel as far as 10 m from their host plant and move at speeds of up to 72 km/h. Though it's a member of the gourd family, which contains many popular edible plants, the squirting cucumber fruit is slightly poisonous and not eaten by any animals. The plants are commonly found in arid regions around the Mediterranean Sea and were written about as early as the first century CE, when they were described by Pliny the Elder, a Roman naturalist, author, and military commander.

When Box and colleagues started monitoring the plants in the days before seed dispersal, they expected to observe a buildup of pressure inside the fruit. But that's not what they saw at all. "The pressure wasn't building hugely, so it must have already been established weeks prior to launch," says Box. The researchers actually observed a slight contraction of the fruit and a corresponding expansion of the stem, as if the fruit were transferring fluid to it. As the stem became more rigid over the course of several days, the fruit rotated from a near-vertical hanging position to a 45° angle, which created an optimal trajectory for the ejected seeds, as shown in the figure below.



(a) IN THE DAYS BEFORE seed ejection, fluid pressure increases in the stem of the squirting cucumber; the pressure changes the orientation ϕ of the fruit and maximizes the distance traveled by the seeds. **(b)** Once the fruit breaks from the stem, it ejects all its seeds in a few hundredths of a second. (Image adapted from F. Box et al., *Proc. Natl. Acad. Sci. USA* **121**, e2410420121, 2024.)

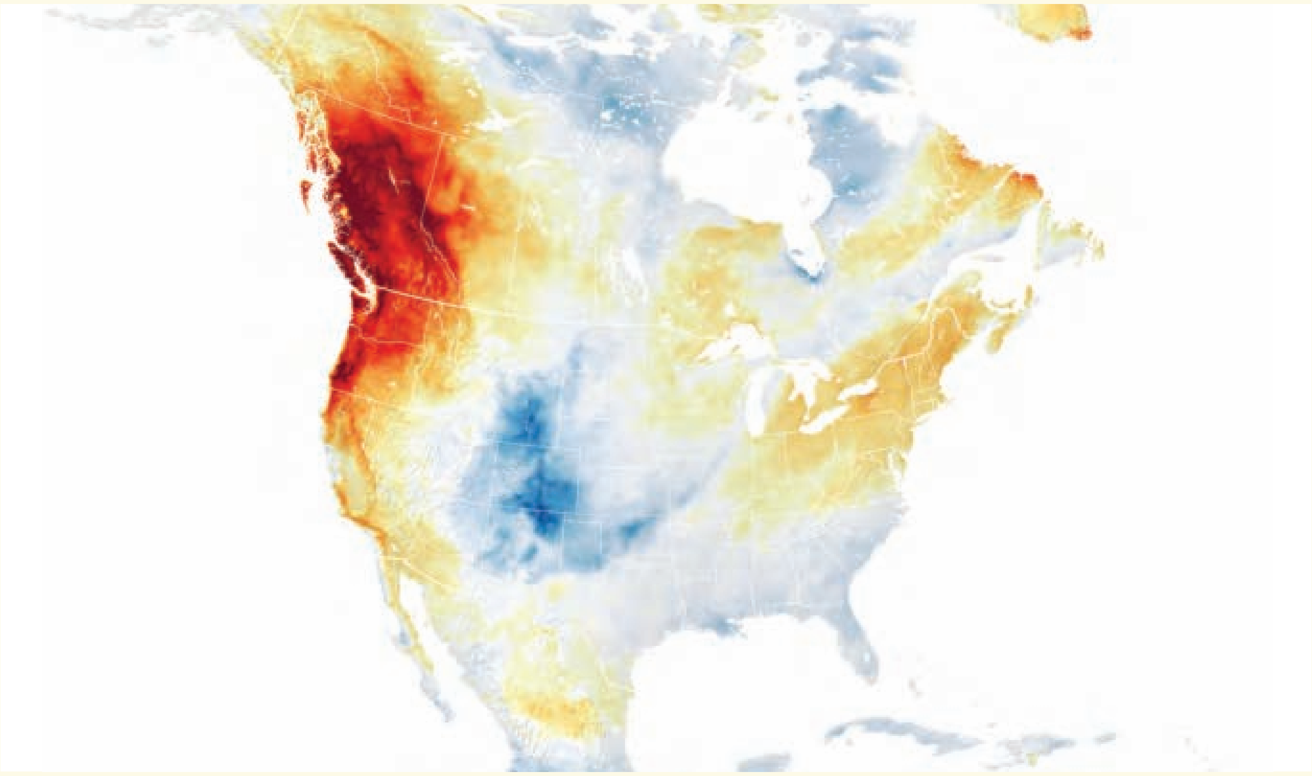


A STILL FROM HIGH-SPEED VIDEO shows the moment a squirting cucumber fruit detaches from its stem and ejects a stream of fluid and seeds that can travel as far as 10 m, at speeds of up to 20 m/s. (Image from Dominic Vella.)

Each cucumber fruit contains about 50 seeds, which are pushed out of the fruit in a matter of milliseconds. The first seeds fly out the fastest. A recoil of the stem imparts a rotation to the fruit, so that it spins toward a vertical orientation. That rotation, combined with the slowing speed of the ejected seeds, leads to an even dispersal of the seeds over a wide area. The research team used numerical models to simulate the effects of changing the fluid pressure in the stem or fruit and found that the squirting cucumber already has the optimal parameters. A higher pressure in the fruit than the observed 170 000 Pa drop, for example, caused more rotation that meant some seeds were launched straight up in the air and landed nearby.

The squirting cucumber has already inspired designs for targeted drug-delivery systems that use hydrogel capsules, and Box hopes that unveiling the details of how it operates will yield more bioinspired engineering designs. For the next growing season, he'd like to observe the plants for several weeks, not just days, before seed dispersal. He hopes to capture the process of fluid-pressure buildup that was unexpectedly missed in the first round of observations. The squirting cucumbers "really blew our minds," says Box. (F. Box et al., *Proc. Natl. Acad. Sci. USA* **121**, e2410420121, 2024.)

Laura Fattaruso



TEMPERATURES ON 27 JUNE 2021 in the northwestern US and southwestern Canada were as much as 15 °C higher than the 2014–20 average for that time. An atmospheric river of warm, moist air contributed to the record-breaking temperatures. (Image by Joshua Stevens, NASA Earth Observatory.)

Atmospheric rivers bring anomalously high temperatures

Narrow bands of water vapor, long known for the torrential rains they deliver, also transport vast amounts of heat.

A few years ago, Juan Lora noticed persistent warm and rainy conditions during Connecticut winters. The professor of earth and planetary sciences at Yale University thought that atmospheric rivers may be the culprit. Found in the lower atmosphere, atmospheric rivers are narrow plumes concentrated with water vapor that start in the warm subtropics and move thousands of kilometers to midlatitude areas and polar regions. Roughly 6–10 are found in the atmosphere at any one time, and they can transport water in volumes similar to or larger than what rivers can on land.

Most study of atmospheric rivers has focused on their hydrologic effects, although some researchers have studied their thermodynamics at regional scales. Lora and graduate student Serena Scholz have now analyzed the temperature effects of atmospheric rivers at a global scale. They found that in various locations over periods of hours to months, atmospheric rivers raise surface temperatures several degrees above the climatological average.

Lora and Scholz analyzed the turbulent and radiative heat fluxes through the atmosphere in a 43-year-long data set of space-based observations. They found that atmospheric rivers across North America and Eurasia were associated with average positive temperature anomalies of 5 °C. In polar regions during wintertime atmospheric-river events, the near-surface temperature anomalies climbed to 15 °C. On hourly time scales, the data indicate that the largest temperature anomalies in the midlatitudes are associated with storms that occur during atmospheric-river events.

The researchers have concluded that above-average temperatures in atmospheric rivers arise predominantly from the long-range transport of heat from the tropics. Water-vapor effects are a contributor too: When flows of warm, moist air meet at the surface, some of the warm air is forced to rise. As it does so, it releases heat when it encounters cold air and as the water changes phase to liquid. The researchers' results show a local warming effect from the convergence of water vapor. Warming is fueled further by longwave radiation getting trapped near the surface by an atmospheric river's clouds, in a transient, enhanced version of Earth's greenhouse effect.

Scholz and Lora's analysis focused on anomalies within the spatial bounds of atmospheric rivers. Some case studies, however—including research on a 2021 heat wave during which parts of the northwestern US and southwestern Canada saw surface temperatures reach 49 °C—show anomalous temperatures far from the atmospheric river itself and even after it has passed. That evidence means that the effects of atmospheric rivers could be more pronounced than Scholz and Lora's study estimates. (S. R. Scholz, J. M. Lora, *Nature* **636**, 640, 2024.)

Alex Lopatka

How Pluto got its biggest satellite

Pluto and Charon may have briefly merged before being bound in orbit. Other objects in the outer solar system may have assembled into binaries in a similar fashion.

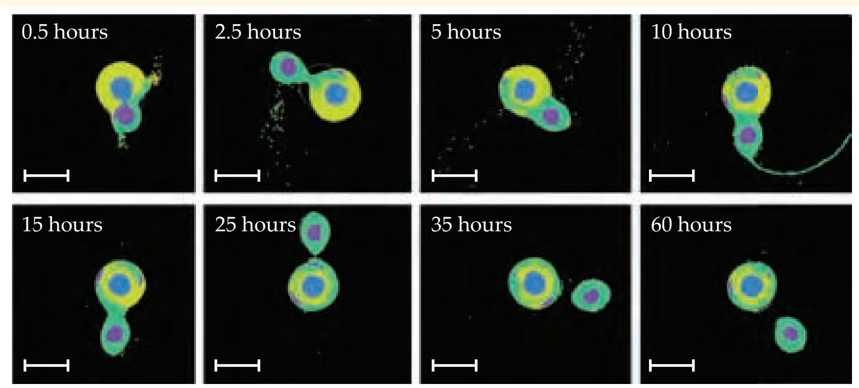
At about one-eighth the mass of Pluto, Charon is a satellite unusually close in mass to the body it orbits. Since the 1980s, astronomers have inferred that the binary system formed following the collision of two proto-bodies. Simulations of the system predicted a formation scenario in which proto-Charon grazed proto-Pluto, and the system lost enough angular momentum to match its current state.

Those simulations, however, treated the colliding objects as fluids. C. Adeene Denton of the University of Arizona wondered whether that was a reasonable assumption, considering that the proto-bodies that formed the Pluto–Charon system were smaller and not traveling as fast as other modeled impactors.

When Denton and her collaborators ran new simulations that factored in the material properties of the proto-bodies' ice and rock, the colliding bodies deformed less than they did in the fluid simulations. Grazing collisions became hit-and-run events where Charon escaped the system entirely. The simulations indicate that to match current observations of the binary system, proto-Charon would have had to hit proto-Pluto at an almost 45° angle and slightly penetrate Pluto's interior. Within about 60 hours, Charon would have been pushed away by the angular momentum of Pluto and captured into a close orbit.

PLUTO (LOWER RIGHT) AND CHARON (UPPER LEFT) are shown in a composite, enhanced-color image taken by NASA's *New Horizons* spacecraft. The bodies' relative sizes are approximately to scale; the distance between them is not. (Image by NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute.)

Denton and her team have dubbed the interaction "kiss and capture." The formation scenario may help explain when and how Pluto developed a subsurface ocean, evidence for which has been provided by observations of Pluto's surface from NASA's *New Horizons* and other missions. Tidal forces exerted on Pluto by Charon as it retreated from its close post-capture orbit could have been the source of the heat that melted the ice and formed the ancient ocean. Data from a future orbiter mission could provide the detailed understanding of Pluto's interior needed to support the scenario suggested by the modeling.



IN A SIMULATED CASE of kiss and capture, Charon (green and purple object) and Pluto (yellow and blue) exchange material following a collision, and the angular momentum of Pluto forces Charon away. The scale bar represents 2000 km. (Figure adapted from C. A. Denton et al., *Nat. Geosci*. **18**, 37, 2025.)

The Kuiper belt contains other bodies in binary systems with masses that are within a few orders of magnitude of Pluto and Charon's. Although no known ones have mass ratios like Pluto and Charon's, some scientists have suggested that the binaries share a common formation history. Denton says she suspects that the kiss-and-capture regime may prove to be a better fit for their formation than previous theories. (C. A. Denton et al., *Nat. Geosci*. **18**, 37, 2025.)

Jennifer Sieben PT

Japan accelerator pursues nanobeams to boost luminosity

Squeezing beams of electrons and positrons for the Belle II experiment at the SuperKEKB facility proceeds with halting progress.

Accelerator physicists at the SuperKEKB electron–positron accelerator in Tsukuba, Japan, are celebrating their December 2024 world-record luminosity of $5.1 \times 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$. At the same time, they are scratching their heads about how to reach their target luminosity, which is roughly an order of magnitude higher. Success has implications both for Belle II, the onsite experiment that studies B mesons and other particles, and for future electron–positron colliders.

The researchers' two-pronged approach to increasing luminosity is conceptually simple: "First, we put in more particles, and then we squeeze the beam," says Mika Masuzawa, a leading accelerator physicist at SuperKEKB. In practice, though, it's anything but, she notes. The aim is to use powerful magnets to squeeze the beams to about 50 nm in the vertical dimension and create a so-called nanobeam. So far, they've gotten down to 260 nm. For comparison, conventional beam sizes are on the order of microns.

Higher luminosity means more particle collisions per unit time and thus faster data accumulation. From the "narrow perspective" of the Belle II experiment, "we want more luminosity to do more physics," says Thomas Browder, a professor at the University of Hawaii at Manoa who represents US universities in the experimental collaboration. "From the perspective of future accelerator projects, they have to see that nanobeams are not a dead end."

THE BELLE II EXPERIMENT gets a makeover before its 2024 run. (Photo from the KEK/Belle II collaboration.)

The promise of nanobeams

SuperKEKB consists of two 3-km rings, with 4 GeV positrons circling in one and 7 GeV electrons in the other. The resulting collision energy is a sweet spot that yields B-meson pairs, allowing for the study of their various decay pathways and products. Both the experiment and the accelerator were upgraded before starting up in 2019—Belle II is the follow-on to the Belle experiment, and SuperKEKB had an earlier, lower-luminosity incarnation as KEKB.

For its upgrade, Belle II was outfitted with more-sensitive detectors and with new software that makes the experiment more robust against beam-related background signals. "The only part we retained was the crystal calorimeter," says Browder. It's difficult to pinpoint the cost of the upgrade, he says, because many contributions were in kind, and they came from many countries. About 700 researchers from 123 institutions in 28 countries make up the Belle II collaboration.

The SuperKEKB upgrade was mainly to introduce nanobeams. The Japanese government footed the bill, ¥31.4 billion (now roughly $225 million). In addition to getting higher luminosity for the same amount of current, the nanobeam approach, if it works, will use less power for a given luminosity. That, notes Browder, is significant: Electricity costs have surged in Japan in recent years, starting with the 2011 Fukushima Daiichi nuclear disaster (see Physics Today, May 2011, page 18, and November 2011, page 20), and more recently because of the COVID-19 pandemic and the war in Ukraine. And the value of the yen has nose-dived. All those factors have led to a curbing of run times for SuperKEKB.

For the most part, says Browder, SuperKEKB can squeeze a single positron or electron beam. But when two squeezed beams interact, they blow up and grow several times larger in diameter.

BELLE II SCIENTISTS in the experiment's control room celebrate the first collisions of the 2024 run. (Photo from the KEK/Belle II collaboration.)

Other concerns about the accelerator include low injection efficiency, according to CERN's Frank Zimmermann, who in January chaired the annual international review meeting for SuperKEKB. "The injected beam is much larger than the design value," he says, "which makes further squeezing at the collision point difficult." Sudden beam loss, which aborts a run and can damage both accelerator components and the detector, is another ongoing problem at SuperKEKB.

Nanobeams are difficult, Browder says. "There are many unanticipated problems in the hardware, and there are new accelerator phenomena in the beam–beam interactions at nanoscales." For now, SuperKEKB is the only particle accelerator that is actively working on nanobeams. "We are concerned about the progress," says Belle II spokesperson Karim Trabelsi, a researcher at the CNRS in France, "but we think the accelerator team is on the right track."

Cracks in the standard model

The Belle II team needs higher luminosity to increase the collision rate in order to spy rare events, infer the existence of dark-matter particles, and make precision measurements to glimpse deviations from theory. "We need much larger statistics than have previously been available," says Trabelsi. "The idea is to have a huge amount of data on forbidden decays—decays not allowed by the standard model—which would be signs of new physics," he says. "And Belle II can do a good job in the dark sector because of the clean positron–electron environment. We can study all the signatures."

Peter Križan is a Belle II researcher based at the University of Ljubljana in Slovenia. He notes that the decay of a B meson to a kaon, a neutrino, and an antineutrino has been observed at Belle with higher-than-expected probability. "It's super exciting. It's a crack in the standard model," he says. "But it's not conclusive. We need more data."

CERN's Zimmermann and accelerator physicists from other facilities are troubleshooting with the SuperKEKB team. "We are trying to help them measure and correct their optics, simulate beam–beam effects, and compute beam losses around the ring," says Zimmermann. With a new software package developed at CERN, he says, simulations can optimize collimator settings, for example. "In principle, with our model, we could help in many ways."

Among the recommendations that Zimmermann's review panel made in January are for the SuperKEKB team to explore shaping the incoming beam phase space by using nonlinear magnets. The panel also said that the team should continue investigating sudden beam loss "until one or more physical reasons and mechanisms have been found and verified beyond doubt." Another recommendation is to "develop accelerator conditions" such that Belle II can restore the use of one of its key new detectors, which was turned off to protect it from sudden beam loss events.

The SuperKEKB accelerator team has cycled through various possible explanations for sudden beam loss. Accelerator physicist Masuzawa is confident that the team has identified the culprit: dust from a goopy vacuum sealant. "We cleaned the area, and the sudden beam losses almost disappeared," she says. Zimmermann says that he is hopeful but not yet convinced that the sealant is the sole explanation.

Mastering nanobeams at SuperKEKB would also benefit future projects like the Future Circular Collider (FCC) that CERN envisions. The FCC would be about 90 km in circumference and, in its initial electron–positron incarnation, would operate at collision energies up to 365 GeV. A similar project in China, the Circular Electron Positron Collider, would also require nanobeams. (See Physics Today, September 2020, page 26, and "China plans a Higgs factory," Physics Today online, 17 December 2018.)

"It's better to understand the problems at SuperKEKB, but it's unlikely that the FCC would have the same problems," says Zimmermann. If SuperKEKB achieves a 50 nm vertical-beam height, that would be excellent, he adds, but if the collaboration doesn't reach its nanobeam goals, "it doesn't necessarily bode poorly for future machines, although it could be bad for public perception."

Still, particle and accelerator physicists see nanobeams as a must for such future machines. Keeping power use in check, says Browder, would be necessary to limit electricity costs, prevent melting components, and maintain a reasonable carbon footprint.

Toni Feder

Researchers share computational tricks at unique Los Alamos conference

Scientists encompassing multiple disciplines and security clearance levels spent more than a month discussing how to efficiently capture both small- and large-scale phenomena in calculations.

Last April, Los Alamos National Laboratory nudged open the security gates and welcomed outside researchers from biophysics, plasma physics, materials science, Earth systems studies, and more for an unusual month-long conference.

The goal of the inaugural Scale Bridging Meeting and Workshop was for interdisciplinary scientists to share the challenges they face and the tricks they employ when it comes to solving complex computational problems. The Los Alamos organizers also hoped that the gathering would lead to advances in the simulations that physicists use to understand—and thus maintain and modernize—nuclear weapons.

"Often, what you find in science in general is you have these silos, and people are making advancements in their own silo and often reinventing things that other fields have already developed," says Jesse Capecelatro, an engineer at the University of Michigan who attended the meeting. "I think this cross-fertilization is really important for advancing science as a whole, and that was sort of the vibe."

That academic researchers were conversing with scientists doing research that is at least partially classified added intrigue to the proceedings.

Making a guest list

Chris Fryer, a computational physicist at Los Alamos who co-organized the meeting, says the idea came in part from a historical perspective regarding the lab's role in the computational sciences landscape. The lab's secrecy and siloed nature was, perhaps, fine when the Department of Energy was the powerhouse in computation, with world-class supercomputers and computational methods. "Now they're used everywhere," says Fryer.

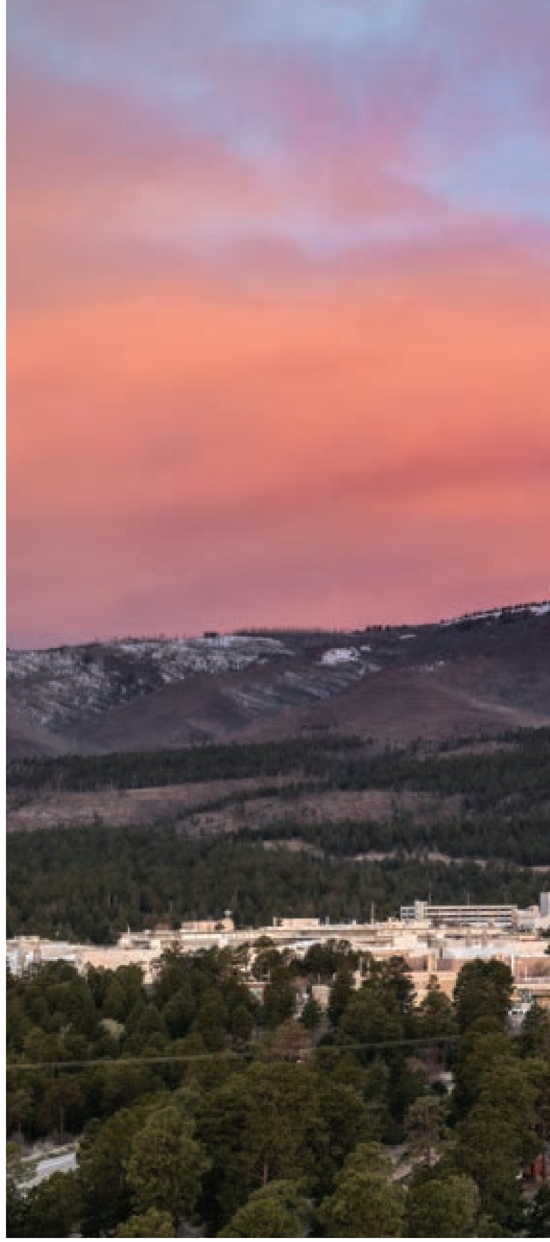
And everywhere, people without security clearances are coming up with clever ideas. "We can't isolate ourselves because we are now a small fraction of all the computational scientists in the world," Fryer says. At the same time, Los Alamos scientists are tackling "stuff that computational scientists across all disciplines are worried about," he says, such as innovative computational methods and algorithms that could make more accurate models of nuclear weapons or airplane wings.

One way to foster an exchange of knowledge, Los Alamos officials thought, would be to host a long, intensive computational workshop in the style of the Aspen Center for Physics, which brings experts together for weeks-long collaboration sessions on focused physics topics. "Los Alamos seemed like a great place to do that with our prowess and long history in computing," says Aimee Hungerford, the deputy leader for the lab's computer, computational, and statistical sciences division.

The organizers settled on the topic of bridging scales: connecting small size and time scales to large ones in a computational problem. Los Alamos scientists saw scale-bridging problems popping up and plaguing their work on nuclear weapons and on basic physics. And they knew that the same issues plagued researchers in other fields.

The organizers both advertised and looked to their home turf for potential attendees. Los Alamos scientists study so many topics, including pandemics, clean energy, and drug design—in addition to nuclear weapons and the related scientific disciplines that inform their design and function. Fryer asked his topically diverse lab colleagues to recommend thinkers in their fields.

In the end, that meant attendees like Paul Ricker, a computational astrophysicist at the University of Illinois Urbana-Champaign who researches active galactic nuclei, the bright centers of distant galaxies where supermassive black holes are releasing energy in the form of relativistic jets. To grok the jets, he has to understand galaxy clusters that are around 3 million light-years across, galaxies that are perhaps 300 000 light-years in diameter, and black holes roughly the size of our solar system. And he hasn't yet.



AN EARLY-MORNING AERIAL VIEW of Los Alamos National Laboratory in April 2019. (Photo from Los Alamos National Laboratory.)

Capecelatro studies fluid dynamics and turbulence and their applications in fields such as renewable energy, disease transmission, and space exploration. "One of the beautiful things is, we actually have a set of equations that describe exactly how fluids move around and interact," he says. But the huge time and size scales cause analytic problems. "Even though we know the equations, there's no analytic solution,

and we don't have any computer big enough to solve them."

The invite list included many people who were familiar not only with scale bridging but also with the lab, its scientists, and its sometimes controversial work. Capecelatro was a postdoc funded by the National Nuclear Security Administration; Ricker did unclassified work at Los Alamos on DOE's Accelerated Strategic Computing Initiative, which was established after the US stopped explosive testing of nuclear weapons and needed better simulations of them. Other attendees had used DOE supercomputers—outside scientists can collaborate with lab researchers on projects and so be included on applications for time on the machines.

Knowledge diffusion

Each morning from the end of April through the end of May, the attendees commuted from their hotels and Airbnbs in town and met for an hour or so to chat about what they'd been pondering overnight. Then they outlined goals for the coming day, went off to think more about them, and reconvened in the evening to talk about what they'd learned.

The discussions weren't always smooth. For instance, the environmental scientists in attendance described the concept of diffusion in terms of Darcy's law, which is used to describe the flow of a fluid through a porous medium; astrophysicists and others had no familiarity with that term. "This is why it's good to bring people together, because at some point it's like, 'I don't understand what you're saying. Write up the equation on the board,' " says Fryer. "And you write the equation, and you go, 'So we do have a common language. It's called math.' "

Once they got their lexicon under control, the researchers went over the tools they've been using to bridge scales. Those include stochastic methods, like Monte Carlo simulations, and finite-volume methods that take a continuous equation and break it down into small parts that can be represented on a grid.

During discussions, people came across new methods that weren't common in their own disciplines. Ricker is keen on heterogeneous multiscale modeling. In hydrodynamic simulations, Ricker explains, you move forward in time in finite steps, and you see how the system changes at each step. "The time step that you take is really long compared with the characteristic time scales of the small scale," he says.

To account for that, Ricker learned through discussions, you can do a sort of sub-simulation. "In between one of these giant steps, you actually run local simulations of the small scales that are resolved but that don't cover the entire domain, that just cover the small region, and then only go for the duration of that one step," he says. Within the giant step, the local sub-simulations take many small steps and make a prediction. Ricker is interested in seeing how the technique might benefit his work on active galactic nuclei.

Other astrophysicists embraced a technique employed by materials scientists. Following a supernova explosion, radiation travels through and interacts with the clumpy stellar wind. The x-ray photons that astronomers detect are often more energetic than calculations predict because those calculation methods don't account for the small-scale interactions that trigger shocks and energize the outgoing radiation.

ENGINEER JESSE CAPECELATRO of the University of Michigan was among the interdisciplinary scientists who participated in the Los Alamos scale-bridging workshop. (Photo from the Department of Mechanical Engineering, University of Michigan.)

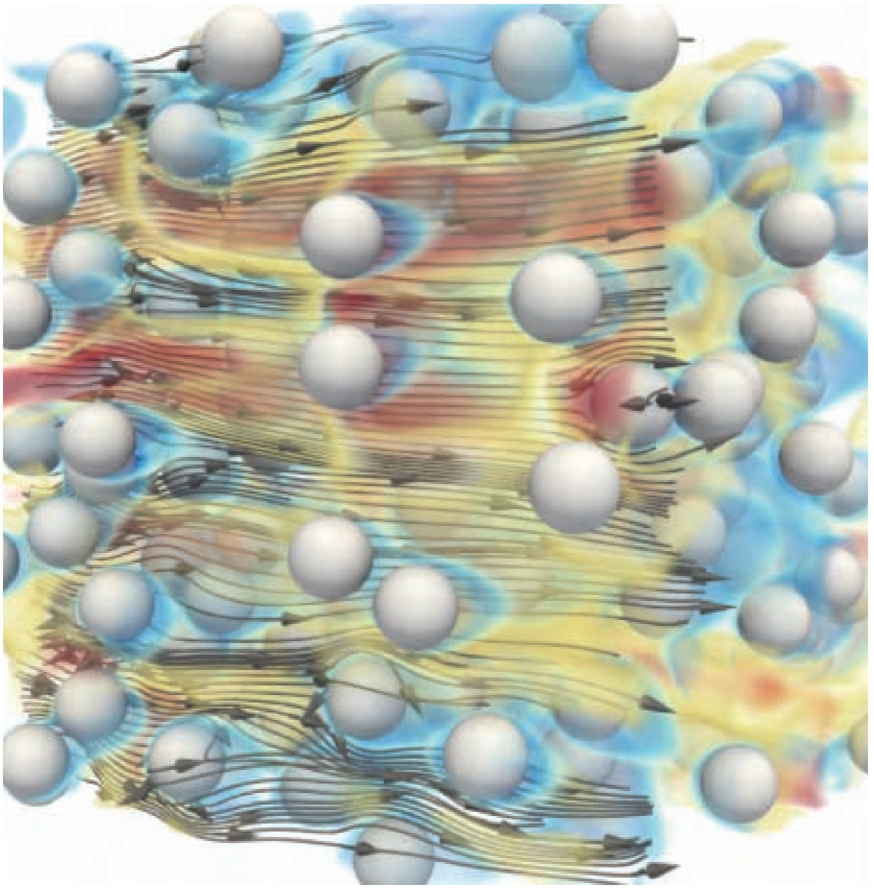
Materials scientists at the meeting described ways to preserve multiple effects that they quantify from the microscale. To do that, they break down a material into imagined components; each piece has its own characteristics that together determine the properties of the whole. An initial calculation might involve how pairs of adjacent pieces interact; subsequent iterations might involve groups of three, then four. With each refinement, the model of the whole grows more accurate while retaining the information of its parts. If astronomers can similarly break down a supernova remnant into such pieces, they may be able to capture the multiscaled interactions between the radiation and circumstellar material in the same simulation.

The back-and-forth learning flowed between disciplines and between academic and national lab scientists. Sometimes, the lab scientists have pinned down more detailed physics in their simulations because they're dealing with real-world problems of high consequence and can't abide the large error bars of some astrophysics calculations. "They have a lot of practical problems to address," Ricker says. But that has a flip side. "There's a problem focus that I think is less true in academia, where you're more wide ranging, and maybe if an interesting idea comes up, then you're willing to go off in this direction."

That intellectual freedom can lead to more creativity. And academics' more frequent and less managed interactions with students and colleagues can make them better at rendering their ideas comprehensible to people from different backgrounds. "We don't have anything we can't talk about, and there's obviously stuff that they can't talk about," says Ricker about national lab scientists like Fryer. That secrecy can limit both sides' ability to collaborate. "The type of problems that they're working on, I don't have clearance to know a lot of those details," says Capecelatro. "And so it's interesting to be in a setting where you have to sort of guess why they care about certain things."

The workshop's results, however, will be wide open. Fryer is writing up the conclusions for publication in a peer-reviewed journal. He hopes that scientists, particularly early-career researchers, from any relevant discipline can learn to bridge scales from the month on the mesa.

Sarah Scoles



A VISCOUS FLUID flows through a suspension of particles in a 2022 simulation from Jesse Capecelatro and colleagues. (Image from A. M. Lattanzi et al., *J. Fluid Mech*. **942**, A7, 2022.)

Q&A: Historian of science Jahnavi Phalkey starts a museum

The founding director at Science Gallery Bengaluru in India aims to "bring science back into the culture."

JAHNAVI PHALKEY. (Photo from LastBenchStudio.)

Not for the first time, in late 2017, Jahnavi Phalkey took a sharp turn in her career: She left King's College London, where she was on the faculty as a historian of science, to establish Science Gallery Bengaluru in India.

Years earlier, after earning two master's degrees in civics and politics, she pivoted for her PhD to study the history of experimental nuclear physics in India. This time, though, the decision to switch directions was harder: It involved both moving across the world and giving up her academic dream job and tenure. "I became a difficult person to live with," she says. "Finally, my husband asked, 'When you are 70 will you regret having done this? Or will you regret not having done this?' I decided to give it a try."

Part of an international network of galleries that focus on bringing art and science together, the Bengaluru site opened its doors in January 2024 with an exhibition on carbon. It is currently working on a year-long quantum festival to coincide with the 2025 International Year of Quantum Science and Technology (see PHYSICS TODAY, January 2025, page 7).

Phalkey oversaw permitting, design, and construction of the gallery. She is also in charge of fundraising and managing people. Along the way, she says, "I have been demoralized and frustrated. I have had some very low lows. But I never felt like quitting." And now that the gallery is open, she says, "I look at it and think, 'Why did I think I could do this?' " Her favorite parts are designing a new kind of public space for knowledge and conceptualizing ideas for the exhibits.

PT: How and why did you make the switch from civics and politics to the history of science?

PHALKEY: I did my undergraduate studies and my first master's degree in Bombay [now Mumbai], my hometown. After my second master's degree, which I did at the University of London on the politics of Asia and Africa, I returned to India to do a PhD at the Indian Institute of Technology Bombay. I was working on silent cinema. But about a year into my PhD, I began to feel that the kinds of questions I was expected to answer were not very interesting to me. The questions were all meant to be about why filmmakers chose certain topics and how that related to the sociopolitical context and things like that.

At that point, I didn't know there was a discipline called history of science and technology, but I knew I was not happy with what I was doing. I wrote a bunch of applications to study abroad.

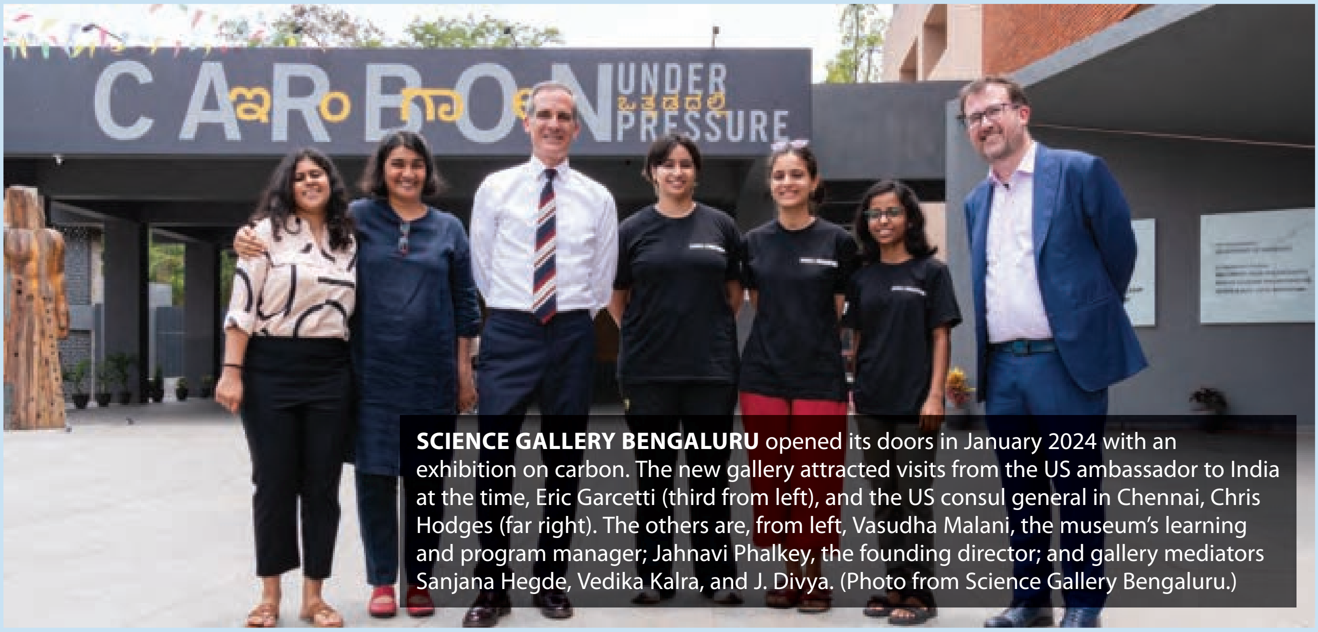
The one I had the least idea about was Georgia Tech and the history of science. I told myself that I would try it for six weeks, and if I didn't like it, I would switch to Sciences Po [the Paris Institute of Political Studies], where I also had an offer of funding. I went to Georgia Tech in 2000 and got my PhD there in 2007.

PT: What did you like about the program?

PHALKEY: I felt like I was learning things I knew nothing about, and they were exciting. I also liked the cohort I was studying with. The joy of American graduate school is that it leaves you room to explore. You are allowed to float until you find what you want to sail with. That was wonderful.

PT: What did you end up sailing with?

PHALKEY: In the first or second semester, I became drawn to certain questions about Cold War history of science. I felt that if I wanted to write a thesis on something along those lines, then I needed to know some physics—enough to be able to talk with physicists convincingly. If someone said "field," "particle," "bombardment," or "cyclotron," I could not *not* know it. That prompted me to audit undergraduate physics courses.



SCIENCE GALLERY BENGALURU opened its doors in January 2024 with an exhibition on carbon. The new gallery attracted visits from the US ambassador to India at the time, Eric Garcetti (third from left), and the US consul general in Chennai, Chris Hodges (far right). The others are, from left, Vasudha Malani, the museum's learning and program manager; Jahnavi Phalkey, the founding director; and gallery mediators Sanjana Hegde, Vedika Kalra, and J. Divya. (Photo from Science Gallery Bengaluru.)

Among the books I read, the one that made me choose not only my PhD topic but also the area I would research with utmost love was called *Lawrence and His Laboratory: A History of the Lawrence Berkeley Laboratory*, by John Heilbron and Robert Seidel. In my work, I could show that what happens with the state, what happens with policy and regulation, deeply affects what can or cannot happen in a lab. And also that institutions of the state are formed around research to determine the course of research. Heilbron and Seidel's book allowed me to see how totally enmeshed politics, science, and society are. It set me on my path.

During my coursework at Georgia Tech, I felt we were studying history as though science happened only in the US and Europe. But I thought something must have happened in India too. That curiosity took me back to India. I studied six labs, the first ones that wanted to establish and continue experimental nuclear physics in India.

PT: How did it work out?

PHALKEY: The state of Indian archives is quite poor. When I was doing my PhD, in many ways I had to assemble my own archives—by begging and borrowing. You meet individuals, establish trust, and ask people to do you favors.

When I started writing, I realized I could put together a decent narrative from the first three labs—in Calcutta, Bangalore, and Bombay [now Kolkata, Bengaluru, and Mumbai]—from when they were trying to establish nuclear physics starting in the late 1930s until the 1960s. The competition between those labs, their relationships with each other, and how they functioned before the Second World War, after the war, and during Indian independence became a narrative that could be woven together in an interesting way. That became my dissertation. Later, I made a film about one of the others: Chandigarh has the world's oldest functional cyclotron. It had been built at the University of Rochester in 1936 and in 1967 was sent to India.

PT: Where did your career take you after you finished your PhD?

PHALKEY: My first postdoctoral project was at the Deutsches Museum in Munich, where I was a scholar in residence. Then I taught the history of science and technology and other courses. In 2011, I got a faculty appointment at King's College London. I got tenure, and I was there until seven years ago, when I moved to India to establish Science Gallery Bengaluru.

PT: What enticed you to move back to India?

PHALKEY: I was not looking to leave my job in London. I think I was in the regular band of misery that academics usually occupy—you know, doing fine.

But a recruitment agency called me, and the proposal sounded interesting. I was having discussions with museum board members about what needed to be done—not having an interview—because, in a very respectful way, I had nothing to lose. Then they invited me to India.

I met with a group of 13 people who interviewed me. They offered me the job that same day. Then I spent a few miserable summer months trying to decide whether to take it.

PT: Tell me about Science Gallery Bengaluru.

PHALKEY: The vision statement that I operate with is "Bring science back into the culture." Our exhibitions are interactive and focus on intersections of art and science. Activities include hands-on workshops, master classes, tutorials, film and zine making, hackathons, game development, and more. This year the topic is quantum; a possible future topic is the calorie, which would be about food, nutrition, and energy and the journey of a measurement from physics to nutrition.

We are also creating resources like portable exhibits, online learning resources, and activity handbooks that will go to public libraries. By reaching the libraries, we can potentially reach 5 million young people.

The pioneering idea in Bengaluru is the public–lab complex. We have five experimental spaces that we hope will soon go live. We will run them on a fellowship model, where we invite proposals and bring people from across disciplines to share the space. Each lab can take 15–17 people. We will have five fellows that come for 10 months and other spots on a more short-term, ad hoc basis.

The idea is to get people in to explore an idea and fine-tune it in conversation with others to the point where it can be taken to a university or industrial lab. I am aiming at anyone who has passion.

Two things I insisted on are to reduce barriers to entry: We remain free to the public, and everything we do is bilingual—in the local language Kannada (which, unfortunately, I do not yet speak) and English.

PT: Do you miss being a professor?

PHALKEY: I miss supervising my PhD students. I miss the reading and writing—well, I don't love writing, but I do want to write. My mind feels dehydrated; it has been deprived for a long time of the nourishment of new knowledge and intellectual insights gleaned by reading, writing, and thinking.

PT: Where do you want to be in five years?

PHALKEY: I am actively thinking about that. My contract runs out in three years. The board and I will evaluate whether the institution is strong enough and whether it needs me or needs fresh blood. I could see myself returning to academia.

Toni Feder

Women leave physics at a rate similar to that of men, bibliometric study suggests

Although women continue to be underrepresented in the physical sciences, the rate at which they leave the field is on par with that of men. That's according to an August 2024 study in the journal *Higher Education* that examined the publication patterns of researchers in 16 broad disciplines within science, technology, engineering, mathematics, and medicine.

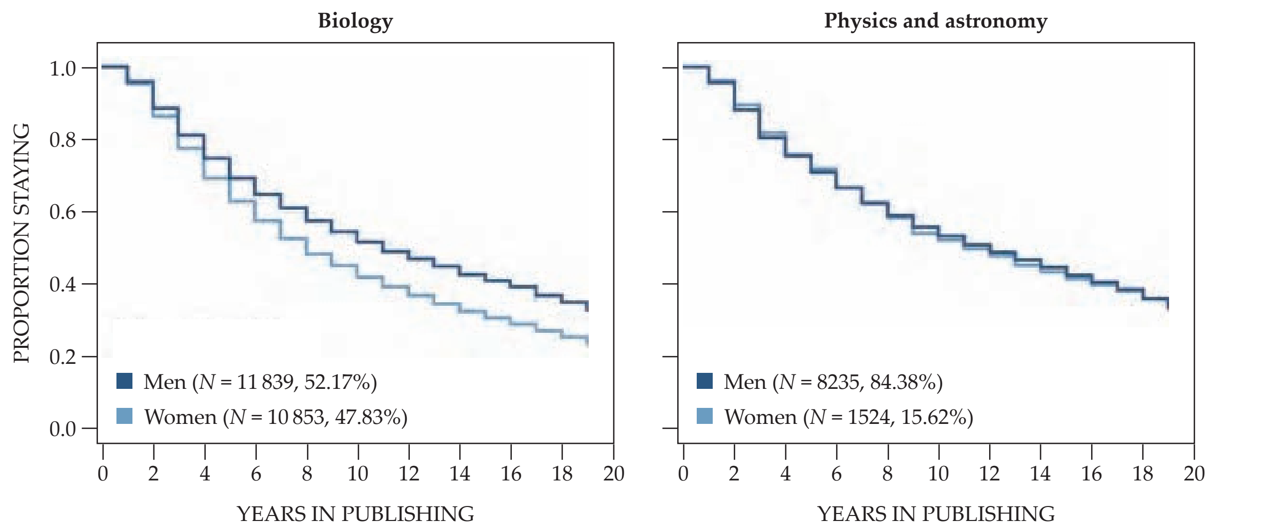
Using data from Scopus—a global database of publications and citations—Marek Kwiek and Lukasz Szymula of the Adam Mickiewicz University in Poznań, Poland, tracked the publishing careers of researchers in the 38 countries of the Organisation for Economic Co-operation and Development. They focused on more than 140 000 scientists who began putting out papers in the year 2000 and more than 230 000 who started doing so in 2010; both groups were tracked until 2022. A cessation in publishing before 2019 was used as the indicator that a scientist had left research.

Kwiek and Szymula found that about one-third of scientists who started in 2000 had left after 5 years, half had left after 10 years, and two-thirds had left by 2022. The differences in attrition rates between men and women varied by discipline. In biology, women, who made up nearly 48% of the year-2000 cohort, left at significantly higher rates than men throughout the study period. In contrast, in physics and astronomy, the attrition rates were similar for men and women. Of the 1524 women, 28.1% had left after five years and 66.9% had left by 2022; for the 8235 men, those numbers were 29.2% and 66.5%, respectively. That trend also bore out in fields such as computer science and mathematics.

The authors note the limitations of a bibliometric analysis; for example, some of the researchers who were classified as leaving the field may have taken a science-related job that didn't involve publishing research. And recent studies with different methodologies have suggested that in academia, women leave at higher rates than men at every stage of their careers.

For a breakdown of attrition rates and related data presented by Kwiek and Szymula, see https://doi.org/10.1007/s10734-024-01284-0.

Tonya Gary



(Figures adapted from M. Kwiek, L. Szymula, *High. Educ.*, 2024, doi:10.1007/s10734-024-01284-0.)

FYI SCIENCE POLICY BRIEFS

Stay up to date on science policy with *FYI*

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APS suggests selective R&D on carbon dioxide removal

The American Physical Society released a report in January that recommends cautiously pursuing R&D on various methods for removing carbon dioxide directly from the atmosphere. But the report stresses that the technologies have extensive resource requirements and should not be viewed as an alternative to reducing emissions. The report highlights the energy-intensive nature of engineered approaches, such as direct air capture using chemical processes, and the substantial land areas needed for natural processes that capture carbon in plant matter or rocks. Accordingly, it recommends that funding agencies request that proposals for R&D on any CO_2 removal approach identify the expected energy demand, the power source, and the land area needed and impacted.

The report also highlights the need for economic policies that balance the costs and benefits of carbon-removal strategies. For example, it states that chemical direct air capture at scale is expected to cost hundreds of billions of dollars per gigaton of CO_2 but that those high costs could be offset with emissions-reduction policies that impose a cost for carbon emissions. The report anticipates that even with sharp emission reductions, atmospheric CO_2 removal on the scale of 1–20 gigatons per year may be necessary by later this century to avoid a surface temperature rise of more than 2 °C. —CZ

Fermilab searching for new director

Fermilab director Lia Merminga abruptly stepped down in January, with no reason given for the resignation. Merminga had been expected to remain as director under the new management contract that began this year. One potential precipitating factor is that on its 2024 report card from the Department of Energy, the lab received its lowest marks since the current lab appraisal process began in 2006. The lab failed to meet expectations in five out of eight categories, including grades of C+ in program management and contractor leadership and a C in business systems. (The DOE Office of Science defines a B+ grade and above as meeting expectations.)

Merminga was appointed director in April 2022 and was the first woman to hold the position. Young-Kee Kim, a physics professor at the University of Chicago and former Fermilab deputy director, is serving as interim director, and the lab has launched a search for a new director. —CZ PT

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

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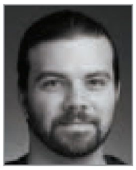
A gravitational lens in the Fornax constellation. (Image from ESA/Hubble and NASA, S. Jha; acknowledgment: L. Shatz/CC BY 4.0.)

Sebastian Fernandez-Mulligan is a PhD candidate in the program in the history of science and medicine at Yale University in New Haven, Connecticut. For his dissertation, he is examining how ideas from statistical physics influenced information theory, economics, and art. This feature is adapted from his article "From the model to the glance: How astronomers learned to see gravitational lenses, 1960–2020," *Historical Studies in the Natural Sciences*, volume 54, page 461, 2024.



Learning to see gravitational lenses

Sebastian Fernandez-Mulligan

In the 1970s and 1980s, iconoclastic astronomers used diagrams, computer models, and their own intuition to convince the community that they had observed celestial objects that noticeably bend background light.

Strong gravitational lenses are hard to find. Since the late 1970s, when the first one was observed, astronomers have discovered only a few hundred. But that is about to change. In the next decade, a new generation of astronomical sky surveys will probe the cosmos with unprecedented sensitivity. Scientists predict that the data from those surveys will contain more than 100 000 lenses. The first data release, coming from the space telescope *Euclid*, launched in July 2023, is slated to occur this month.

Gravitational lensing is a consequence of general relativity: Massive objects curve the space around them and bend the trajectories of passing photons. Sometimes the effect is minor; in what is termed weak gravitational lensing, the paths of photons are only slightly warped. Strong lensing occurs when the light from a background object is so severely deflected by a massive foreground object that astronomers observe it as two or more distinct images. Those images can appear distorted or magnified. By boosting the brightness of the images, strong lenses can allow astronomers to see extremely distant sources that would otherwise be too faint to observe. With a vast sample of lenses in hand, astronomers hope to conduct statistically robust studies of high-redshift galaxies.

Since the 1980s, astronomers have relied on learned visual intuition to find gravitational lenses. Certain signatures become visible only after years of work, certain shapes become important only after one has seen them many times, and certain faint objects can be spotted in an image field only by an expert. The seasoned astronomer becomes well versed in those tacit skills. With thousands of images to comb through, quick

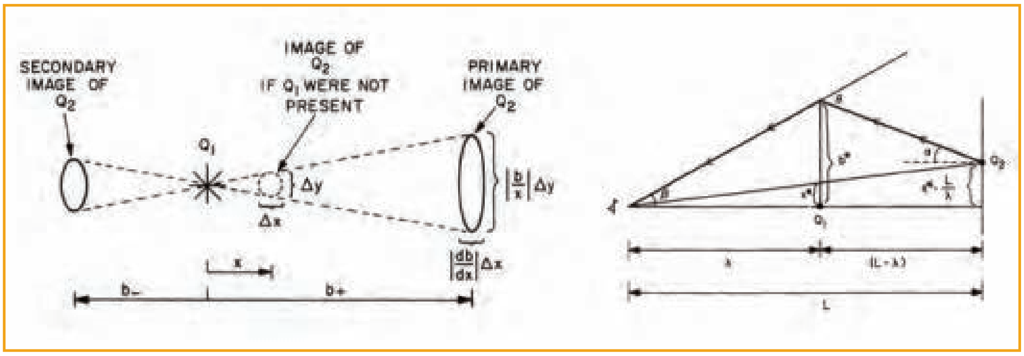


FIGURE 1. EARLY ARGUMENTS FOR THE EXISTENCE OF GRAVITATIONAL LENSES relied heavily on geometric schemata based on simple optics models, such as these images from a 1974 paper by J. Richard Gott III and James Gunn. (Images from ref. 7.)

and intuitive visual analysis is a key aspect in the data-processing pipeline. In a glance, the trained eye sees things that amateurs cannot.

The oncoming deluge will overwhelm even the quick, intuitive glance: 100 000 lenses cannot be found by hand. Recent work has thus focused on developing and deploying algorithms that can automate the search for gravitational lenses. But the increasing sophistication of algorithms has not spelled the death of observational intuition. When the programs are tested, the control is often a human astronomer, who combs through the same simulated dataset and uses their visual intuition to discover gravitational lenses. The success of the model is predicated on how well it compares with the trained eye.

The history of gravitational lensing provides insight into how that intuition was formed and how it became accepted. Rather than take that skill for granted, the astronomy community should acknowledge its historical development. Visual markers that seem obvious today—for example, a doubly imaged quasar or giant lensed arcs—were not initially viewed as clear signs of lensing. Their path to clarity was marked by befuddlement and contestation. By looking at the historical development of intuition, astronomers can ask a question about the present: What role does intuition play in today's computational age?

Visualizing what cannot be seen

Gravitational lensing was an active area of theoretical research during the 1920s and 1930s, when scientists were clamoring to confirm or contest the conclusions of general relativity. Arthur Eddington proposed gravitational lensing in 1920; his ideas were independently echoed by Orest Khvolson in 1924. Albert Einstein himself privately toyed with the concept in 1912 before publishing a short paper on lensing in 1936.[1] The following year, maverick astronomer Fritz Zwicky made one of the earliest arguments that gravitational lensing could be used to measure the mass of intervening galaxies.

But by the 1940s, as more astronomical observations solidified the credibility of relativity, work had all but ceased. Although lenses had offered an observable example of spacetime curvature, their predicted rarity made them unappealing research topics for observational astronomers. Even Einstein shared such pessimism, concluding his paper with the proclamation that "there is no great chance of observing this phenomenon."[2]

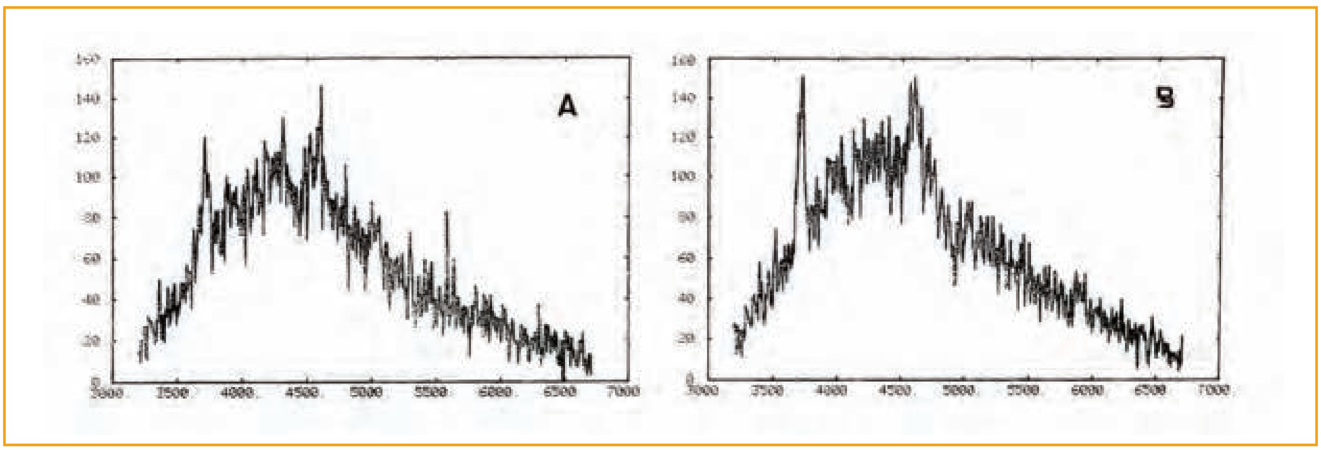


FIGURE 2. TWO QUASAR SPECTRA taken by Robert Carswell and Dennis Walsh on 29 March 1979, which they later identified as evidence of a gravitational lens. The first spectrum is on the left; the second, at right, was taken just a few moments later. (Images from ref. 8.)

As long as astronomers believed that gravitational lenses were impossible to observe, work on them remained sporadic. That pessimism remained until Maarten Schmidt's 1963 discovery of the first quasar (see the article by Hong-Yee Chiu, Physics Today, May 1964, page 21) sparked renewed interest in gravitational lensing. The newly found objects were puzzlingly bright—so bright that some astronomers argued that they might be the result of magnification from gravitational lensing. Married collaborators Jeno Barnothy and Madeleine Barnothy Forro were the most radical proponents of that theory, arguing that quasars were simply lensed galaxies. They predicted that there were hundreds of lenses across the sky.

Other scientists used the attention of the quasar discovery to highlight additional potential lensing applications. Astrophysicist Sjur Refsdal, for example, rigorously defined how lenses could allow astronomers to infer the mass of intervening galaxies or to measure the Hubble constant through a lensed supernova flash. As he and coauthor Jean Surdej later wrote, his and others' work was received as "particularly promising because of the recent discovery of quasars by Schmidt."[3] Lenses had transitioned from mathematical oddities to observational possibilities.

But how could they be found? No prior observations existed. There was no standard practice to replicate, no routine data to collect, and no agreed-on logic to follow. Although astronomers predicted that double images could occur, they had no empirical example to search for in practice. Using existing tools, scientists had to develop techniques that would make lenses visible both to themselves and to their colleagues.

Nigel Sanitt, a graduate student at Cambridge University in the early 1970s, sought to turn possibilities into observations. Roger Blandford, Sanitt's office mate at the time, remembered "berating him for working on a phenomenon that was unlikely ever to be observed."[4] Despite those apprehensions, Sanitt forged on with his thesis work, and he isolated five candidates for gravitational lensing from a catalog of radio sources. Of the five, he argued that one, 3C 268.4, exhibited high potential for lensing because a secondary image was present near the source.

That interpretation of 3C 268.4 was contested. What Sanitt argued was a "faint . . . companion image 2.5 arcsec away,"[5] other astronomers such as Jerome Kristian had previously identified as a "closer galaxy about [2.5 arcsec] to the south of the quasar."[6] Sanitt used the radio position data and the mathematical theory of gravitational lensing to argue that the faint image was indeed a lensed image and not a distinct galaxy.

Because the analysis of the telescope image was disputed, Sanitt's publication relied little on visual data. Instead, he used geometric schematics to logically buttress his reading of existing data. That style of argumentation was peppered throughout several papers in the 1970s. Further studies, such as the work of J. Richard Gott III and James Gunn, relied on theoretical drawings to make arguments about the possibility of observing lenses[7] (see figure 1).

FIGURE 3. RAY WEYMANN, pictured in 1970. In collaboration with Robert Carswell and Dennis Walsh, he coauthored the 1979 paper announcing the observation of the first gravitational lens. (Image courtesy of the AIP Emilio Segrè Visual Archives, John Irwin Slide Collection.)

Those papers achieved mixed success. Stick-figure schematics did not convince the astronomy community that gravitational lensing had been observed. But astronomers nevertheless welcomed the geometric drawings: They became the standard visualizations for a phenomenon that had not yet been observed.

Is seeing believing?

In 1979, possibilities became observations. At 2:00am on 29 March of that year, atop Kitt Peak National Observatory in Arizona, Robert Carswell and Dennis Walsh were midway

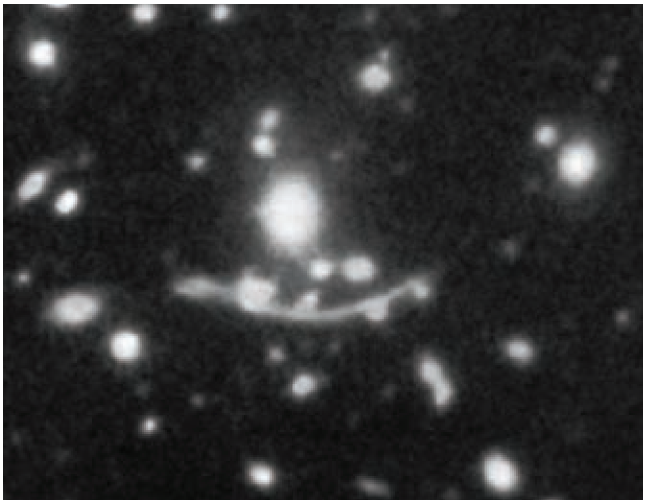


FIGURE 4. THE GIANT ARC found in the Abell 370 galaxy cluster, imaged in the visible spectrum. Arcs are now one of the telltale signs astronomers look for when searching for gravitational lenses. (Image adapted from NOIRLab/NSF/AURA/R. Lynds, V. Petrosian/CC BY 4.0.)

through an observation run to survey quasars. Having already slogged through a long list of objects, they plugged in the next series of pointing coordinates. The telescope heaved toward its programmed position. Two bright blue dots appeared on the viewfinder: the double object 0957+561. Two years earlier, Carswell and Walsh's collaborator Anne Cohen had measured the accurate optical position of that strange pair—seemingly two quasars that were very blue, very bright, and only six arcseconds apart.

Carswell and Walsh quickly measured a spectrum and estimated the redshift. When they looked at their results, they were shocked. Walsh recalled "two strong emission lines, the same two emission lines. Same redshift. Clearly, we'd made a mistake." Assuming they had accidentally measured the same object twice, the duo repeated their observations. The second measurement rolled in, and the two spectra remained identical[8] (see figure 2). For the blue quasar pair, the similarity in both categories meant, in the words of Carswell and Walsh, that "the initial conditions, age and environment influencing the development of the [sources] have been so similar that they have evolved nearly identically."[9]

Confused by their results, Carswell and Walsh reached out to Ray Weymann (see figure 3), a colleague working at the University of Arizona's Steward Observatory. Whereas Carswell and Walsh had been looking at emission lines—namely, sharp peaks in the spectrum—Weymann studied the absorption features, or discontinuous dips in the spectrum. Intervening objects, such as clouds of interstellar gas, are opaque to photons at certain wavelengths. When light reaches a telescope after passing through gas clouds, portions of the spectrum become attenuated, much like how sunglasses block UV light before it reaches our eyes. Weymann measured the spectrum of each source and found, once again, that the objects had the same redshift. More striking was that the objects had the same absorption features. And the two ostensible quasars were far enough apart that an intervening cloud of gas would need to be unprecedentedly large to cover both.

Weymann was the first to propose a gravitational lensing explanation. Having recently been asked by a colleague to examine the claim that quasars were gravitationally lensed galaxies, Weymann was well versed in the theoretical developments of the 1960s. If the two blue dots were images of a single gravitationally lensed source, he argued, then their spectra would be similar. And if a gas cloud sat in front of the original source, it would not need to be extremely large to explain the absorption line similarities. Carswell, Walsh, and Weymann published a paper in May 1979 arguing that their results were the first observation of a gravitational lens.[9]

But seeing is a tricky thing in astronomy. Observations occur at a wide range of wavelengths, and objects that look one way in the visible spectrum often look quite different in UV or radio wavelengths. Other colleagues scrambled to get multiwavelength data on the sources. "I remember well the mixed reaction [the paper] received," Walsh recalled.[10] Some astronomers noted that the shape of the two quasars did not look nearly as identical in radio images as they did in optical images. They showed that one of the two objects seemed to have an extended trail in the radio regime and argued that the dual objects were actually distinct. For months, debates raged over whether the sources were truly identical.[11]

Criticisms petered out as more lensing candidates were identified from observational data. Just a year later, Weymann and a group of collaborators published results arguing that the triple quasar PG1115+08 was three lensed images.[12] As the results rolled in, the practice of observing a gravitational lens stabilized: Astronomers needed to demonstrate that the sources in question had identical spectral signatures. As he told me in a 2022 interview, Weymann recalled that moment as an inflection point: "The notion that the gravitational lens really exists and that we can actually observe it triggered the realization of the reality of looking for instances of it." That was the thorny knot of discovery: To search for lenses, astronomers had to believe that they could be observed. To do so in the 1970s was to search for double, or even triple, quasars.

Modeling mysteries

In 1987, a new anomaly electrified the attendees of the American Astronomical Society annual meeting. Roger Lynds and Vahé Petrosian announced "the existence of a hitherto unknown type of spatially coherent extragalactic structure having ... narrow arc-like shape, [and] enormous length."[13] Stretching over 100 kiloparsecs, the arc (see figure 4) puzzled astronomers. What was its origin? Some thought it was a shock wave from galactic explosions, others saw it as evidence for galaxy cannibalism, and still others asked whether it was the deformed images of a gravitational lens.

The arc was found in Abell 370, one of about 2700 galaxy clusters included in a well-known catalog compiled by

FIGURE 5. THE VERA C. RUBIN OBSERVATORY, which will carry out one of the next-generation sky surveys, under construction in Chile in 2021. (Image from the Rubin Observatory/NSF/AURA/O. Rivera/CC BY 4.0.)

George Abell in 1958. Although astronomers had been observing objects from that catalog for years, they had discarded the arc as an observational artifact—perhaps a scratch on the glass plate used to record the image. But Lynds and Petrosian took electronic photographs. With no glass to scratch, the arc became an astronomical anomaly.

When Geneviève Soucail returned with a spectrum, things got stranger. Not only was the redshift the same across the entire arc, but it was estimated that the object was twice as far from Earth as any other galaxy in the Abell 370 cluster. Along with the redshift, the emission lines were also the same across the entire object; moreover, the spectrum had a break at about 4000 angstroms, which is characteristic of galaxies.[14]

Of the gamut of explanations, Soucail's team argued that the arc was the signature of a gravitational lens. But the researchers were faced with a challenge: There was only one arc. Unlike in the case of the double quasar, the astronomers could not simply compare spectra to prove the lensing origin. Instead, they turned to models. The increasingly powerful computational resources available in the 1980s allowed Soucail and her team to generate a simulated schematic of the lensing system, which they published in the article next to an image of the system. Side by side with the observational evidence, the model gave meaning to the arc. Lynds and Petrosian rapidly followed up with their own lensing models.

By making sense of arcs such as the one in Abell 370, the schematics transformed them into signatures of gravitational lensing. Arcs quickly became a key part of astronomers' intuition. Up late on an observation run in 1988, Patrick Henry and one of his graduate students pointed the telescope at Abell 963. A huge arc appeared on the screen. In a 2022 interview, Henry recalled immediately turning to his graduate student and joking, "Let's jump on it. A quick paper and we will . . . become rich and famous." When I asked Henry if he had taken a spectrum of the arc, he replied, "I'm not sure anyone ever got a spectrum of 963." Painstaking spectroscopy and analysis gave way to an intuitive assessment of the image.

As the coterie of astronomers studying gravitational lenses expanded in the 1990s, funding was found for large-scale search programs. The first of those, the MIT search program for gravitational lenses led by Bernard Burke, identified five gravitational lenses, the largest sample to date.[15]

The procedures of those search programs highlight how important intuition had become. The surveys began with an automated program that directed a radio telescope to map the positions of more than 6000 sources. Burke and his team then manually identified sources that had multiple, visually similar objects in close proximity, and those sources would be optically imaged at the 4-meter telescope on Kitt Peak and the 5.1-meter telescope at Palomar Observatory in California. With optical images in hand, manual analysis became even more important. Astronomers combed through the images and selected 40 candidates for intense spectroscopic study. They subsequently chose four for further examination. Throughout the process, visual analysis and intuitive skills were the grease between the gears of the data pipeline. Only at the end of the analysis pipeline did astronomers deploy their models.

Detection had become intuitive. As the number of known lenses increased rapidly in the 1990s, detection depended heavily on the visual examination of thousands of images. That kind of analysis continues today. At the University of Chicago, Michael Gladders trains the next generation of scientists in a hands-on astronomy course. As he told me in a 2022 interview, he entered a classroom in 2020 with 120 000 images of the sky. Dividing the portfolio among the students, he told them to be "fairly reflexive. If you're looking at them one every two seconds . . . you're done in an afternoon of work!" Just as the professionals analyze their datasets, the students powered through thousands of images to find just a few lenses, building their intuition as they went.

Whither intuition?

The scale of gravitational lens astronomy is shifting. Since the 1970s, astronomers have identified several hundred lenses through visual identification. With the next generation of sky surveys, scientists expect that they will observe more lenses than ever before. The *Euclid* survey is expected to ultimately find more than 150 000 galaxy–galaxy lenses. Later this year, the Vera C. Rubin Observatory (see figure 5) is expected to see first light. Its survey is predicted to observe thousands of lensed quasars and more than 100 000 galaxy–galaxy lenses. Data from those projects and others that are planned or under construction, such as the Square Kilometre Array Observatory, will give researchers unprecedented surveys in the optical, near-IR, and radio wavelengths. Astronomers will soon be working with a few hundred thousand lenses.[16]

For the first time, scientists will have a massive sample of gravitational lenses from across the cosmos. But they will be forced to work differently: To process the incoming datasets, astronomers will increasingly rely on mechanized algorithms, rather than visual identification, to find lenses. Some of those automated methods have been designed to look for explicit shapes, such as arcs or rings; others rely on machine-learning algorithms that have been trained on simulated datasets of gravitational lenses. Each of the methods promises labor-saving efficiency over the visual inspection of images.

But those techniques have not and will not erase the importance of the human eye. The swell of AI tools, alongside older algorithmic procedures, is often accompanied by claims of human obsolescence.[17] But the onset of mechanization has not made tacit skills irrelevant. As astronomers search for more accurate and more efficient methods, they consistently benchmark new algorithms against the visual examination by their colleagues. Although algorithms are faster than manual inspection, they often miss subtle cases of gravitational lensing, such as wispy arcs or complex visual deformations. In a recent comparison using data from the Kilo-Degree Survey, algorithms proved less accurate than human observers at identifying lenses. All the automated routines missed the "jackpot lens," an extremely rare case where the lensed images formed two full rings of light from two different background sources.[18]

On the eve of a data deluge, intuition thus serves a new purpose—as an ideal. Rather than doing away with the importance of astronomical intuition, algorithmic tools have merely shifted its role in the process of detection. The history of gravitational lens observations highlights that such intuition is constantly under reevaluation. Before spectroscopic experiments convinced the astronomy community that two objects could be one, double quasars were not an obvious instance of gravitational lensing. Not until models accurately replicated the mysterious arcs did they turn into clear markers. Observational intuition is constantly being reevaluated as a product of past experiments, theories, and models. The successes of computational algorithms only become legible through all-too-human standards. As astronomers continue to develop models, it is important that they continue to develop their eyes.

Think you can spot a gravitational lens?
Go to physicstoday.org/lenses.

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PT

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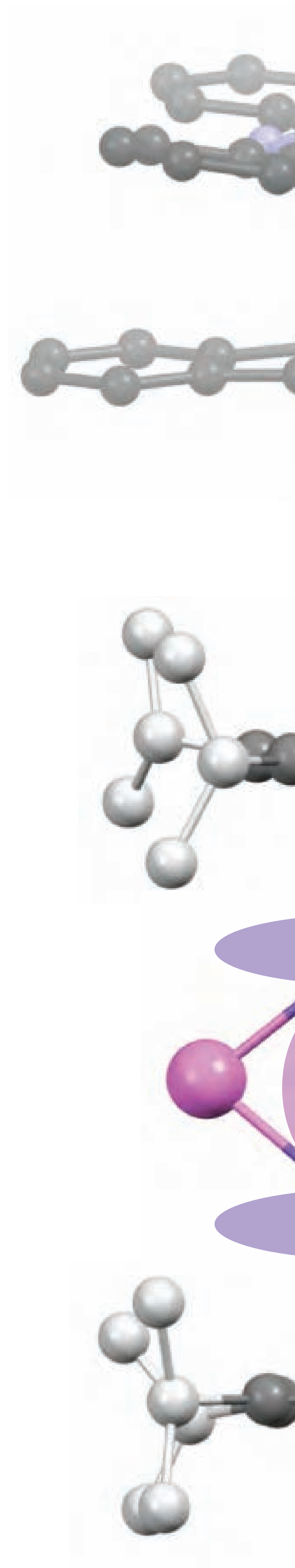
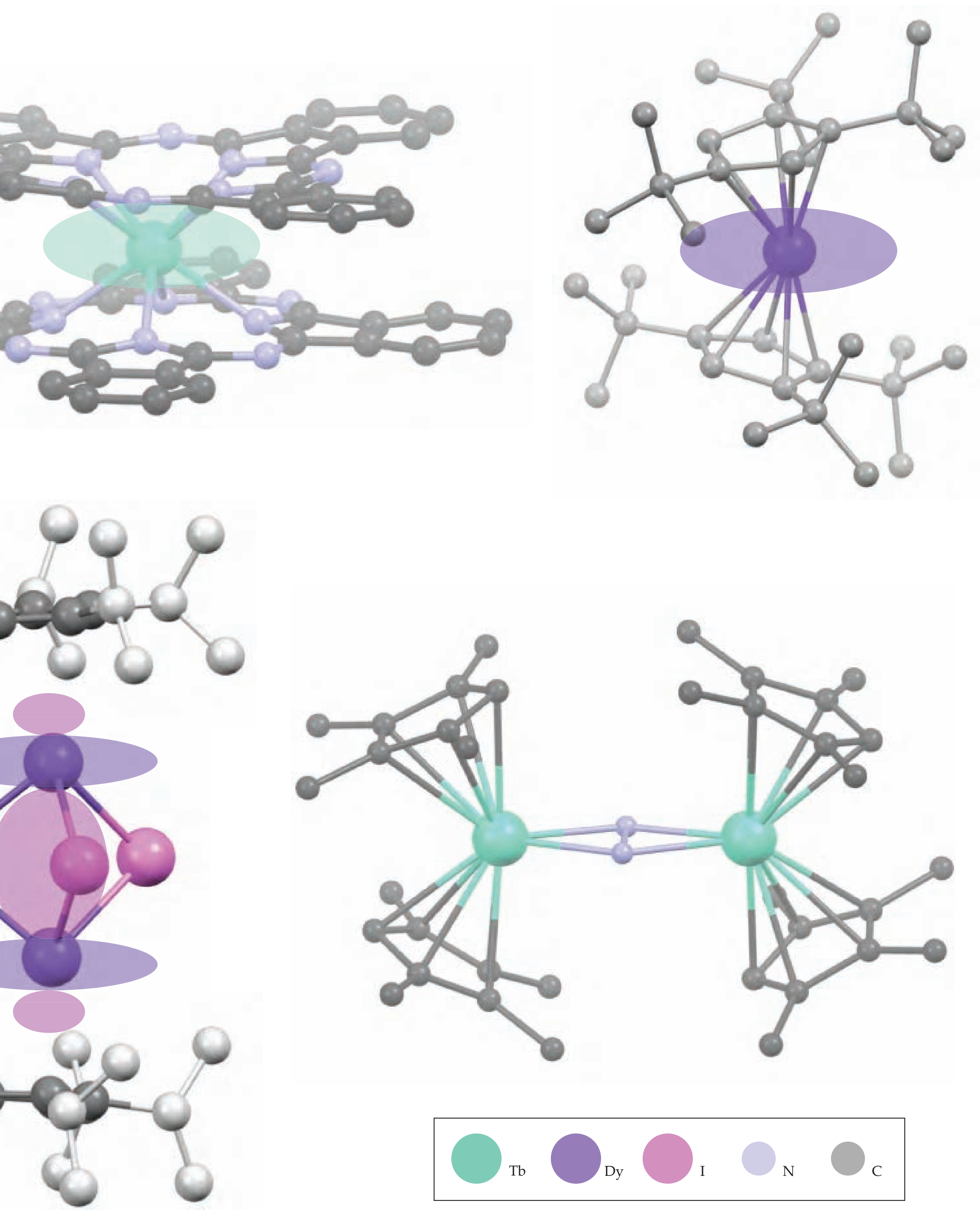


MAKING QUBITS FROM MAGNETIC MOLECULES

Stephen Hill

Bottom-up synthesis of such molecules provides physicists with a rich playground to study newly discovered quantum effects and a means to store information at the scale of individual atoms.



The evolution of magnetic molecules. Lanthanide-based $[Tb(Pc)_2]^-$ (top left) and $[Dy(Cp^{ttt})_2]^+$ (top right) have oblate 4*f* densities (exaggerated here) that enhance magnetic anisotropy. Two lanthanide atoms can increase the magnetic moment; examples include $[(Cp_2^{Me4H}Tb)_2N_2]^-$ (bottom right) and $(Cp^{iPr5})_2Dy_2I_3$ (bottom left), which has shared dysprosium $5d_{z^2}$ orbitals. (Pc^{2-} is a phthalocyanine dianion, and Cp^-, a cyclopentadienyl anion; superscripts refer to organic substitutions on Cp^- rings.)

The idea that a molecule could act as a magnet that manifests previously unobserved quantum behavior can be traced to theoretical predictions of a magnetic analogue to quantum mechanical tunneling of a particle through a potential energy barrier. The magnetic version would involve tunneling through an energy barrier that hinders reorientation of the magnet's north and south poles. Observation of the effect would require measurements on nanoscale objects that are much smaller than any that could be fabricated via the top-down methods—involving shrinking larger objects—that were available at the time that the idea first emerged.

An important breakthrough came from studies of molecular metal oxide clusters created via bottom-up, atom-by-atom chemical synthesis. The molecules were designed to mimic protein reaction centers, which play important roles in various biological processes, including photosynthesis. They would lead to the first demonstration of magnetic bistability—in which a magnetic dipole can be switched between the up and down metastable states—of purely molecular origin[1] and give rise to the term "single-molecule magnet." An SMM is an isolated molecule that can be magnetized and retain alignment of its north and south poles below a characteristic temperature, known as the blocking temperature.

Magnetic bistability can be observed through hysteresis, in which magnetic behavior is history dependent. The underlying physics of magnetic bistability in tiny particles was established by research on nanoparticles that were fabricated via traditional top-down methods for their potential use in classical information storage. As shown by the gray line in figure 1a, the particles will retain a preferred magnetic alignment, or polarity, while being subjected to a changing magnetic field, until the applied field is strong enough to reverse the polarity.

The first SMM ever made contained 12 magnetic manganese ions (see figure 1a), coupled by weak interactions through bridging oxygen atoms; that coupling produces a ground state with a collective magnetic moment of 20 μ_B (1 μ_B is the magnitude of a lone electron's magnetic moment). The energy barrier to reorientation of that moment is rather low, about 6 meV, and results in a blocking temperature of just 4 K. Above that temperature, thermal excitations cause the alignment of the magnetic moment to fluctuate (see figure 1b).

Quantum tunneling of magnetization

A significant discovery arose from studies of Mn_{12} crystals: periodic steps in magnetic hysteresis curves[2] (see figure 1a). The behavior is attributed to the previously predicted quantum tunneling of magnetization (QTM). Analogous to the quantized energy levels of a particle in a box, the allowed magnetic-moment orientations and the corresponding energies of an SMM are quantized (see figure 1b). Because Mn_{12} has 20 unpaired electrons, there are multiple quantum states (discrete orientations) on each side of the barrier, as opposed to just the up and down states for a single electron.

A magnetic field applied along the preferred magnetization axis—the so-called easy axis—tilts the energy landscape to favor states with aligned (up) magnetic moments (see figure 1b). When the field is swept, magnetic levels on opposite sides of the energy barrier are brought into and out of resonance. When on resonance, the magnetization has a finite probability of tunneling through the barrier. Through QTM, SMMs with magnetic moments pointing down may reorient, or relax, toward the up state; in contrast, classical relaxation over the energy barrier requires the help of thermal energy. As a manifestation of QTM, steps in the macroscopic magnetization of the crystal thus reveal the quantum nature of the Mn_{12} SMMs.

The discovery of resonant QTM opened up a new playground for physicists to explore quantum magnetization dynamics. Meanwhile, chemists realized that they could exert remarkable synthetic control over the magnetic interactions responsible for QTM and the magnetic energy barrier. The result was an interdisciplinary field that continues to grow.

Much effort has been directed toward increasing SMM blocking temperatures, with the lofty goal of designing SMMs that function as classical memory storage at liquid-nitrogen temperatures (77 K) and above. That would enable data storage densities of 100 Tb/in^2 (16 Tb/cm^2), two orders of magnitude higher than modern commercial devices. But therein lies a fundamental tension: QTM accelerates magnetization relaxation and is, therefore, detrimental to classical information storage. Physicists, however, recognized that magnetic molecules could potentially lead to next-generation quantum technologies.

Indeed, early theoretical work demonstrated the possibility of performing a quantum search algorithm using the discrete states of the Mn_{12} molecule.[3] That led to a bifurcation of effort: Work continued on improving SMM properties for classical data storage, while a new thrust emerged on developing molecular spin qubits.

Improving SMMs for classical data storage would require shutting down QTM and creating molecules with signifi-

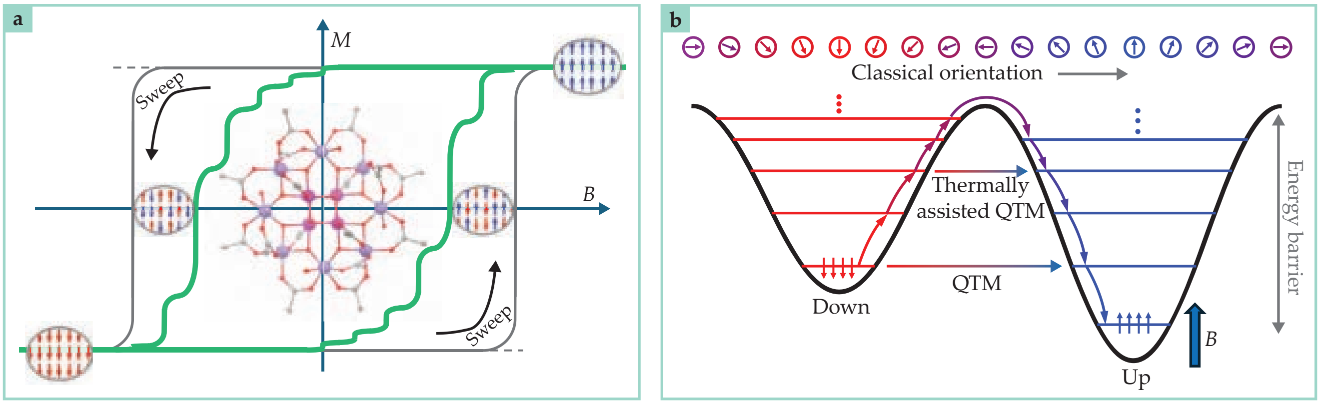


FIGURE 1. (a) THE CLASSICAL MAGNETIZATION RESPONSE (gray lines) of nanomagnets subjected to an applied magnetic field *B* contrasts with the stepwise response (green lines) of single-molecule magnets (SMMs), such as manganese-12 acetate, shown at center[1] (Mn^{4+}, pink; Mn^{3+}, purple; oxygen, red; carbon, gray). At low temperatures, the magnetization *M* saturates when the applied field is strong enough to overcome the energy barrier to spin reorientation (red and blue arrows). Stepwise relaxation is produced by quantum tunneling of magnetization (QTM).[2] **(b)** The classical dependence of energy on magnetic orientation is shown by the black curve; horizontal lines denote quantized SMM energy levels. An applied magnetic field tilts the energy landscape to favor up-oriented magnetic moments. Classical magnetization reversal occurs via thermal activation over the barrier. Relaxation through the barrier can occur by QTM with or without the input of thermal energy.

cantly greater energy barriers. Molecular symmetry, which chemists can control, plays a crucial role: In a cylindrically symmetric system, the magnetic quantum states are orthogonal, so QTM does not occur. Although no molecule has perfect cylindrical symmetry, maintaining a high symmetry helps. (Mn_{12} has a fourfold axial symmetry, as seen in figure 1a). Increasing the collective magnetic moment of an SMM also suppresses QTM, in the same way that increasing particle size diminishes the probability of spatial tunneling.

A molecule's magnetic moment arises from both the orbital and spin momenta of unpaired electrons. It is the orbital momentum that responds to the local molecular structure and produces the interactions that pin the magnetic moment along a preferred axis. Transition metals' *d* orbital electrons tend to participate in chemical bonding, which dramatically suppresses the orbital momentum and results in low SMM energy barriers. That fundamental limitation brought work with transition metals to a stall.

Transition to lanthanides

A major advance was made when a single terbium ion encapsulated between two dianions of the organic molecule phthalocyanine (Pc^{2-}; shown in the top left of the opening image) was found to display SMM behavior with a classical energy barrier of about 75 meV, more than an order-of-magnitude increase relative to Mn_{12}.[4] The magnetism of Tb^{3+} and other lanthanide (Ln) ions arises from unpaired electrons in contracted 4*f* orbitals. Unlike *d* orbital electrons, those unpaired electrons do not participate directly in chemical bonding, and thus they enhance the orbital contribution to magnetism relative to transition metals.

For Ln compounds, the energy barrier arises from the electrostatic interaction between the anisotropic 4*f* electron density and the electric field imposed by the host ligands—the nonmagnetic, often organic portion of the molecule that bonds to the magnetic ion. Emerging design strategies, primarily involving dysprosium and Tb,[5] have produced a huge number of new SMMs with barriers exceeding Mn_{12} by more than an order of magnitude.

Tb^{3+} and Dy^{3+} make the best SMMs because they have large spin–orbital magnetic moments and the most pronounced anisotropies of their 4*f* electron densities. Dy^{3+} also benefits from a fundamental theorem in quantum mechanics for systems with an odd number of unpaired electrons (Dy^{3+} has five); the theorem strictly forbids QTM in the absence of a magnetic field. Despite the much larger classical energy barriers in Ln-based SMMs, however, increases in blocking temperature were initially modest. The main reason is the onset of additional through-barrier relaxation via thermally assisted mechanisms involving QTM (see figure 1b) and short-lived virtual quantum states produced by vibrationally assisted Raman processes.

Researchers recognized that the optimum SMMs, designed for pseudo-cylindrical symmetry, would involve Dy^{3+} with axial ligands but no equatorial ligands, which would disrupt symmetry and promote QTM. It required some remarkable chemistry to realize such a molecule ($Dy(Cp)_2$; see the opening image, top right), which includes a pair of

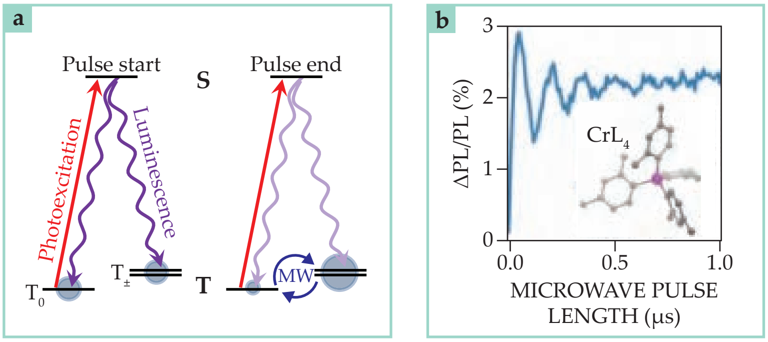


FIGURE 2. SPIN-DEPENDENT OPTICAL ACTIVITY means that a microwave-controlled qubit state is observable via photoluminescence (PL). **(a)** Excitation from the ground triplet level T_0 to the excited singlet state S and accompanying luminescence back to the T_0, T_+, or T_- triplet level drives the spin population (blue circles) from T_0 into the $T_\pm$ states, which alters PL intensity. Manipulation of the spin population between triplet states using pulsed microwave (MW) radiation can thus be monitored via changes in PL intensity. **(b)** Coherent microwave cycling, known as Rabi oscillation, of the spin population between triplet levels is measured by changes in PL emissions; the inset depicts the CrL_4 molecule, with parts of the ligand (L) that are amenable to chemical tuning highlighted. (Images adapted from ref. 12.)

cyclopentadienyl (Cp^-) ligands[6] and has a sandwich structure similar to $Tb(Pc)_2$ (see the opening image, top left). There are some key differences, however: Compared with Pc^{2-}, Cp^- is more compact, which produces a much stronger interaction with the oblate Dy^{3+} 4*f* electron density and leads to a huge classical energy barrier of about 250 meV.

Bulky substituents—affectionately termed "shrubbery"—on Cp^- rings prevent equatorial interactions with the Dy that promote QTM. Cp^- rings are also extremely rigid, which leads to high-frequency intramolecular vibrations. Additionally, the shrubbery lowers intermolecular phonon frequencies so that vibrations are sparse in the intermediate frequency range required to promote under-barrier Raman relaxation. The resulting $Dy(Cp)_2$ SMM maximizes performance based on the magnitude of the barrier, with blocking temperatures that approach 77 K.[6]

Fundamental limits

Despite remarkable progress, SMMs based on single Ln^{3+} ions have hit fundamental limits. Their magnetic moments are dictated by atomic, not molecular, considerations. And molecular chemistry does not allow further concentration of negative axial charge close to Ln^{3+} ions. Work on other oxidation states (Ln^{2+} and Ln^{4+}) is challenging and runs into the same issues. Hence, there is little scope for improvement. The only solution, therefore, is to couple multiple Ln ions. That, however, represents a monumental task. Standard synthetic strategies tend to result in weak coupling between Ln magnetic moments because of the contracted nature of 4*f* orbitals, particularly for Ln^{3+}. The moments therefore tend to relax independently in molecules containing multiple Ln^{3+} ions.

One solution to weak coupling involves bridging the ions with ligands that are radicals—that is, they themselves possess an unpaired electron. Direct overlap of the Ln 4*f* density with the diffuse spin density on the ligand leads to enhanced magnetic interactions. By bridging two Tb^{3+} ions with a N_2^{3-} radical (see the opening image, bottom right), Jeffrey Long, William Evans, and coworkers achieved an SMM with a large spin–orbital moment and a blocking temperature of 14 K,[7] which held the record until the discovery of $Dy(Cp)_2$.

Coupling via the extra, odd radical electron also shuts down QTM, leading to greatly enhanced magnetic coercivity (the field needed to flip the magnetization of the SMM). One may rationalize that effect on the basis that simultaneous QTM of two Ln moments is far less probable than one. The Ln moments, however, may start to relax independently once the thermal energy exceeds the coupling interaction energy. Moreover, the side-by-side arrangement reduces the overall axiality at each Ln site in the SMM (shown in the opening image, bottom right). Those factors contribute to relatively low blocking temperatures. Consequently, a set of even-more-demanding design challenges emerges: further enhancing Ln–Ln coupling while also maintaining axiality.

The strongest magnetic coupling (up to an electron volt) arises between electrons that reside on the same atom or occupy the same set of molecular orbitals. The question, then, is whether direct magnetic orbital overlap within a Ln_2 molecule can be achieved. The contracted nature of the 4*f* shell makes that almost impossible for Ln^{3+}. In some cases, however, an electron added to a Ln^{3+} ion (reducing the oxidation state to Ln^{2+}) will occupy a more extended 5*d* orbital rather than the open 4*f* shell. The 5*d* orbital offers a possible strategy for achieving direct orbital overlap. Long and coworkers have employed that approach by sandwiching a pair of Dy ions between two rigid Cp^- ligands, with three iodide (I^-) ligands holding everything together[8] (see the opening image, bottom left).

In the $(Cp)_2Dy_2I_3$ molecule, an extra electron is shared between the Dy^{3+} ions. It occupies overlapping, hybridized 5*d* orbitals, thus mediating strong magnetic coupling. The result is a highly robust and large spin–orbital magnetic moment. Moreover, the molecular geometry is highly axial, which gives rise to a classical energy barrier of about 300 meV. Blocking temperatures that approach 80 K emerge, with a coercivity exceeding 14 T at 60 K, surpassing even the coercivity of commercial samarium and neodymium magnets.

Molecular spin qubits

With the goal of classical storage in mind, the best examples of SMMs have been optimized to suppress QTM and behave classically. But quantum effects are appealing for a different type of memory application: the molecular spin qubit.

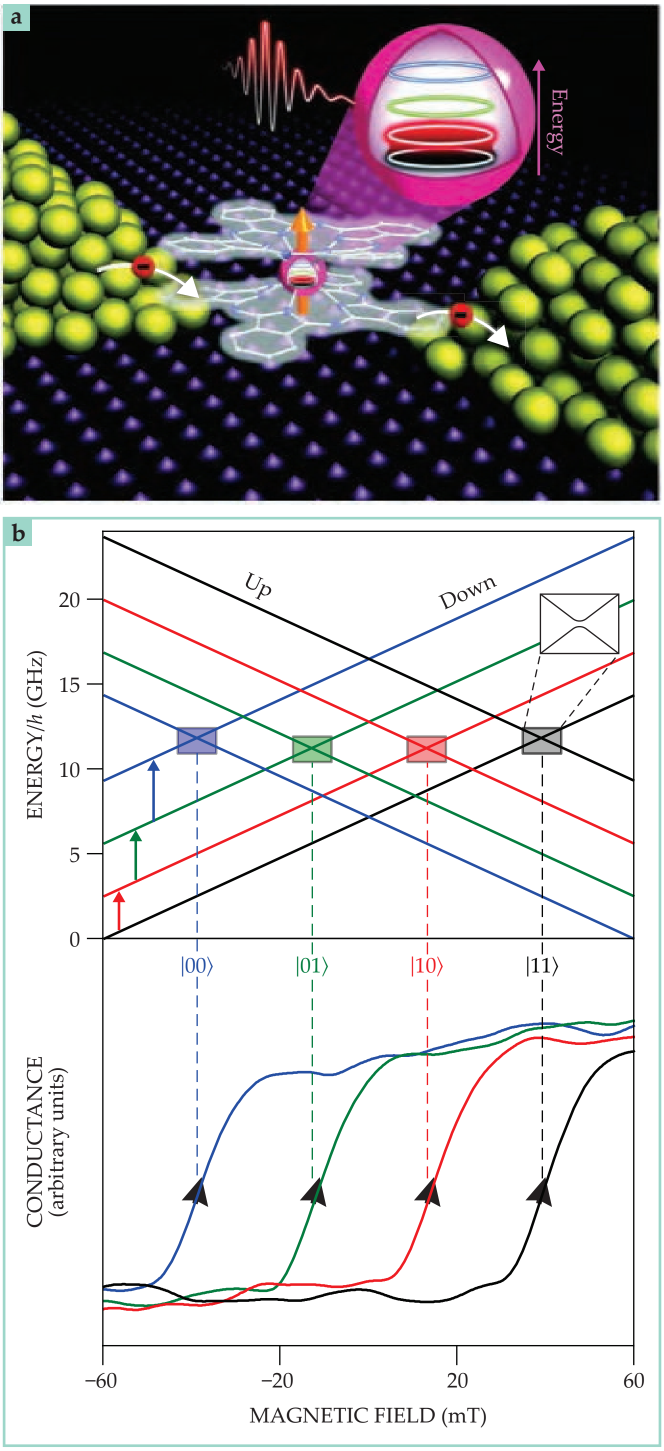


FIGURE 3. (a) A SINGLE-MOLECULE TRANSISTOR encodes information in the nuclear spin states of a single molecule. The single-molecule magnet $Tb(Pc)_2$ is anchored to gold source and drain electrodes. White arrows denote current flow; the orange arrow represents the electronic spin–orbital moment, and the inset depicts the four nuclear hyperfine levels encoding the qudit states $|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$. **(b)** In a magnetic field, the unequal splitting of the four nuclear hyperfine levels (here normalized by Planck's constant *h*) allows selective microwave mixing of nuclear states (colored arrows). Resonant quantum tunneling of magnetization (QTM) occurs when hyperfine levels associated with the same nuclear state meet (colored rectangles), whereupon they mix and undergo a so-called avoided crossing (inset). At ultralow temperatures (25 mK), that manifests as a jump in the transistor's conductance at specific values of the applied magnetic field, which enables electronic readout of the nuclear qudit. (Images adapted from ref. 13.)

The beauty of molecular chemistry is in its building-block approach. Start with a promising molecular spin system, make deliberate synthetic modifications to fine-tune the spin physics and coherence, build in additional functionality such as optical or electrical activity, and, finally, add linkers to facilitate intermolecular connectivity and attachment to suitable substrates. To a good approximation, each molecular spin qubit and the associated linkers are identical, which makes the approach scalable. In 2003, George Christou, colleagues, and I first demonstrated a method to link pairs of magnetic molecules and observe the quantum mechanical coupling between them,[9] akin to the coupling between spin qubits hosted in semiconductor quantum dots.

The simplest molecular spin qubit comprises a single unpaired electron: a quantum two-level system that is agile and can be coherently driven using microwave electromagnetic fields. In 2007, Arzhang Ardavan and coworkers considered the question of whether spin relaxation times in such a molecule, Cr_7Ni, would permit quantum information processing.[10] They concluded that energy relaxation (the decay between classical spin-up and spin-down states, also known as spin–lattice relaxation) is slow, and quantum memory times are limited by the coupling of spin qubits to the nuclear magnetic moments of surrounding hydrogens—that is, protons—of which there are typically many in molecular systems. Importantly, that work identified strategies for synthesizing molecules with improved quantum memory times, also known as coherence times.

The first wave of studies that followed focused on understanding and mitigating processes that contribute to electron spin relaxation in molecular qubits. The molecular approach enables exquisite chemical control in a way that is simply not possible in conventional solids. For example, by exploiting variations in the identity, rigidity, and coordination geometry of the ligands, chemists can exert direct control over the interactions that influence spin–lattice relaxation.[11] That control is important because spin–lattice relaxation ultimately limits quantum memory times, particularly at the elevated temperatures necessary for quantum sensing.

Low-temperature electron spin decoherence is mediated primarily by magnetic coupling to protons, which have large moments relative to other nuclei. That coupling results in unwanted entanglement with the environment. Nuclear isotope

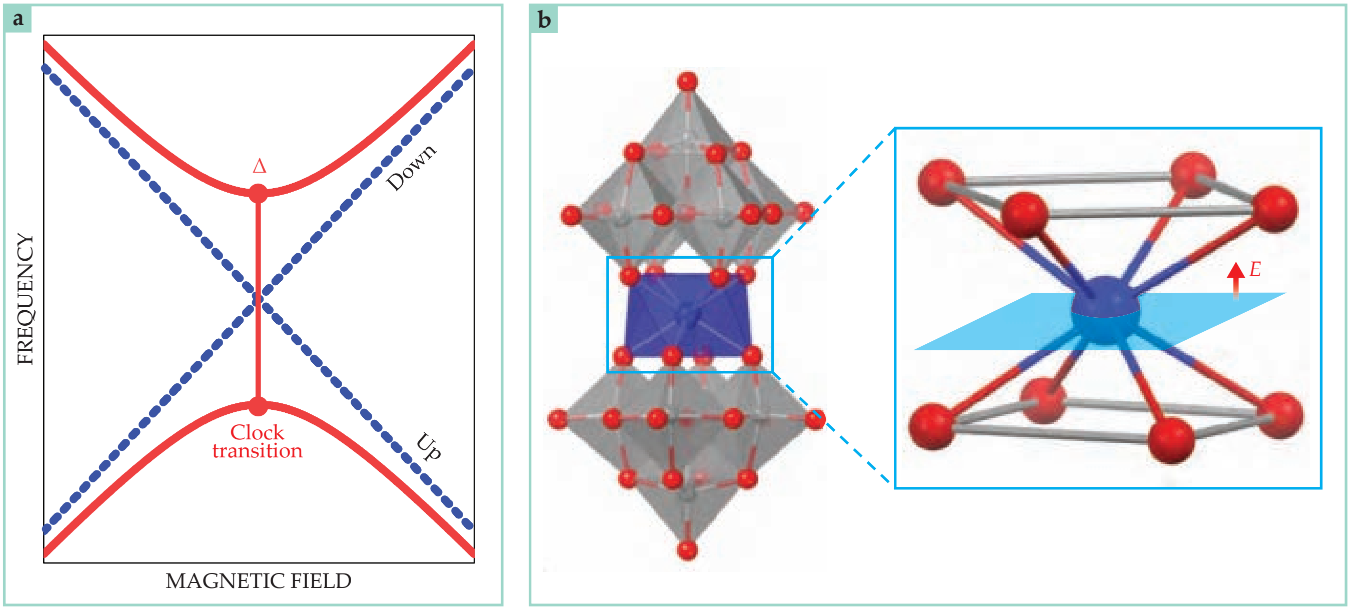


FIGURE 4. (a) CLOCK TRANSITIONS are avoided crossings between up and down magnetic states at certain values of the magnetic field. That physics is responsible for mixing single-molecule magnet (SMM) quantum states with opposing magnetizations; the gap minimum reflects the quantum tunneling of magnetization (QTM) frequency. The ideal SMM for classical memory storage has no gap (dashed lines). By contrast, spin qubits benefit from large QTM gap minima, where the transition frequency Δ is insensitive to magnetic field fluctuations, which leads to enhanced quantum memory coherence.[15] **(b)** The molecule $Ho(W_5O_{18})_2$ is shown here with an expanded view of its core. An applied electric field *E* displaces the Ho^{3+} ion from the midplane, thereby tuning the clock-transition frequency Δ. (Image adapted from ref. 16.)

labeling—for example, replacing ^1H with ^2H—allows for investigation of the physics and a means of controlling it. Also, by diluting molecular qubits in either solid or frozen solution matrices to suppress electron spin–spin relaxation, researchers have achieved quantum memory times approaching milliseconds at liquid-helium temperatures and microseconds at room temperature.[11]

Chemists and physicists are now working collaboratively on the next steps. Spin manipulation is usually achieved using magnetic resonance techniques, although they lack detection sensitivity and spatial resolution because of the millimeter microwave wavelengths employed at typical laboratory magnetic field strengths of 0–10 T. A major attraction of the nitrogen–vacancy (NV) defect center in diamond is its spin-dependent optical activity, which enables initialization and readout of individual qubits (see the article by Christopher Anderson and David Awschalom, Physics Today, August 2023, page 26). As demonstrated by Danna Freedman, David Awschalom, and colleagues, one can chemically engineer the same optical–spin interfaces in molecules.[12]

The Cr^{4+} ion has two electrons in partially filled *d* orbitals. A strong ligand then provides the necessary ingredients for optical spin-state initialization and readout. Those ingredients, sketched in figure 2, are a triplet ground state with aligned electron spins that can be coherently manipulated, using microwaves and narrow absorption lines in the near-IR, to an excited singlet state in which the spins are oppositely aligned. The combination of those two properties allows selective laser excitation from a targeted triplet level into the singlet state, followed by nonselective emission back to the triplet states.

The system can be initialized by optically pumping the spin population out of the given triplet level (see figure 2a). Microwave pulses can then be used to perform single-qubit operations between the triplet levels (see figure 2b), with a final readout of the spin population achieved by monitoring changes in the photoluminescence emission. Crucially, chemists can fine-tune the optical–spin interface to move the field forward.[12]

A single-molecule transistor

One of the landmark results in molecular magnetism is the implementation of a quantum search algorithm that uses the nuclear spin states associated with a $Tb(Pc)_2$ SMM trapped in a single-molecule transistor[13] (see figure 3a). The method relies on the bistability of the Tb^{3+} ion's spin–orbital moment, which can flip via resonant QTM only when there are avoided crossings, or gaps, between the lowest two electronic levels at specific magnetic field intensities (see figure 3b). Because of hyperfine coupling to the ^{159}Tb nucleus, those levels are further split into four nuclear sublevels. Consequently, the Tb^{3+} spin–orbital moment is sensitive to the quantum state of the nuclear qudit—a quantum system with *d* states, four in this case—and, when the spin–orbital moment flips, it induces a jump in the conductance of the transistor.

The magnetic field of the conductance jump therefore provides a direct readout of the molecule's nuclear state. It is then possible to perform quantum logic operations on the nuclear qudit states with selective microwave pulses and use the transistor for the final readout of the nuclear qudit state. Working in such a system, Wolfgang Wernsdorfer and coworkers generated a coherent superposition of the nuclear states and then used the transistor's localized microwave electric fields to evolve the system to the desired quantum state, thereby demonstrating, for the first time, the feasibility of molecular-scale quantum logic devices.[14]

Symmetry-lowering interactions in molecules such as $Tb(Pc)_2$ generate the avoided crossings between electronic levels; the size of the gap reflects the QTM frequency and is dictated by the degree of symmetry breaking. In 2016, some colleagues and I showed that a holmium molecule, $Ho(W_5O_{18})_2$, with pseudo-fourfold symmetry, hosts so-called clock transitions (see figure 4a), where the sensitivity of the qubit transition frequency to the variations in the local magnetic field vanishes.[15] (See PHYSICS TODAY, May 2016, page 17.) That property results in decoupling of the qubit from most magnetic noise sources and leads to enhanced coherence and quantum memory times approaching 10 μs at 5 K.

Recent work has demonstrated electrical coupling to the spin in the $Ho(W_5O_{18})_2$ molecule.[16] An electric field applied along the pseudo-fourfold axis influences the displacement of the Ho^{3+} ion away from the midplane (see figure 4b), thereby affecting the ion's electric dipole moment. In turn, that displacement modulates the clock-transition frequency, again demonstrating the possibility of local electrical control of a spin qubit.

A drawback of $Ho(W_5O_{18})_2$ is fast spin–lattice relaxation, which ultimately limits the quantum memory time. That is because of the strong electronic coupling of the anisotropic 4*f* charge density to ligand vibrations. Several lutetium (Lu^{2+}) molecules have now been synthesized with a filled 4*f* shell and a lone unpaired electron occupying a mixed 5*d*/6*s* orbital. One of those molecules has a large clock-transition frequency of 9 GHz.[17] Crucially, the molecules have an almost-pure spin magnetic moment that is only weakly coupled to the surrounding ligand vibrations; that results in energy-relaxation times on the order of milliseconds, which leaves lots of room for further enhancement of quantum memory times.

Progress and future challenges

The past 10 years have witnessed significant breakthroughs in the field of molecular magnetism, with well over an order-of-magnitude increase in SMM blocking temperatures,[6,8] which were stagnant for the previous quarter century, and major advances in the performance of molecular spin qubits,[11] including development of optical[12] and electrical[13,16] interfaces. But much work remains to be done. In the case of SMMs, an important chemical step is scaling up the synthesis of molecules with three or more strongly coupled Ln moments. Molecules with metal–metal bonds between transition metals should also not be ruled out; the challenge in such systems will be to prevent quenching of the orbital moment that imparts the required magnetic anisotropy.

It will also be important to develop methods for addressing individual SMMs on nanometer length scales, which will require approaches for organizing molecules on surfaces or at interfaces.[18] That will be challenging because the current leading SMMs have an absence of equatorial ligands, which makes them highly reactive in all but the most inert environments.

In the area of quantum spin science, one can envision near-term sensing applications, perhaps in combination with targeted chemical sensitivity, something that is harder to achieve using existing solid-state spin qubits, such as NV centers. Realization of such applications will require further optimization of spin–lattice relaxation times for high-temperature operation. Although devices based on spin ensembles will surely have some utility, those applications should spur further chemical optimizations, with the ultimate goal of single-spin sensors.

In the longer term, wiring together molecular spin qubits is a critical step toward developing quantum logic gates. That will require chemical design of molecules with multiple quantum resources, such as electron–nuclear qudits and molecules with many coupled spin qubits. Further scale-up will require hybrid approaches that use optical or microwave photons or molecular wires, such as graphene ribbons,[18] to interconnect individual molecular spin qubits and for longer-range communications. Here, one can imagine selectively entangling pairs of molecular qubits by electrically bringing them into and out of resonance with a microwave transmission line. With continued rapid progress, there are real possibilities that molecules can contribute to next-generation quantum communication and computing.

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PT

Frédéric Joliot-Curie. (Photo by CTK/Alamy Stock Photo.)

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France's Oppenheimer

William Sweet

Frédéric Joliot-Curie was one of the first to conceive of the nuclear chain reaction. But the ardent advocate of nuclear disarmament paid a high price for his political convictions.

When Albert Einstein wrote to President Franklin D. Roosevelt on 2 August 1939 apprising him of the threat that an atomic bomb might be built, he naturally drew attention to work by Leo Szilard, the first person to realize that it might be possible to build the bomb, and Enrico Fermi, who would build the world's first reactor. But the operative second paragraph gives primacy not to them but rather to a French physicist, Frédéric Joliot, a name largely lost to the general US reader.

"In the course of the last four months it has been made probable—through the work of Joliot in France as well as Fermi and Szilard in America—that it may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements would be generated."

Who was Joliot, and how did he come to be forgotten in the US?

Joliot and his wife, Irène, daughter of Marie Curie and Pierre Curie, came to fame in 1934 with their discovery that radiation can induce a previously stable material to become radioactive—a discovery so important that it was instantly recognized with the 1935 Nobel Prize in Chemistry. That made for a beautiful and unequaled symmetry: Marie and Pierre had discovered natural radioactivity in radium and polonium; Frédéric and Irène found it was possible to invent and fabricate new radioactive elements at will, opening up a world of applications, first of all in nuclear medicine. Joliot naturally drew attention to those applications in his 1935 Nobel address, but he also referred to the possibility of generating a "chain reaction" in radioactive materials.

At the end of the 1930s, on the eve of the outbreak of World War II, Joliot scoped out the technical requirements of a nuclear reactor and filed patents on such a device. At that point, in the estimation of the famed British physicist Patrick Blackett, Joliot's team led the world in thinking about how atomic energy could be harnessed and almost certainly would have built the world's first reactor, had the Nazis not invaded.[1,2]

At the end of the war and occupation, Joliot personally brought the potential of nuclear energy to the attention of Charles de Gaulle and Raoul Dautry, who had been the armaments minister in 1939–40 and would become France's reconstruction minister after the country was liberated. Meanwhile, under the eyes of the Gestapo, Joliot used his Paris lab to secretly manufacture radios and munitions for the French Maquis guerrilla bands. Although arrested twice, he got himself released both times with the help of an influential German physicist.[1]

Immediately after the war, Joliot built France's first nuclear reactor and thus, for better or worse, can be considered the father of the country's atomic program. But because he always strongly opposed the development of nuclear weapons, he was equally a father of the global movement to abolish them.

Joliot was gifted, gutsy, and—not least—good-looking and personable. He had influential friends everywhere. From 1945 to 1950, he would be not only France's top scientist but the country's top science administrator. But at the end of the decade, with the imminent invention of the hydrogen bomb and the French government starting to eye its own atomic bomb development, a kind of McCarthyism took hold in France, and Joliot was stripped of his administrative positions and all policy advising. It is here that his story closely parallels that of J. Robert Oppenheimer's. (For more on Oppenheimer's life, see "Oppenheimer in the *PT* archives," Physics Today online, 21 July 2023.)

FRÉDÉRIC JOLIOT-CURIE AND IRÈNE JOLIOT-CURIE working in their shared laboratory in 1935. (Photo by Zuri Swimmer/Alamy Stock Photo.)

Early years

Joliot was born in 1900 and was the last of his mother's six surviving children. His father was a cloth wholesaler, and later in life, Joliot would sometimes say that experimentalists should be like small-business owners—flexible about means and ends. Enormously good at making things with his own hands, he was a talented experimenter from a young age, and he often turned his mother's kitchen into a veritable chemistry lab.

Upon completing high school and after some initial stumbles, Joliot was admitted to the prestigious École de Physique et Chimie Industrielles (now ESPCI Paris), where Marie and Pierre worked. There, he caught the attention of its director of studies, Paul Langevin, who was one of France's leading physicists at the time, and not so incidentally, a one-time lover of Marie Curie. Langevin recommended Joliot to her, and she hired him as her lab assistant, a position in which he proved to be a "ball of fire," she would say. There he met Irène, and they fell in love and were happily married. The two adopted the surname Joliot-Curie, and Irène would be a close collaborator in all their early scientific work.

Starting in 1929, Joliot published a series of papers, sometimes with Irène and sometimes alone, that explored the properties of polonium. It has the useful characteristic of emitting lots of high-energy alpha particles but practically no other radiation.[2] Typically, when Joliot found that he needed a Geiger counter to pursue the work, he simply built one himself—such an instrument wasn't a standard piece of equipment that could be bought at the time. Similarly, he made a Wilson cloud chamber that enabled him and Irène to observe and photograph the tracks left by certain kinds of nuclear disintegration processes.

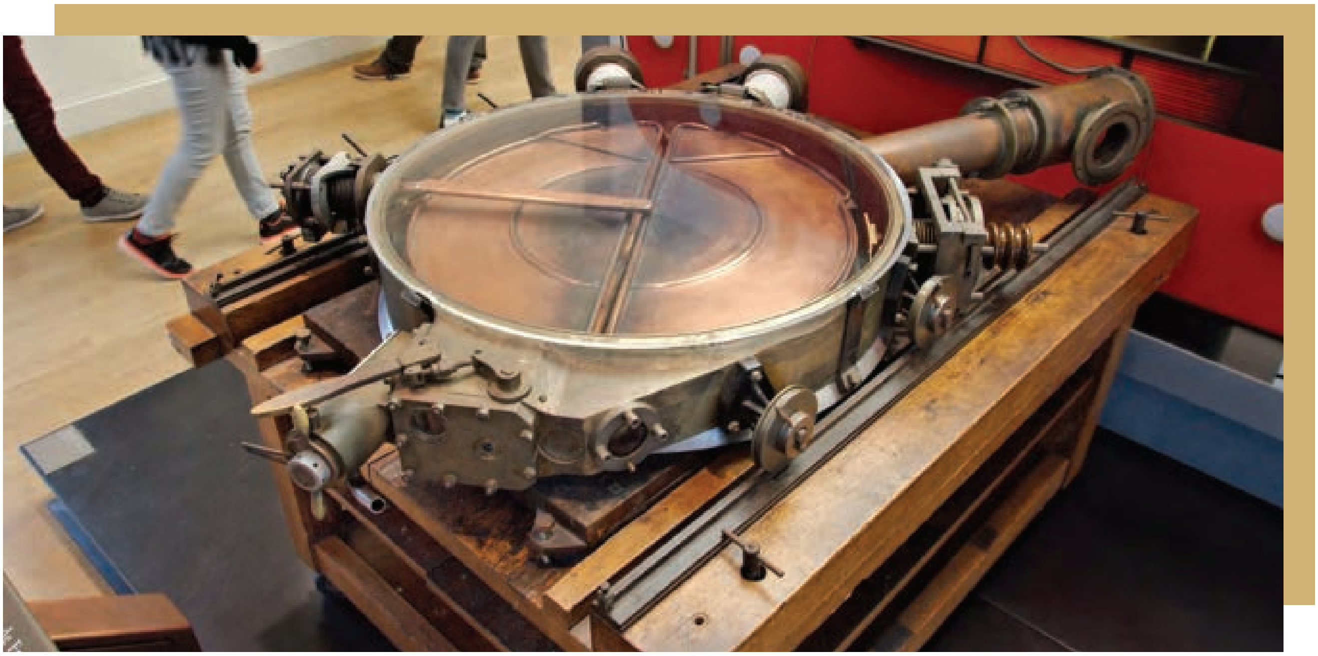
The Joliot-Curies figured out by 1931 how to prepare highly radioactive polonium sources. It was a technical achievement and consequential, Blackett observed, because at that time—before the development of large accelerator facilities—strong sources were the essential means with which to study nuclear structure.

In 1932, the Joliot-Curies turned to the study of what happens when boron or beryllium atoms are bombarded with alpha particles from polonium. They initially misinterpreted the results, leaving it to James Chadwick at the Cavendish Laboratory in the UK to appreciate that they had discovered the long-sought neutron. The existence of such a particle had been postulated well before, but no trace of it had been found before then.

After Caltech physicist Carl Anderson discovered the positron that same year, the Joliot-Curies turned to its study, initially doing experiments to determine whether the atomic nucleus might consist of a neutron and a positron. That work led to the discovery of artificial radioactivity. When investigating what would happen when a thin sheet of aluminum foil was irradiated by polonium, they were astonished to find that the aluminum continued to emit radiation after the source was removed. "It was as if handling a stick of wood could induce it to burst into flower," says historian of science Spencer Weart.[3]

Without pretense or false modesty, the Joliot-Curies announced their discovery in the 15 January 1934 issue of France's *Comptes Rendus*. An English translation reads: "For the first time it has been possible to make certain atomic nuclei radioactive using an external source. This radioactivity can persist for a measurable time in the absence of the source which excites it."[4] A month later, in California, Ernest Lawrence would confirm the discovery using his cyclotron, and he and Joliot established what would become a long professional friendship, despite Lawrence's more conservative politics.

Because of that discovery, all kinds of radioactive materials could now be made and applied widely in biology and medicine. Joliot would take note of those applications in his 1935 Nobel lecture, but he also said presciently "that scientists, building up or shattering elements at will, will be able to bring about transmutations of an explosive type, true chemical chain reactions. If such transmutations do succeed in spreading in matter, the enormous liberation of usable energy can be imagined."



THIS CYCLOTRON was used by Frédéric Joliot-Curie and Irène Joliot-Curie in the late 1930s in Paris during the course of their nuclear-physics research. (Photo by Frédéric Bisson/CC BY 2.0.)

Just two years earlier, Szilard had had his famous epiphany on a London street corner in which he envisioned a nuclear chain reaction. And three years later, Otto Hahn, working with Fritz Strassmann in Berlin and with Lise Meitner and Otto Frisch through correspondence, would discover nuclear fission.

France's first nuclear reactor

Following the discovery of fission in 1938, Joliot conducted a quick and clever experiment, using the Wilson cloud chamber he had built, in which he was able to photograph the fragments that resulted from the splitting of uranium and thorium. Shortly thereafter, working with Lew Kowarski and Hans von Halban, the two men who would be his closest collaborators in that period, he examined the technical requirements of a nuclear power reactor. In a handful of patent applications and technical papers written that summer and fall, they explained that the system would comprise some combination of uranium, hydrogen, and oxygen, with cadmium acting as a reactivity poisoner and controller. The reactor would need a fluid or gas to provide cooling and to drive a turbine system.

The three men recognized that to achieve critical mass—the smallest amount of material that could yield a self-sustaining nuclear reaction—it would be necessary to either enrich uranium to boost the fissile uranium-235 fraction in natural uranium or substitute deuterium for hydrogen to make heavy water. They did not recognize that uranium-238 could capture high-energy neutrons and form plutonium, an element that would be discovered only a few years later.

At that point, Szilard sought unsuccessfully to persuade Joliot to refrain from publishing his work. Weart has enumerated several reasons why Joliot decided to publish: "For one thing, Joliot believed strongly in the international fellowship of scientists. . . . For another, if he and his colleagues failed to publish, they might well be eclipsed by those who did. . . . And if they failed to be first to publish discoveries, the French might have trouble getting the money they would need to pursue the development of industrial nuclear energy." What is more, with private papers about nuclear fission circulating widely, it was scarcely likely that Germany and the Soviet Union would remain unaware of what was going on. (See the article by Weart, Physics Today, February 1976, page 23.)

When World War II broke out, Joliot and his colleagues—having recognized the key role that heavy water might play in harnessing nuclear energy—focused on the strategic importance that the world's only existing supply of heavy water might play.[5] At that point, the sole facility in the world that produced heavy water was Norsk Hydro's plant in Norway, which supplied it to scientists for research experiments. The story of how Norwegian commandos, acting on British intelligence, destroyed the plant when the Nazis invaded is one of the war's rather well-known tales. (It has been dramatized on film, and in Norway, it has been sanctified as one of the most glorious episodes of the war.) What is less well known is that Norsk Hydro also had a stock of heavy water it had already produced, and that alarmed the French.

In a confidential memo to French armaments minister Dautry, Joliot recommended that France immediately buy 400 kilograms of uranium metal from the US for experimental purposes and obtain Norway's 200 kilograms of heavy water. He explained: "A mixture suitably made up of uranium and deuterium presents in the present state of our knowledge all the conditions favourable for the development of chain reactions, etc., and consequently for the huge release of atomic energy."[6]

A French lieutenant, Jacques Allier, was dispatched to Norway to arrange for the stock to be "borrowed." It was then transported to France in 26 5-liter canisters, which were specially manufactured by a Norwegian craftsman to camouflage their contents, and was received in Paris on 26 March 1940.

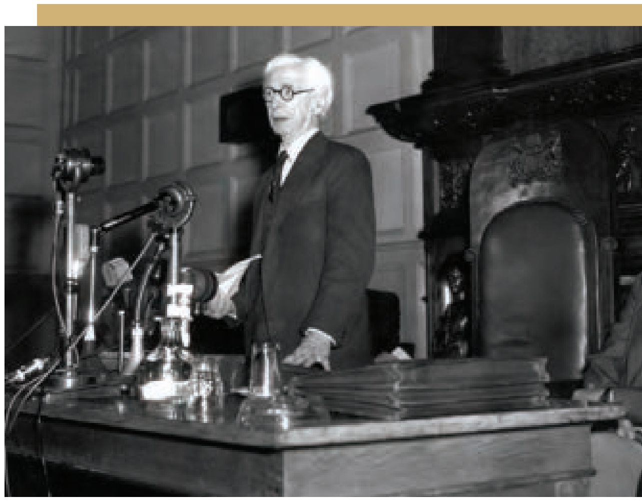
After Germany's invasion that spring, Joliot had the canisters transferred to Clermont-Ferrand in central France, where they were stored in a bank vault and then in a prison. But when that, too, proved unsafe, given that the Germans had assumed effective control of the whole country, Joliot had Kowarski and Halban take the stock to the UK. They left from Bordeaux and arrived at Falmouth on 21 June, and Joliot instructed them to proceed with the construction of a nuclear reactor.

Had the war not intervened, might Joliot have been the first to demonstrate a self-sustaining nuclear chain reaction, as Blackett suggested? It is a complicated question, and Blackett's hindsight assessment is speculative by definition. On the one hand, the 1939 patent filings by Joliot, Kowarski, and Halban seem to contain nothing resembling a diagram of an actual reactor. The filings are entirely conceptual. On the other hand—and it's a big other hand—Joliot always was incredibly good at making things. So perhaps he would have succeeded.

When Germany invaded France, Joliot chose to stay in Paris. Perhaps he wanted French work in atomic physics to proceed at a high level so that the country could be well positioned in the postwar period. But as a fervent patriot who always had been political, he also wanted to contribute to France's liberation. Evidently, because of his fame and prestige, he was made the titular head of the French Resistance, and in that capacity, Joliot made his Paris lab a munitions factory.

The Germans were not completely oblivious to his activities. The Gestapo twice took him into custody, but both times he was sprung at the behest of an influential German physicist, Wolfgang Gentner. When Joliot had built his first Geiger counter 10 years earlier, he had sought Gentner's advice.[7] A close professional friendship developed, and as luck would have it, Gentner was dispatched to Paris during the occupation to keep an eye on French scientists. He negotiated an agreement that allowed Joliot to keep his lab running, provided that he conduct research with strictly peaceful applications, and it was Gentner who saved Joliot when his lab was caught doing the opposite.

Soon after the liberation of France, Joliot reminded future president de Gaulle and future reconstruction minister Dautry about atomic energy's industrial potential. Starting in 1947, Joliot would supervise the design and construction of France's first reactor, Zoé, in the Paris suburb Fort de Châtillon. (Zoé was an acronym for zero power, uranium oxide, and *eau lourde*, or "heavy water".) Kowarski was a project manager, having already built the first non-US heavy-water reactor in Canada during the war as part of the Manhattan Project. Zoé went critical on 15 December 1948. The day after, France's High Commission for Nuclear Energy said that a long-term program had begun, and the next step would be the construction of two heavy-water reactors.



BERTRAND RUSSELL issued on 9 July 1955 the Russell–Einstein Manifesto, which highlighted the dangers of nuclear weapons. The document was cosigned by several prominent scientists, including Frédéric Joliot-Curie, who had proposed the appeal to Russell. (Photo from the Smith Archive/Alamy Stock Photo.)

In the years that followed, France initiated the world's most ambitious program of reactor construction, but not by the route Joliot and the commission had proposed. Like the UK in the 1950s, it developed a gas-cooled graphite reactor. In the 1960s, France adopted a light-water reactor whose design was overseen by US Navy admiral Hyman Rickover. But it was Joliot who got the ball rolling. With Halban and Kowarski, he fathered the heavy-water reactor and France's *tout-nucleaire* ("all-nuclear") energy program.

Changing political winds

From 1945 to 1950, Joliot was France's most prestigious scientist and the country's top science administrator. He was head of the CNRS, France's counterpart to the US's NSF. He was the leading scientist at the newly created Atomic Energy Commission. He spearheaded the construction of the Saclay research laboratories, France's counterpart to US national labs. He was an adviser and board member of many organizations. He had the ear of everybody at the top, and his counsel in all things nuclear was always sought.

But at the end of the 1940s, with Cold War clouds gathering, Joliot came under attack, first in the US and then in France. It is here that his life begins to closely parallel Oppenheimer's, but with a twist: Oppenheimer was accused of having Communist associations, whereas Joliot actually was a Communist.

During the war, as president of the Resistance, Joliot had joined the Communist Party, which in France, unlike in the US, had a mass following. Presumably, that was partly because French Communists formed the backbone of the Resistance. But his joining was a small step, given his sympathies.

Working at a steel mill factory in Luxembourg as a student, Joliot rubbed shoulders with workers from France, Germany, and Belgium, and he became concerned about issues of income distribution and wealth. His father had been a Communard, a supporter of the revolutionary Commune of Paris in 1871, and his mentor Langevin had been a Dreyfusard—a supporter of Alfred Dreyfus, the French officer who had been vilified by France's radical right because he was Jewish. During the Spanish Civil War, Frédéric and Irène had been fervent supporters of the republic. After World War II, with so many French Communists having served in the Maquis guerrilla bands, and with many French people voting for Communist representatives, nobody looked askance at Joliot being a card-carrying member of the party.

The trouble began on 27 December 1948, when *Time* magazine ran an article with a headline calling the Zoé reactor "A Communist's Atomic Pile." The *New York Herald* soon chimed in, calling Zoé a "veritable threat."[8] Initially, the accusations had little traction in France. "As the Cold War intensified, however," says historian Gabrielle Hecht, "successive governments found Joliot-Curie's communist affiliations increasingly embarrassing."[9] Another historian, Lawrence Scheinman, has speculated that among policymakers, there probably was an "unarticulated fear that other forms of [US] aid, military or economic, might suffer if France did not remove Joliot-Curie."[10]

In addition, a lobby in France was developing that favored the pursuit of nuclear weapons, analogous to the US lobby that wanted the hydrogen bomb. Joliot had always opposed nuclear weapons. And on 5 April 1950, he gave a speech to a congress of the French Communist Party in which he said that "the imperialists would like to launch a new war against the Soviet Union and the popular [Socialist] democracies."[11] He said that never would Communist scientists support such a war with their knowledge. A few weeks later, on 28 April, Joliot was expelled from policymaking circles.

In a flash, Joliot went from being France's most influential scientist to being ostracized. Colleagues and friends who had sought him out at conferences now shunned him. Isolated and with little left to lose, Joliot's political positions became increasingly one sided and myopic. During the opening years of what came to be called the Cold War, he and the organizations that he was affiliated with sat by silently while the Soviet Union took control over all of Eastern Europe. In Joliot's eyes, the Soviet Union could do no wrong, and the West could do no right. One of Joliot's biographers has called those years tragic; I prefer to think of them as just sad.

Yet Joliot was not without redeeming qualities. In the early 1950s, he became an outspoken advocate of nuclear disarmament and at times had a real impact. Joliot was instrumental in the formulation of the 1950 Stockholm Appeal, which called for the absolute ban of nuclear weapons and was the opening salvo in what would become a global nuclear disarmament movement. Like Oppenheimer, he strongly opposed the development of the hydrogen bomb by the US and the Soviet Union.

Following a broadcast by the philosopher Bertrand Russell in 1954, Joliot wrote to Russell and asked whether he would be open to formulating a joint declaration of scientists on the perils of nuclear weapons. Russell said that he would, provided it be nonpartisan and cast no blame. That proposal led to the issuance of the Russell–Einstein Manifesto of 9 July 1955, which Joliot cosigned with 10 other eminent scientists. And yet later that year, the Joliot-Curies were not invited to an Atoms for Peace conference—an important step in the creation of the International Atomic Energy Agency and the Nuclear Non-Proliferation Treaty.

Irène Curie died on 17 March 1956 of leukemia. A scientist friend attributed her death, like Marie's, to "our occupational disease." Joliot died of liver disease, possibly from radiation exposure, on 14 August 1958, at the age of 58. He and Irène had always been athletic, skiing in the Alps during winters and swimming in Brittany during summers. But like so many men of his generation, Joliot had been a lifelong chain smoker.

Were Joliot alive today, what would he have to say? No doubt he would be dismayed that Russia has fallen into the hands of a right-wing authoritarian, who brandishes his nuclear arsenal and conducts nuclear combat exercises. He would be equally dismayed that nuclear weapons, far from being beyond the pale, have become more entrenched than ever around the globe. Nine nuclear states, not just two, have nuclear weapons, and Iran is on the way. Still, he might find a glimmer of hope that one nuclear state, South Africa, gave up its arsenal, showing that it *is* possible to put the genie back in the bottle. Perhaps most of all, Joliot would regret that there are no individuals alive today who, like Einstein and Russell, rise so high above the fray that they can command the world's attention with an appeal for nuclear sanity.

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NEW PRODUCTS

Focus on photonics, spectroscopy, and spectrometry

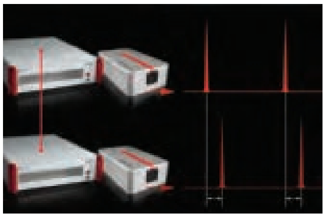
The descriptions of the new products listed in this section are based on information supplied to us by the manufacturers. Physics Today can assume no responsibility for their accuracy. For more information about a particular product, visit the website at the end of its description. Please send all new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

Andreas Mandelis

Compact modulated laser for bioimaging

Hübner Photonics has added a 594-nm-wavelength laser to the Cobolt 06-01 modulated laser series. The 06-DPL 594 nm has 100 mW output power. It can be directly modulated in either digital or analog mode up to 50 kHz, making it suitable for exciting red fluorophores, such as AF594, mCherry, and mKate2, that are often used in optogenetics and other bioimaging applications. Active power control during modulation ensures an ideal linear optical response and stable illumination from the first pulse and for any duty cycles and power levels. All Cobolt lasers are manufactured using proprietary HTCure technology; the resulting compact, hermetically sealed package provides a high level of reliability and immunity to varying environmental conditions. Cobolt lasers can be used in both laboratory and industrial environments. ***Hübner Photonics Inc***, *2635 N First St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

Dual-color laser system



Toptica has released its FemtoFiber ultra dual-color laser system for multicolor nonlinear microscopy applications. The femtosecond fiber laser features two synchronized laser lines, making it suitable for simultaneous multicolor imaging and fluorescence lifetime imaging. It offers the advantages of a shared oscillator design for all-optical synchronization, a fixed delay between the two colors with minimum jitter, and a single electronic trigger output as a reference for time-correlated single photon counting and gated detection. Laser wavelength tuning is not needed. The FemtoFiber ultra dual-color laser system facilitates enhanced imaging of biological samples; in particular, metabolic imaging can especially benefit from the laser's ability to perform simultaneous NADH (nicotinamide adenine dinucleotide hydrogen) and FAD (flavin adenine dinucleotide) measurements. ***Toptica Photonics Inc***, *1120 Pittsford Victor Rd, Pittsford, NY 14534, www.toptica.com*

Ebook on UV, visible, and near-IR microspectroscopy

AZoM, which reports news about materials science, has published the ebook *UV-Vis-NIR Microspectroscopy for Materials Research: Key Applications and Case Studies*. The information was sourced, reviewed, and adapted from materials provided by Craic Technologies, based in San Dimas, California. The ebook presents a comprehensive overview of cutting-edge microspectroscopy technologies and their applications and highlights how UV, visible, and near-IR microspectroscopy enables innovations in fields such as materials science, forensic analysis, nanotechnology, and life sciences. It offers insights into materials such as actinides, lanthanides, perovskites, liquid crystals, organic LEDs, and quantum dots. Case studies cover thin films and single crystals and their optical properties; effects of dopants and local defects on material performance; and guidance on integrating microspectroscopy in material development, from initial optimization to quality assurance. The ebook also introduces Craic Technologies' instrumentation and software solutions. It is available on the Craic Technologies page on AZoM's website. ***AZoNetwork UK Ltd***, *Neo, 4th Fl, 9 Charlotte St, Manchester M1 4ET, UK, www.azom.com*

Optical beam-combining system

Sutter Instrument's Lambda 721 system combines up to seven separate LED cubes with different spectra into a single common output beam. The cubes contain the LED, the collimating optics, and a filter. They are easily exchanged and installed without tools and without the need for a dichroic ladder, which restricts how the light sources are changed and in what order they are introduced into the optical path. With the Lambda 721, any LED cube can be placed in any of seven positions and in any order. Semrock STR filters are used for wavelength selection and beam reflection. Each cube is collimated before entering the optical path through the band-pass filter. The filters also function as mirrors that reflect the collimated beams from the previous light sources. Applications for the optical beam-combining system include fluorescence microscopy, calcium imaging, optogenetics, and high-speed wavelength selection. ***Sutter Instrument***, *1 Digital Dr, Novato, CA 94949, www.sutter.com* PT

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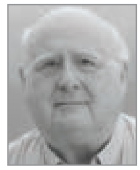


As the world turns—irregularly

Duncan C. Agnew

The length of the day varies by milliseconds over the course of weeks, years, and centuries. Conservation of angular momentum explains why.

From noon to noon, the day has long served to define the passage of time. That duration, based on the observed position of the Sun, inherently varies over the course of a year (see the Quick Study on the equation of time by Anna Sajina, Physics Today, November 2008, page 76).

Yet even as measured against the fixed stars (today defined by extragalactic radio sources), Earth's angular velocity $\omega(t)$ is not some constant ω_0; a wide range of geophysical processes cause it to fluctuate slightly. Those variations in $\omega(t)$ allow geophysicists to test models for those processes: The better that a model's predicted fluctuations match the observations, the more likely it is that the model is accurate.

We experience $\omega(t)$ from the solid part of Earth; the changes in $\omega(t)$ come from the fluids that move around on the surface and deep inside. The relevant equation is the definition of the angular momentum L in terms of all Earth's fluid and solid parts:

$$L = C_\mathrm{a}\omega_\mathrm{a} + C_\mathrm{h}\omega_\mathrm{h} + C_\mathrm{s}\omega + C_\mathrm{c}\omega_\mathrm{c}, \qquad (1)$$

where the C's are the moments of inertia around Earth's spin axis and the ω's are the average angular velocities. The subscripts label the various parts: a is the gaseous atmosphere above the solid surface; h, the liquid above the solid surface—that is, the hydrosphere; s, the solid part (with the subscript for ω_s omitted); and c, Earth's liquid (and, in part, solid) core.

We can rearrange equation 1 to express ω in terms of everything else and do a perturbation expansion in all the variables. When the variations are expressed as normalized fractional changes—defining $\Delta_\omega(t) = (\omega(t) - \omega_0)/\omega_0$ with respect to some reference value ω_0 and likewise for the other variables—the result for variations in ω is

$$\Delta_\omega = (\Delta_L/C_\mathrm{s}\omega) - \Delta_{C\mathrm{s}} - \sum_{k=\mathrm{a,h,c}} r_k(\Delta_{Ck} + \Delta_{\omega k}). \qquad (2)$$

The factors r_k are the relative moments of inertia, C_k/C_s: $r_\mathrm{a} \approx 1.5 \times 10^{-6}$, $r_\mathrm{h} \approx 5 \times 10^{-4}$, and $r_\mathrm{c} \approx 0.13$. In the summation, $r_k\Delta_{Ck}$ can be viewed as the *mass* terms, from the change in C_k from mass redistribution, and $r_k\Delta_{\omega k}$ the *motion* terms, which originate in fluid flows relative to the solid Earth.

The figure shows, over successively longer times, the past fluctuations in Δ_ω and the dominant contributions that arise from the right-hand side of equation 2. For historical reasons, changes in ω are commonly expressed as variations in the length of day—that is, the number of milliseconds that a clock using Earth's rotation would depart from atomic time over a day. That value is also nondimensional; 1 ms/d is a change in Δ_ω of -1.157×10^{-8}. The figure plots $-\Delta_\omega$ to match the length-of-day sign convention: A decrease in Δ_ω is a longer day.

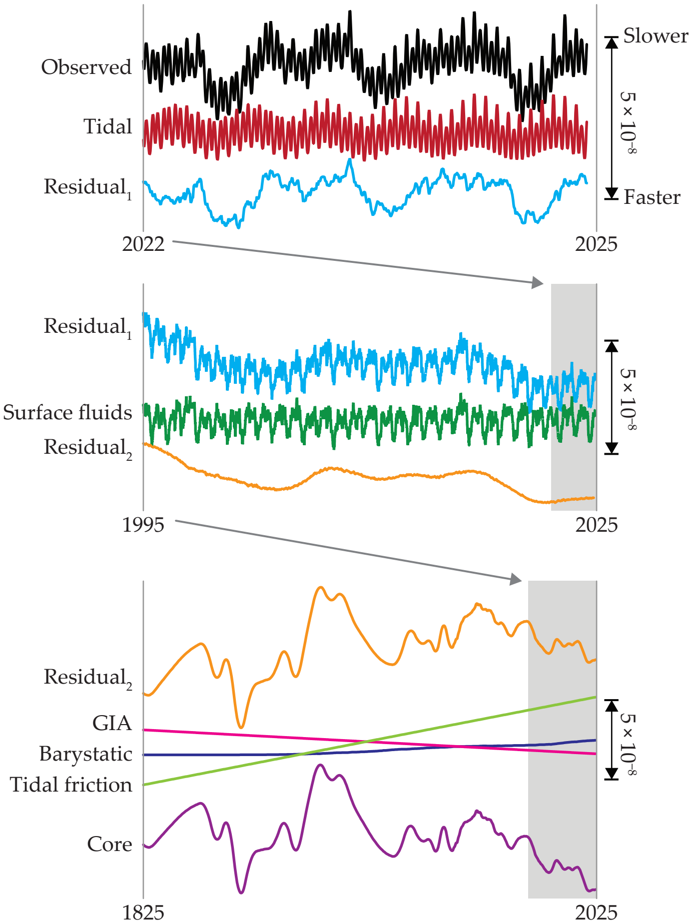
Years and decades

The top frame of the figure shows the past three years of changes in Δ_ω (black line). On that time scale, the dominant contributors are changes in $\Delta_{C\mathrm{h}}$ and $\Delta_{C\mathrm{s}}$ caused by the tidal deformations of the ocean and solid Earth; the deformations can be viewed as bulges aligned with the lunar and solar gravitational fields. Because of the inclinations of Earth's rotation axis and the Moon's orbit, the tidal contributions to the moments of inertia vary. They peak when the corresponding body is over Earth's equator: twice per year for the Sun and every 14 days for the Moon. Given models of the tidal response of the ocean and Earth, we can compute the expected changes (red line) and subtract them; that the residual ($\mathrm{Residual}_1$, blue line) has no remaining tidal fluctuations validates the models at those time scales.

The middle frame looks at the past three decades. The blue line extends $\mathrm{Residual}_1$—that is, Δ_ω with tidal effects removed—from the top frame (corresponding to the gray region). It shows a clear, though irregular, seasonal change and other fluctuations. Below it are the variations (green line) expected from observation-based models of Earth's atmosphere and ocean. The largest contribution, especially at seasonal time scales, comes from changes in $\Delta_{\omega\mathrm{a}}$, which are due largely to variations in the winds of the upper atmosphere. Fluctuations in the air-mass distribution affect $\Delta_{C\mathrm{a}}$ and must also be included to match the observed Δ_ω. The resulting residual ($\mathrm{Residual}_2$) is shown in orange.

Longer variability

The bottom plot again repeats the process of subtracting known sources of variability, this time over two centuries. The data extend to well before the advent of atomic clocks in 1955; the reference clock used instead is the motion of the



THE RATE OF EARTH'S ROTATION is constantly fluctuating. Plotted here are the fractional changes in the rotation rate over different time scales, from the past three years (**top**) to the past 200 (**bottom**). Many geophysical processes contribute to the fluctuations, as discussed in the main text; at the bottom of each frame are the residual variations left over after accounting for the factors above it. The scale bars denote a fractional change in rotation rate of 5×10^{-8}, or a 4.3 ms change in length of day. Upward on the plot corresponds to longer days (slower spin).

Moon—the lunar occultations of stars can be timed with great accuracy.

There are three long-term effects that change Δ_ω. The first is glacial isostatic adjustment (GIA). During the last glacial period, which ended roughly 11 000 years ago, large ice sheets covered Hudson Bay and the Baltic Sea, and their weight caused the ground surface to drop. When they melted, the load was removed, and the surface rebounded toward its elevation with no load—so-called isostatic equilibrium. Because Earth's mantle is not perfectly elastic, the rebound is still going on; over the time period shown, it can be regarded as steady. Because the rebound is transforming Earth into a less oblate, more spherical shape, it decreases C_s and causes Earth to spin faster (magenta line).

A second effect, termed barystatic, comes from changes in Δ_{Ch} as water is redistributed between higher and lower latitudes. Since 1900, and recently at an accelerating rate, melting of the polar ice caps and the Greenland ice sheet has redistributed mass from those areas to the global ocean. That increases Δ_{Ch} by an amount that over the past century has been large enough (dark blue line) to cancel out the decrease from GIA.

The third effect was the one first detected and identified: tidal friction, another consequence of the tidal deformation of the ocean and Earth. Because tidal bulges are slightly offset from the gravitational potential—high tide is slightly delayed from the Moon being straight overhead—the tidal mass distribution exerts a torque on the Moon (and likewise on the Sun). There's an opposite torque on Earth that causes Δ_L and hence Δ_ω to decrease with time (light green line). Because the total angular momentum of the Earth–Moon system is conserved, the Moon accelerates and recedes from Earth. Measurements of that recession rate, currently 40 mm/yr, give the best estimate of tidal friction: It dissipates about 3.5 TW of energy, mostly into the ocean. Extrapolating the recession rate backward in time implies that the Moon must be 1.5 Gyr old. Its age is known to be much greater, approximately 4.5 Gyr, which means that over most of geological time, tidal friction must have been smaller.

Subtracting those three long-term effects leaves the fluctuations in purple at the bottom of the figure. The only possible source for them is motion in Earth's liquid core. Such motion produces Earth's magnetic field, which varies irregularly. The changes in Earth's field and the residual changes in Δ_ω provide much of our information about the core's complex magnetohydrodynamic behavior.

Over the past 50 years, $\Delta_{\omega c}$ has steadily decreased and the solid Earth has spun faster—with significant implications for global time standards. Unlike the tides and the weather, motions in the core cannot be predicted with any confidence, so beyond a year in the future, Earth's exact spin rate becomes more and more uncertain.

Additional resources

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Window shades respond to weather

No person or electricity is necessary to open and close these window shades. On an early afternoon in March 2023, at a research building of the University of Freiburg, located in southwestern Germany, the adaptive shades unfurled themselves into a mostly closed configuration, as shown here. It was 17.5 °C outside, with a relative humidity of 37.4%. In weather that is colder and damper, a common combination in Freiburg, the shades curl. That allows more sunlight to come in through the window and warm the indoor environment. The designers—Tiffany Cheng, Yasaman Tahouni, and Ekin Sila Sahin, all at the University of Stuttgart, and their colleagues—were inspired by biological materials such as pine cones that passively change shape in response to moisture.

The team's prototype shades are made of renewable cellulose. The structure consists of fiber-like strands that swell in a preferred direction when they absorb moisture, and that swelling makes the entire shade panel bend. Initial tests show that the shades' curling depends predominantly on humidity and to a lesser extent on temperature. More work is necessary to determine how effective the shades can be in climates where hotter days are humid and colder ones are dry. Adaptive window shades won't eliminate the need to heat and cool buildings, but they may help lower the energy requirements for building operations, which are responsible for 27% of global carbon dioxide emissions. (T. Cheng et al., *Nat. Commun.* **15**, 10366, 2024; photo courtesy of Tiffany Cheng.) —AL