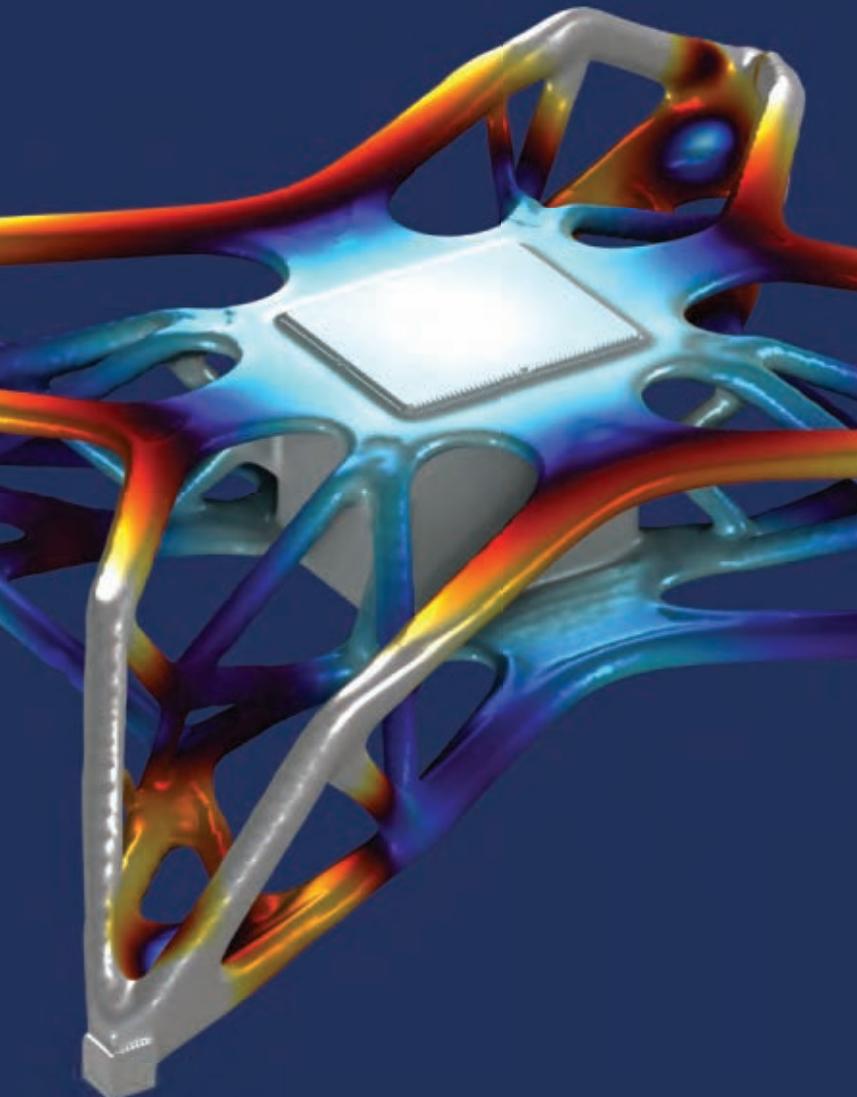


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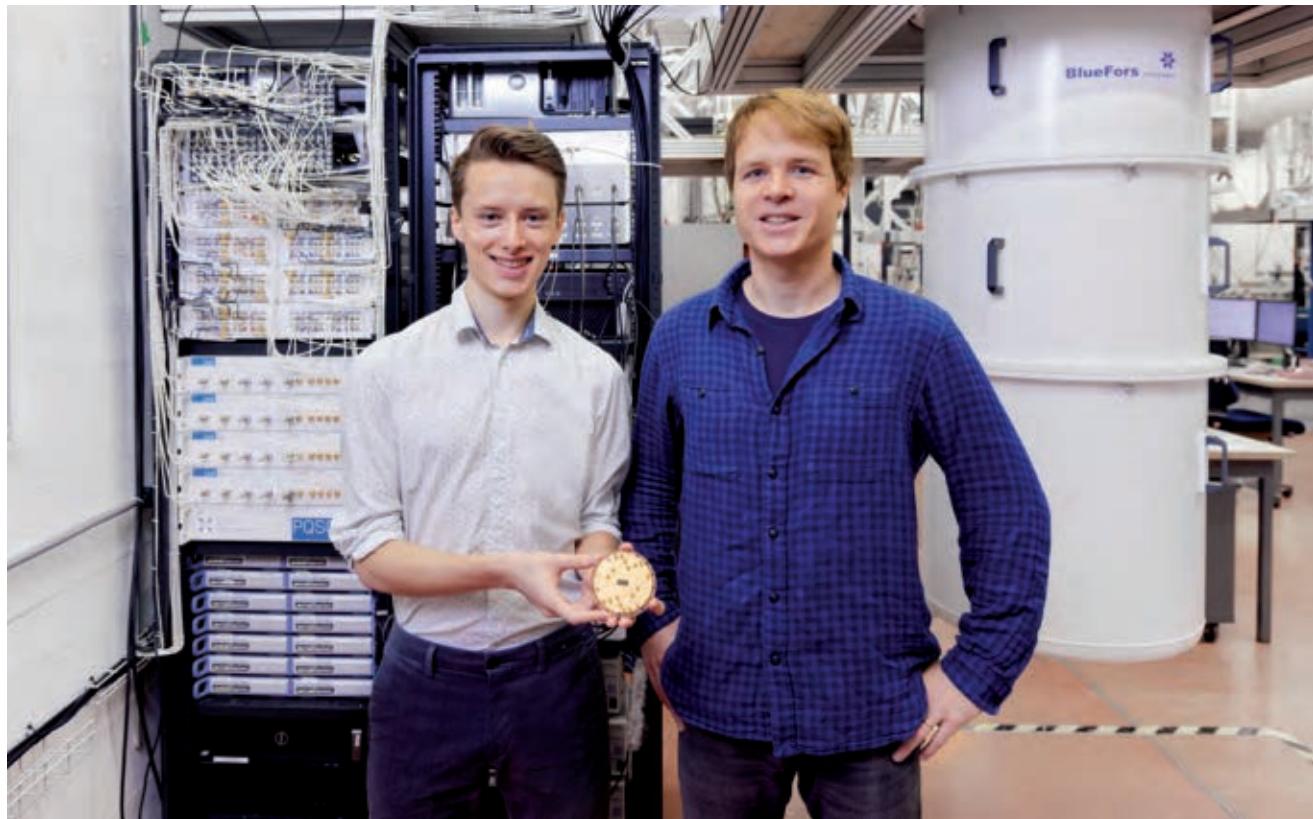
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Extracellular space

**Coulomb-explosion
imaging**

**Germany's
energy policies**

**Micrometeorites
on the Moon**



Nathan Lacroix and Sebastian Krinner, ETH Zurich

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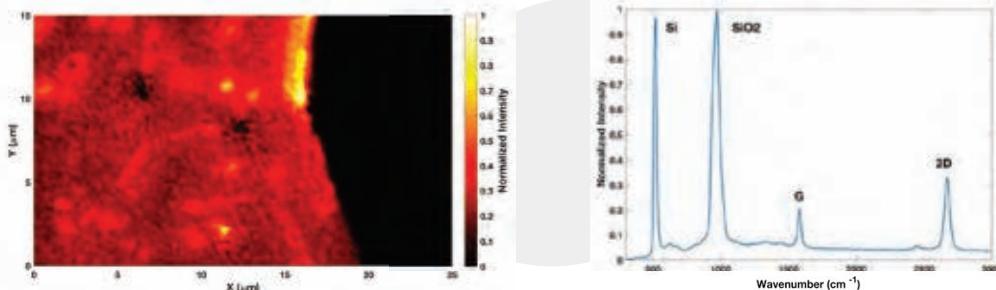
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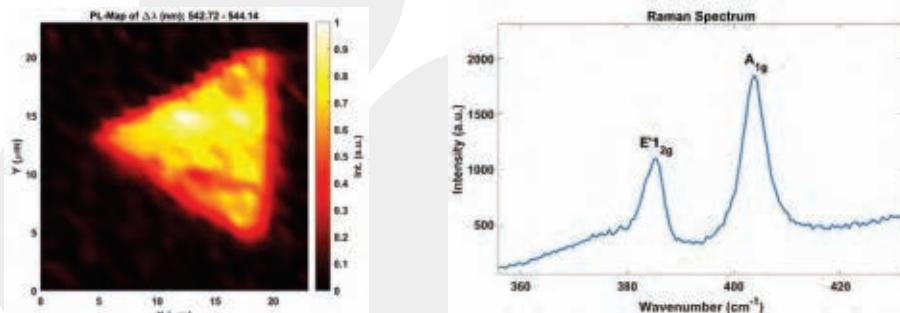
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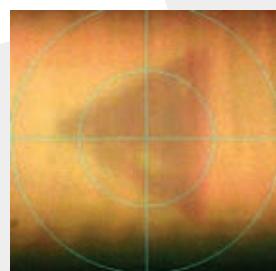
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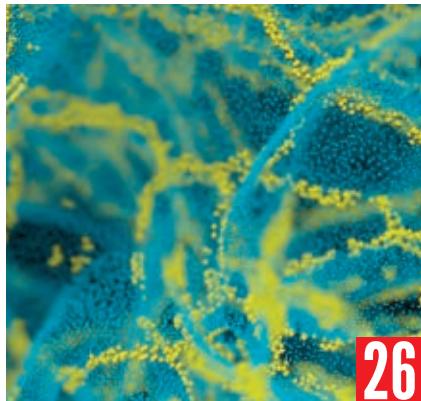
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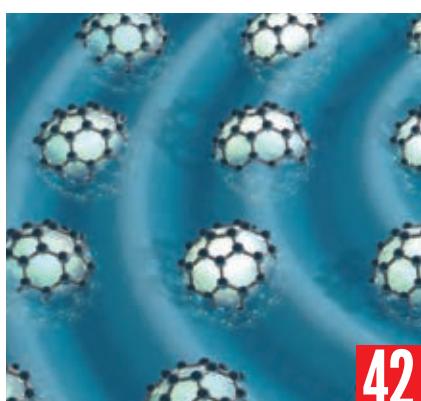
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Charles Nicholson

Innovations in diffusion analysis and imaging techniques have gradually revealed the ubiquity and importance of extracellular space.

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Christopher Dunlap

At the end of the Cold War, two South American rivals built a system of nuclear safeguards that culminated in the 1991 founding of a bilateral organization, ABACC. Can that nonproliferation regime be exported?

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Martin Rodriguez-Vega, Maia G. Vergniory, and Gregory A. Fiete

Illuminating materials with lasers can create intriguing magnetic and topological states of matter.



ON THE COVER: In *Neural Migration*, the artist and neuroscientist Greg Dunn depicts radial glia (black) creating new neurons (white). On page 26, Charles Nicholson focuses not on brain cells but on the gaps between them. Unlike the vast open spaces shown on the cover, most extracellular space in real brain tissue is only tens of nanometers wide and thus difficult to probe. Diffusion analysis and imaging techniques have gradually been able to characterize that space, which is essential for passing electrical and chemical signals. (*Neural Migration*, 2021, Greg Dunn, www.gregadunn.com.)

PHYSICS TODAY (ISSN 0031-9228, coden PHTOAD) volume 75, number 5. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to PHYSICS TODAY, American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Views expressed in PHYSICS TODAY and on its website are those of the authors and not necessarily those of AIP or any of its member societies.



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Helium shortage

Helium is again in short supply, forcing some scientists to shut down nuclear-magnetic-resonance spectrometers, scanning tunneling microscopes, and other pieces of equipment that require the noble gas to stay cold. PHYSICS TODAY's David Kramer reports on the fourth major helium shortage since 2006.

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Farm Hall

In 1945 Allied intelligence recorded the conversations of 10 German nuclear scientists who were detained at Farm Hall in England. PHYSICS TODAY's Ryan Dahn explores why, 30 years after the public release of the transcripts, historians are still debating if the Nazi regime was pursuing an atomic bomb.

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The death of expertise has been exaggerated

Charles Day

In June 2011 the National Academies Press made all of its reports freely available to anyone to download. The press is the publisher for the National Academies of Sciences, Engineering, and Medicine (NASEM). When people access the free reports, NASEM presents users with an optional request: "Please take a moment and tell us how you will be using this PDF." Two and a half million people worldwide have since left a comment.

Diana Hicks of Georgia Tech and her collaborators have used machine learning to analyze all the comments that originated in the US.¹ The largest group of users turned out to have personal IP addresses rather than academic or business ones. That finding is heartening to those worried, as the authors put it, about "information bubbles, fake news, the spread of misinformation, manipulation of social media users, Twitter bots, etc."

About 23% of downloaders left comments, which ranged from single words, such as "research," to multiple sentences, such as "I have a long-time interest in astronomy. I am a newspaper reporter but probably cannot use this in my work. One never knows, however." To crunch through the heterogeneous data, Hicks and her collaborators used a natural-language classification algorithm called BERT (Bidirectional Encoder Representations from Transformers). The result was a 64-term taxonomy of report usage divided into six broad categories.

Of the broad categories, "education and research" accounted for the largest share at 48%. Next came "governance" at 18% and "information activity" at 17%. The third-placed category encompasses recreational learning of the kind I do when I read scholarly books about art, history, and literature.

In their paper, Hicks and her collaborators list the 25 most downloaded NASEM reports out of the 10 275 included in their study. The top three are *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (206 000 downloads), *The Future of Nursing: Leading Change, Advancing Health* (125 000 downloads), and *How People Learn: Brain, Mind, Experience, and School: Expanded Edition* (74 000 downloads). Education, health, and policy accounted for almost the entire top 25.

The absence of basic science from the top 25 prompted me to ask Hicks about the 2010 astronomy and astrophysics decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics*. (The most recent decadal survey fell outside the study's time range.) She told me that the report had been downloaded 28 000 times, which placed it at 37 on the most downloaded list. As for the comments, the report attracted a lower than average fraction that were classified as research. Whereas personal use accounted for 8% of average usage, it



accounted for 22% of the 2010 decadal survey's usage. It was clear from the comments that the report was popular among amateur astronomers.

It's not surprising that the most downloaded reports are about topics that affect people's lives rather than, say, the prospects for research in biological physics, which is the subject of one of NASEM's most recent reports.² But I can't help wondering if another factor is at play. The two most downloaded reports in Hicks and company's study were covered in the *New York Times* and elsewhere, as was the 2010 decadal survey. It's conceivable that media coverage is a necessary condition for a NASEM report to be popular. Indeed, a 2017 survey by the Pew Research Center found that most Americans receive science news through general media outlets.³

Newspapers, radio stations, TV channels, and other media have to make money to survive. The editors and producers who decide what science news to publish and broadcast have to gauge what interests their audiences. Should NASEM and other science organizations follow mainstream media and prioritize public interest when it comes to reports? It would be a pity if biological physics and other topics that the general public considers esoteric were no longer the subjects of reports. Still, given the resources deployed to produce them, some consideration should be given to the likely, not hoped-for, readership.

The research conducted by Hicks and her collaborators illuminates the rewards for successfully engaging the public. In the concluding paragraph of their paper, they write: "The overall impression is of adults motivated to reach higher, seek out the most credible sources, engage with challenging material, and use it to improve the services they provide or learn more about the world they live in."

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1. D. Hicks et al., *Proc. Natl. Acad. Sci. USA* **119**, e2107760119 (2022).
2. National Academies of Sciences, Engineering, and Medicine, *Physics of Life*, National Academies Press (2022).
3. C. Funk, J. Gottfried, A. Mitchell, *Science News and Information Today*, Pew Research Center (2017).

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Commentary

Researching around Europe: A personal reflection

Seven years ago in Spain, I was waiting in one of Barcelona's central train stations, ready to jump on the same train I had been taking for the past four years of my undergraduate career. My life at the time was pretty vibrant: I'd wake up, go to track-and-field training, attend university lectures, give private science lessons, and then go back to training again.

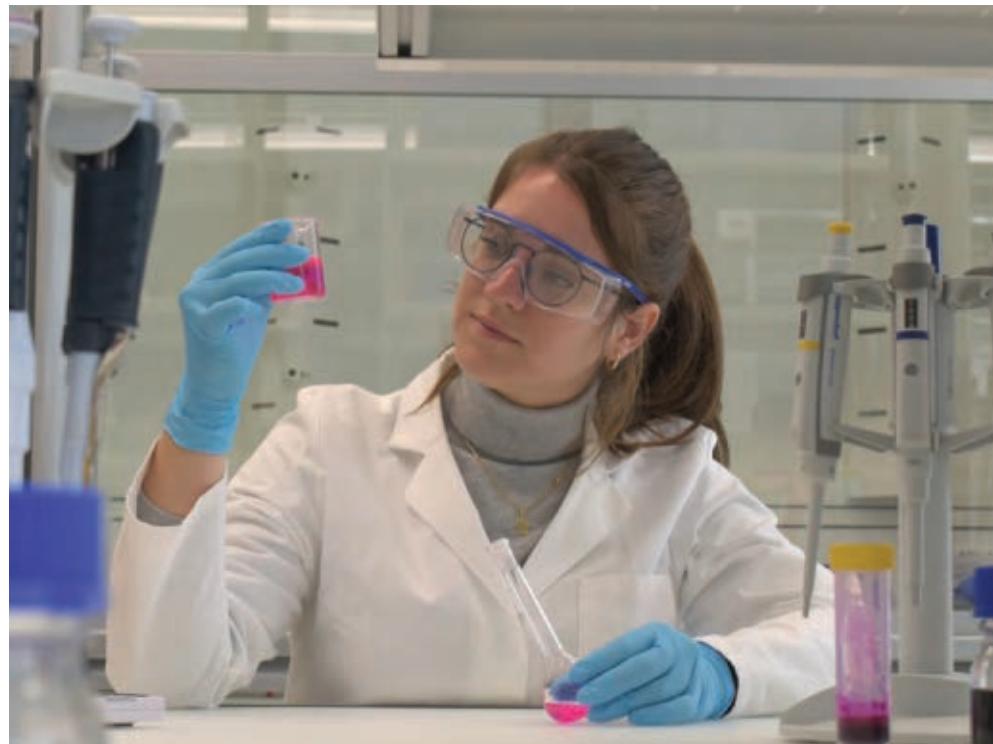
Those commutes were my only spare time, so it is not surprising that it was during one of those daily rides that I had an epiphany: "I don't want to take this train every single day anymore," I thought to myself.

I was nearly at the end of my studies, and I knew I needed a change. But what I didn't know was that my realization would take me on an adventure around Europe. That seven-year-long journey would lead me to become not only a more complete person but also a better scientist.

As an undergraduate at the Autonomous University of Barcelona, I studied nanotechnology. Combining physics, chemistry, and biology, the major was the perfect fit for my young and curious mind that wasn't sure which scientific field it wanted to marry yet. I loved my lectures, which provided me with answers for many of my everyday questions. As a keen runner, I better understood what I should eat before competitions. As a not-so-keen cook, I also understood why my granddad was slowly adding oil to smashed garlic to stabilize aioli, a delicious Mediterranean version of mayonnaise.

Unlike the lectures, the research training was not so enjoyable. My classmates and I did not have many opportunities for real hands-on research experiences. With a spirit of trying to figure out whether academic research was the right career path for me, I decided to change gears and experience new forms of education. And as much as it was a scary thought at the time, I was also ready to leave my home country of Spain.

I applied and was accepted to a two-year master's program in nanomaterials at Utrecht University in the Netherlands.



CARLA FERNANDEZ RICO has conducted research in Spain, the Netherlands, the UK, and Switzerland. She is seen here examining a sample of fluorescent colloidal particles in her current lab at ETH Zürich.

The program seemed very appealing to me as it was heavily based in practical research and taught in English, the vehicular language of science. Attending Utrecht was the first time I had really stepped out of my comfort zone. I took a deep dive into a different society and gained an incredible new level of maturity. Academically, I finally experienced the direct application of theoretical concepts, as the taught courses were tightly related to the research done on campus.

My experience in Utrecht transformed my view of both science and life. Research-wise, such a positive experience wouldn't have been possible without the help of my excellent master's project supervisor, Samia Ouhajji. When I felt lost during my project because experiments wouldn't work, she gave me a great piece of advice: Sometimes you have to accept

that you can't control everything and must let things go. She patiently guided me on the unknowns of scientific research and didn't judge my English, which was sloppy at the time. I now understand how pivotal it is for young researchers to have good mentors at the early stages of their development, as it shapes their future approach to science.

To complete my master's degree, Utrecht required me to do a five-month internship at a different university or at a company. It was the perfect opportunity to explore the world a little further and learn about new scientific cultures. After a few Skype calls with Roel Dullens, then a professor at the University of Oxford, I joined his group as an intern. Half a year later, I would return to Oxford as a PhD student, with Roel as my adviser.

Truth be told, deciding to stay in the

UK for my PhD wasn't an easy choice, especially because I was starting to feel a little homesick. Nonetheless, I had established a great relationship with my future supervisor, which I knew would be a critical factor in enjoying my PhD journey. Also, during my internship, I'd learned that I liked the city and my group. So I decided to stay.

The next four years in Oxford were full of ups and downs, as any PhD journey promises to be. In a way, I had arrived almost by chance to one of the top universities in the world, and it took me about six months to leave behind my insecurities about not being good enough. But once I got my balance back—learning to carefully juggle work, sports, and home—I managed to have a great and productive PhD experience, in a rather special place, as Oxford is.

After I successfully obtained my doctorate in physical chemistry, I was again left deciding what to do next. Having decided to stay in science, I felt ready to dive into something more interdisciplinary than my thesis topic while still honoring my nanotechnology roots. I contacted Eric Dufresne, the principal investigator of an amazing materials group at ETH Zürich, and ended up joining his group as a postdoctoral fellow. With this opportunity, I wasn't held back as much by the lingering feeling that it was time to go home. I guess over the years I have had time to refine what I call my "personal recipe for balance," and I'm now better able to pursue my curiosity and explore new social and scientific cultures without it costing me too much energy.

Looking back, I've realized one of the best things about moving to different countries to do research is that it forces you to take on different lenses through which to view science. In my case, I don't

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think I could have developed as much of an interest in its fundamental aspects if I had stayed in Barcelona. In Spain, more scientific funding goes to applied research, which intends to provide immediate solutions to problems. And as much as that type of science is necessary, diving into fundamental problems is intrinsically the other side of the coin, and both are equally needed for sociotechnological progress. In my experience abroad, I have found that funding bodies in the Netherlands, the UK, and Switzerland have been more ready to support both fundamental and applied science.

Rather than saying which places are better for doing research, I will say that moving to different countries has allowed me to become a more complete scientist—one who asks both "What is this useful for?" as I learned to do in Spain, and "How does this work?" as I practiced in the UK and the Netherlands. In the same way a microscope characterizes different features depending on the lens being used, I feel that I am now able to appreciate subtleties in my research and come up with problem-solving approaches in ways I simply wasn't able to before.

Sometime in the future, I hope to go back to Barcelona and bring with me all the knowledge I've gathered from around Europe. But for the time being, my adventurous spirit still tells me to make the most of my time in Zürich—and maybe even explore a bit further. Let's see what the next stop is!

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LETTERS

Space-colonization complications

Charles Day's column "Space barons" (PHYSICS TODAY, September 2021, page 8) discusses how the Sun will eventually reach its red-giant stage and "humanity will need a new, distant haven that only spacecraft can reach." Day writes that "in so far as commercial space travel will make that possible, we should commend it however grudgingly." Also, in the book *The High Frontier: Human Colonies in*

Space (1977) and in a September 1974 article in PHYSICS TODAY (page 32), Gerard O'Neill of Princeton University explores the idea of space colonization. More immediate threats, however, might well cause us to become extinct long before the Sun's red-giant stage.

Thorny questions arise: Which species might be chosen to survive? Would fiat, a random drawing, or voting decide the selection of future "leavers" and "stayers"? Should the prospect of escape from Earth be skewed in favor of the descendants of funders (a pay-to-play system)? Might our descendants muck up a future nest just as quickly as we have fouled our current one? Might we decide that humanity has been a failed experiment not to be protected from oblivion?

Perceived existential threats and our responses could change over eons, adding an element of uncertainty to decisions we might make today about distant havens. Moreover, we don't know how humans will evolve in the future.

The column asks, "Equity of access aside, is it a bad thing when rich people fund science?" Certainly, setting aside equity of access raises questions of morality, fairness, and justice. And rich people funding science can mean that the astonishingly wealthy are dictating priorities that impact the survival of the wider population. Such priorities might naturally trend toward sending a favored few to "sexy" distant havens that lurk in the dim future, with slim odds of success and at the expense of egalitarianism and more immediate needs of the populace.

On reflection, there are many alternatives to grudging commendation. Planet Earth has already demonstrated itself to have been a sustainable home for plants, and that could perhaps be replicated on a distant haven.

Evan Jones
(revwin@yahoo.com)
Sacramento, California

Corrections

April 2022, page 25—The figure caption should state that the Vera C. Rubin Observatory is scheduled to see first light in 2023.

April 2022, page 48—Ronald Bracewell, not Roland Bracewell, proposed using a twirling space-based interferometric array to detect exoplanets. **PT**

Coulomb-explosion imaging tackles an 11-atom molecule

Until now, the technique was thought to work only on molecules with no more than about five atoms. A powerful x-ray source leaves that limit in the dust.

Sometimes the only way to get a good look at something is to destroy it. When archaeologists excavate a site, they forever disrupt the context of how the artifacts they find were arranged in the ground. For gas-phase chemists, the molecules of interest are so small and move so fast that they can't be directly imaged—unless they're blown to bits.

X-ray diffraction and electron diffraction, cousins of the similar but less destructive crystallography techniques used for studying ordered solid samples, have found success in resolving the structures of isolated biomolecules and viruses. (See PHYSICS TODAY, April 2011, page 13.) When it strikes a single molecule, the x-ray or electron pulse breaks bonds and destroys the specimen. Even so, a small fraction of the photons or electrons scatter elastically, just as they do in a crystal. From those particles' diffraction pattern, researchers can extract structural information.

A complementary technique, Coulomb-explosion imaging, is especially well suited to studying smaller molecules in detail. Like diffractive imaging, it involves blasting a molecule with a pulse, usually of photons, that's powerful enough to expel the molecule's electrons, break its chemical bonds, and drive the now positively charged atoms to repel one another. But rather than studying the scattered photons, Coulomb-explosion imagers collect the charged fragments of the molecule itself. By measuring the fragments' momentum and modeling the trajectories the ions followed as they flew apart, researchers can deduce the atoms' starting positions: the molecular structure.



FIGURE 1. REBECCA BOLL works on the Small Quantum Systems instrument at the European X-Ray Free-Electron Laser. Wrapped in aluminum foil is the reaction microscope, which captures the charged fragments of molecules blown up by the powerful x-ray pulses. The foil insulates the equipment while the researchers bake out the residual gases. (Courtesy of European XFEL/Jan Hosan.)

Coulomb-explosion imaging has revealed exotic molecules that are too weakly bound to study spectroscopically (see PHYSICS TODAY, July 2015, page 10) and reaction pathways that had only ever been observed indirectly (see the Quick Study by Tomoyuki Endo, Chen Qu, and Heide Ibrahim, PHYSICS TODAY, July 2021, page 62). But despite those successes, researchers have limited use of the technique—at least in its purest form—to molecules with approximately five or fewer atoms.

Two assumptions lay behind that presumed restriction. Getting a good Coulomb-explosion image requires placing a positive charge on every atom in a molecule, so that all the pair-wise atomic interactions are dominated by Coulomb repulsion rather than electronic attraction. Researchers assumed that it wouldn't be possible to simultaneously ionize every atom in a large molecule. They also assumed that they could reconstruct a

molecule's structure only if they detected all of its ionic fragments—a daunting task for larger molecules when the detection efficiency for each ion hovers around 60%.

Now, working at the European X-Ray Free-Electron Laser, or EuXFEL, Rebecca Boll (seen in figure 1), Till Jahnke, and colleagues have shown that neither of those assumptions is valid—at least for some molecules.¹ When they pummeled 2-iodopyridine (shown in figure 2a) with the EuXFEL's powerful pulses of soft x rays, the molecule easily expelled enough electrons to ionize all 11 of its atoms.

And even when the researchers detected as few as three of the atoms from any given molecule, the momentum distributions built up from repeated Coulomb explosions were crisp enough to distinguish all five of the molecule's carbon atoms (as seen in figure 2b) and all four of its hydrogen atoms (shown in figure 2c). A theory team led by Robin Santra and his student Julia Schäfer per-

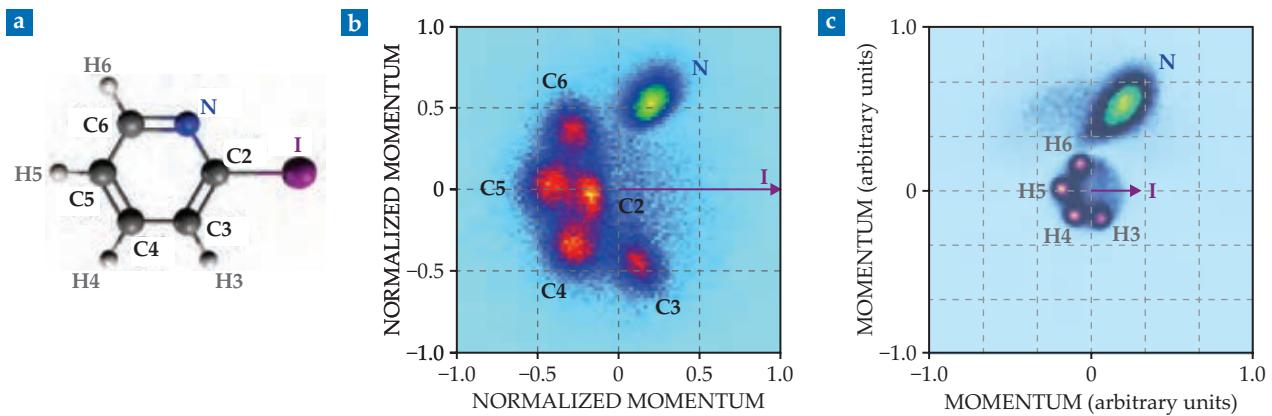


FIGURE 2. THE 11-ATOM MOLECULE 2-iodopyridine is laid bare by Coulomb-explosion imaging. (a) The molecular structure, which was already known, centers on a rigid, planar ring of carbon and nitrogen atoms. (b) When x-ray ionization breaks the chemical bonds and sends the atoms flying apart, the six ring atoms are readily distinguished by their momentum. (c) So are the four hydrogen atoms, the lightest and most challenging atoms to detect. (Adapted from ref. 1.)

formed simulations to relate the momentum measurements back to the molecular structure. The results are a first step toward transforming Coulomb-explosion imaging into a general technique for studying the structures and dynamics of not-so-small molecules.

Unexpected clarity

The researchers didn't set out to overturn the assumptions of Coulomb-explosion imaging. "If we'd said in our proposal that we wanted to image every individual atom in these molecules, we would have been laughed out of the room," says Boll. Rather, the project started with the more modest aim of exploring molecular ionization dynamics under the influence of XFEL pulses.

Before the EuXFEL came on line in 2017, Boll and Santra were part of a team using SLAC's Linac Coherent Light Source (LCLS), also an XFEL, to study ionization of iodomethane (CH_3I) and iodobenzene (similar to 2-iodopyridine, but with an all-carbon hexagonal ring).² They noticed that the XFEL pulses, thanks to multiphoton absorption, removed an astonishing number of electrons from both molecules. Absorption was concentrated on the iodine atom, which had the largest absorption cross section in the molecule, and produced charge states as high as I^{47+} . That's no small feat when the atom has only 53 electrons to begin with.

The charge seemed to spread efficiently from the I atom to other parts of the molecule. In iodobenzene, the researchers saw carbon atoms as highly charged as C^{4+} . But they didn't know which C atoms they were seeing—the

ones adjacent to the I atom or the ones on the opposite side of the ring. And the LCLS experiment wasn't equipped to help figure it out.

Boll and Santra didn't think that Coulomb-explosion imaging could distinguish two atoms of the same element in the same molecule—at least, not without detecting every atom in the molecule, which for a structure as large as iodobenzene would be nearly impossible. But the technique can easily distinguish atoms of different elements because of their different masses.

The original plan for the new EuXFEL experiment, then, was to replace one C atom at a time with a nitrogen atom. If the N atom in 4-iodopyridine (on the opposite side of the ring as the I atom) ended up just as highly charged as the one in 2-iodopyridine, it would follow that the charge is readily redistributed around the ring.

The researchers expected the pattern formed by all the other atoms to be a featureless blob. But to their surprise, when they plotted the C atoms' momentum, the data formed five distinct bunches, one for each position around the ring. The four hydrogen atoms showed an even cleaner bunching. So even if the researchers detect only one of the C or H atoms from a given Coulomb explosion, they can tell which one it is just by measuring its momentum.

What a coincidence

The 2-iodopyridine molecules tumble randomly through space on their way to their destruction by the XFEL beam. The distributions in figure 2 require reorient-

ing the data, molecule by molecule, into a common reference frame with the horizontal axis defined by the I atom's momentum and the vertical axis determined by the N atom's.

The reorientation is possible because the researchers did what's called coincidence mapping: They made their beam of 2-iodopyridine so dilute that each x-ray pulse interacted with at most one molecule. Only under those conditions could they be sure that all the ions detected in a single shot came from the same parent molecule. The data in figure 2 are for threefold coincidences: shots in which they detected the I atom, the N atom, and at least one other. The researchers also collected momentum data for up to eight-fold coincidences, which look similar.

Coincidence-mapping experiments can take a long time to build up a meaningful data set. The EuXFEL's high repetition rate, up to 570 pulses per second for these experiments, helps. Without access to such a high-powered facility, other research groups have explored an alternative technique called covariance mapping: simultaneously ionizing many molecules (usually after physically aligning them with polarized light) and using sophisticated data analysis techniques to make up for the fact that they can't definitively trace any two atomic fragments to the same parent molecule.

Covariance mapping has yielded some structural, and even dynamical, information for molecules with more than 20 atoms.³ "But those experiments are always losing some information," says Jahnke. "For example, if you're looking at an ensemble of molecules doing some

dynamical process, those molecules aren't all doing the same thing." Coincidence mapping, although time-consuming and experimentally challenging, yields that molecule-by-molecule information.

Toward molecular movies

In their theoretical analysis, Santra and Schäfer didn't focus on determining bond lengths, bond angles, or other structural details. The equilibrium structure of 2-iodopyridine, like those of most similarly sized molecules, is already known. Instead, starting from that established structure, the theorists simulated the Coulomb-explosion process and showed that it yields momentum distributions much like the ones that were observed. If necessary, they could iteratively adjust the starting configuration to converge on an unknown molecular structure.

Of greater interest than equilibrium structures, though, are the insights that Coulomb-explosion imaging can offer

for molecules in motion: An ultrashort laser pulse initiates a chemical reaction, and the XFEL pulse instigates a Coulomb explosion tens or hundreds of femtoseconds later. Most of what researchers know about what happens during a reaction they learn indirectly, either by studying the reaction products (see, for example, PHYSICS TODAY, February 2019, page 14) or by spectroscopically probing the molecules midreaction (see PHYSICS TODAY, December 1999, page 19). Coulomb-explosion imaging provides a more direct look.

One barrier to studying the dynamics of 11-atom molecules is figuring out how best to visualize all the data. The two-dimensional momentum plots in figure 2 are deceptively simple, because there's no reason different atoms' momenta need to be plotted on the same pair of axes. Each of the 11 atoms has its own 3D momentum, so one would need 33 axes to plot them all (or 27, after factoring out

the translations and rotations that don't affect the underlying dynamics).

"X-ray diffraction and electron diffraction can resolve molecular structures," says Santra, "but they're purely three-dimensional. They can't map out the whole molecular phase space, which is our goal. With Coulomb-explosion imaging, we're still not detecting everything, but we can get so much more information than traditional techniques provide."

Johanna Miller

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Glass ages in material time

The long-standing assumption that the same relaxation processes underlie linear and nonlinear aging is now backed up by experiments.

Follow a tour guide around a European city and you're likely to hear the tale that old cathedral windowpanes appear uneven because over hundreds of years, the glass has slowly flowed toward the bottom of the pane. That story is just a myth; such flow in silica would require at least geological time scales.¹ But glassy materials, molecular and otherwise, do slowly evolve toward a metastable equilibrium state—a process known as aging.

Physical aging involves rearrangements in the atoms, molecules, or colloidal particles that make up a glassy material. Such materials are characterized by a glass-transition temperature T_g at which the system falls out of equilibrium because the time scale for rearrangements surpasses that of observations. Below T_g , the materials display nonlinear aging: The evolutions of their densities and other properties are not proportional to the

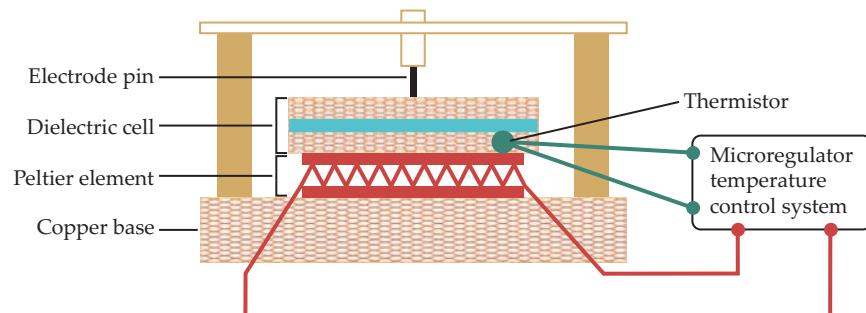


FIGURE 1. A MOLECULAR LIQUID (turquoise) undergoes structural relaxation, known as aging, after being subjected to small temperature changes. The evolution of the 50- μm -thick layer's capacitance reflects changes in its microscopic configuration. An electrode and dielectric cell measure the liquid's capacitance; a thermistor and a Peltier element monitor and regulate its temperature. (Adapted from ref. 4.)

temperature changes. Because the materials are out of equilibrium, the actual form of the relationship is difficult to model or predict.

In 1971 Onbathivel Narayanaswamy postulated that when exposed to sufficiently small perturbations, a material's response will be in the linear regime.² He also asserted that a glass's nonlinear properties could be extracted from that linear relationship by replacing the regular lab time with a so-called material time: a nonuniformly stretched time that reflects a material's evolving state. The lab

time t and material time ξ are connected by $\gamma(t) = d\xi(t)/dt$, where γ is the time-dependent aging rate.³

Although the material-time formalism has since been widely and successfully used to describe glass aging, it has never been directly tested. Without experiments sufficiently precise to reach the linear regime, extensions to the nonlinear regime have relied on assumptions about, rather than measurements of, linear behavior.

Now Birte Riechers and her coworkers at Roskilde University in Denmark

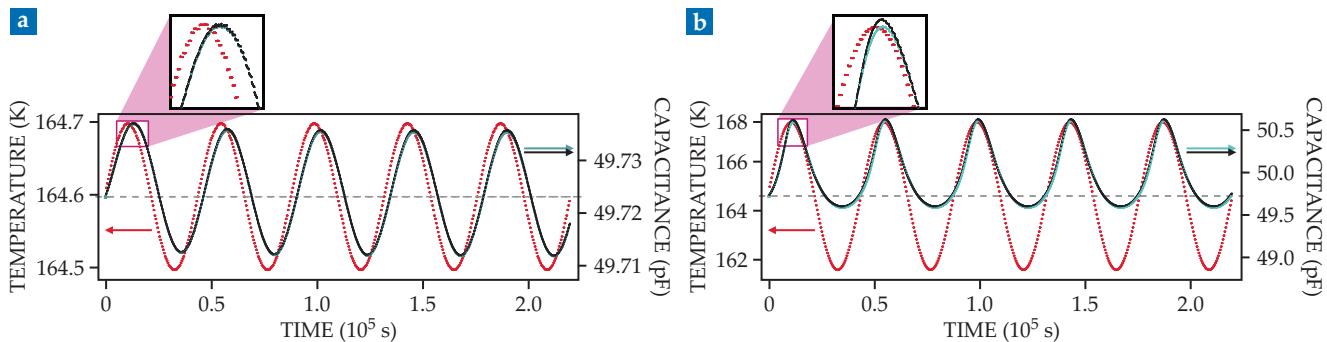


FIGURE 2. GLASSY MATERIALS AGE in response to temperature changes. (a) When a molecular liquid is subjected to a sinusoidal temperature protocol (red) with a sufficiently small amplitude, its capacitance (green) varies proportionally and closely matches theoretical predictions (black). (b) A larger-amplitude temperature change produces a nonlinear response if the liquid is close to its glass-transition temperature. When the linear-regime measurements are used to rescale the material's response function, however, the nonlinear behavior can still be accurately predicted. (Adapted from ref. 4.)

have observed both the linear and nonlinear regimes in a glass-forming molecular liquid.⁴ After performing a series of careful measurements to establish the material's response to small changes in temperature, they were able to accurately, and with no adjustable parameters, predict its nonlinear behavior after larger temperature jumps.

Slow motion

The time it takes for a glassy system to find an equilibrium configuration is extremely temperature dependent. Just a 1% change in temperature can increase the time frame by a factor of 10. The slowing is caused not by a lack of thermal energy but by the particles trapping each other and preventing rearrangements toward an equilibrium configuration. Such traps might look like cages formed by surrounding molecules or like complicated tangles of polymers. The slowness causes a mismatch: The material's temperature can change rather quickly, but its configuration can't.

"This work started a bit as an experimental challenge to ourselves," says Kristine Niss, who, with coauthor Tina Hecksher, led the experimental side of the project. Riechers and her fellow postdoc Lisa Roed wanted to see how small they could make the temperature jumps and whether they could, in fact, observe the linear regime, which required tiny temperature jumps of tens of millikelvin.

Niss's group studies liquids whose small molecules form amorphous solids, rather than crystals, below T_g . Such materials have many practical applications and include pharmaceuticals and glasses for electronic displays. Rearrangements in response to temperature jumps cause

the liquid's density to change, but that response is too small to measure directly, especially with such small jumps. Instead, the researchers measure the capacitance of a thin layer of the liquid as a proxy for its density.

To get a sufficiently high signal-to-noise ratio from their existing experimental setup, shown schematically in figure 1, Riechers and Roed had the idea to study liquids whose molecules have high dipole moments. Such liquids have higher capacitances, which offer clearer signals, even though the liquids also have a more complicated density–capacitance relationship than those with lower dipole moments.

The entire experiment took a year to complete. The researchers had an existing setup, but they had to decide the new project was important enough to commit the apparatus to a single experiment for that long. The measurement ran uninterrupted during Denmark's coronavirus lockdown, with Riechers coming in approximately once a week to check on it and make any necessary modifications.

During the first 36 weeks, the researchers subjected a thin sample of the liquid to temperature steps around a reference temperature of 164.6 K. At that temperature, the sample takes about 12 hours to relax to structural equilibrium—sufficiently long that the sample reaches a homogeneous temperature before any significant structural relaxation has taken place.

The step sizes varied from 10 mK to 3 K and went both up and down. After each jump, the sample's configuration was allowed to equilibrate, which could take days or even weeks. During that time the

researchers measured its capacitance at 10 kHz. A Peltier element kept temperature fluctuations to less than a millikelvin, and an ultraprecise capacitance bridge enabled resolution at the level of a few attofarad.

Those capacitance measurements yielded two important pieces of information. One was the linear response function $R(t)$ that characterizes the sample's relaxation over time in the linear regime. The researchers confirmed that they had, in fact, found the linear-aging regime by showing that for jumps of 10–100 mK, the normalized response functions collapsed onto a single curve. The analysis and normalization were nontrivial. Says Niss, "The challenge is to use robust methods that do not cheat oneself into 'massaging' the data to fit the theory."

The other output was the material's temperature-dependent aging rates. For a given thermal protocol, those can be used to nonlinearly transform the lab time into a material time. The new time scale, which reflects on the system's configurational evolution, can be thought of as akin to the proper time in an accelerating relativistic system.

Predictable aging

The idea to push beyond linear aging, which was the project's original target, and probe the nonlinear regime came from discussions with Jeppe Dyre, who led the theoretical side of the project. The last 15 weeks of data acquisition were dedicated to more complicated temperature-change protocols and probing the nonlinear regime.

Figure 2a shows the material's response to a small-amplitude sinusoidal

temperature variation (red). The predictions and data (black and green, respectively) overlap so closely that it's hard to distinguish the two in the plot. The thermal protocol produced a proportional change in the measured capacitance, which confirmed that the material was indeed in the linear regime.

The larger-amplitude temperature oscillation in figure 2b reached the nonlinear regime. As expected, the shape of the capacitance curve became asymmetric and differed from that of the temperature protocol. Still, the prediction made by extending the linear regime through the material-time formalism reflected the shape accurately and even captured transient behavior that made the first oscillation slightly different from the rest.

The ability to extend linear-response properties to the nonlinear regime can be explained if the same relaxation mechanisms are at work, which is plausible

for a material that isn't pushed too far out of equilibrium. The researchers support that understanding with simulations showing that by using the fluctuation-dissipation theorem with equilibrium fluctuations, they could predict the glass's nonlinear aging. In the future they hope to demonstrate that connection in experiments.

But for larger temperature jumps of around 2.5 K, the researchers' ability to predict $R(t)$ from linear aging started to break down. The divergence between experiment and theory suggests the emergence of a more strongly nonlinear aging regime in which different relaxation mechanisms are at play.

Still lacking is a microscopic picture of what exactly material time is and why it can bridge linear and nonlinear behavior. Dyre and his postdoc Ian Douglass propose that it could reflect how fast the slowest particles in an aging glass are

moving. But exactly which aspects of the structure are involved, and how, is still part of the mystery of material time.

Another open question is how far the material-time formalism extends. Although the data already indicate a breakdown after sufficiently large temperature jumps, exactly why the theory breaks down is unclear. Niss and Dyre are also looking to extend their aging studies to glasses formed through other means, such as compression or shear, and to nonlinear responses to large electric fields.

Christine Middleton

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A lunar micrometeorite preserves the solar system's early history

Geochemical analyses confirm that a 200 μm speck of lunar soil likely originated somewhere other than the Moon.

Meteorites and other hunks of space rock have been colliding with the Earth and Moon for their entire history. Counting impact craters on both bodies provides some estimate of the flux of material bombarding the inner solar system. And if it can be measured, a meteorite's composition yields information about the geological processes that were responsible for its formation.

Discoveries of meteorites on Earth, though, are rare. Many burn up in the atmosphere before reaching Earth's surface. For the ones that do make it to the ground, flowing water or other erosive processes often break them down. Slower-moving plate-tectonic activities also hide evidence of impacts.

The cold, dry Antarctic desert offers conditions more favorable for the preservation of meteorites, and, consequently, more are found there than anywhere else on Earth. But the Moon is an even better

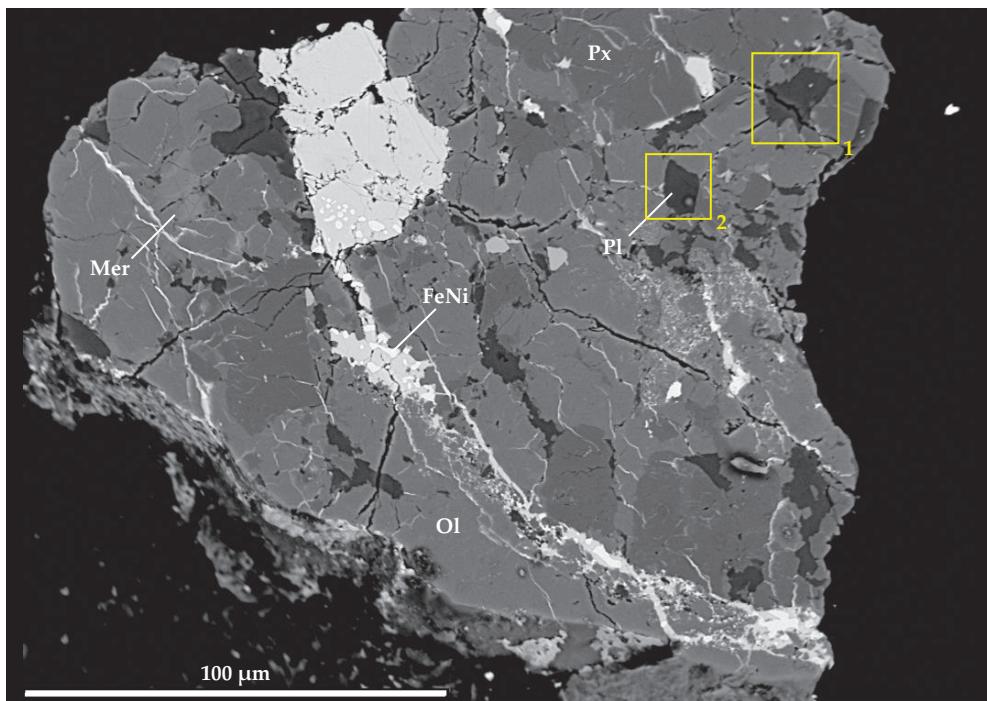


FIGURE 1. THIS SOIL FRAGMENT is a small piece of the material collected by the Soviet Luna 16 mission in September 1970. The backscatter-electron image shows a metal sulfide vein, a component not common to material that originated on the Moon. Chemical analyses of plagioclase (Pl), pyroxene (Px), olivine (Ol), and merrillite (Mer) provide further evidence that the sample came from ordinary chondrites, a common class of stony meteorites that accreted with other materials to form several planets in the solar system's early history. (Adapted from ref. 2.)

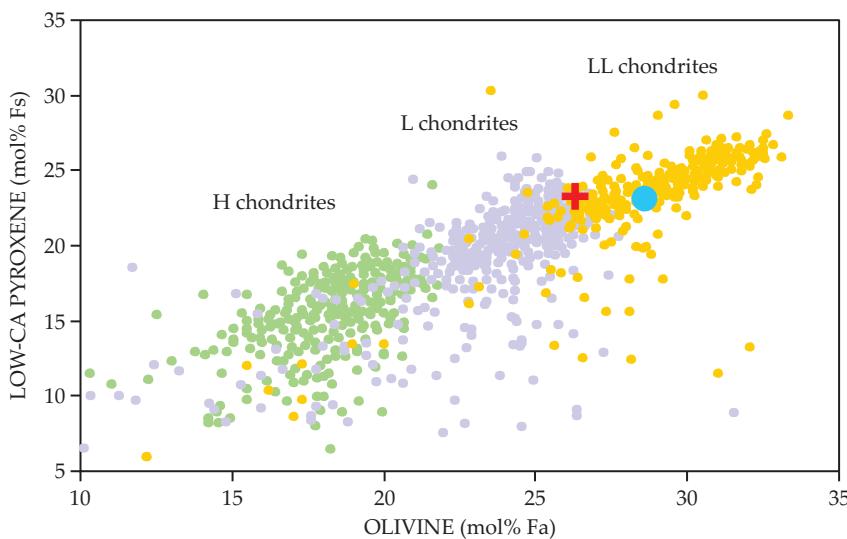


FIGURE 2. GEOCHEMICAL ANALYSES of the mineral components fayalite (Fa) and ferrosilite (Fs) found in the *Luna 16* soil sample (red cross) indicate it has a composition that's most similar to that of LL chondrites (yellow circles), meteorites with low metal concentrations. The composition of the fragment is also similar to that of the near-Earth Itokawa asteroid (blue circle). (Adapted from ref. 2.)

hunting ground for finding meteorites because of its lack of atmosphere, limited erosion, and absence of plate tectonics.¹

Half a century ago, six US Apollo missions and three Soviet Luna missions to the Moon collected rock samples of roughly 380 kg and less than ½ kg, respectively. Curators of those collections have wisely preserved much of that material over the years for future studies (see the article by Brad Jolliff and Mark Robinson, PHYSICS TODAY, July 2019, page 44). More recently, the Chinese Lunar Exploration Program's *Chang'e 5* returned from the Moon in December 2020 with 2 kg of material that will soon be made available to the international community for analysis.

Luna 16, which in September 1970 was the first robotic sampling probe to land on the Moon, returned to Earth with lunar soil—the sandy fraction of the Moon's rock-strewn surface. The region where the sample was taken, the Mare Fecunditatis basin, features a huge impact crater that was subsequently filled with basaltic magma. The surface there consists of that solidified basalt pockmarked with the remains of many small impact events.

One recovered fragment of soil from the *Luna 16* mission was recently studied by Svetlana Demidova of the Vernadsky Institute of Geochemistry and Analytical Chemistry in Moscow and her colleagues.² The fragment had already been identified

in 1990 as a micrometeorite.³ Demidova and her team found that the tiny micrometeorite dates from the early solar system and that it probably struck the Moon no earlier than 3.4 billion years ago and perhaps around 1 billion years ago.

Extralunar

Researchers have already analyzed and categorized large volumes of material collected from the Moon's surface. Geochemical analyses offer precise measurements of the isotopic composition of minerals and other properties. That information is useful for determining whether a sample originated from the Moon.

Extralunar and local materials can easily mix, though, especially after an impactor pulverizes the surface. Isotope measurements, therefore, aren't always reflective of a material's origins. One strategy to overcome that limitation is to look for relatively pristine material with exotic components that could come only from asteroids or meteorites.

The soil fragment was first identified as a micrometeorite after it was magnetically separated from other material recovered by *Luna 16*. Mineral chemistry analyses classified the sample as an ordinary chondrite, a category that includes about 77% of meteorites. It's a class of stony meteorites made of material accreted from a parent asteroid and characteristic chondrules—small, round sili-

cate grains that formed from molten droplets during planetary formation (see PHYSICS TODAY, March 2015, page 14).

With a diameter of just 200 μm , the soil sample defied most measurement techniques, which in the 1990s required milligrams of material and yielded large uncertainties. But geological and chemical instrumentation and analysis have been steadily advancing for the past 10–15 years. Now researchers can study a sample with a length scale as small as the soil fragment and a mass as small as a nanogram.

In evidence

To learn more about the sample's history, Demidova and her colleagues used a suite of geochemical tools to interrogate the speck of soil, shown in figure 1. One exotic component that they found is a metal sulfide vein, which isn't produced by lunar processes. Illia Dobryden, of the RISE Research Institutes of Sweden, used Raman spectroscopy to analyze the plagioclase (Pl) mineral phases, highlighted by the yellow squares. The results showed evidence of shock metamorphism, a pressure-induced change to the mineral's crystal structure that's indicative of an impact event.

Martin Whitehouse of the Swedish Museum of Natural History, Renaud Merle of Uppsala University, and Alexander Nemchin of Curtin University completed the isotopic analyses. The secondary-ion mass spectrometry method they used was in its infancy in the 1970s when the sample was recovered and is now a standard analysis approach for rare specimens. The minimally destructive analytical technique directs a focused ion beam on a sample to eject ions from the surface and direct them to the mass analyzer.

The oxygen-isotope composition of the olivine (Ol) and pyroxene (Px) in the sample, in particular, is distinct from that of lunar rock. The sample's composition most closely matches that of ordinary LL chondrites—the subtype that originates from an asteroid parent body with low metal concentrations.

Additional evidence for the chondritic origin comes from the proportion of the iron-rich components fayalite and ferrosilite that are found in olivine and low-calcium pyroxene, respectively. Figure 2 shows the composition of those minerals in the sample and in other meteorites. The geochemical evidence agrees with

the isotope results and seems to suggest that the sample comes from LL chondrites, although it does somewhat overlap the population of L chondrites.

Date of entry

The soil sample also contains merrillite—a phosphate mineral with trace amounts of uranium and lead. That mineral grain in the sample, therefore, afforded the researchers the opportunity to determine the fragment's age using uranium–lead radiometric dating. The resulting age of 4.5 billion years is consistent with the time that chondrites were thought to be forming in the early solar system.

Finding such an old meteorite fragment that struck the Moon surprised Whitehouse. "It means that the grain didn't experience particularly high temperatures above 400 or 500 degrees," says Whitehouse. Above that threshold, lead atoms generated by the decay of uranium would diffuse out of the crystal, which would reset the U–Pb chronometer.

The fragment could have crashed in the vicinity of the *Luna 16* landing site or have been transported there as ejecta from an impact elsewhere on the Moon's

surface. The landing site is characterized predominantly by basaltic rocks that were present before the sample slammed into the surface. The timing of the basalt deposition, therefore, limits the age of the impact event. Based on the basalt's age, Demidova and her colleagues suspect that the fragment arrived on the Moon no earlier than around 3.4 billion years ago.

Itokawa-like

Given the number of inferences needed to estimate when the micrometeorite may have landed on the Moon's surface, the 3.4-billion-year timing is far from guaranteed. Curiously, the soil sample has a similar mineralogical composition to a sample of the near-Earth Itokawa asteroid. An Itokawa sample was retrieved by Japan's *Hayabusa* mission in 2010 and was determined to be 1.3 billion–1.5 billion years old.⁴

That similarity leaves open the possibility that the fragment hit the Moon more recently than 3.4 billion years ago, after the merrillite grain crystallized. The fragment may have originated from an object with a composition similar

to that of Itokawa. Demidova and her colleagues refer to that possible object as "Itokawa-like" and suggest that it could have impacted the Moon or shed some material as it passed through the Earth–Moon system.

"We still don't know why it is so similar to Itokawa samples. But we cannot prove the Itokawa origin," says Demidova. "The next steps are to search for some other meteorite debris." With ample lunar samples remaining in the Apollo, Luna, and *Chang'e 5* archives, more micrometeorites should be recoverable to help learn more about the Moon's impact history.

Alex Lopatka

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PHYSICS TODAY

Further delays at ITER are certain, but their duration isn't clear

A halt to construction, pandemic-caused delays in deliveries, labor strife, and concerns about potential beryllium exposure are among recent challenges to the fusion project.

New troubles are bedeviling ITER, the massive international fusion experiment, on two fronts: at the reactor site in southern France and at the Barcelona, Spain, office that coordinates the 45% share of in-kind contributions the massive project receives from the European Union (EU).

In late January, France's Nuclear Safety Authority (ASN) ordered a halt to assembly of the ITER vacuum vessel after finding misalignments between the welding surfaces of the first two 440-ton stainless-steel vessel sections. The pair, the first two of nine segments that when joined will form a torus that contains the fusion plasma, had been damaged in transit from South Korea, where they were built.

ASN further told the ITER Organization (IO), which manages ITER construction and is not affiliated with the French government, that the two-meter-thick concrete radiological shielding that's to be installed around the reactor is inadequate to protect personnel once experimental operations get underway in 2025. ASN also expressed concern that any increase to the shielding could cause the total weight of the reactor to exceed the 140 000-ton capacity of its earthquake-resistant foundation. The three issues will need to be satisfactorily addressed before ASN will lift its construction hold.

The EU's executive branch, the European Commission, now estimates that completion of ITER construction will be delayed by at least 17 months beyond its official 2025 completion date, not counting any additional delay that could result from the ASN-ordered hiatus. Massimo Garibba, deputy director general of the commission's energy directorate, told a 28 February hearing of the European Parliament Committee on Budgetary Control that the stretch-out is attributable to delays in the manufacture of one-of-a-kind components and to short-

falls in contributions from several of the member states. The ITER parties are China, the EU, India, Japan, Russia, South Korea, and the US.

A re-baselining of the ITER construction timeline will be presented to the governing ITER Council in June, says Alain Bécoulet, head of ITER's engineering domain. The new schedule won't be official until the council's ratification, expected in November. But the "tsunami of COVID" has delayed the project on the order of 20 months, Bécoulet acknowledges, and has created havoc with construction scheduling. Components being built in South Korea and Italy have been delayed by late deliveries from the manufacturers' own suppliers. "On top of that, each time you have a sector and you try to get a transporter, you are told, 'I'm sorry—I have no boats available for six months to a year, and it's 10 times more expensive than you expected,'" he says.

Since the seven ITER partners use different accounting practices to determine the value of their in-kind contributions, an official cost estimate for ITER construction has never been compiled. The EU in 2017 estimated its 45.6% share of the project will total €18.1 billion (\$19.6 billion) from 2017 to 2035, the year experiments with tritium are currently scheduled to begin. By extrapolation, the total ITER cost during that period would be €41 billion if the entire project were to be undertaken in the EU. In 2018, using the US's 9% share of ITER as a basis, the US Department of Energy estimated ITER's total cost would be \$65 billion if all the work were to be done in the US. (See "ITER disputes DOE's cost estimate of fusion project," PHYSICS TODAY online, 16 April 2018.)

Bécoulet says he expects that ASN will lift its hold by early fall, allowing assembly to resume in November, just a couple months behind schedule. That



shouldn't further delay project completion, he says. "ASN is used to seeing fission reactors one after another, and they know whether they're good or not immediately. This is a learning process. And we are learning with them."

The vacuum vessel sections are 17 meters tall and 6–7 meters wide. "You have to fit them together to a fraction of a millimeter," Bécoulet says. When the sections are assembled, slight adjustments have to be made to account for dimensional nonconformities. The IO was told by ASN last year that it hadn't satisfactorily demonstrated its procedure for making nuclear-grade welds.

ASN deemed the two-meter-thick concrete radiation shield planned to encapsulate the fusion to be insufficient. But Bécoulet says the regulator's concern was actually caused by the IO's "overscrupulousness." Instead of the "envelopes and margins" that ASN requested, the IO provided a highly detailed three-dimensional model. "The problem is that if you say you will give them a very detailed map, then they will follow the details," he says. "We are trapped by giving too many details, and the details are



A SECTION of the ITER vacuum vessel, shown here at the ITER site in France, after its shipment from South Korea. When all nine sections are assembled, they will form the toroidal chamber that will contain the fusion plasma. The French nuclear regulatory agency halted assembly of the first two sections in January, after finding that misalignments caused by damage during shipment would prevent them from being properly welded.

still evolving as the design is being finalized. And they don't like that—they just want something stable. So we are considering modifying slightly our level of communication and commitment."

Reactions to employee suicide

In Spain, meanwhile, executives of Fusion for Energy (F4E), the EU entity that manages Europe's share of in-kind contributions to the project, are pledging to hire additional staff, provide counseling services, and take other steps to address employee complaints of its poor management and excessive workloads.

Discontent at the agency came to a head last November after a three-member investigatory panel appointed by F4E's governing board found no direct link between job pressures and the suicide of an F4E engineer in May 2021. In a note he left, Mario Gagliardi called his suicide

his "final gesture," saying in reference to his job, "I found myself to be the scapegoat of an unsustainable situation for years."

Most of the 440-member F4E workforce staged a half-day strike in response to the panel findings. In their strike notice to F4E management, the three trade unions at the site complained of "the continuous degradation of the F4E working environment including management style, workload, lack of respect of the formal process and paying lip service to the social dialogue processes."

F4E management and the unions both requested a more thorough investigation into the causes of the suicide by the European Anti-Fraud Office, or OLAF. Cristiano Sebastiani, a representative for one of the trade unions, says employees must be given full protections against retaliation for them to testify. OLAF has yet to

agree to open an investigation.

F4E's director, Johannes Schwemmer, told the European Parliament hearing that a "psychosocial-risk-assessment survey" found that excessive workload is a "risk factor" for the F4E workforce. An F4E spokesperson says that the assessment was not specifically linked to the suicide. Since joining F4E in 2016, Schwemmer stated, the amount of work under his management has doubled from €500 million to €1 billion annually. F4E is currently managing 98 separate ITER component projects, each having an average value of about €100 million.

F4E management has requested its governing board and the European Commission for approval to hire 34 additional employees. The request is pending, says an F4E spokesperson.

F4E has committed to other morale-boosting measures, including additional medical and psychological services, and regular meetings and discussions among management, staff, and trade unions. Yet Schwemmer defended F4E's management record at the 28 February hearing, saying that annual personnel turnover is below 3% and job security is high.

Sebastiani, however, attributes low turnover to the dedication of F4E staff to the ITER project. "Building the reactor is more than just a job," he says. "It's what they have been living for. They are strongly motivated, and they only want to work there."

As for management promises for workplace improvements, Sebastiani says, "It's always the same. First you deny and when you can't deny anymore, you start saying you weren't aware and then promise to change everything. What is clear is that the director must be told that the address for F4E is .eu, not .com. It's not a commercial entity. It's a European institution, and the rules are to be respected."

Beryllium issues

Robert Winkel, the IO's expert on beryllium, resigned his post in March, after supervisors ignored his recommendations, he says, and failed to consult him on occupational exposure to the toxic metal. The ITER vacuum chamber walls are to be lined with 12 tons of beryllium to protect them from damage by fusion neutrons and to absorb stray oxygen molecules. Kathryn Creek, also a beryllium expert and Winkel's wife, left her IO job



AERIAL VIEW of the ITER site in May 2021. The cryoplant, magnet power conversion facility, and electrical switchyard are located to the left of the tokamak complex and assembly hall at center. The heat-rejection plant and central offices are to the right.

two years ago, blaming pressure from managers to water down her recommendations on beryllium protections.

At 0.2 micrograms per cubic meter, the US and EU standard, beryllium's occupational exposure limit is one-fifth that

of hexavalent chromium, the next lowest limit for a toxic metal. But France observes its own limit of 2 micrograms, Creek says. Of a projected 450 ITER staffers who will be exposed to beryllium throughout the project's lifetime, 100 could be expected

to develop chronic beryllium disease if adequate protections aren't implemented, Creek says. That statistic is based on experience from workers at US DOE facilities that handle beryllium, which is used in nuclear weapons.

Chronic beryllium disease is a debilitating condition that develops many years after exposure and goes undetected or can be misdiagnosed with x rays and CT scans. Diagnosis requires a specialized lymphocyte proliferation test. About 18 000 such tests are performed in the US each year, but France has no labs to perform them, Creek says.

"The fundamental problem is that beryllium isn't recognized in France or Europe as a serious threat, like it's known to be in the US," says Winkel. "Consequently, there are no people with experience in how to safely manage it." Beryllium, however, has long been used in Europe for space applications and in particle detectors.

Creek and Winkel's specific concern involves exposures that will occur during maintenance in ITER's operational phase, when ports to the vacuum chamber that hold diagnostic instruments will be opened and beryllium particles will flow into enclosed workspaces known as hot cells. They say that 4–20 air changes in the hot cells per hour are necessary to adequately filter the particles. But the IO's current design will provide less than one change per hour, Winkel says.

Bécoulet says that as a nuclear facility, ITER will provide the same level of protection to beryllium exposure as it will to radiation. "The machine is made not to release anything," he says. "If you remove anything from the machine, as it is a nuclear machine, it will be done in a completely sealed environment."

Bécoulet says that the original choice to use beryllium in ITER was "nonsense" for multiple reasons, including its toxicity and cost. ITER's design was based on the Joint European Torus in the UK, which also uses beryllium. Already, plans call for a different material, likely tungsten, to replace beryllium during ITER's tritium phase.

But Bécoulet would like to see beryllium eliminated altogether at ITER, and he says that could yet happen. "It is an option; it is possible, but I don't want to oversell it." A change at this point could further delay construction, he says. "We should have considered this earlier."

David Kramer

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Germany's green transition regains momentum

The country aims to be climate neutral by 2045.

In the years leading up to and following Germany's September 2010 law in support of the *Energiewende*—the transition to renewable energy—the country was a world leader in efforts to counter climate change. It made great strides in creating a market for photovoltaics, increasing electricity production from renewable sources, passing legislation to make new construction more energy efficient, and getting the public on board. But by the latter 2010s, the transition had stalled: Deployment of wind and solar farms had slowed, and progress in the industrial, heating, and transportation sectors was at a standstill or even backsliding.

Now a combination of domestic and international developments has reinvigorated the *Energiewende* in Germany. Extreme weather events are on the rise worldwide, including floods that killed 196 people in western Germany last summer. Statements by the Intergovernmental Panel on Climate Change (IPCC) express increasing urgency. In a 4 April press release accompanying the publication of the final section of its sixth assessment report, for example, Jim Skea, cochair of the IPCC's Working Group III, which focuses on climate change mitigation, said, "It's now or never, if we want to limit global warming to 1.5 °C. Without immediate and deep emissions reductions across all sectors, it will be impossible."

Germany's new government, elected last fall, has ambitious climate goals. It has pledged €200 billion (\$220 billion) through 2026 toward infrastructure for decarbonization and climate protection purposes. In 2019 the country voted to phase out coal-fired power generation by 2038; now the government is shooting for 2030. The European Union aims for

net-zero greenhouse gas emissions, or climate neutrality, by 2050; Germany's new government affirms the aim set last year to best that by five years. "The old government was ramping up too," says Ferdi Schüth, a chemist at the Max Planck Institute für Kohlenforschung in Mülheim an der Ruhr who has long worked on energy issues. "But the mindset of the new government is more aggressive in terms of renewables."

And although Russia's invasion of Ukraine focuses attention on fears of a wider war and the immediate needs of refugees, it also highlights the precariousness of relying on coal, oil, and gas imports from Russia and the need for energy independence. Without gas from Russia, "we don't know if we can heat buildings and fuel industries next winter," says Cyril Stephanos, who heads Energy Systems of the Future, an initiative to support the energy transition run jointly by the German Academies of Sciences.

In the short term, Stephanos says, Germany will depend more on lignite coal—it's the only viable domestic substitute for gas in the electricity sector. Nuclear power is in the final stages of being phased out in Germany, and renewables can't be ramped up quickly enough. But longer term, he says, Russia's war in Ukraine will help accelerate climate protection. "Switching from fossil fuels to renewables will make us more independent."

"In principle, we have the necessary tools to decarbonize," Stephanos says. "Over the next decade, we need to develop technologies for hydrogen transport and storage." Other challenges include diversifying energy imports, overcoming public resistance to wind farms, persuading the public to make lifestyle changes, and

implementing decarbonization equitably, without imposing undue burdens on lower-income people.

Green electrons

The transition to green energy will quadruple Germany's demand for renewable energy, according to estimates by the sister think tanks Agora Energiewende and Agora Industry in their 2021 publication *12 Insights on Hydrogen*. Using renewable energy for electric vehicles, electric heat pumps, and hydrogen production will drive that increase. Germany aims to triple the number of wind farms, increasing their total coverage from 0.9% to 2% of the country's land area. Also planned are more off-shore wind farms and photovoltaic fields. The share of renewable energy in electricity consumption grew steadily from around 6% in 2000 to 46% in 2020, says Ortwin Renn, a social scientist and scientific director of the Institute for Advanced Sustainability Studies in Potsdam. In 2021, it slipped to about 41%.

Still, Germany cannot meet its own electricity demands with domestic renewable energy. "We could import solar energy from Greece or North Africa, for example," says Renn. "We need to expand and modernize the European grid for that." And, he stresses, the war in Ukraine has intensified the need to diversify energy. The federal minister for economic affairs and climate action, Robert Habeck, "is going all over the world looking for liquefied natural gas." Progress on the *Energiewende*, Renn says, "depends on how things evolve in the coming months."

The *Energiewende* has wide public support—about 80%—"until someone wants to put a wind turbine near your house," says Renn. "We need to get over NIMBY [not in my backyard]." It would



OFF-SHORE WIND FARMS typically produce more energy than land-based ones, but more of both are needed to ramp up renewables in Germany. (Photo by Martina Nolte, licensed under <https://creativecommons.org/licenses/by-sa/3.0/de/legalcode>.)

	Industry 	Transport 	Power sector 	Buildings 
No regret	<ul style="list-style-type: none"> ▶ Reaction agents (Direct Reduced Iron steel) ▶ Feedstock (ammonia, chemicals) 	<ul style="list-style-type: none"> ▶ Long-haul aviation ▶ Maritime shipping 	<ul style="list-style-type: none"> ▶ Renewable energy backup, depending on wind and solar share and seasonal demand structure 	<ul style="list-style-type: none"> ▶ Heating grids (residual heat load *)
Controversial	<ul style="list-style-type: none"> ▶ High-temperature heat 	<ul style="list-style-type: none"> ▶ Trucks and buses ** ▶ Short-haul aviation and shipping ▶ Trains *** 	<ul style="list-style-type: none"> ▶ Absolute size of need given other flexibility and storage options 	
Bad idea	<ul style="list-style-type: none"> ▶ Low-temperature heat 	<ul style="list-style-type: none"> ▶ Cars ▶ Light-duty vehicles 		<ul style="list-style-type: none"> ▶ Building-level heating

* After using renewable energy and ambient and waste heat as much as possible. Especially relevant for large existing district heating systems with high flow temperatures. Note that according to the United Nations Framework Convention on Climate Change common report format, district heating is classified as being part of the power sector.

** Production is currently more advanced for electric than for hydrogen heavy-duty vehicles and buses. Heavy-duty hydrogen vehicles to be deployed at this point in time only in locations with synergies (ports, industry clusters).

*** Depending on distance, frequency, and energy supply options.

help, he says, for the public to be involved in decisions about where wind farms are placed and for individuals or municipalities to reap benefits from the electricity the wind turbines produce. "People should develop an emotional attachment to the turbines and their contributions to decarbonization."

The price of carbon emissions needs to be sufficiently high to increase the attractiveness and competitiveness of renewables, says Schüth. "More renewables is number one. Everything hinges on that."

Intersecting energy sectors

Fossil fuels for industry, transportation, and heat together make up roughly 80% of Germany's energy consumption—just 20% is from electricity. Long-distance trucking, maritime shipping, and aviation are among the most difficult activities to power with renewable energy. Scenarios such as electric tracks for trucks are being floated and tested. But the greening of trucking and aviation will have to rely on synthetic fuels based on green hydrogen when they become available at an industrial scale and competitive cost. Emissions may also be lowered with carbon capture and storage.

Significant progress, however, has been made with electric personal vehicles (see PHYSICS TODAY, April 2022, page 22). "Soon they'll be cheaper than combustion cars in terms of total cost of car ownership," predicts Frank-Detlef Drake, who heads research and technology at the electric utility E.ON SE in Essen. Germany's new government aims to increase the number of electric vehicles on

GREEN HYDROGEN, produced with renewable energy, complements green electrons, but it should be reserved for "no-regret" uses. This table outlines uses for green hydrogen as recommended by the think tanks Agora Energiewende and Agora Industry. (Adapted from Agora Energiewende, Agora Industry, *12 Insights on Hydrogen*, 2021, fig. 4.)

the road from fewer than 1 million today to 15 million in 2030. But for their widespread adoption, a convenient network of charging stations is needed. Such a network could be built with money from the government's €200 billion infrastructure pot.

Germany aims for half of all home and business heating to be climate neutral by 2030. That goal is in line with Agora's estimate of Europe needing to reduce its consumption of natural gas in buildings by 42% for it to stay on track to limit warming to 1.5 °C above preindustrial levels. And to achieve Germany's goal of climate neutrality by 2045, Agora calculates that 1.75% of buildings must be retrofitted annually to improve energy efficiency. The country has for years had a retrofit goal of 2%. Currently, only one out of every hundred buildings is renovated annually to improve energy efficiency, according to Germany's Ministry for Economic Affairs and Climate Action.

Decarbonizing the heat sector is complicated. For new construction, "we have good standards," says Drake. "The challenge is existing buildings. They are tough." Most of the country's buildings are heated with natural gas.

Renovating existing buildings involves insulating them and converting their heating systems to electric heat pumps, which work like reverse refrigerators, sucking heat from the outside air or ground and

depositing it in a water or air heating system. In densely populated areas, centralized district heating can be installed or converted to use green energy.

Another possibility for heating would be to mix green hydrogen with natural gas in existing gas pipelines. The idea, Renn explains, would be to produce hydrogen gas with renewable energy. About 20% hydrogen could be used without corroding the pipelines, experts estimate. "It's counterintuitive, since you make clean hydrogen and then contaminate it, but financially it could be a good idea, at least for a while. It seems odd to let our existing infrastructure rot."

But Barbara Saerbeck, a senior associate at Agora Energiewende, notes that neither natural gas boilers nor hydrogen-powered heating systems provide climate-neutral and efficient use of green energy. "Relying on a still rare and expensive energy carrier such as hydrogen for heating buildings is not a viable path to climate neutrality," she says. "It's crucial to switch to green-energy-based fuel in the power sector, district heating, and buildings." She also notes a lack of skilled workers. "For years, people have built fossil-fuel heating systems. We need to train people to work with electric heat pumps." With a concerted effort and clear legal requirements, she adds, a switch to heat pumps and insulated buildings is possible "without overburdening any-

one in terms of planning or finances."

Insulating walls and windows and converting to heat pumps is expensive. About half of residents in Germany are tenants, and they may hesitate or be unable to invest in properties they don't own. Landlords, meanwhile, may choose not to invest in renovations that lower their tenants' utilities bills. The question of who would pay is tricky.

The greening of mobility also introduces equity issues. On a day-to-day level, rising gas prices—and their far-reaching consequences—sting low-income people more than high-income people. And buying an electric car, despite government subsidies, is still out of financial reach for many people. Recently the German government promised to give €300 to all households to help with surging gas costs, but such handouts are a Band-Aid, not a real solution to inequities associated with the Energiewende, says Renn.

Green molecules

Major challenges in the transition to a green economy are industry—the manufacture of steel and chemicals in particular rely heavily on fossil fuels—and long-haul aviation, trucking, and maritime shipping. Those are areas where hydrogen and hydrogen-based fuels could play a crucial role. Another area would be as backup power generation for intermittent solar and wind sources. In *12 Insights on Hydrogen*, Agora notes that hydrogen and hydrogen-based fuels are anticipated to supply 14–25% of global energy demand; the percentage in Germany is similar.

Hydrogen contributes to the energy transition only if it's produced with renewable energy. The cleanest approach is water electrolysis powered by green electricity. Hydrogen can be transported as a liquid, as a gas, or in a chemical form such as ammonia. Experts agree that Germany will have to import hydrogen because the domestic wind and solar electricity sources are not sufficient for both direct electrification and electrolysis. To that end, the German government is talking with Australia and countries in Africa and South America that have abundant low-cost solar and wind energy.

A bottleneck is transportation from German ports to points of use, says Robert Schlögl, a chemist at the Max Planck Institute for Chemical Energy Conver-

sion in Mülheim an der Ruhr. He heads a collaboration in Germany that was awarded €135 million last June to study hydrogen transport and other aspects of green hydrogen for energy, including safety, standardization, storage, conversion to and from ammonia, and more.

In a separate collaboration, Schlögl and colleagues are working on hydrogenating carbon dioxide to make methanol for use in heavy industry. The team is testing its synthetic fuels with steel and cement demonstration projects. Germany's steel industry emits 20 million tons of CO₂ annually, says Schlögl. "If we can produce enough methanol with green hydrogen, we can shrink those emissions by 90%." Methanol could also be used to fuel ships, airplanes, and cars, possibly providing "a viable alternative to electric cars," he says.

Agora, for its part, favors other approaches for personal cars, and says hydrogen should be used for applications where better alternatives are unavailable (see the "no-regret" row in the chart on page 24). But Schlögl says that while the main use will be heavy industry, he is "open to all end uses."

Accelerated energy sovereignty

On 24 March, a month into the war in Ukraine, Agora Energiewende published *Regaining Europe's Energy Sovereignty*. Relying on new internal studies, the report is meant to advise European Union leaders as they hasten to wean their countries from Russian fossil-gas imports, while also helping to achieve climate targets. With 15 recommended actions and €100 billion in new funding, the report says, Europe can achieve energy sovereignty within five years.

A press release accompanying the report says that "a concerted crisis effort" to improve energy efficiency could enable replacement of 80% of today's Russian gas imports by 2027; the addition of liquefied natural gas could bring that up to 100%. Those efficiencies could be accomplished, it says, by reducing fossil-gas use by 480 TW hours in buildings and 223 TW hours in industry, plus scaling up production of renewable energy by 500 TW hours. Governments "need to ban the installation of new gas boilers and increase financial support to unleash a heat pump revolution," Matthias Buck, Agora Energiewende director for Europe, says in the press release. And Eu-

rope "must scale renewable energies as fast as possible, pulling all stops."

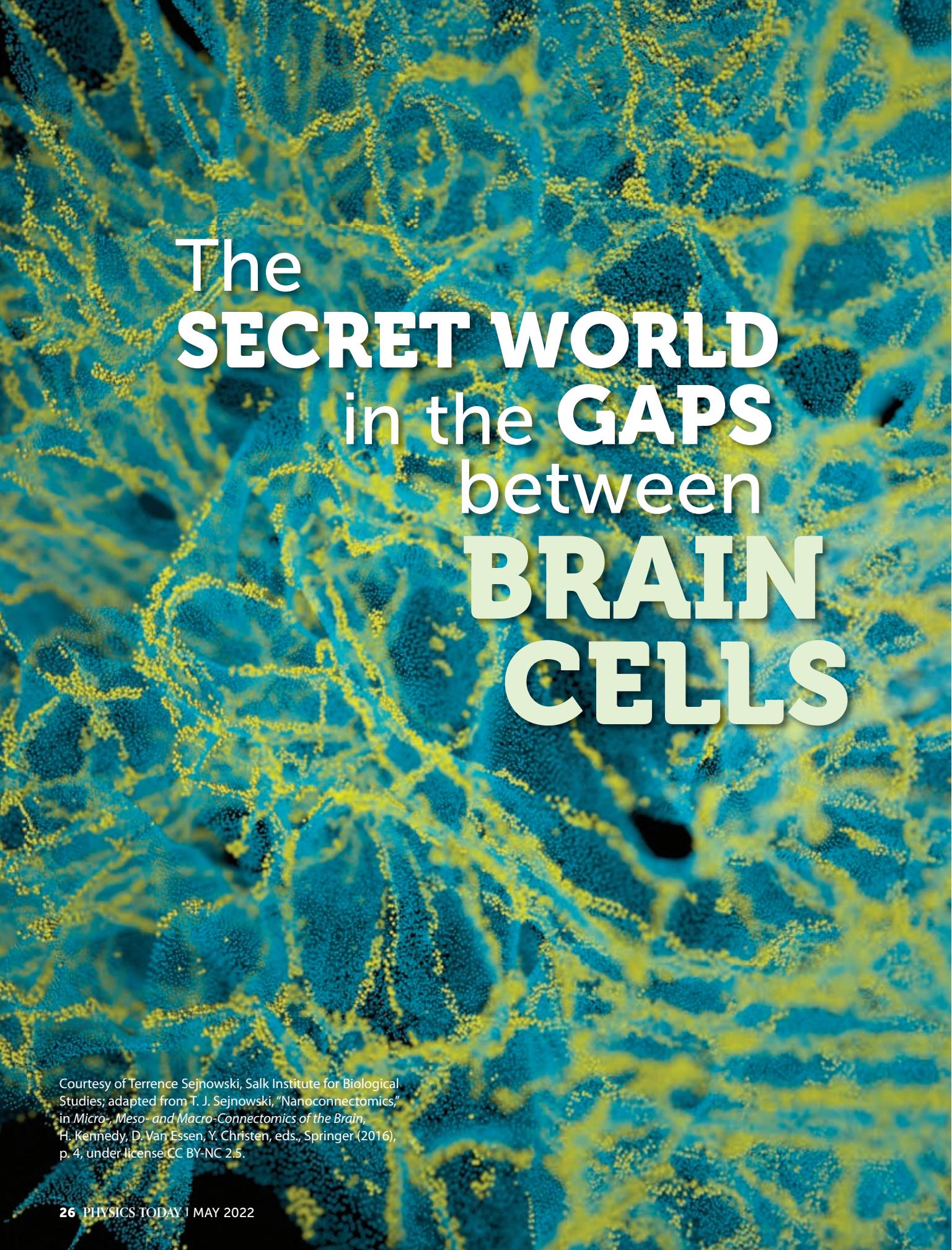
Christopher Hebling is the director of the hydrogen technologies division at the Fraunhofer Institute for Solar Energy Systems in Freiburg. "With each IPCC report, it seems we have lost the game already," he says. "Everyone agrees that climate change is humanity's biggest challenge." But, he adds, people like to go on vacation, they like to drive their own car, and they want to live in bigger apartments. "Money is not the missing link. It's governance and buy-in. The coming years are the most decisive for humanity." Germany's national target of 2045 for climate neutrality is unrealistic, he says. "But it sharpens the visions and nails down the targets."

Individuals will have to change their behavior to reach climate goals. "We need to be transparent about that," says Schüth. The goals for the Energiewende in Germany and beyond are ambitious, he says. In seeking solutions, "we tend to extrapolate linearly. But we should be ready to work for radical change."

Toni Feder PT



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The **SECRET WORLD** in the **GAPS** between **BRAIN** **CELLS**

Courtesy of Terrence Sejnowski, Salk Institute for Biological Studies; adapted from T. J. Sejnowski, "Nanoconnectomics," in *Micro-, Meso- and Macro-Connectomics of the Brain*, H. Kennedy, D. Van Essen, Y. Christen, eds., Springer (2016), p. 4, under license CC BY-NC 2.5.

Charles Nicholson is an emeritus professor in the department of neuroscience and physiology at the New York University Grossman School of Medicine in New York City.



Charles Nicholson

Innovations in diffusion analysis and imaging techniques have gradually revealed the ubiquity and importance of extracellular space.

A

map of the US with only the state boundaries shown appears fairly blank, but zooming in to a region of a large city shows a complicated collection of buildings delineated by streets. The brain turns out to be similar—deceptively simple until you look closely.

Given its extraordinary properties, brain tissue is surprisingly unprepossessing. The human cerebral cortex appears to be made of a whitish substance about as featureless as blanmange. Its monotony is broken only by the folding of the cortical surface that enables more brain tissue to pack in the skull. The same featurelessness holds true for a small sample of brain tissue when removed and viewed under a light microscope. But if appropriate dyes are applied, vast numbers of distinct cells appear.

Beginning in the 19th century and continuing through today, light microscopists have focused on the shapes of and connections between brain cells and given little thought to the spaces between them. The advent of electron microscopy finally supplied the necessary resolution to discern how cells were stacked together, as shown in figure 1.

It's now known that every cell in the brain is separated from its neighbor by a fluid-filled extracellular space (ECS), which forms sheets and tunnels, as shown on page 26 in a computer reconstruction of the ECS in a rat's brain. That interstitial fluid is predominantly an aqueous solution of sodium chloride with small concentrations of many other essential substances, such as potassium, calcium, and several amino acids and peptides. The ECS also hosts a sparse extracellular matrix of larger molecules. The space between cells is exceedingly narrow—much of it only tens of nanometers wide—and thus one of the most difficult domains of the brain to study in the living state. But without the ECS, electrical signals wouldn't pass between neurons, metabolic substances and chemical signals wouldn't disseminate, and drugs wouldn't reach their targets. The long

journey to finally observe and understand the ECS was made possible by innovations in the analysis of molecular diffusion.

Invisible ECS

Evidence for a substantial ECS emerged slowly. Early electron microscopy measurements suggested

little or no gaps between brain cells. Then in the 1960s some heretical microscopists, such as Anthonie Van Harreveld of Caltech, argued that the procedures used by most microscopists to prepare brain tissue for observation caused the ECS to collapse. They showed that if the tissue was instead rapidly frozen, gaps could be seen between the cells.¹

Another limitation of electron microscopy images is that they're taken on dead tissue. Recognizing that drawback, other researchers in the 1960s used live tissue injected with solutions of select radiotracers that were not expected to enter cells. A radiotracer, or radioactive tracer, is a chemical compound with one or more atoms replaced by a radioisotope so that the tracer's position or concentration can be monitored by its radioactive decay. Those tracers penetrated brain tissue, which hinted that there must be spaces between cells. But the initial results were ambiguous as to what space the tracers were moving in.

Getting quantitative results from radiotracers required work from such pioneers as Joseph Fenstermacher of the National Cancer Institute in Bethesda, Maryland, and Clifford Patlak of the National Institute of Mental Health, also in Bethesda.²⁻⁴ In the 1970s, they combined physiological expertise with quantitative analysis to understand the diffusion of cell-impermeant tracers, such as radiolabeled sucrose, into brain tissue. By fitting a solution to the diffusion equation to experimental spatial concentration profiles, they extracted the radiotracer's effective diffusion coefficient D^* in brain tissue.

The effective diffusion coefficient was always smaller than the free diffusion coefficient in water D , indicating that molecular

diffusion in brain tissue was hindered. Measurements also revealed the fraction of the brain that radiotracers were permeating. Those regions were the ECS. But the use of radiotracers required large brains—and thus large animals, such as rabbits, dogs, or monkeys—and yielded data at only one point in time in each experiment.

Many of the limitations of the radiotracer method were overcome with the introduction of two techniques: the real-time iontophoresis (RTI) method in 1980 and the integrated optical imaging (IOI) method in 1993. My research group developed those techniques, which are often referred to as examples of a point-source paradigm.^{2,4,5} Soon after the introduction of the RTI method, Eva Syková at the Czech Academy of Sciences in Prague adopted the technique and has since applied it to clinically important problems, including ischemic stroke, brain tumors, and aging.²

To the point

In the RTI method, a micropipette and an ion-selective microelectrode with micrometers-wide tips are inserted in living brain tissue.^{2,4,5} A current passes through the micropipette, which contains an ionic solution of a chosen small probe molecule that stays in the ECS, and a precise number of cations or anions are released into the brain, a process known as iontophoresis. The probe molecules then diffuse through the ECS, and the concentration as a function of time is measured about 100 μm away by the ion-selective microelectrode (see the box on page 29).

The RTI method gives results in minutes, which enables the recording of dynamic changes in ECS properties through repeated measurements. Another major advantage of the RTI method is that it can reveal simultaneously D^* and the fraction of the brain's volume taken up by ECS, both averaged over the small region of brain tissue between the source and microelectrode. And no radioactive substances are required.

The hindrance to diffusion is characterized by a dimensionless parameter known as the tortuosity $\lambda = \sqrt{D/D^*}$, and by the volume fraction α , which is the volume of the ECS divided by the volume of the whole tissue in the measurement region. In essence, the brain is a porous medium. Such mediums are also found in other disciplines, including geophysics, hydraulics, and materials science, and are characterized by those same two parameters—although the definition of tortuosity may vary, and extracellular volume fraction is often called porosity.

The RTI method is constrained by the availability of microelectrodes that are sensitive to molecular probes of interest. So far, they can be fabricated to sense only a few specific small molecules, and overwhelmingly, the method has used the cation tetramethylammonium, with a molecular mass of 74. Because they're so small, those molecules approximate a point in space and are thus valuable for mapping geometry, but many molecules of biological interest are much more spatially extended.

About a decade after the first implementation of the RTI method, researchers extended the point-source paradigm to macromolecules with the introduction of the IOI method.^{2,3} Again, a micropipette released molecules, but those molecules had fluorescent markers on them so that the distribution could be imaged by optical microscopy. The intensity distribution, representing the concentration of fluorescent molecules, could then be measured and fitted to a solution of the diffusion equation to give the tortuosity averaged over about 100 μm (see the

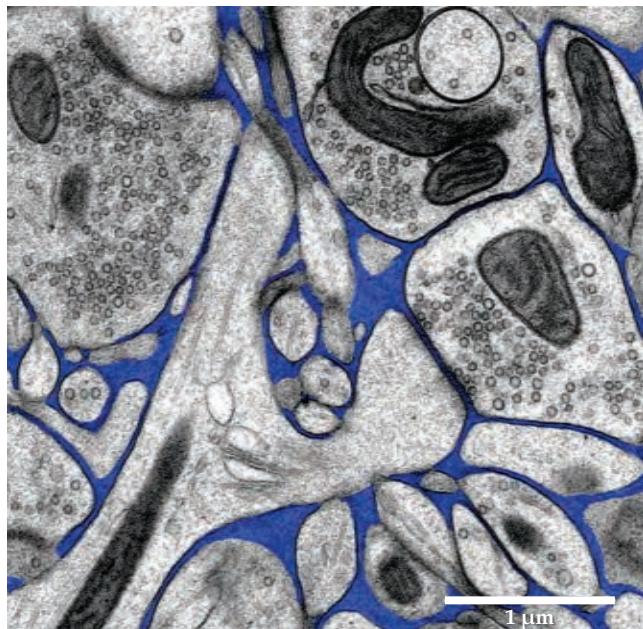


FIGURE 1. BRAIN TISSUE is more complicated than it appears at the macroscopic level. The brain's apparent featurelessness hides a complicated microscopic structure of brain cells (grayscale) and extracellular space (false colored in blue) between those cells, shown here from a transmission electron micrograph of an adult mouse's cerebral cortex that has been cryo-processed to preserve the spaces between cells. (Courtesy of Graham Knott, Swiss Federal Institute of Technology, Lausanne; adapted from ref. 1.)

box on page 29). The volume fraction, however, was not available because the molecules were released by a brief pressure pulse, and the number of them could not be reliably quantified. Over the decades, the IOI method's time resolution has shrunk to 1 s, a tenfold improvement over the original technique.⁶

Although the point-source paradigm was successful, the spatial resolution of the RTI and IOI methods was, at best, tens of micrometers, and electron microscopy and macromolecular diffusion behavior indicated that the ECS was tens of nanometers wide. Now, an era of discovery is on the horizon with the introduction of techniques that rely on superresolution optical microscopy with a resolution of 50–150 nm.

One such technique is superresolution shadow imaging (SUSHI), developed in the laboratory of Valentin Nägerl of the University of Bordeaux in France.⁷ The SUSHI technique is based on stimulated-emission-depletion microscopy. In that technique, some of the fluorophores deposited on a sample are temporarily deactivated so that when a laser spot shines on them, only a small central area lights up and thus the resolution is improved beyond the diffraction limit. In the SUSHI method, the fluorophores are administered as a dye solution that permeates the ECS, and the method images the local volume occupied by them.

Laurent Cognet's group at the University of Bordeaux proposed another approach that tracks carbon nanotubes more than 100 nm long and about 1 nm wide.⁸ Those nanotubes have an optical response in the near-IR and offer a spatial resolution of about 50 nm. The probes are tracked as they wander in the ECS, and those results measure the diffusion properties and the ECS's local structure. The nanotube technique and the SUSHI

method have revealed that the ECS structure is very heterogeneous, a conclusion supported by recent advances in electron microscopy on rapidly cooled tissue, such as in figure 1. By contrast, the RTI and IOI approaches indicate that, when averaged over about 100 μm , ECS properties appear quite uniform.^{4,5}

Physics of diffusion

The key physical concept underlying the radiotracer method, the point-source paradigm, and single-particle tracking is diffusion. The diffusion of molecular signals, metabolites, and drugs in the brain is vitally important for the brain's normal functioning and for medical interventions. It's also vital for understanding how specific probe molecules reveal structural information about the ECS. And underlying diffusion is the random walk.

Water's concentration in a beaker or in the interstitial fluid of the ECS is about 50 moles per liter, whereas small probe molecules are introduced at a concentration of millimoles per liter or less. At the temperature of the human body, about 37 $^{\circ}\text{C}$, such probe molecules move because of thermal energy and collide constantly with water molecules and occasionally with the cell walls bounding the ECS. Each collision sends the probe in a random direction until it's redirected by the next collision; that ever-changing trajectory is a random walk. Given enough walkers and sufficient time, random walks explore the whole of a domain. And if the fruits of that exploration can be analyzed, then the structure in which the molecules move becomes apparent, as shown in figures 2a and 2b.

With the help of superresolution optics aided by computation, emerging single-particle tracking methods follow one probe particle moving through the ECS to yield unprecedented local detail, as shown in figure 3. But they are confined to the volume that the probe can explore before it escapes the limited view of the high-magnification optics. Those methods are also constrained because usually only one probe can be tracked at one time.⁸

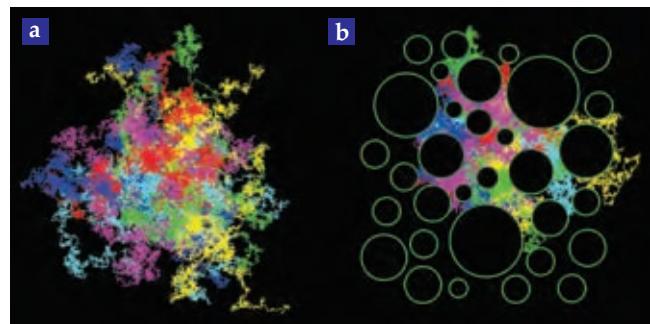


FIGURE 2. RANDOM WALKS explain how probes diffuse through brains. In these simulated two-dimensional random walks, 50 particles start at the center of each image and take 1500 steps of equal size but in random directions either (a) unimpeded or (b) surrounded by circular obstructions that represent cells. Each of the 50 particle trajectories was assigned one of six colors. The particles spread farther in the absence of hindrance.

By contrast, in the point-source paradigm, typically about 10^{14} probe molecules are injected into the brain, and each one sets off on a random walk. The concentration distribution measures the aggregate of all those evolving trajectories and can be analyzed on a macroscopic scale by solving the diffusion equation, which is a partial differential equation otherwise known as Fick's second law (see the box below). The diffusion equation works for probe molecules because the probability distribution of a random walk is described by the same equation. The same math adapts seamlessly from a random walk analysis at the microscopic (submicrometer) scale and to a solution of the diffusion equation at the macroscopic (tens of micrometers to centimeters) scale. The radiotracer, RTI, and IOI methods perform a volume average over all the probe's random walks and report the results as an effective diffusion coefficient.

After a population of molecules is released from a point

QUANTIFYING THE ECS

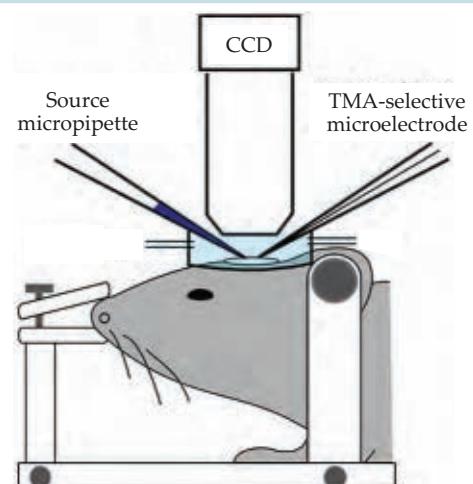
Two diffusion-based measurement techniques, real-time iontophoresis (RTI) and integrated optical imaging (IOI), explore the extracellular space in an anesthetized rat or mouse. In the RTI method, a source micropipette releases a burst of small ions, typically the cation tetramethylammonium (TMA), at a depth of about 200 μm below the surface of the brain. An ion-selective microelectrode positioned about 100 μm away then detects the diffusing molecules. The micropipette and microelectrode can alternatively be inserted parallel to one another to access almost any region of the brain.

The concentration C recorded by the microelectrode changes with time t and can be fitted with an appropriate solution to the diffusion equation²

$$\frac{\partial C}{\partial t} = D^* \nabla^2 C + \frac{Q}{\alpha},$$

where D^* is the effective diffusion coefficient, Q is a source function representing the released molecules from the micropipette, and α is the volume of the extracellular space divided by the volume of the whole tissue. Nonlinear curve fitting enables both α and D^* to be extracted and the tortuosity to be calculated from D^* .

For the IOI method, only the source micropipette is required. A brief applied pressure pulse releases fluorescent molecules in the ECS, which gradually spread. An overhead microscope and CCD (top of image) track that spread over time. The fluorescence intensity as



a function of distance is fitted with a solution to the diffusion equation—in this case, a Gaussian curve—and D^* is extracted from that fit. (Figure adapted from ref. 16.)

and undergoes subsequent random walks, the molecules' distances r from the release point at a given time t are related to the molecules' effective diffusion coefficient in the chosen medium D^* according to an equation proposed by Albert Einstein in 1905: $D^* = \langle r^2 \rangle / 2dt$, where d is the number of spatial dimensions and $\langle r^2 \rangle$ is the average of the squares of all the distances, known as the mean-square distance. Efforts to track single probes in the brain are still new, so the tortuosity is still estimated from concentration measurements, as explained in the box on page 29. The mean-square distance, however, can be used in computer simulations of random walks, as in figures 2a and 2b, and more elaborate models.⁹

Does advection contribute?

Since the radiotracer experiments of the 1960s, researchers have accepted that diffusion takes place in the ECS. But from time to time, the idea surfaced that advection—that is, the transport of substances by bulk flow of the interstitial fluid filling the ECS—might also occur. Important evidence for advection came around 1980 from Helen Cserr of Brown University. She performed a different type of tracer experiment that extended over longer time periods and over multiple brain compartments. She showed that injected radiotracers of different molecular weights and sizes cleared from the brain at the same rate.

The physics of diffusion and advection are different. Diffusion from a point source is rapid in the vicinity of the source but quickly diminishes with distance, and the travel time depends on the size of the molecule. Flow-mediated advection, on the other hand, maintains speed and can carry material over long distances. Cserr argued that the weight-independent clearing rate in the ECS indicated that the main transport mechanism was some overall flow of the interstitial fluid that carried all radiotracers with it. If the mechanism was diffusion, on the other hand, then the tracers would have cleared at distinct rates related to their molecular sizes.² But she and others couldn't directly show such bulk flow or advection.

The possibility of flow in the ECS has since received further support. Recent work suggested that the flow originates in the perivascular spaces, which form a sheath around the many blood vessels that penetrate the brain. Cerebrospinal fluid enters the sheaths surrounding arteries near the brain surface and then moves into the brain. The proposed idea is that some of that fluid leaves the perivascular spaces and moves through the ECS to exit at the perivascular space around veins. Flow in the perivascular space has been established, but flow in the ECS is not yet confirmed.¹⁰

Maiken Nedergaard of the University of Rochester in New York proposed that ECS flow pattern, which she called the glymphatic system,¹⁰ in 2012. She speculated that the glymphatic system may flush waste material out of brain tissue. Such waste material includes amyloid-beta protein, which is thought to play a role in the development of Alzheimer's disease.

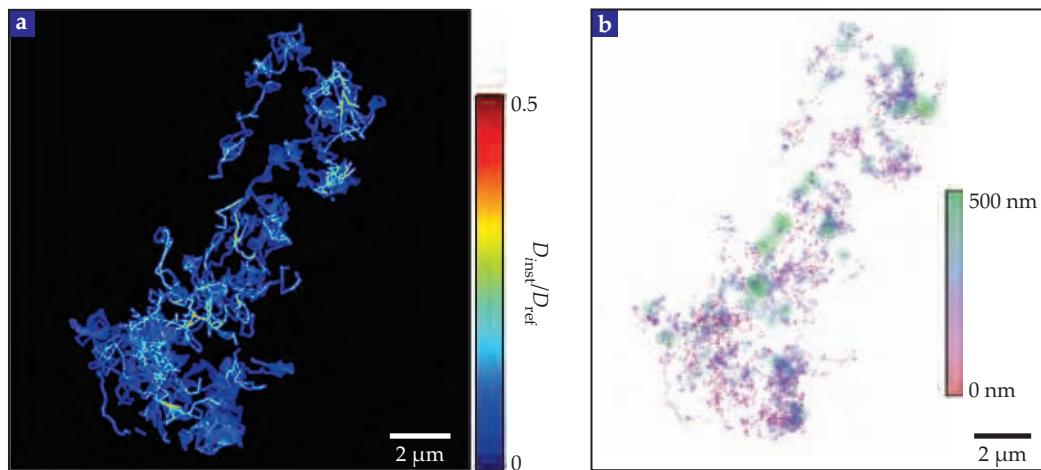


FIGURE 3. SINGLE-PARTICLE TRACKING and superresolution

imaging reveal the local structure of the extracellular space. **(a)** Single-walled carbon nanotubes diffuse through a living slice of an adult mouse's brain with the instantaneous diffusion coefficients relative to unimpeded diffusion ($D_{\text{inst}}/D_{\text{ref}}$, colorscale) mapped here. **(b)** Those diffusion measurements can be translated into a map of the local size of the extracellular space. (Adapted from ref. 8.)

Lessons learned

In 1979 I drew an illustration, shown in figure 4a, of the ECS on a logarithmic scale. I based the sketch on the latest (at the time) electron-microscopy images, radiotracer data, preliminary RTI experiments, and information about the network of interstitial macromolecules, known as the extracellular matrix. The illustration remains surprisingly valid over 40 years later.

On the left, figure 4a shows the surface of a cell and the ECS at highest magnification, even finer than the typical tens-of-nanometers distance between cells. Within the ECS is not just an ionic solution but also an extracellular matrix of long chain molecules collectively called glycosaminoglycans and proteoglycans.¹¹ Those chains were long thought to adorn cell membranes and have now been identified in detail, as shown in figure 4b. The matrices exist throughout the ECS, but those around neurons, known as perineuronal nets, have been the most characterized.¹² Those nets are primarily made of a negatively charged chondroitin sulfate and hyaluronan. The matrix molecules' function, density, distribution, and possible contribution to viscosity are only approximately known. Diffusion experiments have shown that some substances can rapidly but transiently bind to matrix components, which leads to a decreased D^* and an increase in the tortuosity measured with those substances.³

At the magnification of a few micrometers, electron microscopy, shown in figure 4c, reveals an ECS structure (white) that resembles the corresponding part of figure 4a with one difference: The actual ECS is uneven in size and contains many enlargements, also shown in figure 1. The SUSHI technique supports that conclusion (see figure 4d).

At the 10–100 μm scale, diffusion measurements from the analysis of probe molecules become relevant. Radiotracers provided a preliminary estimate that the ECS occupied 15–20% of brain tissue volume. The RTI method confirmed that result and found similar values for diverse brain regions in rats, mice, humans, some nonmammalian vertebrates, and even octopuses.² The ECS volume fraction is at least 20% in the sleeping or anesthetized brain but intriguingly seems to contract in the awake state¹³ to around 15%. The surprisingly high volume of ECS can

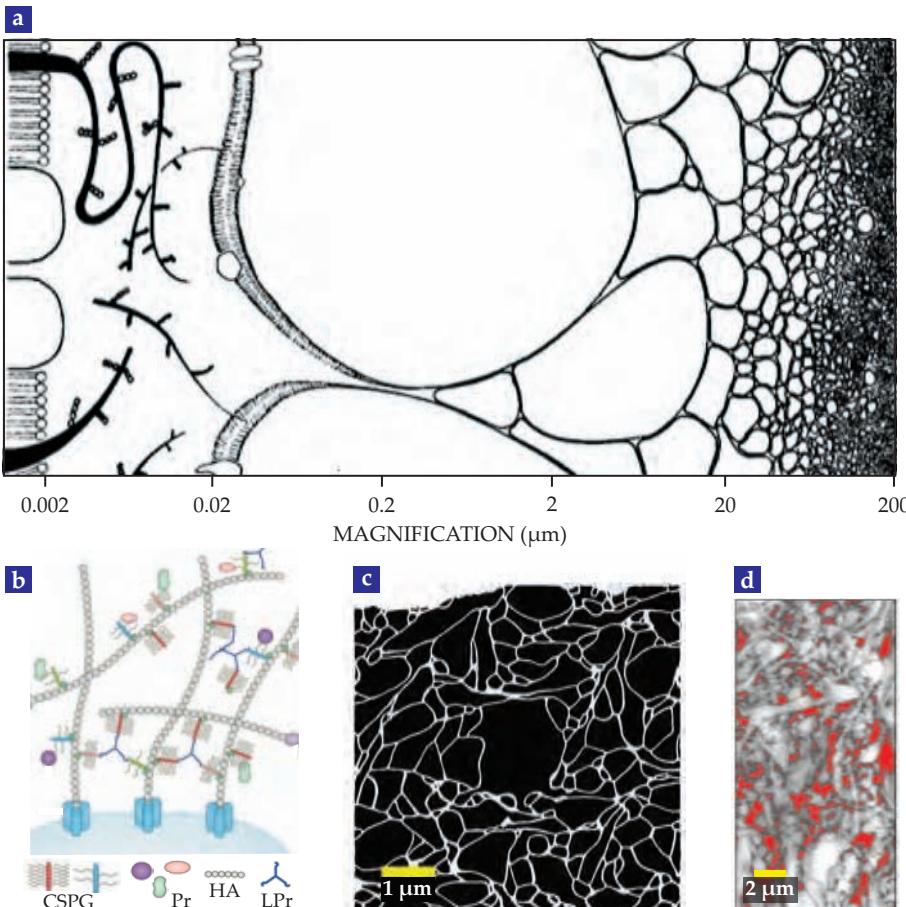


FIGURE 4. THE EXTRACELLULAR SPACE (ECS) looks different at various length scales. (a) Depicted logarithmically from high magnification (left) to low magnification (right), the ECS evolves from tendrils of extracellular-matrix molecules to the cell membrane's lipid bilayer to whole cells. (Adapted from ref. 14.) (b) The matrix molecules have hyaluronan backbones (HA), which are embedded in the neuronal membrane and to which chondroitin sulfate proteoglycans (CSPG) attach. Proteins (Pr) and link proteins (LPr) adorn the CSPGs. (Adapted from ref. 12.) (c) Electron microscopy reveals a micrometer-scale slice of a rat's hippocampus. To account for the tissue-preparation process, a computer algorithm expanded the ECS (white) to the expected 20% volume fraction. (Adapted from ref. 17.) (d) Superresolution shadow imaging shows part of a mouse hippocampus with an image of the ECS (red) superimposed. (Adapted from ref. 7.)

be understood by imagining that the outer membrane of every cell, including its extensions, is accompanied by a thin atmosphere of ECS and that any given volume of brain tissue has an enormous number of cells.

Why does brain tissue have so much ECS? One answer is that, in order to exchange electrical signals, nerve cells maintain a potential difference between their insides and outsides. That potential arises from a difference in ionic concentrations across the ion-selective cell membrane that creates a battery. So there must be a reservoir of ions external to the membrane, which is maintained by active transport of ions across cell membranes.

Another reason for the ECS is that substances need to diffuse between cells. Some of those substances, such as glucose, are involved in cellular metabolism, and some are waste products of metabolism. Those substances move to and from the vast network of blood vessels that permeate the brain. Other substances are signaling molecules that pass between cells. That chemical communication channel has long been discussed¹⁴ and today is widely accepted and commonly called volume transmission.^{11,15}

Diffusion measurements also reveal that molecules are hindered as they move through the ECS,² as quantified by the tortuosity factor λ . Typically, λ is about 1.6 for molecules much smaller than the average width of the ECS. That tortuosity value means that small molecules, including many drugs, have an effective diffusion coefficient in the brain that is only 40% of that in an unhindered, free medium such as water, where $\lambda = 1$. When the hindrance was discovered, researchers speculated

that it arose because diffusing molecules must go around cells rather than traveling through them. Monte Carlo simulations showed that the explanation was insufficient,⁹ however, and that if it were true, the tortuosity value would not exceed $\sqrt{3}/2$.

The experimentally measured tortuosity suggested that dead spaces in the ECS cause additional delays to diffusing molecules.¹⁶ Electron micrographs and superresolution optical images, such as those in figures 1, 4c, and 4d, reveal local enlargements or voids, which might be forms of such dead spaces. When diffusing molecules enter a dead space, they take longer to find an exit than if they were moving down a tube of uniform diameter, and the hindrance, as measured by the tortuosity, is thus higher.

The IOI method showed that larger molecules are more hindered than smaller ones, probably because of increased interaction with the cell walls that bound the ECS. That assumption enabled an estimate of the ECS's width, in addition to its relative volume. The estimate³ was about 38–64 nm; by comparison, the cell body of a typical neuron is about 10–50 μm wide. As noted previously, the ECS is not uniform in size but has many enlargements or voids, which optical methods suggest can be several hundred nanometers wide.^{7,8} So the estimated width is an average value.

Finally, dramatic changes in ECS volume have been shown to occur in pathological conditions, such as ischemia or stroke, when the local blood flow is cut off to part or all of the brain. The resulting lack of oxygen and glucose causes cells to rapidly swell and thus shrink the ECS volume fraction as some of the interstitial fluid's salt enters cells and water follows suit to maintain osmotic balance. In that process, the ECS volume fraction drops as low as 5%, and the tortuosity increases² to around 2.0. Similar changes occur in what's known as spreading depression or spreading depolarization—a condition thought to

BRAIN CELLS

underly some types of migraine headache—when diffusion appears to briefly stop altogether.⁶

A place for discovery

Just as the streets—with their constant streams of pedestrians, cars, and buses—are an essential element of a city, so too is the ECS an essential element of the brain. Streets define a city because they clearly delineate the buildings and allow the efficient exchange of people and goods between them. Similarly, the ECS permits the cells of the brain to maintain their identities and participate in intercellular molecular commerce. The ECS is a highly connected porous medium, so just like people in a well-designed city, molecules in the brain have many routes to move from one location to another.

Where cities and the ECS part company is that the layout of cities is largely two-dimensional, whereas the ECS is three-dimensional. Electron microscopy and superresolution optical methods provide only a 2D picture. A 3D electron-microscopy reconstruction of brain tissue exists, but it does not preserve the width of the ECS. To account for that limitation, a computer algorithm reinflated the reconstruction, as shown in figure 4c, so that the ECS had a volume fraction of 20%. But the algorithm could not accurately re-create local variations.¹⁷ Cryofixation electron microscopy does preserve the ECS but to date has not lent itself to 3D reconstruction because the rapid freezing is confined to a thin layer of the brain.

In addition to being 3D, the ECS is a dynamic structure that varies on multiple timescales. The change in volume fraction between sleeping and waking states shows variance sustained over hours,¹³ while an analysis of spreading depression saw dra-

matic changes in volume fraction over tens of seconds or minutes.⁶ Recently, rapid extracellular volume pulsations lasting a second or so have been detected during epileptiform activity.¹⁸

History suggests that the present technical limitations are only temporary. The diffraction-limited resolution of light microscopy previously seemed insurmountable but is now beaten regularly. So too will present techniques likely be refined or replaced by the clever application of physical concepts, and with them will come new discoveries about the ECS's interstitial content, traffic patterns, and its functional significance.

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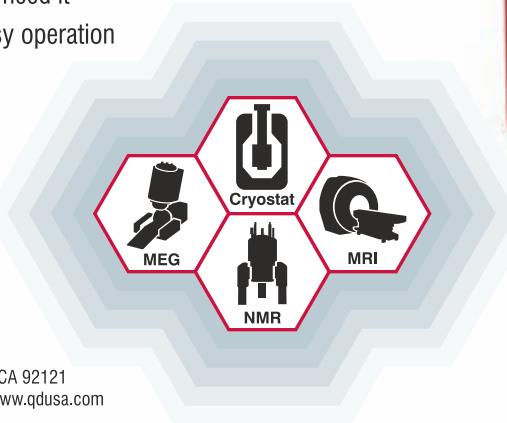
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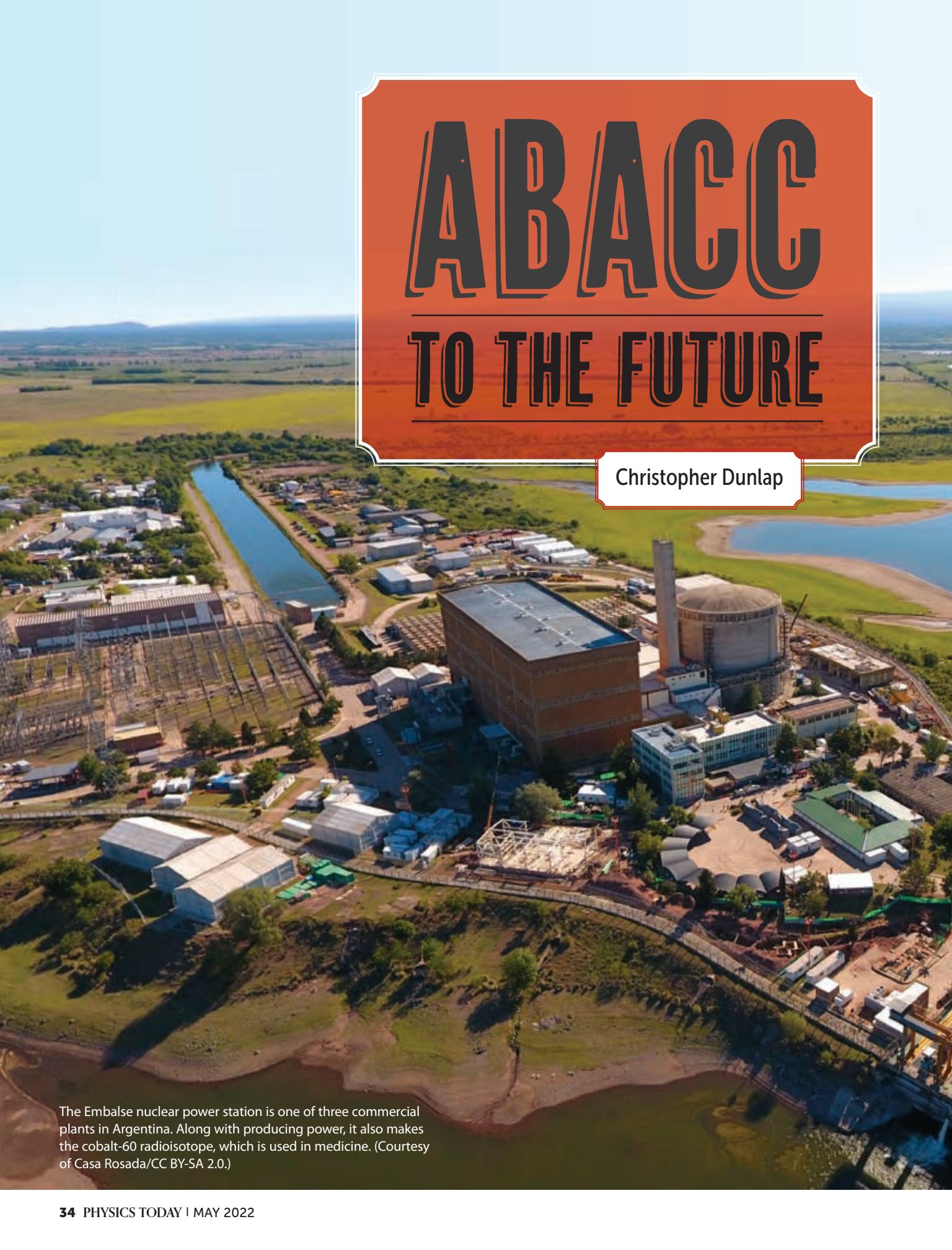
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An aerial photograph of the Embalse nuclear power station. The image shows a large industrial complex with several buildings, including a prominent yellow rectangular building and a tall, thin cooling tower. The station is situated near a river, with a long, narrow canal or bridge extending from the facility into the water. The surrounding area is a mix of industrial structures and green fields, with a town visible in the distance. The sky is clear and blue.

ABAC TO THE FUTURE

Christopher Dunlap

The Embalse nuclear power station is one of three commercial plants in Argentina. Along with producing power, it also makes the cobalt-60 radioisotope, which is used in medicine. (Courtesy of Casa Rosada/CC BY-SA 2.0.)



Christopher Dunlap is a historian of Latin America. His research focuses on the political, diplomatic, and technological history of Argentina's and Brazil's nuclear energy programs. He is based in California.



**At the end of
the Cold War,
two South American
rivals built a system
of nuclear safeguards
that culminated in the
1991 founding of a
bilateral organization,
ABACC. Can that
nonproliferation
regime be exported?**

The late 1980s and early 1990s were a banner era for nuclear nonproliferation: As Cold War tensions eased, the US and USSR (and later Russia) agreed to massive reductions in their nuclear arsenals. Two regional powers in South America—Brazil and Argentina—also made significant progress in the realm of nonproliferation during that hopeful time.

The two neighbors were designing an elegant solution to the vexing problem of nuclear weapons proliferation: the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials. Known as ABACC, its initials in Spanish and Portuguese, it remains the world's only bilateral nuclear safeguards agency. What makes the agreement even more remarkable is the neighbors' historic role as "rivals rather than mortal enemies" amid centuries of competition for prestige and regional dominance.¹

This article traces the historical trajectory of ABACC, explains its functions as a technical organization in monitoring nonproliferation compliance between two advanced South American nuclear energy programs, highlights its importance as a model 30 years after its creation, and outlines its implications for future diplomacy to eradicate nuclear weapons across the globe.

A brief nuclear history

Brazil entered the nuclear age exactly one month before the first atomic bomb was dropped on Hiroshima, Japan, on 6 August 1945, when officials agreed to supply the US with monazite sands through a secret agreement signed in Chapultepec, Mexico.² Abundant in the Brazilian coastal states of Rio de Janeiro, Espírito Santo, and Bahia, those sands contained thorium minerals needed by the Manhattan Project³ for a reaction that transformed thorium-232 into fissile uranium-233.

In Argentina, Brazil's chief competitor for continental and regional prestige, political and military leaders were startled into action by the atomic bombing of Hiroshima and Nagasaki. They quickly signed a decree in late September 1945 prohibiting the export of uranium, with the justification that "these minerals will be used within a comparatively short time in the process of obtaining power applicable to industrial uses."⁴

Both countries made it clear that they aimed to keep abreast of global developments in the field of nuclear energy. In south-east Brazil, scientific institutions fostering atomic research grew near major population centers in the decade after World War II. They often developed from or alongside existing universities that provided advanced training in physics and engineering. In Argentina, the remote Andean town of Bariloche grew from a sleepy hamlet in 1945 into a national scientific and technological center by 1962 in large part from an ambitious and ill-fated gamble on a nuclear energy program based on the fusion of small atoms.

By the mid to late 1960s, South America's two premier powers in nuclear research began to shift some of the energy they had previously poured into nuclear infrastructure and human capital into the diplomatic realm. They adroitly forged an alliance at the negotiating table that paved the way for the signing of the Treaty of Tlatelolco in 1967, which prohibited signatories from Latin American and Caribbean nations from developing or hosting nuclear weapons. It was the world's first treaty establishing a nuclear-weapons-free zone.

Despite that success, relations between the neighbors began to sour shortly after the treaty's signing. The cause was an acrimonious dispute over large-scale hydroelectric dams—Brazil's Itaipu Dam and Argentina's Corpus Dam—that were planned to be constructed on the Paraná River. For that reason, neither country ended up ratifying the treaty. The Tripartite Agreement between Argentina, Brazil, and Paraguay brought the hydroelectric dam conflict to a peaceful conclusion in 1979.

In the following year, the first major bilateral cooperation agreement between Latin America's most advanced nuclear energy programs marked a key diplomatic breakthrough, yet neither country made any promises to renounce a potential path toward nuclear weapons. In fact, authoritarian military governments in Brazil and Argentina significantly accelerated the development of their technologically advanced nuclear programs in the 1970s and early 1980s. That led to widespread concern among nuclear nonproliferation advocates and experts—particularly in the US—that one or both South American neighbors might join the small club of nuclear weapons states.

As early as 1974, however, Argentine and Brazilian nuclear energy officials, engineers, and diplomats began to take cautious yet recognizable steps toward increasing technical cooperation, particularly in nuclear power development. The landmark nuclear



FIGURE 1. RAÚL ALFONSÍN being inaugurated as president of Argentina on 10 December 1983. (Courtesy of the Presidency of the Nation of Argentina/CC BY 2.0.)

cooperation agreement reached in 1980 by military presidents Jorge Rafael Videla of Argentina and João Figueiredo of Brazil, for example, led to informal bilateral meetings of technical experts.

Those efforts were boosted when electoral democracy returned to Argentina under President Raúl Alfonsín in 1983 (see figure 1) and to Brazil under President José Sarney in 1985 (see figure 2). The neighboring leaders had a warm relationship that fostered more expansive cooperation on nuclear energy technologies, which they formalized with a 1985 bilateral declaration committing both countries to the exclusively peaceful use of such technologies. Cross-border technical cooperation culminated with the founding of ABACC in 1991, which created the level of mutual confidence and trust needed for the South American neighbors to firmly establish themselves as non-nuclear-weapons states. The two former rivals finally ratified the Treaty of Tlatelolco in 1994 and entered the Nuclear Non-Proliferation Treaty later in the decade.

Today Argentina and Brazil are two of the six non-nuclear-weapons states in the world that possess uranium-enrichment capabilities. In addition to their five operational nuclear power plants, the two countries operate a remarkable 72 nuclear facilities, which include commercial and research reactors, facilities for conversion and fuel fabrication, storage facilities, and research institutions (see figure 3).

In examining ABACC, the diplomatic-technical solution that ensured Argentina's and Brazil's peaceful intentions for their nuclear energy development, I hope to show not only the



FIGURE 2. JOSÉ SARNEY taking the oath of office as vice president and acting president of Brazil on 15 March 1985. Sarney's running mate, Tancredo Neves, fell ill the day before the inauguration and died on 21 April, which led Sarney to assume the presidency. (Courtesy of the Federal Senate of Brazil/public domain.)

innovative qualities of the 1991 South American safeguards agreement but some potential ways to rebuild a more stable global nonproliferation infrastructure in 2022 and beyond.

What is ABACC and what does it do?

The South American neighbors are triply bound to never develop nuclear weapons by a sort of nesting doll of nonproliferation commitments: ABACC, the Treaty of Tlatelolco, and the Nuclear Non-Proliferation Treaty. ABACC provided the trust necessary for Brazil and Argentina to accede to the two treaties, but it remains largely unknown even in those nations. According to its website, its objective is almost entirely technical: "to administer and apply the Common System of Accounting and Control of Nuclear Materials, whose aim is to verify that the nuclear materials in all the nuclear activities of the two countries are not deviated towards nuclear weapons."

But the unusual organization is undergirded by the mutual confidence built during the last third of the 20th century, which has enabled the two countries to provide transparency to their nuclear energy activities. Organized to assure Argentina, Brazil, and the international community that all nuclear facilities in the two countries are used for exclusively peaceful purposes, ABACC is run by a small and tightly knit bilateral group of technical professionals and diplomatic leaders. A four-member commission oversees all ABACC activities; it comprises two Argentine members (currently Gabriela Martinic of Argentina's Ministry of Foreign Affairs, International Trade, and Worship and Agustín Arbor González of the Nuclear Regulatory Authority) and their Brazilian counterparts (currently Marcelo Paz Saraiva Câmara of Brazil's Ministry of Foreign Affairs

and Paulo Roberto Pertusi of the National Nuclear Energy Commission).

The secretariat, ABACC's operational arm as well as its organizational face, represents ABACC to Argentine and Brazilian national authorities. It is headed by one Argentine official and one Brazilian official, who are joined by five more representatives from each nation.⁵ A budget officer manages the organization's financial resources.

Other bilateral pairs of officials are responsible for four related, but distinct, areas of ABACC activities: technical support (the calibration and maintenance of equipment for inspecting and safeguarding nuclear facilities), accounting and control of nuclear materials (the analysis of accounting data and transmission to national authorities and the International Atomic Energy Agency, or IAEA), operations (planning and performing inspections in coordination with national authorities and the IAEA), and planning and evaluation (annual planning of inspections and design of procedures used at each facility). An institutional relations officer coordinates institutional actions with political authorities in both countries, supports the secretariat in conducting nonproliferation and safeguards activities, prepares annual reports and promotional materials, and maintains ABACC's website.

Only 10 additional ABACC officials work with the secretariat and commission to coordinate, analyze, and carry out inspections upholding nuclear accounting and control policies at 51 nuclear sites in Argentina and 26 in Brazil, which include uranium and fuel-fabrication installations, enrichment facilities, commercial power reactors, research or subcritical reactors, R&D institutions, and storage facilities. Because Argentina and Brazil neither possess any nuclear weapons nor desire to develop them, the inspection infrastructure in the two countries might seem like a mere afterthought to a US audience. Political authorities and ABACC officials, however, take their mission extremely seriously. In 2020, for example, 889 inspector-days were devoted to upholding the terms of the common system.

That year, ABACC experts performed 114 inspections of Argentine and Brazilian nuclear installations and made an additional 70 site visits to verify detailed technical information about the design of certain facilities. Inspectors also made 650 non-destructive measurements, performed 177 weighing tests, and collected 34 samples of nuclear material to test for the presence of the fissile uranium-235 isotope.⁶ ABACC's comprehensive inspection plan covers all nuclear facilities in the two countries but focuses particularly on each one's most potentially problematic installations for nuclear proliferation: Brazil's centrifuge-enrichment facilities and Argentina's natural uranium-power reactors and its fuel conversion and fabrication plants.

The directors reflect

In December 2014 I had an extraordinary opportunity to speak at length with ABACC's then-directors of planning and evaluation, Orpet Peixoto of Brazil and Sonia Fernández Moreno of Argentina (who is currently serving another term in that position), at the organization's headquarters in Rio de Janeiro. The two directors were remarkably candid and described details about ABACC's operations and goals that go far beyond what can be gleaned from an annual report or website. As they noted, inspectors work their regular jobs at nuclear facilities across Argentina and Brazil but are recommended by each nation's

nuclear commission to serve in ABACC duties. Argentine engineers and technical experts inspect Brazilian facilities and vice versa.

Fernández explained to me that ABACC calls on experts in the fuel-cycle and engineering processes and on nuclear safeguards specialists. In contrast to the IAEA, whose inspectors examine facilities and technologies that they may not know in detail, ABACC inspector teams know well the technical specifics of any facility they visit. Peixoto noted that ABACC's inspectors are not the organization's employees but rather serve as ABACC secretariat staff during safeguards missions. An intensive inspection training program thus has an important secondary function: It transforms nuclear technicians into inspectors who are united toward a dynamic mission—keeping up with the changing details of safeguards and updated inspection practices.

By providing up-to-date training and equipment, ABACC keeps itself relevant and ahead of changes in the details of nuclear safeguards and accountancy. For example, in 2019 each country held a one-week training course on the ABACC-IAEA Joint Auditing System for Accounting Records and a four-day course on containment and surveillance systems. In that same year, the southeastern Brazilian city of Resende hosted a three-day workshop on inspection procedures in fabrication plants. (Resende, approximately 160 kilometers northwest of Rio de Janeiro, is an important center of nuclear activities in Brazil and hosts a nuclear fuel fabrication facility, a uranium conversion plant, and Brazil's uranium enrichment plant.)

Maintaining and replacing highly specific technical equipment across a vast geographic space is another challenge that ABACC's planners and experts face. Its 2019 annual report highlighted the Next Generation Surveillance System equipment installed at Argentina's Atucha I and II nuclear power plants and the successful installation of remote verification equipment for the surveillance systems of Atucha II and Brazil's Angra 2 plants (see figure 4).

ABACC's budget—shared equally by Argentina and Brazil—is approximately \$5 million annually.⁷ That budget does not allow for ABACC to operate its own laboratories, so inspectors instead use existing facilities in the two countries. Samples from Brazil might be analyzed in Argentina or vice versa. Peixoto noted that a key mission of ABACC is to "strengthen the capacity" of the labs in both member countries when possible.

In addition to financial exigencies, the lab-sharing arrangement has its roots in the nuclear cooperation between Argentina and Brazil that started in the 1980s. Prior to that time, each country had been responsible for its own safeguards; in the middle of that decade, a technical working group was created. It met every month, alternating its gatherings between the two countries, to hash out a common system of accountancy and control, or "a sort of mini-IAEA." The group combined ex-



FIGURE 3. A MAP OF important nuclear sites in Brazil and Argentina. The two countries operate a total of 77 nuclear facilities, including five commercial power plants. All of them are subject to regular inspection by ABACC experts.

pertise and knowledge of technical details at the national level into a unified bilateral system based on trust and cooperation.

At several points in our conversation, Fernández and Peixoto seemed to believe it was easier to describe ABACC as what it isn't—neither a nuclear police organization, nor an organization like the European Atomic Energy Community (Euratom) that doesn't answer to national nuclear authorities, nor a nuclear-weapons-free-zone treaty—than what it is: A rigorous bilateral inspection organization built on mutual confidence and technical cooperation that provides a unified voice for Brazil and Argentina to the IAEA on matters regarding nuclear safeguards.

Policy potential: ABACC without the A or B?

ABACC leaders are aware of both the organization's uniqueness and its creation as a solution to specific problems in and



FIGURE 4. THE ANGRA nuclear power station, located in the southern part of the state of Rio de Janeiro. The only commercial facility in Brazil, it consists of two pressurized water reactors; a third is under construction. (Courtesy of FURNAS Centrais Elétricas/IAEA Imagebank/CC BY-SA 2.0.)

between Brazil and Argentina. They have, however, been exploring parts of the world where they think an ABACC-like model might eventually succeed or where they can provide advice about a verification and safeguards solution. Peixoto and Fernández both envisioned a near future—perhaps 30 years from now—where the IAEA would have “too much to do” to inspect a growing number of nuclear installations to ensure peaceful use in the world’s declared non-nuclear-weapons states.

The global community has “a lot to learn from ABACC,” said Peixoto proudly. But he also admitted that it would be challenging to develop a bilateral or regional safeguards and verification model among countries whose mutual-confidence level or nuclear weapons status differs from that of Brazil and Argentina. Yet Peixoto believed that parts of the ABACC system could work even in the notoriously unstable Middle East, where Israel is the sole nuclear weapons power. Fernández, on the other hand, was less sanguine about the prospects of an ABACC model taking hold outside of its South American home countries. In Brazil and Argentina, she explained, mutual confidence was first built between the neighboring countries’ nuclear engineers and technicians. In a process that remains geographically and historically unique, that trust then trickled upward to national political leaders.

Peixoto added to Fernández’s concerns about the potential for extending the ABACC model to other parts of the world, but along technical lines rather than those of mutual confidence

in political relations. In the mid 1980s, a working committee began to oversee the work of technical groups in creating two compatible nuclear systems in Argentina and Brazil. Only then was it possible to make the political decision to create ABACC, which is a separate international agency independent of Brazilian and Argentine political leadership.

Furthermore, both directors agreed that many nations are much more comfortable with the idea of joining a nuclear-weapons-free zone than a rigorous inspectorate, an argument that is borne out in practice: ABACC has two members, but 114 countries are members of nuclear-weapons-free zones in Latin America, the South Pacific, Southeast Asia, Central Asia, and Africa. The road to exporting ABACC to other parts of the world will not be easy. As Peixoto and Fernández described it, three challenging conditions were necessary to found ABACC: technical alignment, mutual political and military confidence building, and the two nations’ willingness to submit

to the stricter requirements of an inspection agency. So will ABACC remain one of a kind?

Partnering with the IAEA

The outlook may not be quite so bleak. ABACC has technical cooperation agreements with the European Union, the US, South Korea, and the IAEA. Among those partnerships, collaborations with the IAEA and the US Department of Energy are the most frequent and best documented in ABACC’s annual reports. In the 2019 report, for example, the organization highlighted its participation in the IAEA’s destructive analysis intercomparison exercises, a partnership with the IAEA in developing a new laser-system technology for dry storage of fuel elements at Argentina’s first nuclear power plant, and continued efforts to implement a new method to sample uranium hexafluoride. DOE, on the other hand, has sent nuclear material samples to be tested by South American inspectors and assisted ABACC in updating the nondestructive measurement systems at Brazil’s two uranium-enrichment facilities.

Even more intriguing is the potential of exporting the ABACC model to a different context, such as the Korea Peninsula, which is famously divided between the authoritarian, nuclear-armed North and the prosperous but non-nuclear-armed South. ABACC secured a technical cooperation agreement with the South’s Korea Institute of Nuclear Nonproliferation and Control (KINAC) in 2006. Although the agreement is nominally limited to “nuclear material accounting and control,” it also includes generic provisions, such as the “exchange of scientific and technical information” and short visits by scientists, engineers, and other staff to safeguarded nuclear facilities. More specific components of safeguards R&D, including technology for sample analysis and measurement, are also part

of the agreement. Fifteen years after its inception, the ABACC-KINAC agreement is still in force. It continues to be automatically renewed every two years.

In contrast to the more nebulous terms of the KINAC arrangement, the 1999 agreement between ABACC and Euratom (the European Union's 27 member nations plus the UK and Switzerland) specifies safeguards approaches for such facilities as enrichment plants, commercial reactors such as Argentina's Embalse power plant, and fabrication facilities and areas of cooperation in "containment and surveillance technology for nuclear material," "nuclear safeguards training courses," and "procurement, characterization and use of standards [for] nuclear material."

Silver linings?

In 2022 any potential ABACC-type bilateral or regional agreements seem far away. In the Middle East, a hard-right nationalist bloc continues to hold significant influence in nuclear-armed Israel. Meanwhile its rival Iran is no longer constrained in its nuclear ambitions by the 2015 Joint Comprehensive Plan of Action, which was unilaterally scrapped by the Trump administration in 2018 despite Iranian compliance with the agreement. On the Korea Peninsula, although South Korea seems willing and able to engage in technical cooperation agreements with innovative partners such as ABACC, nuclear-armed North Korea shows no inclination toward joining any kind of similar agreement with the rival South.

In both of those hot spots, there is a nuclear imbalance: One state in a conflictive relationship possesses nuclear weapons but the other does not. For that reason, an ABACC-type model does not seem likely to be successful in those cases. Somewhat counterintuitively, however, one wonders whether an ABACC model might work between two nuclear-armed rivals, such as India and Pakistan. Progress has certainly been made toward one of the three conditions Peixoto and Fernández cited as necessary for ABACC's founding—namely, mutual confidence building: the two South Asian powers have now coexisted as nuclear-armed neighbors for almost 25 years, which in itself requires a great deal of mutual confidence building. Nevertheless, tensions remain high, and, clearly, more must be done in that area.

Additionally, it seems plausible that Pakistan and India might be able to establish technical cooperation on nuclear safeguards. Developing the mutual will to enter a rigorous system and calendar of inspections appears to be the biggest challenge that must be overcome to establish an ABACC-like solution in South Asia. In general, ABACC represents a promising nonproliferation model that can be adapted to other parts of the world either in lieu of or in collaboration with increas-



FIGURE 5. RAFAEL MARIANO GROSSI, director general of the International Atomic Energy Agency, delivering the opening remarks at a July 2021 conference in Rio de Janeiro commemorating the 30th anniversary of ABACC's founding. (Courtesy of Dean Calma/IAEA/CC BY 2.0.)

ingly overworked IAEA inspectors. But the geopolitical context and regional dynamics in the most prominent potential nuclear hot spots across the world currently seem unfavorable to such a solution.

Of course, at the height of the dispute over hydroelectric energy plans in the 1970s, politicians, diplomats, and nuclear experts in Argentina and Brazil would have agreed that the prospects of realizing an institution like ABACC were illusory at best. ABACC's transformation over the past 30 years from a fragile collaboration between two presidents and national nuclear commissions into a durable organization with a \$5 million annual budget has been remarkable (see figure 5). One can only hope that in the next 30 years its model will inspire leaders far from South American shores to further nonproliferation efforts.

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Quantum materials

OUT OF EQUILIBRIUM

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Illuminating materials with lasers can create intriguing magnetic and topological states of matter.

Martin Rodriguez-Vega, Maia G. Vergniory, and Gregory A. Fiete

To appreciate some of the most interesting quantum phenomena associated with electrons in a material, imagine a flock of birds. Although each individual bird has its own flight pattern, the flock as a whole moves in sync and avoids any collisions. Such collective motion is ubiquitous in nature and is behind a central concept in condensed-matter physics: emergence. It describes how assemblies of objects behave in ways fundamentally different from their individual constituents. Examples include social networks and superconducting materials, whose collective properties come from pairs of electrons. As Nobel laureate Philip Anderson explains in his 1972 article “More is different,” understanding that collective behavior is a fundamentally different task than understanding isolated components.¹

Most theories developed to understand collective behaviors in materials hold only in the presence of equilibrium conditions, such as when energy is conserved. But releasing a physical system from that equilibrium constraint—for example, by introducing a time-dependent external force—can lead in quantum materials to exotic states of matter that have no equilibrium analogue. Such states are highly sought in the field of quantum many-particle systems. A good illustration is a time crystal, an externally driven time-dependent system in which particles in the lowest energy state are in constant, repetitive motion (see the article by Norman Yao and Chetan Nayak, PHYSICS TODAY, September 2018, page 40). In cases for which new behavior emerges from correlations between constituents, one can subtly modify Anderson’s article title and argue that “shaken is different.” Time-dependent disturbances in a material can unlock new quantum

behaviors. In the laboratory, laser light can supply the amount of “shaking” needed for the job.

In this article we discuss the properties of quantum materials in out-of-equilibrium conditions induced by laser irradiation. Remarkably, light pulses from a laser can also control the ordered states of a material. That control has led to important insights in such strongly correlated materials as high-temperature superconductors.² Laser parameters, such as intensity, polarization, and frequency, are important variables for tuning material properties out of equilibrium. Lasers and other selectively chosen drives open the possibility of creating—at ultrafast speeds—systems with tailor-made physical properties at the touch of a switch.

To follow the important ideas in the field of out-of-equilibrium quantum materials, we first develop some intuition for the concept of a quantum material. What kinds of ordered states can arise from interactions

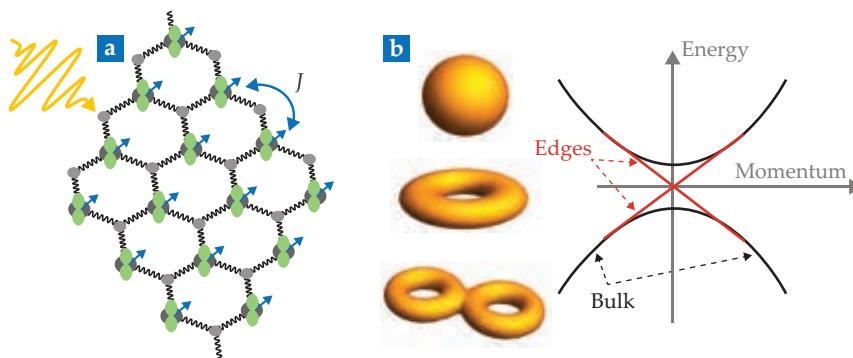


FIGURE 1. A REAL-SPACE illustration of a quantum material (a) displays interacting degrees of freedom: electron spins (blue arrows), electron orbitals (green lobes), phonons (black springs), and an incoming laser beam (yellow). The magnetic exchange parameter J reflects the energy of different orientations of two magnetic spins. (b) A material's topological aspects are distinguishable by its number of “holes.” In an insulator, topology in the electronic states can appear as a protected surface or edge state (shown in red) in the material's energy-momentum diagram.

among electrons, and what kinds of topological properties can emerge? We then discuss how laser irradiation can modify those properties.

Topology, energy bands, and collective modes

Think of a quantum material as a collection of atoms that have interacting electrons and nuclei and that exhibit emergent behavior and topological properties—that is, properties that are impervious to local defects. Figure 1 illustrates that mathematically: A sphere and a torus are topologically distinct. The two objects have different numbers of “holes” in their structures. (A hole can be understood as an obstruction to contracting a loop on the surface.) And only a defect that changes the number of holes in a material's structure can change its topology. (See the article by Arthur Ramirez and Brian Skinner, PHYSICS TODAY, September 2020, page 30.)

Ever since the discovery in 1980 of the integer quantum Hall effect in two-dimensional systems, topological phases have played an important role in the field. With their extension to 3D systems in the late 2000s, topological phases have come to dominate the landscape of solid-state physics. Topology is an intrinsic property of electronic band structure, which describes the energy-momentum relations of electrons in a crystal lattice. Different topological materials exhibit previously unknown phases of matter. For example, many topological materials are insulating in the bulk but conduct an electric current on the surface or edges.

The modern theory of topological band structure—topological quantum chemistry—is built on symmetry-based considerations and complements chemical theories of bonding, ionization, and covalence. Consequently, it describes the global properties of all possible band structures. And its application to solids has resulted in fast searches for existing compounds and rapid predictions of new materials. Detailed studies have shown that topological materials are far more common than previously thought.³

Despite its dramatic successes, topological quantum chemistry does not extend to materials whose collective modes—lattice vibrations called phonons and magnetic fluctuations

called magnons—and their interactions are fundamental to understanding the material behavior. Instead, one must consider such strongly correlated materials on a case-by-case basis. For example, the Coulomb interactions between electrons can produce insulating materials that even electronic band theory would predict to be metallic.⁴ Such interaction-induced insulators are called Mott insulators. They are often described in terms of local moment (spin) models with collective spin excitations and a Hamiltonian,

$$H = \sum_{ij} J \mathbf{S}_i \cdot \mathbf{S}_j,$$

in which J signifies how strongly interacting spins \mathbf{S} are coupled (the magnetic exchange energy), and i and j are space indices that label the positions of the local magnetic moments. Remarkably, in Mott

insulators, certain circumstances may favor “fractionalized” topological states in which the electron, an otherwise fundamental particle, is split apart.⁵ Such exotic states that combine topology and strong Coulomb interactions between electrons are good examples of emergent collective quantum behavior. (See the article by Philip Anderson, PHYSICS TODAY, October 1997, page 42.)

In the context of nonequilibrium quantum materials, collective modes play an outsized role because they are often the most interesting to selectively excite with a laser. Each collective mode—induced by correlations that result from interactions—possesses different excitation energy scales. Across materials, however, one can discern a range of distinct energies. For example, in insulating materials, the excitation energy of electrons can be measured in electron volts. On the other hand, lattice and spin collective modes are typically less energetic: Phonon energies are in the few tens to low hundreds of millielectron volts, and magnons are in the few millielectron volts or even lower. That energy hierarchy, combined with constraints imposed by the symmetries of the material, opens the door to selective mode excitation in quantum materials. See the box on page 47 for a discussion of crystal symmetries and their influence on phonons.

Among all the possible collective modes, phonons draw special attention because their excitation by laser radiation can modify a crystal's lattice structure and profoundly affect its electronic phase. Technological advances in intense ultrashort terahertz light pulses allow researchers to selectively excite phonons coherently (see the article by Joe Orenstein, PHYSICS TODAY, September 2012, page 44). That exquisite control differs from the effect of traditional lasers—whose light is in the electron-volt range—that produce electron excitations but with incoherent dynamics and considerable heating. Those consequences hinder the use of visible wavelength lasers in technological applications based on the manipulation of the state of a quantum material.

Achievements with laser driving

An important caveat is that direct laser excitation works only

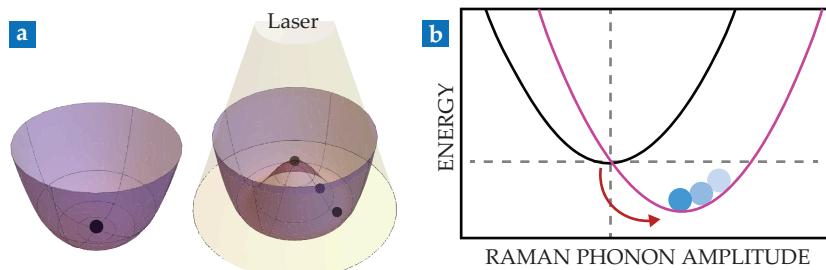


FIGURE 2. ENERGY CONFIGURATION in a material. (a) The black dots represent the ground state. The presence of laser light modifies the material's energy configuration and effectively produces a new ground state. (b) When a Raman phonon is excited by a laser beam, it shifts the energy minimum, produces a distorted lattice, and elicits new behavior. The blue dots illustrate the relaxation of the material (in progress) to a new energy minimum.

for certain types of phonons as determined by the symmetries of the material. For example, in materials with inversion symmetry—those whose structure is the same for an atom at position r as for an atom at position $-r$ —the lattice excitations can be divided into so-called Raman phonons that are even under inversion and IR phonons that are odd under inversion. Only IR phonons directly interact with laser light because they have a finite dipole moment. Raman phonons are “optically silent” at their resonant frequencies. If an IR phonon is excited with strong enough laser light, however, nonlinear interactions between the phonons can excite Raman phonons with fascinating consequences. The mechanism is known as nonlinear phononics.

In their groundbreaking work, Matteo Rini, Andrea Cavalleri, and coauthors showed in 2007 that exciting an IR phonon in the insulating material $\text{Pr}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$ can temporarily distort its orthorhombic lattice.⁶ Such lattice modification, in turn, drives the electronic states into a high-conductivity phase that survives for several nanoseconds. The concept of nonlinear phononics was introduced by Cavalleri and coauthors four years later.⁷ They showed that one could leverage nonlinear phonon-phonon interactions in $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ —an insulating perovskite with a rhombohedral distortion—to manipulate the crystal lattice and electronic structure. They demonstrated the electronic structure change, induced by phonon pumping with laser light, by using time-resolved reflectivity. The nonlinear mechanism prompts phonons to oscillate around new equilibrium positions, as shown in figure 2. From that early study, examples of the types of order that researchers can control in materials have grown rapidly.

Ferroelectrics compose an important class of quantum materials with ordered states. They possess a nonzero electrical polarization vector along a crystal axis at low temperatures. That ordered state has many applications, including energy harvesting and storage and ultrasound medical devices. One can also manipulate ferroelectric states using electric fields. But the switching rates from such fields are modest. To overcome that problem, researchers can turn to ultrafast lasers. Cavalleri, Roman Mankowsky, and colleagues⁸ applied intense laser pulses in resonance with an IR phonon on lithium niobate at about 20 THz. Time-resolved second-harmonic-generation measurements—a technique sensitive to inversion symmetry breaking—showed that the polarization switches direction for 0.2 ps before reverting to its initial state. That capability opens

a new ultrafast switching route for ferroelectrics.

In the search for a longer-lived effect in ferroelectric order, Cavalleri's team also considered strontium titanate, an incipient ferroelectric.⁹ As a function of applied strain, the compound transforms into a ferroelectric state. The lower the temperature, the lower the strain required for the transition. In their experiment, the researchers irradiated the sample with 20 THz femtosecond laser pulses in resonance with an IR phonon and tracked the time-dependent second-harmonic-generation signal. Their measurements revealed that the light-induced ferroelectric phase lasted for hours.

Irradiating magnets

Magnetism is perhaps the correlated electronic state people encounter most in everyday life. Storage and manipulation of information is one of the most relevant applications of magnetism in modern society. To that end, controlling the magnetic order by means other than magnetic fields has intrinsic appeal. It can increase information processing speeds and decrease device sizes. Nonlinear phononics could provide such a path, and recent experiments have already shown encouraging results.

Ankit Disa and colleagues considered the antiferromagnet cobalt fluoride.¹⁰ The crystal's piezomagnetism is what makes it so intriguing. Under applied stress, the crystal acquires a net magnetic moment. Figure 3 shows a representation of the individual magnetic moments. In their experiments, the researchers identified a suitable phonon that could mimic the effect of the applied stress. That phonon, however, could not be excited directly by a laser beam. The researchers excited it indirectly using a nonlinear phonon process that simultaneously excites two other degenerate IR phonons. From Faraday rotation and circular dichroism measurements, they extracted the magnetic moment as a function of time. And that moment turned out to reach values two orders of magnitude larger than what can be achieved in equilibrium.

Dmytro Afanasiev and colleagues examined dysprosium ferrite (DyFeO_3) as a function of temperature.¹¹ The material is a complex magnetic system with multiple magnetic phases. Driving an IR phonon in its lattice to large amplitude can nonlinearly excite a Raman mode that modifies the magnetic interactions between the transition metal and rare-earth ions. Consequently, Afanasiev and coworkers achieved an antiferromagnetic-to-weakly-ferromagnetic phase transition.

Andrzej Stupakiewicz and colleagues achieved an elusive switching of magnetization states through ultrafast phonon excitation.¹² They took thin films of yttrium iron garnet, a ferromagnet widely used in today's technology, and irradiated it with IR laser pulses. The initial magnetic configuration, whose magnetic moments aligned with one of the cubic symmetric axes, transformed into a switched four-domain pattern. The magnetization switching mechanism is associated with the excitation of phonons, which produces macroscopic strains in the material.

Although by no means exhaustive, those experiments exemplify the high degree of control over correlated states that one can access by using ultrafast lasers. The next natural step in the control of quantum materials is to look for analogous

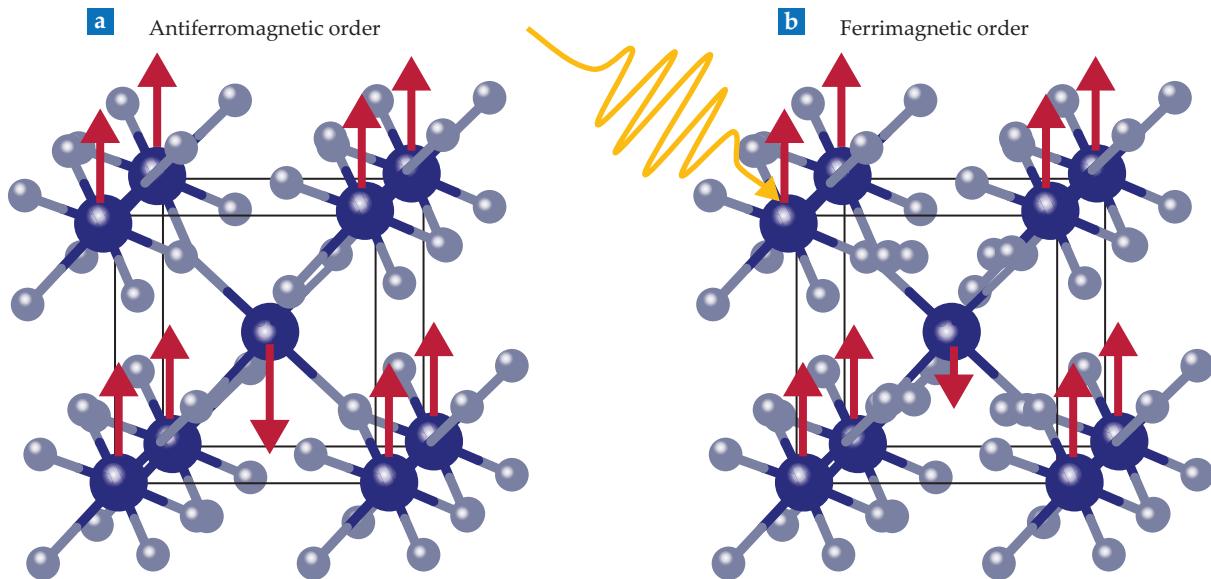


FIGURE 3. AN ANTFERROMAGNET becomes ferrimagnetic under laser light. (a) Cobalt fluoride is normally antiferromagnetic at equilibrium, with magnetic moments (red arrows) that are spin up at corner sites and spin down in the center of its unit cell. The net magnetic moment is zero. (b) In its laser-induced distorted lattice, CoF_2 becomes ferrimagnetic, with magnetic moments that are both spin up and spin down, but whose net magnetic moment is now finite. The displaced atoms (relative to the antiferromagnetic lattice) produce that net moment.

phonon control of topological states. James McIver and co-authors used ultrafast laser pulses to induce a more general phenomenon, an anomalous quantum Hall state in graphene¹³—an exotic state of matter in which conducting states appear on the edge of the material and the bulk is insulating.

Unlike the examples we just discussed, graphene is a gapless semiconductor (see the article by Andrey Geim and Allan MacDonald, PHYSICS TODAY, August 2007, page 35). As such, electronic excitations are unavoidable when phonons are targeted, which complicates the picture of photon absorption. Phonon control of topological states, however, could be available in the insulating antiferromagnet MnBi_2Te_4 and related materials, in which magnetic order and topology are intertwined.¹⁴ Thus it may only be a short time before we have experimental examples of phonon-induced electronic topological states.

Theoretical aspects

All the experiments described above have motivated the research community to redouble their efforts to understand quantum materials out of equilibrium and to devise theoretical tools to explain the observations. They are also likely to empower researchers to predict new states achievable under a laser drive.

The current theory of nonlinear phononics is based on a combination of group theory and first-principles calculations.¹⁵ Group theory allows for the symmetry classification of phonons and provides the symmetry-allowed interaction terms between the phonons that define the potential energy. And first-principles calculations provide the phonon energetics, such as their frequencies and anharmonic interaction strengths (see the article by Andrew Zangwill, PHYSICS TODAY, July 2015, page 34).

To determine the lattice dynamics, researchers solve a set of differential equations derived from the symmetry-constrained

energy potential, including the driving term introduced by the laser interaction with the IR phonons. The solutions describe the transient lattice distortions. First-principles calculations help to determine the new electronic ground state provided the electrons relax much faster than the lattice does and follow that relaxation adiabatically. Besides providing the theory for the experiments discussed earlier, the approach has produced predictions that await experimental verification.¹⁵

More accurate simulations of light-induced effects in quantum materials could be achieved by using frameworks that are based on time-dependent density functional theory¹⁶ or extensions of it. Current theoretical efforts, such as the Octopus project at the Flatiron Institute in New York City and the SALMON project at the University of Tsukuba in Japan, are focused on the real-space computation of light-matter interactions. Those first-principles approaches could, at least in principle, capture the dynamics of all the relevant interacting degrees of freedom and provide accurate descriptions of light-induced effects with increased predictive power. Such schemes are computationally expensive, though, and limited by system sizes and simulation time scales.

Challenges ahead

One of the major challenges facing people who study quantum materials out of equilibrium is identifying potential candidates with desirable responses from the vast number of materials that can be controlled with light. Generalizations to magnetic materials provide even more candidates to consider for phonon control of topological electronic states.¹⁷ But predicting systems that are likely to exhibit other correlated or topological states, such as charge density waves and topological superconductors, remains difficult. As we mentioned earlier, most strongly correlated materials are introduced into the literature on a case-

PHONONS IN GROUP THEORY

Symmetry is one of the most fundamental concepts in physics. It is also quite useful. The symmetry of a crystal lattice in its equilibrium state determines the symmetries of the lattice's vibrational modes, even when the crystal is out of equilibrium. Selectively exciting specific modes with a laser can tailor the topology of a material's electronic band structure and manipulate its magnetic states. The figure illustrates the equilibrium lattice symmetries of chromium triiodide (CrI_3), a two-dimensional magnetic insulator at low temperatures. Blue dots represent chromium atoms, and purple dots iodine atoms. The CrI_3 lattice has twofold rotational symmetry about the center of a chromium hexagonal lattice unit because of the lower symmetry arrangement of the iodine atoms.

The application of symmetry to physics has far-reaching implications and is much broader than lattice vibrations. In her 1918 work "Invariant variation problems," Emmy Noether showed that symmetries are mathematically associated with conserved physical quantities. The conservation of energy, for example, is associated with the time-translational symmetry of physical laws derived from time-independent Hamiltonians.

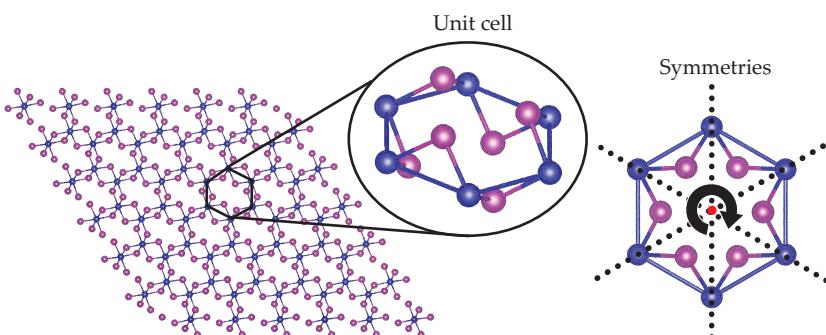
Each quantum material is characterized by its own set of crystal symmetries, which are the mathematical operations that when performed on a material structure leave it unaltered. Translations and rotations are examples. (See the 2008 book *Group Theory: Application to the Physics of Condensed Matter*, by Mildred Dresselhaus, Gene Dresselhaus, and Ado Jorio, for a pedagogical introduction.)

The collection of crystal symmetries defines the space group of the material, which includes the translational symmetries. Each material is constructed by repeating its unit cell. Typically, the space group of a material is established through a combination of group-theory studies and x-ray or neutron scattering experiments.

Once the material symmetries are

established, one can determine the phonons' symmetries. In the case of phonons excited by light, the discussion can be restricted to long-wavelength phonons. Mathematically, one need consider only point groups. For example, the point group of monolayer CrI_3 is D_{3d} , one of the 32 point groups in three spatial dimensions.

Group theory can also help block-diagonalize the dynamical matrix, which determines the real-space atom motions for each phonon type. That is done by constructing the projection operators for each phonon type. Those displacements do not correspond directly to the actual phonons but form a basis for them. To determine the energetics of the phonons, one must employ density functional theory.



by-case basis. For example, recent experiments by Stephen Wilson's group at the University of California, Santa Barbara, showed that CsV_3Sb_5 has topological electronic bands in its normal state. At low enough temperatures (around 2.5 K), however, it becomes a superconductor. The next step might be to induce dynamical transitions between the material's topological and superconducting states by using nonlinear phononics.

The integration of advanced, time-dependent density functional theory calculations with machine-learning approaches could provide a path to extend the time scales and system sizes that researchers can simulate. Molecular dynamics and spin dynamics simulations have already been integrated with deep-learning frameworks to access large system sizes.

On the experimental side, the lasers used in such experiments as magnetization switching¹² require specialized facilities, such as the FELIX (free-electron lasers for infrared experiments), an international user facility that houses two accelerators in Nijmegen, the Netherlands. Even in the present state of laser technology, the field has experienced rapid progress over the past 15 years in ultrafast light-induced control of ordered ferroelectric and magnetic states. Experimental advances could soon extend to other correlated and topological states in recently synthesized materials, such as those with weak van der Waals interactions between layers.¹⁸ Furthermore, the flexible

control of a lattice by phonon manipulation promises to unlock new functionalities from materials in out-of-equilibrium contexts, in which new phases of matter could emerge. Shaken is indeed different.

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FINDING THE RIGHT PROGRAM FOR YOU

Samantha Pedek, graduate student,
University of Iowa; co-chair, Physics
Congress 2022 Planning Committee

Find Your People and Grad Program at the 2022 Physics Congress

Join hundreds of physics undergrads, grad
school reps, and physics luminaries

Samantha Pedek, 2022 Program Co-chair

Networking is one of the most important aspects of being a young professional. We've all heard the spiel about how networking can have positive impacts on future educational and career-related opportunities, but many of us struggle with making the initial contact that can lead to lasting connections.

In 2016 I attended the Physics Congress (PhysCon), the largest gathering of undergraduate physics students in the United States. Every few years, PhysCon brings together students, alumni, and faculty members for three days of frontier physics, interactive professional development workshops, and networking. It is hosted by Sigma Pi Sigma, the physics honor society, and anyone interested in physics can attend.

Networking at PhysCon was unlike any other professional development experience I had as an undergraduate physics student. The sheer number of like-minded people was daunting—hundreds of physics and astronomy undergraduates, representatives from graduate schools and summer research programs, employers from all over the country, and well-established pro-

fessionals at the height of their careers were all under one roof for three days.

PhysCon has continued growing in attendance, scope, and opportunities, and you won't want to miss the next one! In celebration of the 100th anniversary of Sigma Pi Sigma, an extra-special PhysCon is planned for October 6–8, 2022 in Washington, DC. With a little preparation, you'll have the chance to narrow down your graduate school search, meet potential employers, and make lasting connections with people heading down similar career paths.

The most direct opportunity to meet with representatives from physics and astronomy grad programs and potential employers occurs during the Expo, which encompasses both a grad school fair and a career fair. During the Expo, attendees can visit booths to learn more about a program, company, or undergraduate research experience as well as get tips and advice on applying. When I attended, seeing the wide variety of vendors enabled me to start thinking about my life after col-



Samantha Pedek



The Physics Congress is a high-energy, hands-on weekend designed explicitly for undergraduate physics students.
Photo courtesy of SPS National.

NETWORKING TIPS

Before you attend a networking event, craft and practice your **elevator pitch**—a 30-second narration of who you are professionally, what you've accomplished, and where you hope to go in the future.

If you're attending an in-person event as a prospective student or employee, **business cards** (or contact cards) show that you're serious about your future and make it easy for new contacts to connect with you.

BE AN SPS INTERN

The Society of Physics Students summer internship program offers 10-week, paid positions for undergraduate physics students in science research, education, communication, and policy with various organizations in the Washington, DC, area.

www.spsnational.org/programs/internships.

lege, and I was blown away by the versatility that a degree in physics can provide.

A more subtle opportunity to build your network as a young professional is to engage with attendees you don't already know, between events or at meals. Shuffling between workshops, plenaries, and banquets will be hundreds of people with lived experiences similar to yours. Be adventurous and sit at a meal or workshop table with strangers! You might find yourself next to a professor from a graduate school you're interested in, or even from a school you didn't realize you should be interested in. A quick conversation can leave a lasting impression.

A straightforward way to meet students and professionals is to go to the poster sessions, as a presenter or an attendee. These are excellent opportunities to have one-on-one interactions with others and to learn about new topics. Seeking out posters in subfields you're doing research in or interested in studying in grad school is a great way to form connections and learn about current research in the field. My favorite question to ask a presenter is "Can you tell me more about your re-



2019 Physics Congress attendees visit one of the many graduate school booths in the exhibit hall to learn about the program and check out physics demonstrations. Photo courtesy of SPS National.

search?" They likely have an answer prepared, which can be a bridge to more natural conversation.

The physics and astronomy community is quite small, so if you meet people at PhysCon, you're likely to run into them again. Almost a year after I attended PhysCon 2016, I was a Society of Physics Students intern. Of the 14 of us, over half had met previously, largely at PhysCon. Having that shared experience helped me connect with the other interns right from the start. We even looked back at old PhysCon photos and tried to spot one another in the background, which was wildly entertaining.

Attending PhysCon is the networking gift that keeps giving. I have met others who attended in different years and we're still able to bond over our shared experiences. You are bound to find someone with similar interests and goals in a sea of over a thousand physics students, mentors, and advisers. Preparation is the key to successful networking, so practice your elevator pitch, make business cards, and I'll see you in 2022! GSS



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Washington, D.C.
sigmapisigma.org/congress/2022



A clash of cosmologists

It's not easy to write a biography of a single individual, but in his new book, Paul Halpern—a physicist, writer, and historian of science—tackles two: the astronomers George Gamow (1904–68) and Fred Hoyle (1915–2001). As if that weren't enough, Halpern also covers the history of both 20th-century cosmology and the universe itself. Despite that seemingly major degree of difficulty, *Flashes of Creation: George Gamow, Fred Hoyle, and the Great Big Bang Debate* is a remarkable success.

Halpern's book is based on years spent combing through archives and oral histories and conducting interviews. It includes memories from the astronomers' family members: Hoyle's two children, Elizabeth and Geoffrey, the latter of whom wrote several science-fiction novels with his father, and Gamow's son, Rustem Igor, who died last year. Halpern expertly blends those personal details with pertinent information from the published scientific literature at a level appropriate for anyone who cares about science and its practitioners.

Considering the enormous number of hours Halpern must have spent researching and writing, I should perhaps be ashamed to admit that I read it all in one afternoon, scribbling purple notes in the margins. But it really is a page-turner.

Parts of Halpern's story have been covered in more specialized works. Hoyle wrote a 1994 autobiography, *Home Is Where the Wind Blows: Chapters from a Cosmologist's Life*, and there are two other biographies of him. Gamow also wrote an informal autobiography, *My World Line* (1970), and the late Karl Hufbauer wrote a very informative sketch of him for the National Academy of Sciences' 2009 *Biographical Memoirs*.

P. J. E. Peebles recently published his insider's take on how cosmology developed in the 20th century, *Cosmology's Century: An Inside History of Our Modern Understanding of the Universe* (2020). Those interested in the history of competing cosmological theories can consult the historian Helge Kragh's *Cosmology and Controversy: The Historical Development of Two Theories of the Universe* (1996). And every

introductory astronomy textbook on the planet aspires to tell you the history of the universe from the Big Bang to the present.

What makes *Flashes of Creation* special is the broader perspective it takes on the topics and individuals covered in those works. What are the takeaways from that approach? One is Gamow's crucial role in advocating for what would eventually become known as the Big Bang theory: He firmly believed that the universe had changed with time and that significant nuclear processing had occurred early on. That is true, but strictly speaking, the model does not require an initial singularity or bang, only expansion and cooling from very high density and temperature. For that reason, I have always preferred to use the term "evolutionary universe" rather than Big Bang.

That appellation also contrasts well with that of its rival: the steady-state model, which assumes that the appearance, contents, and conditions of the universe have always been the same when considered over large distance scales. Hoyle was the firmest supporter of the steady-state model, and to a considerable extent, it was also his invention, although Hermann Bondi and Thomas Gold proposed something similar.

But the steady-state theory was always a minority view among the global astronomical community. When it was first proposed, many astronomers did not take cosmology seriously; by the time they did, only Hoyle and a few of his close associates were still championing the model.

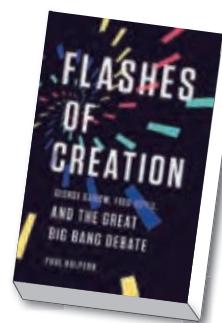
Is the volume free of omissions or errors? No, how could it be? And that's what my purple pen is for. In terms of the former, Halpern's overview of Edwin Hubble's life gives the impression that the skilled observer went straight to the Mount Wilson Observatory after finish-



The physicist and cosmologist George Gamow enjoying a cigarette.

Flashes of Creation
George Gamow, Fred Hoyle, and the Great Big Bang Debate

Paul Halpern
 Basic Books, 2021.
 \$30.00



ing his doctoral work at the University of Chicago in 1917. But that's not quite what happened. Hubble, in fact, rushed to complete his dissertation that year because the US had just entered World War I, and he wanted to volunteer for the army and get to Europe before the war was over. Although he made it to Europe, he did not see combat.

Regarding errors, the situation is a bit more complicated. Many books and articles, including the prepublication version of *Flashes of Creation*, credit Hoyle for hypothesizing that the carbon-12 nucleus

had to have an excited state at about 7.68 mega-electron volts if three helium atoms were to fuse to carbon in stars. In that telling of the story, Hoyle then persuaded the nuclear-physics group at Caltech to look for the state.

In fact, as the Caltech team carefully noted in their 1953 paper, "The 7.68-Mev state in C¹²," they looked for and found a state that had been detected on three previous occasions (and which had not

been found in two other instances). Hoyle did not tell them to look for that state; as they noted in the paper, he pointed out its "astrophysical significance." Fortunately, Halpern rectified his depiction of that incident in the published version of the book.

I am indebted to Halpern for pointing out the significance of many things that happened between Gamow and Hoyle—although I think he missed that both were

members of the International Astronomical Union's former Commission 35: Stellar Constitution for several triennia—and between the universe and its investigators over the years. Other readers will surely feel similarly. So grab your purple pen, enjoy the unusual heroes and some unusual photographs, and read!

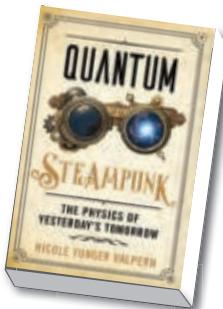
Virginia Trimble

University of California, Irvine

G. D. Falksen, a science-fiction author, wearing a steampunk-style outfit that features an arm mechanism designed by the artist Thomas Willeford.



TYRUS FLYNN/CC BY-SA 3.0



Quantum Steampunk The Physics of Yesterday's Tomorrow

**Nicole Yunger
Halpern**

Johns Hopkins U. Press,
2022. \$29.95

tum thermodynamics in layman's terms. The field has boomed in the past 15 years, in part thanks to Yunger Halpern: Despite her youth, she has already authored an impressive number of highly cited papers, some in collaboration with respected experts and renowned pioneers.

Steampunk is a literary and artistic genre in which Victorian-era settings are juxtaposed with futuristic technologies. Yunger Halpern argues that quantum (or quantum information) thermodynamics has a "steampunk aesthetic" because it applies physical concepts developed in the 19th century to cutting-edge quantum information science. To illustrate that idea, Yunger Halpern precedes each chapter with a short skit written in the style of fin de siècle British English that tells a brief story about Audrey and Baxter, the Victorian-era ancestors of quantum physics protagonists Alice and Bob. By adding literary flair to otherwise dry technical content, Yunger Halpern masterfully conveys in simple terms the variety of complex ideas that characterize the different subfields of quantum thermodynamics. Even if they lack the technical background needed to grasp all the details she discusses, lay readers will learn a lot and gain a clear picture of the goals, tools, and aims of those subfields.

It may seem churlish not to give *Quantum Steampunk* my full blessing. But I hesitate to do so because I wish Yunger Halpern had discussed subfields from

Quantum thermodynamics, today

After hearing the impressive lecture Nicole Yunger Halpern delivered in Barcelona, Spain, upon receiving the biennial Ilya Prigogine Prize for Thermodynamics in 2019—the first time the prestigious award was given for a PhD thesis on quantum thermodynamics—

I knew she would shine in the years to come. Only a few years later, Yunger Halpern has followed through on that promise with an entertaining book, *Quantum Steampunk: The Physics of Yesterday's Tomorrow*, that explains the essence and secrets of the many facets of quan-

BOOKS

other disciplines, such as engineering, that also contributed to the development of thermodynamics in the 20th century. For example, what today's quantum thermodynamicists call "second laws" parallel what engineers call "exergies." Those include investigating the maximum work that can be obtained from a system depending on its constraints, its interactions, and the types of thermal reservoirs it can access. Similarly, what today's quantum physicists call "free energy" parallels the engineering concept of available energy with respect to a thermal reservoir. That concept is well known and should not be confused with the traditional Helmholtz and Gibbs free energies of classical thermodynamics.

Nonequilibrium thermodynamics is another subfield that deserves more attention. At minimum it should be added to the list of related fields that Yunger Halpern believes should be bridged to quantum thermodynamics so that they can trade ideas, insights, and questions. Many new advances in the modeling toolboxes for nonequilibrium irreversible dynamics in various fields—including mechanical engineering, continuum mechanics, solid mechanics, chemical engi-

neering, and mathematical physics—have converged on a common mathematical framework. That structure reveals a great law of nature that I like to call the "fourth law of thermodynamics," and it can also be formulated quantum thermodynamically.

I also take slight issue with one aspect of Yunger Halpern's description of qubits—namely, that they can have "temperatures below absolute zero." After all, Norman Ramsey demonstrated in his famous 1956 paper that "negative temperatures are hotter than positive temperatures" and that those temperatures characterize a set of equilibrium states that are neither below nor even close to absolute zero. Such states tend to give up energy much more readily than states with infinite positive temperature do.

It is also a bit disappointing that Yunger Halpern did not mention James Park and William Band in the brief sketch of the history of quantum thermodynamics in chapter 6. Admittedly, she is correct when she states that detailing the field's history in full would require another book, and she does list a 1978 paper by Park and Band in the references. But they deserve to be considered true pioneers

for their still-overlooked general theory of empirical quantum state determination, which anticipated by three or four decades the field that has now been dubbed quantum state tomography.

Park also published a masterpiece on the "nature of quantum states" in 1968 that every quantum physicist must read, and he proved the no-cloning theorem in 1970, which was 12 years prior to the publication of the famous and often-cited papers by William Wootters, Wojciech Zurek, and Dennis Dieks. Park deserves to be mentioned to quantum steampunkers not only because of his truly farsighted and pioneering contributions but also for the depth and independence of his humble but crystal clear thoughts. His story should also serve as a warning to tomorrow's physicists that it is their duty to read many of yesterday's classic papers before writing new ones.

Despite my quibbles, *Quantum Steam-punk* is an excellent introduction to a burgeoning field. I only hope that Yunger Halpern can find a way to widen the scope of the book in a future edition.

Gian Paolo Beretta
University of Brescia
Brescia, Italy

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NEW BOOKS & MEDIA

The Science of Baseball

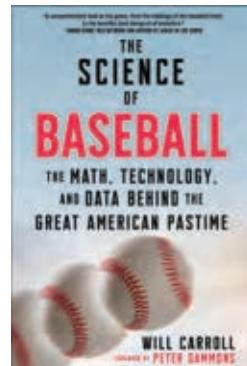
The Math, Technology, and Data behind the Great American Pastime

Will Carroll

Skyhorse, 2022. \$14.99 (paper)

Just in time for opening day comes *The Science of Baseball* by Will Carroll, a sportswriter who specializes in covering injuries. The book explores such topics as the science behind baseball equipment like bats and balls, the effects of sticky substances on thrown balls (see "The physics of baseball's sticky situation," PHYSICS TODAY online, 8 July 2021), and the launch angle and bat speed hitters should aim for if they want to knock a pitch out of the park. Carroll also looks to the future and predicts that climate change will likely force manufacturers to construct bats from "engineered woods" that are made with glue-lamination techniques. His joy for the sport's quirks is infectious: One delightful factoid he relates is that all official baseballs are "rubbed up" with something called Lena Blackburne Baseball Rubbing Mud, which the seller procures from an unknown location in New Jersey.

—RD

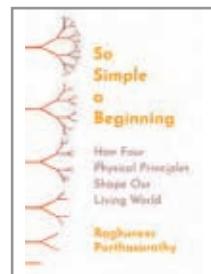


So Simple a Beginning

How Four Physical Principles Shape Our Living World

Raghuveer Parthasarathy

Princeton U. Press, 2022. \$35.00



In this popular-science book, the physicist Raghuveer Parthasarathy endeavors to reveal the wonder of biophysics to lay readers. To tackle that complex subject, Parthasarathy focuses on four fundamental concepts: self-assembly, regulatory circuits, predictable randomness, and scaling. Through discussions of biological components such as DNA, cells, and tissues, he shows how the instructions for building with them and the circuitry required to control their activity are encoded into their physical characteristics; how their random physical processes are predictable; and how their sizes and shapes are determined by gravity and other forces. Dozens of original watercolors and drawings by the author illustrate the nontechnical text.

—CC

Schrödinger in Oxford

David C. Clary

World Scientific, 2022. \$98.00

Authored by the physical chemist David C. Clary, this book focuses primarily on Erwin Schrödinger's time at the University of Oxford from 1933 to 1936 and in 1938—after he was twice forced to emigrate from the European continent. Using quotations from correspondence between Schrödinger and other émigré scientists like Max Born, Albert Einstein, and Francis Simon, Clary outlines well the travails of the refugee scholar. Because his appointments at Oxford were temporary, Schrödinger was constantly looking for a permanent position, which meant that

he was not very scientifically productive while there. Nevertheless, he still managed to publish the famous 1935 paper outlining the thought experiment that became known as Schrödinger's cat. Unfortunately, Clary decided not to discuss the physicist's personal life in the book, which was a major omission: Schrödinger was a misogynist and a serial womanizer who often preyed on underage women.

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Focusing on the so-called Science New Wave, Labocine is a streaming platform that showcases the latest in science-themed cinema—including both fiction and nonfiction, animations, data visualizations, and even raw lab footage. In addition to a database of more than 3000 science films, the site features monthly issues of curated films, in-depth articles about the films' subject matter and creators, live-streamed events, and a networking hub. Although some content is freely available, access to certain parts, such as the monthly video issues and film database, requires a subscription. Aimed at scientists, artists, and educators, Labocine promotes itself as a forum for science-based content that blends disciplines and cultures, celebrates diversity, and challenges stereotypes.

—CC PT

Point of Discovery

Marc Airhart, host

University of Texas at Austin, 2015–

Produced by the University of Texas at Austin's College of Natural Sciences, this podcast highlights scientists and research at the institution. Episodes are typically the length of an NPR segment—namely, 10–15 minutes—and they focus on topics as varied as a pandemic affecting frogs and the way in which animals socially distance when sick. A two-part series from earlier this year focused on the life and work of the legendary theoretical physicist Steven Weinberg, who taught at UT Austin from 1982 until his death in 2021. Featuring interviews with friends and colleagues like Willy Fischler and Katherine Freese as well as excerpts from interviews Weinberg gave during his lifetime, the series provides an excellent overview of both his landmark contributions to the standard model and his philosophical perspective on physics.



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Andreas Mandelis

Laser wavelength characterization

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Laser diodes with automatic power control

A series of 520 nm green laser diodes from Arima Lasers, a Laser Components supplier, features eye-safe operation. The integrated automatic power control switches off the laser source as soon as a certain operating current level is exceeded. The chip contains the electronics as an application-specific integrated circuit and as a photodiode. The laser diodes are installed in a 3.3 mm housing, which protects them from electrostatic discharges up to 10 kV. Depending on the model, they guarantee a stable output power of 5 mW or 10 mW at supply voltages of 5.8 V to 7.0 V (DC). Their pulse width can be modulated up to 2 MHz. *Laser Components USA Inc, 116 S River Rd, Bldg C, Bedford, NH 03110, www.lasercomponents.com*



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Atik Cameras has released the first in its series of highly sensitive cameras for advanced scientific and industrial imaging. The model TE-77 uses the Teledyne e2v CCD77-00 sensor, which features $24 \mu\text{m}^2$ pixels over a 12.3 mm^2 sensor area. Because the camera can be reliably cooled to -60°C , it can achieve very low read noise and detect the faintest signals. Minimal saturation and exceptional detail are achieved as a result of the deep full-well depth of 300 000 e⁻ (summing-well depth of 600 000 e⁻). Another key feature of CCD technologies is asymmetric binning to achieve even greater detail. Multiple options are available, including a 45 mm bistable, high-speed scientific shutter capable of 20.0 ms opening times. The TE-77 is suitable for demanding applications such as chemiluminescence, fluorescence, spectroscopy, microscopy, and bioluminescence imaging. *Atik Cameras Ltd, Unit 8, Lodge Farm Barns, New Road, Norwich NR9 3LZ, UK, www.atik-cameras.com*



Laser for deep-UV Raman spectroscopy

According to Toptica, its TopWave 229 CW laser is a suitable excitation source for deep-UV Raman and deep-UV fluorescence spectroscopy. Key features include its short wavelength, ultranarrow laser linewidth of less than 1 MHz, and output power of 10 mW at 229 nm. For fluorescence-free Raman, excitation below 250 nm is crucial for avoiding the overlap between the spectral regions of the Raman signal and the native fluorescence. In fluorescence spectroscopy, the 228.5 nm emission allows the detection of molecules with fluorescence spectra of less than or equal to 270 nm, which can only be excited with shorter-wavelength light. As a CW laser system, the TopWave 229 is free of the nonlinear and saturation problems common with pulsed-laser sources. To ensure high reliability and consistent, diffraction-limited beam quality ($M^2 < 1.3$), the complete UV beam path is enclosed in a specially sealed compartment. *Toptica Photonics Inc, 5847 County Rd 41, Farmington, NY 14425, www.toptica.com*

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Benchtop confocal microscope



Andor Technology, an Oxford Instruments company, says its BC43 benchtop confocal microscope represents breakthrough instrumentation. Typically, microscopes that capture images in 3D are costly, complex to use, and located in specialized darkroom facilities. That is especially true for confocal technology, which delivers the highest-quality 3D images, particularly in thick and clinical specimens. The BC43 overcomes those challenges by delivering 2D confocal images in milliseconds and generating 3D views in real time. The compact design means it can sit on a bench in a regular laboratory, saving space and time. The cost-effective BC43 is simple to use but can address complex imaging needs for live and fixed specimens. It handles a range of scales, from the subcellular and single-cell levels through those of huge tissue samples and large model organisms. *Andor Technology Ltd, 7 Millennium Way, Springvale Business Park, Belfast BT12 7AL, UK, <https://andor.oxinst.com>*



Scientific CMOS camera with high quantum efficiency

Thanks to its back-illuminated image sensor, the pco.edge 10 bi CLHS scientific CMOS camera from PCO, an Excelitas company, delivers a quantum efficiency of up to 85% and a broad spectrum out to the near-IR. The sensor incorporates microlenses and a full-pixel-height deep-trench isolation for cross-talk suppression, which results in a high modulation-transfer function. By using a high-resolution 10.5-megapixel image sensor with a square pixel size of $4.6\text{ }\mu\text{m}$, the camera provides a large image circle. Thermal stabilization and active sensor cooling produce a very low dark current and readout noise of 0.8 e^- . The sensor technology reduces the noise peak and tail to a level comparable to the noise behavior of CCD sensors. Together with a high full-well capacity, that yields a dynamic range of 25 000:1. The pco.edge 10 bi camera offers high frame rates, of up to 120 fps, and transmission via a fiber-optic link. It is suitable for applications in microscopy and the life and physical sciences. *PCO AG, Donaupark 11, 93309 Kelheim, Germany, www.pco.de*



Compact, piezo-based objective positioning systems

PI (Physik Instrumente) has redesigned its portfolio of compact vertical positioners for microscope objectives, known as PIFOCs. They are suitable for integration in objective revolvers of upright and inverse microscopes. The new P-725 piezo-based lens scanners offer higher dynamics due to optimized levers and steel mounts and are available in three travel ranges: 100 μm , 400 μm , and 800 μm . Handling of the PIFOCs has been optimized: The aperture has the largest possible diameter, and a set of adapter rings can be used to screw in different objectives up to M34 in size. A new cable sheathing makes possible much tighter-bending radii, which help protect the signal- and current-carrying cable from the mechanical strain induced by repeated rotations of the nosepiece to change magnification. The PIFOCs can be used in the life sciences, materials microscopy, quality assurance, and the semiconductor industry. *PI (Physik Instrumente) LP, 16 Albert St, Auburn, MA 01501, www.pi-usa.us*

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Atomic-force-microscopy imaging mode

Nanosurf has announced a new atomic-force-microscopy (AFM) imaging mode available exclusively on the company's DriveAFM platform. According to Nanosurf, WaveMode is the fastest force-curve-based imaging mode that can be applied to all samples and all environments. It is based on CleanDrive, Nanosurf's exclusive photothermal cantilever actuation, which provides stable, low-drift, and high-signal-to-noise cantilever tunes that are insensitive to changes in the environment. WaveMode represents the first commercially available off-resonance mode that can use photothermal actuation of the cantilever—instead of traditional piezoacoustic

actuation—to enable fast, stable, and gentle imaging. WaveMode offers fully automated laser and photodetector alignment. Usable in both liquid and air environments, it is suitable for AFM imaging in life and materials sciences applications. *Nanosurf AG, Gräubernstrasse 12, 4410 Liestal, Switzerland, www.nanosurf.com*

Cooled CCD camera

Raptor has added the Eagle 1MP to its range of cooled CCD cameras. With a back-illuminated CCD sensor from Teledyne e2v (CCD47-10) providing 1056×1027 pixels with $13 \mu\text{m} \times 13 \mu\text{m}$ pixel pitch, the Eagle 1MP enables large-field-of-view imaging and ultra-sharp image resolution. It is housed in Raptor's proprietary PentaVac vacuum enclosure and cooled to -90°C with air and liquid and -80°C with only air to minimize dark current for longer exposures. Using low-noise electronics, the Eagle 1MP offers less than 2.3 e^- readout noise unbinned and programmable binning options up to 16×16 pixels and dual readout rates of 75 kHz and 2 MHz . It comes with a C mount and an integrated shutter, which is closed during readout to avoid vertical smear. According to the company, at $140 \text{ mm} \times 126 \text{ mm} \times 120 \text{ mm}$, the Eagle 1MP is the smallest camera in its class. *Raptor Photonics Ltd, Willowbank Business Park, Larne, Co Antrim BT40 2SF, Northern Ireland, UK, www.raptorphotonics.com*



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Nanoscale IR imaging platform



Bruker has launched its Dimension IconIR nanoscale-IR-spectroscopy and chemical-imaging system. It combines the company's Dimension Icon atomic force microscope and nanoIR photothermal AFM-IR technology to generate chemical and material property mapping with a chemical-imaging resolution of less than 10 nm . The IconIR incorporates Bruker's proprietary PeakForce Tapping mode, which is both sensitive and robust and allows for the study of complex systems with strong mechanical heterogeneities. The standard system supports samples up to 150 mm ; versions for larger samples are also available. According to the company, the platform constitutes the most complete correlative microscopy solution for quantitative nanochemical, nanomechanical, and nanoelectrical characterization. It is suitable for research in a broad range of polymer, geoscience, semiconductor, and life sciences applications. *Bruker Nano Surfaces, 3400 E Britannia Dr, Ste 150, Tucson, AZ 85706, www.bruker.com*

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OBITUARIES

Thomas Korff Gaisser

A scientific trailblazer with a phenomenal legacy, Thomas Korff Gaisser died on 20 February 2022 in Swarthmore, Pennsylvania, after a short illness. He was the Martin A. Pomerantz Professor Emeritus of Physics at the University of Delaware. Tom's friends and colleagues will remember him as a kind person and a giant in the fields of cosmic-ray physics, particle astrophysics, and multimessenger astronomy who supported and inspired his colleagues and the next generation of scientists.

Born on 12 March 1940 in Evansville, Indiana, Tom graduated from Wabash College in 1962 with a degree in physics. He then won a Marshall Scholarship to study in the UK. Sailing there on the *Queen Elizabeth*, he met another Marshall scholar, Julia (one of the authors of this obituary), whom he would later marry. He went on to earn an MS in physics at the University of Bristol.

Tom started his career as a theoretical particle physicist after obtaining a PhD from Brown University in 1967. Following postdoctoral positions at MIT and Cambridge University, he joined the Bartol Research Foundation (now the Bartol Research Institute), where he made the transition to cosmic-ray physics. He would often thank the Antarctic explorer and astrophysicist Martin Pomerantz for his support during that time. Tom's innovative research and engaging personality spurred many to follow his path from high-energy physics to particle astrophysics.

Tom helped prepare the theoretical groundwork for the physics of extensive cosmic-ray air showers. His work motivated others to develop state-of-the-art detectors that study with great precision the properties and origins of cosmic rays. And he contributed much insight to fundamental questions in particle physics.

Inspired by the first data from the Irvine-Michigan-Brookhaven and Ka-

mioka experiments in the 1990s, Tom also laid the theoretical foundations for interpreting the physics of the atmospheric neutrino beam. His continued work on the subject, including his highly cited 1989 *Physical Review D* paper with Giles Barr and Todor Stanev, "Flux of atmospheric neutrinos," led to the successes of the present generation of atmospheric neutrino experiments.

Tom provided early calculations of the antiproton flux in the atmosphere, which is relevant for the search for new physics. He also predicted early gamma-ray and astrophysical neutrino fluxes. Among his other achievements was helping to develop the Sibyll simulation of cosmic-ray hadronic interactions.

Tom's far-reaching and innumerable contributions were internationally recognized. His awards include the 2005 O'Ceallaigh Medal, a Humboldt Research Award in 2009, and the 2015 Homi Bhabha Medal and Prize, given every two years.

But Tom is best known to many physicists for his book *Cosmic Rays and Particle Physics*, based on a one-semester course that he taught while on sabbatical at the University of Wisconsin-Madison and first published in 1990. Tom updated and expanded it with Ralph Engel and Elisa Resconi for a second edition, released in 2016. The book sits on the shelves of scientists and students around the globe and has served as an authoritative reference for a multitude of authors over the years.

As a founder of the IceCube Neutrino Observatory collaboration, which began construction in fall 2004, Tom was a leader whom everyone could count on. He was gracious and provided encouragement to many young scientists. He served the team in many ways, including as IceCube's spokesperson between 2007 and 2011.

Tom was also the soul of IceTop, the observatory's surface array devoted to cosmic-ray physics and used as a veto detector for neutrino detections. Although a theorist, Tom took on the experimental task of building IceTop with gusto and participated during every season of IceCube's construction. For several years he traveled to Antarctica, staying there for weeks at a time to participate in building the surface array. He delighted in the hard physical labor and the camaraderie



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Thomas Korff Gaisser

of everyone—including mechanics, bulldozer drivers, and technicians—engaged in the project. IceTop and IceCube mapped for the first time the cosmic-ray anisotropy in the Southern Hemisphere and performed precision measurements of the cosmic-ray energy spectrum covering a range from 250 TeV to EeV, the largest energies that can be detected.

As an IceCube member, Tom also became an ambassador of Antarctic science in large part through a blog documenting his and his team's expeditions to the South Pole. In recognition of his work with IceCube, an area in Antarctica was named Gaisser Valley in 2005.

Tom published around 250 papers in scientific journals, but he was always especially proud of "Partons in antiquity," which he wrote with Julia, his wife of 57 years. Published in 1977 in the *American Journal of Physics*, the paper pointed out that the idea of confined quarks or partons as constituents of elementary particles was already present in the atomic theory of the ancient Greeks. Although the idea was his, Tom, in his typical fashion, insisted on having Julia listed as the principal author.

We thank Tom's many friends and colleagues for their contributions to this obituary.

Julia Gaisser

Bryn Mawr College

Bryn Mawr, Pennsylvania

Francis Halzen

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Luca Bindi is a full professor of mineralogy and head of the department of Earth sciences at the University of Florence in Italy. **Paul Steinhardt** is the Albert Einstein Professor in Science at Princeton University and author of *The Second Kind of Impossible: The Extraordinary Quest for a New Form of Matter* (Simon & Schuster, 2019) about his and Bindi's search for natural quasicrystals.



Quasicrystals and the birth of the atomic age

Luca Bindi and Paul J. Steinhardt

The first nuclear bomb explosion led to the formation of a novel form of matter, known as a quasicrystal, with an elemental composition that had never been seen before.

At 05:29:45 Mountain War Time on 16 July 1945, a plutonium implosion device was detonated in New Mexico on the Alamogordo bombing range, about 330 km south of Los Alamos, and ushered in the atomic age. The experiment, known as the Trinity test, was part of the Manhattan Project, the US's top-secret effort to develop atomic weapons that was initiated after indications that German scientists were already pursuing their own atom bomb.

One of the Manhattan Project's designs, based on enriched radioactive uranium, was simple enough that it did not need to be tested in advance. The second design, based on plutonium, required a novel method of implosion to rapidly smash together enough plutonium to exceed the critical mass needed to set off a runaway nuclear chain reaction. (See the article by Cameron Reed, PHYSICS TODAY, September 2017, page 42.) The Manhattan Project scientists decided that the Trinity test was essential for determining whether the implosion idea would work and, if so, provide them with firsthand data from an actual nuclear explosion.

The blast released 88 terajoules of energy—equivalent to 21 kilotons of TNT—which was enough to vaporize the 9 m test tower and surrounding copper transmission lines and create a crater about 1.4 m deep and 80 m wide. The fireball fused the

desert sand, consisting mostly of quartz and feldspar, into crusts and droplets now known as trinitite. Most trinitite is greenish, but a rarer oxblood trinitite formed where sand fused with metals from the tower and copper cables.

Although the observers of the test recognized the explosion's awesome destructive power, they did not notice that it also created an unusual form of matter: a quasicrystal, hidden in a sample of red trinitite.

More than a repeating pattern

Before 1984 no one had ever seen or even conceived of a quasicrystal. Scientists thought they had a complete understanding of all the possible ways atoms and molecules can join to make a solid. That knowledge, established nearly two centuries earlier, was codified in a set of principles known as the laws of crystallography. The laws are essential for understanding and controlling the physical properties of matter, such as for making steel, cleaving the facets of a diamond, or manipulating the electronic properties of silicon for use in integrated circuits.

According to those laws, atomic arrangements either are random, as in glass, or are crystalline, as in sugar or table salt. In crystals, the atoms are organized in periodically repeating clusters that pack like building blocks to form a structure with a discrete rotational symmetry, analogous to a tessellation such as a checkerboard or a honeycomb.

A key fact about regular tessellations, noted even by the ancient Egyptians, is that they can comprise only certain tile shapes and possess only certain symmetries. The same rules apply to matter. Periodic materials are thus restricted to having one-, two-, three-, four-, or sixfold symmetry about an axis. Five-, seven-, eight-, and higher-fold symmetry axes are forbidden, as is icosahedral symmetry, which includes six independent fivefold symmetry axes.

About 40 years ago one of us (Steinhardt) and then-student Dov Levine first realized that a quasicrystal, which has ordered but not periodic structure, might be possible. We were inspired by a curious geometric pattern invented a few years earlier by Roger Penrose of Oxford University. He had identified a pair of shapes that fit together without gaps but only nonperiodically in a self-similar pattern of fivefold symmetric clusters of tiles, as shown in figure 1a.

Several theorists independently speculated that some analogous solids may exist, but what that would mean in actuality

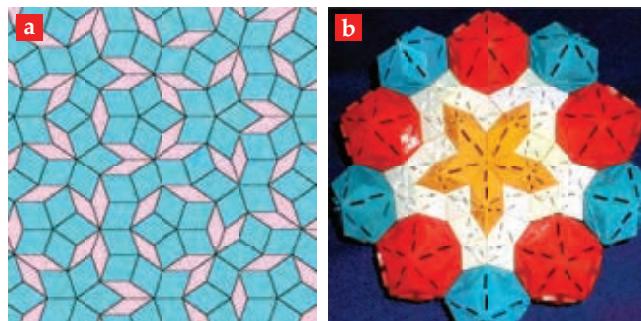


FIGURE 1. QUASICRYSTALS, whose structures are ordered but not periodic, can take different dimensionalities. (a) A two-dimensional Penrose tiling comprises two types of tiles (blue and pink) arranged in a quasiperiodic pattern with crystallographically forbidden fivefold symmetry. A 3D icosahedral quasicrystal (b) comprises four types of polyhedral units with holes and protrusions that constrain the way the units match such that all space-filling arrangements are quasicrystalline. (Photo courtesy of Lorenzo Bindi.)

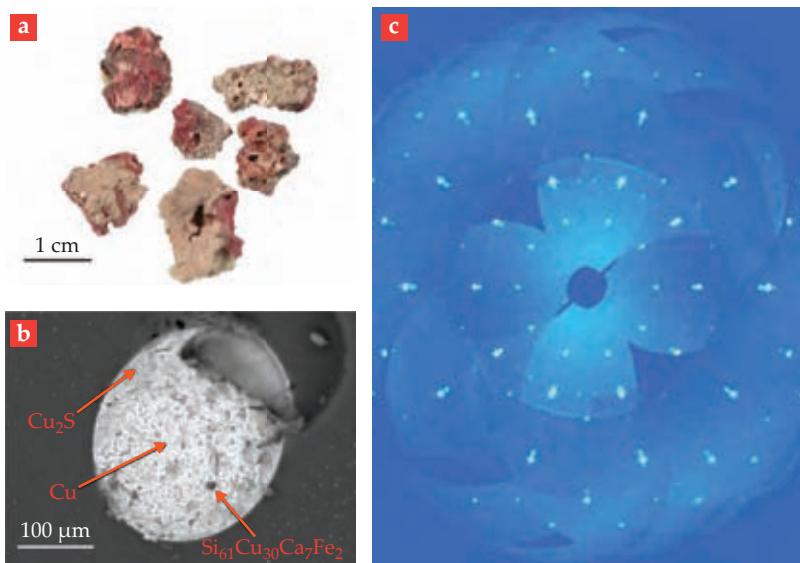


FIGURE 2. TRINITITE, which was created from the first nuclear bomb test, has trace amounts of quasicrystalline material. (a) Samples collected from the Trinity test site are reddish rather than trinitite's more common greenish hue. (b) Metal droplets from the trinitite sample were imaged with a backscattered scanning electron microscope. The quasicrystal is the small, dark gray fragment composed of silicon, copper, calcium, and iron $\text{Si}_{61}\text{Cu}_{30}\text{Ca}_7\text{Fe}_2$. (c) Once extracted from the metal droplet, the quasicrystal fragment was x-ray imaged along its fivefold symmetry axis. The 10-fold symmetric pattern is one of the signatures of an icosahedral quasicrystal. (Adapted from L. Bindi et al., *Proc. Natl. Acad. Sci. USA* **118**, e2101350118, 2021.)

wasn't clear. Levine and Steinhardt identified why the fivefold symmetry in Penrose's tiling was possible and then showed how to generalize the concept to other symmetries and to three-dimensional solids: by replacing periodic spacing between tiles or atoms with quasiperiodic spacings, in which at least two different spacings repeat with frequencies whose ratio is irrational. The theorists also demonstrated a possible 3D quasiperiodic solid composed of polyhedral units and with icosahedral symmetry, shown in figure 1b. They hypothesized that the same may be possible for some combinations of atoms, which they dubbed quasicrystals.

Materializing the concept

The idea of quasicrystals took off in 1984 when Dan Shechtman of the Technion–Israel Institute of Technology and his collaborators accidentally discovered a puzzling aluminum–manganese alloy with icosahedral symmetry. (See PHYSICS TODAY, December 2011, page 17.) The interpretation of the discovery was controversial at first because the alloy's imperfections, such as defects and chemical disorder, left room for alternative explanations—for example, an intergrowth of multiple crystals or a glass made of icosahedral clusters. The issue was settled in 1987 when An-Pang Tsai of Tohoku University and his collaborators discovered what's generally considered to be the first definitive quasicrystal, made of aluminum, copper, and iron.

Since then, more than 100 quasicrystals have been synthesized in the laboratory by melting and mixing precise ratios of different elements and then cooling them. Those experiments incited new debates: Why do quasicrystals form? Are they truly stable forms of matter like crystals? If they are stable, shouldn't they be found somewhere in nature?

Those questions inspired our team's decade-long search for natural quasicrystals. It culminated in Chukotka in far eastern Russia where they were discovered in a 4.5-billion-year-old meteorite, as old as our solar system. Years of study revealed that the quasicrystals formed from a high-pressure shock in a collision between asteroids in outer space. To prove the hypothesis, researchers re-created the meteorite's minerals in the lab through high-pressure shocks produced by firing a high-speed projectile at a stack of materials.

That experiment led researchers to ask whether quasi-

crystals could lurk in remnants of other shock phenomena, such as an atomic blast. So the pursuit of quasicrystals led us to the Trinity test. One of us (Bindi) read an article by Nelson Eby of the University of Massachusetts Lowell and his collaborators that described red trinitite. That fusion of natural sand and human-made metals at high pressures and temperatures seemed a promising place to look for quasicrystals. Each red trinitite sample includes a mix of tiny grains with different compositions and structure. The challenge was to identify possible quasicrystal candidates in 10 μm fragments, extract them by hand, and search their x-ray diffraction patterns for a telltale fingerprint of a quasicrystal: sharp spots arranged in a pattern with the symmetries of an icosahedron.

After many failed attempts, we found the beautiful sample of icosahedral quasicrystal shown in figure 2. It had the same symmetry as the alloys in Shechtman's and Tsai's labs decades earlier and the quasicrystal discovered in the meteorite found in Russia. But the sample from the atomic blast had a composition of silicon, copper, calcium, and iron that had never been seen before and was not predicted to form a quasicrystal. It was also the oldest known human-made quasicrystal, with a precise time of creation that's indelibly etched in human history.

Finding quasicrystals in the material formed in the first atomic blast demonstrates that extreme conditions—for example, asteroidal collisions, shock waves, and atomic blasts—are able to produce novel compositions of quasicrystal. Those discoveries demonstrate that quasicrystals can be robust, possibly even stable, phases of matter. They also suggest new pathways to synthesize quasicrystals that may have useful electronic, phononic, and elastic properties derived from their unique sets of symmetries.

Additional resources

- Università degli Studi di Firenze, "Quasicrystals in the first nuclear explosion" (17 May 2021), www.youtube.com/watch?v=app=desktop&v=AkuLjTIUO7A&t=28s.
- P. J. Steinhardt, *The Second Kind of Impossible*, Harvard Science Book Talk (14 April 2020), www.youtube.com/watch?v=IZEiaF_-FeA.
- P. J. Steinhardt, "Natural Quasicrystals," article collection, <https://paulsteinhardt.org/natural-quasicrystals-2>.

BACK SCATTER

Nuclear surveillance from space

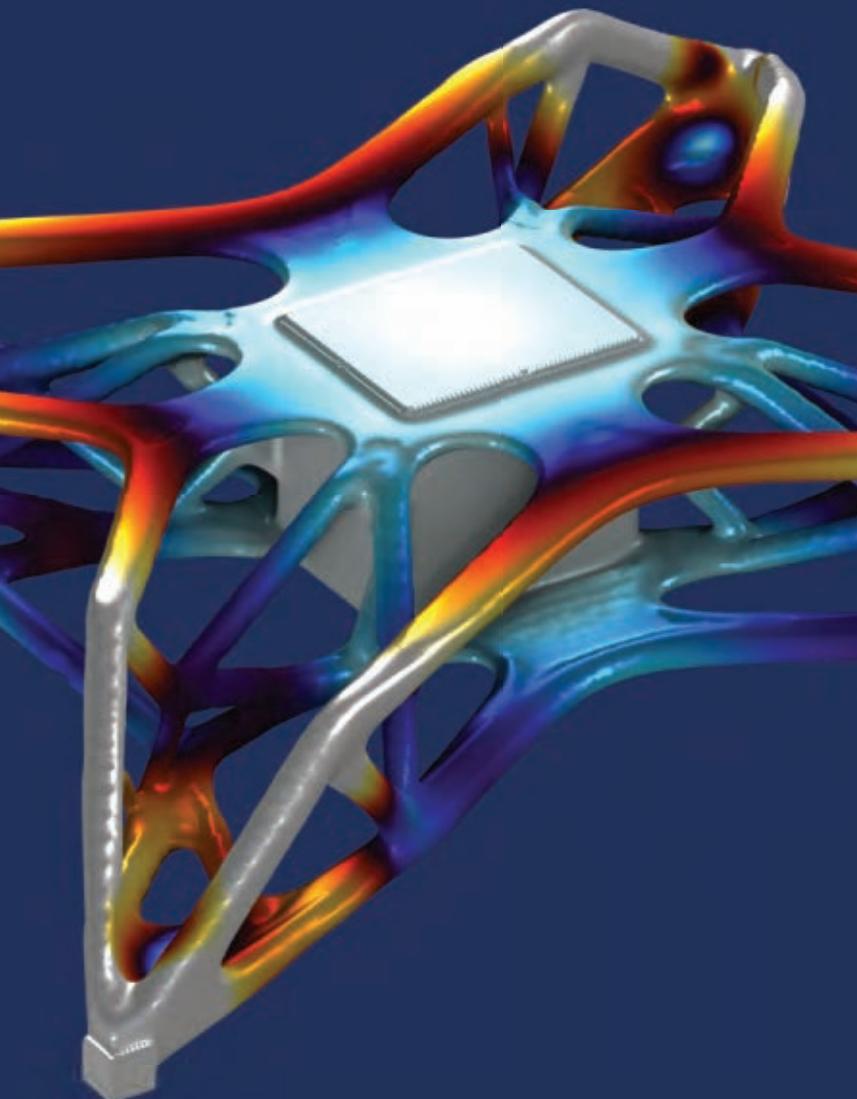
To track the spread of nuclear weapons, nonproliferation experts need to identify new activity at reactors and various other nuclear-related sites. Some of the latest space-based observations of Earth's surface may offer just what the experts need. Steven De La Fuente, a graduate research assistant at the Middlebury Institute of International Studies at Monterey in California, produced the composite image shown here. It was made using high-quality, rapidly updated near-IR data from the satellite-data company Planet Labs and two sets of radar data collected by the Sentinel-1 satellites as part of the European Space Agency's Earth observation program. The image shows North Korea's Yongbyon nuclear-science center as it looked in late February 2021.

The vegetation in the surrounding rural countryside (green) strongly reflects the near-IR band of light and is thus easily separated visually from the bare mountainsides (pink, on the right) and the nuclear site's buildings (pink, on the left), which produce a distinct polarization signature in the two radar bands used in the analysis. Algorithms designed to distinguish rural areas from suburban areas have previously struggled to separate the two regions in optical images. Machine-learning techniques appear more capable of differentiating between the two, however, when the data used are invisible to the human eye. (Image courtesy of Jeffrey Lewis. Radar data from Copernicus Sentinel-1; near-IR data provided by Planet Labs PBC.) —AL

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