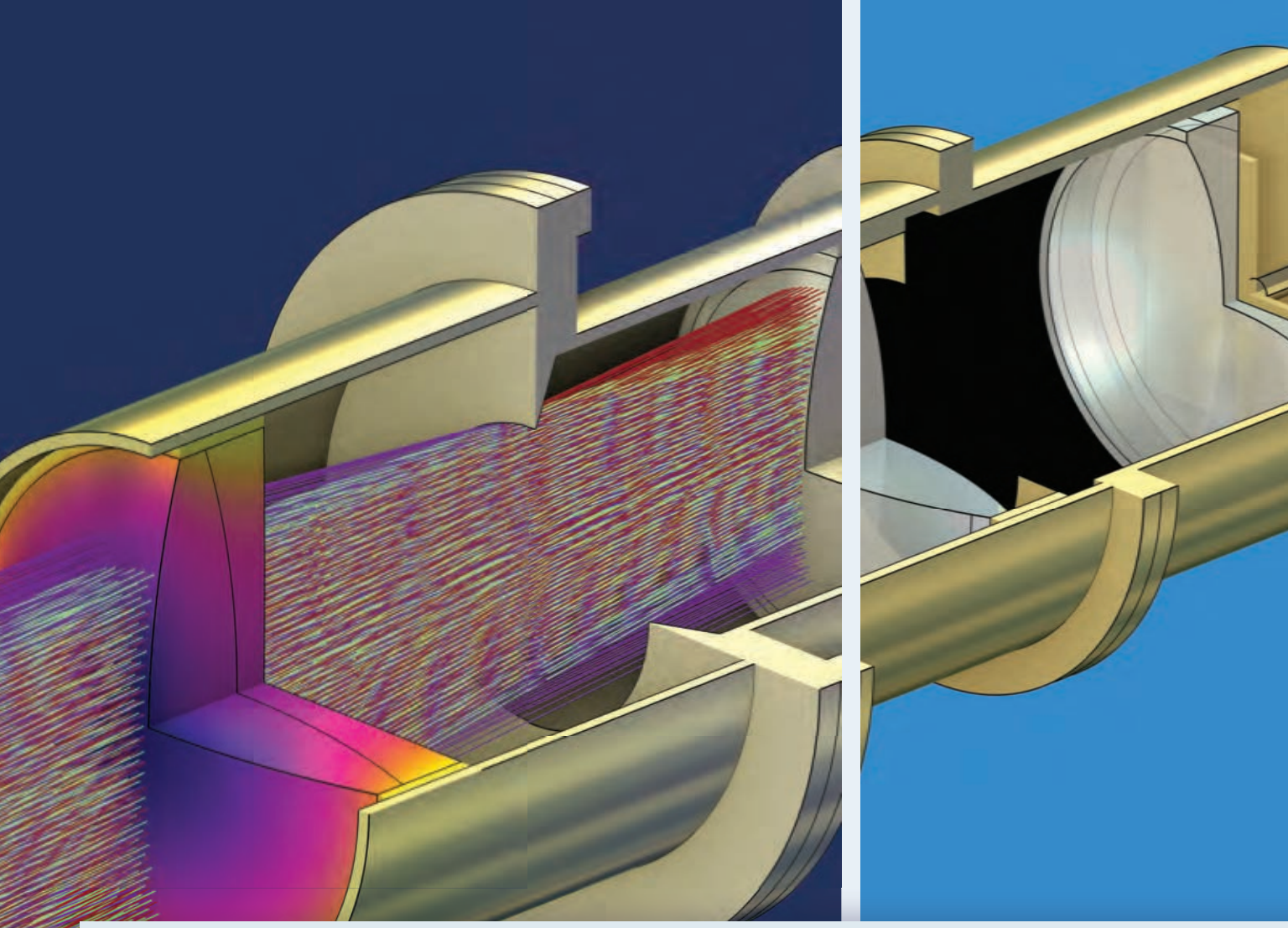


Shine Brighter in Optical Design

with COMSOL Multiphysics®

Multiphysics simulation drives the innovation of new light-based technologies and products. The power to build complete real-world models for accurate optical system simulations helps design engineers understand, predict, and optimize system performance.

» *comsol.com/feature/optics-innovation*

COMSOL

PHYSICS TODAY
June 2023 • volume 76, number 6
A publication of the American Institute of Physics

Nanophotonics' bright future

Optical analogues to NMR

John Herschel's reform of science

An alpha-particle mystery

rf/microwave instrumentation

Other ar companies: modular rf • sunar rf motion • ar europe

We're with you all the way

A Kilowatt On Your Desk

More Compact Power Than Ever Thought Possible

Generate 200 V/m up to 1 GHz with a single phase input voltage.

For more information on AR Amplifiers, visit www.arworld.us

Or contact us at info@arworld.us & 215.723.8181

PHYSICS TODAY OCTOBER 2023

MARK YOUR CALENDAR

5TH ANNUAL CAREERS & RECRUITMENT ISSUE

Enhanced exposure opportunities for recruiters and exclusive careers-focused content for job seekers across the physical sciences

For more information on advertising in the special issue & online, contact PTjobs@aip.org.

Voltage Controlled Current Source

Your science. Our tools. SRS.

- Sources/sinks AC & DC current
- Analog voltage control input
- 1 nA/V to 50 mA/V gain
- 200 kHz bandwidth
- ±50 V compliance
- Ultra-low noise design
- RS-232 & optical fiber interfaces

The Model CS580 Voltage Controlled Current Source creates new capabilities for researchers needing an ultra-low noise current source in a flexible, easy to use instrument.

The CS580 is a natural companion to sensitive AC instruments such as lock-in amplifiers, providing a easy way of generating precision current directly from an AC or DC control voltage.

The CS580 is a welcome addition to any research lab studying semiconductors and transport phenomena, superconductivity, or nanotechnology, to name just a few.

Model CS580 ... $3395 (U.S. list)

SRS Stanford Research Systems
www.thinkSRS.com • Tel: 408-744-9040

www.thinksrs.com/products/cs580.html

Time to get excited.

Advance your research faster with the best lock-in amplifiers for periodic signal detection, control and analysis.

Which frequency range matches your requirements?

MFLI
DC to 500 kHz / 5 MHz

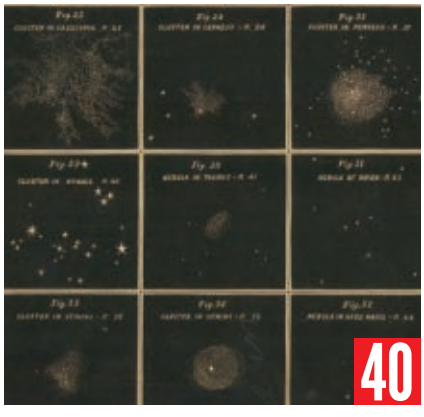
HF2LI
DC to 50 MHz

UHFLI
DC to 600 MHz

New GHFLI
DC to 1.8 GHz

New SHFLI
DC to 8.5 GHz

Zurich Instruments

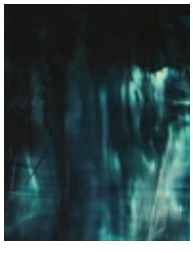


PHYSICS TODAY

June 2023 | volume 76 number 6

FEATURES

SPECIAL FOCUS ON OPTICAL ENGINEERING



ON THE COVER: In this detail of the 2017 painting *That We May See in a Chamber Things That Are Not 6* by Kate Nichols, silver nanoparticles are laid atop glass. Today's uses of metal nanoparticles go well beyond art. In their article starting on **page 24**, Jennifer Dionne, Sahil Dagli, and Vladimir Shalaev describe the underlying physics behind using plasmonic and other nanophotonic resonances for sustainable chemical manufacturing and pathogen detection, among other practical applications. (Courtesy of Kate Nichols, artist, and Donald Felton, photographer.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

NASA/JPL-CALTECH

Mars funding

The costs for NASA's planned mission to retrieve samples of Martian regolith and return them to Earth are rising rapidly. In the aftermath of newly announced delays to other missions, criticism that the Mars mission is siphoning money from other projects is building among scientists and members of Congress.

physicstoday.org/Jun2023a

SOUTHERN COMPANY/TERRAPOWER

HEU-fueled reactor

Along with two industry partners, the Department of Energy is planning to build a research reactor that runs on weapons-grade uranium, the agency revealed in a recent document. The proposed experiment seems to clash with DOE's long-standing policy that the fuel not be used for new civilian projects.

physicstoday.org/Jun2023b

GREG OTTINO

Unionization efforts

Federal and state legislation, along with the pandemic, have set the stage for graduate students to push for contracts with their universities that guarantee fair wages, health care, and protection from harassment. Rachel Berkowitz talks with some of the physics students involved in efforts across the country.

physicstoday.org/Jun2023c

Physics Today (ISSN 0031-9228, coden PHTOAD) volume 76, number 6. 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.

PHYSICS TODAY

www.physicstoday.org

DEPARTMENTS

South Carolina State University

Orangeburg, SC
www.scsu.edu

Assistant Professor of Health Physics

The Department of Biological and Physicals Sciences at South Carolina State University seeks candidates to fill the assistant professor of health physics opening. The candidate will teach graduate and upper-level undergraduate courses for the Master of Science in Energy and Environmental Studies and undergraduate courses for the radiation concentrations for the Bachelor of Science in Chemistry and Physics at SC State on the main campus located in Orangeburg, South Carolina. These will be both in-person and online courses. In addition, the candidate will be expected to advise and recruit students, develop and improve programs, develop and administer online courses, conduct scholarly research and participate in committee assignments.

Apply Here

Job No: 492519

Minimum Requirements

A doctorate degree in Physics or a closely related field is required. The candidate must have a research base in the area of radiation science area. Must have a solid commitment to graduate teaching and student recruitment, program improvement and development, scholarly research activity, excellent communication skills, and personal concern for the student.

SUPPORT SCIENCE

At AIP Foundation, we're passionate about the impact of the physical sciences community, and with your support, we can strengthen our efforts to preserve the history of physics, foster future generations of physicists, and create a more diverse and equitable scientific enterprise.

AIP Foundation is an independent not-for-profit corporation launched in 2020 to generate philanthropic support for the American Institute of Physics, focused on history and student programs, our library, and actions to advance diversity.

Show your support of the physical sciences community through the following AIP programs:

- **Center for History of Physics**
- **Niels Bohr Library & Archives**
- **Society of Physics Students**
- **Sigma Pi Sigma**
- **Diversity Action Fund**

AIP Foundation

To learn more about how you can support AIP programs visit **foundation.aip.org**

Another way to prevent cheating

ISTOCK.COM/PHEELINGS MEDIA

I read with great interest Toni Feder's report on efforts by the teaching community to prevent cheating (PHYSICS TODAY, August 2022, page 25). I would like to point out what I believe is an opportunity for learning institutions to act against predatory sites that host stolen test materials.

A safe harbor provision in the Online Copyright Infringement Liability Limitation Act (OCILLA) protects such sites if they don't know that they are hosting copyrighted material. According to the law, the sites can lose that protection if the copyright owner notifies them of the infringement. That requires a serious effort from the affected party to find the materials at the sites and notify the hosts. In my case, I have stopped doing that for a simple reason: Even if the materials are removed, they are usually back up in a matter of days as other students repost them.

But OCILLA also indicates that the sites may be liable if there are red flags that they ignored. Students often upload their problems in the form of screenshots or pictures, which advanced sites make searchable by scanning the text. That means that the next time a similar picture is uploaded, the sites have the technology to detect material that the instructor has already flagged as copyrighted. By accepting the material a second time, they may be violating the red-flag criterion.

I hope that colleges and universities explore that legal route as a way to reduce the unbearable levels of cheating that has put online education in serious trouble.

José Menéndez
(jose.menendez@asu.edu)
Arizona State University
Tempe

Laudable lectures

In William Thomas's commentary "Elitism in physics: What happens when the profession's cultural scaffolding comes down?" (PHYSICS TODAY, September 2022, page 10), the author notes that Richard Feynman's famous introductory undergraduate course "proved by his own admission to be of dubious pedagogical value." Indeed, in his preface to the *Feynman Lectures on Physics*, Feynman noted that he didn't think he "did very well by the students." But as someone who attended Caltech in the 1960s, I'd like to note that I—and it seemed many of my classmates—did not hold that same opinion.

In the 1960s and 1970s, the *Feynman Lectures* formed the basis of Caltech's two-year sequence in introductory physics. I entered the university as a freshman in the fall of 1966. During the first quarter of the year, the freshman physics lectures (based on the *Feynman Lectures*) were delivered by Robbie Vogt, a young and charismatic member of the faculty and eventual provost of Caltech. As Vogt concluded his final lecture of the term, we freshmen—all 210 of us—rose as one for a standing ovation. The thunderous applause continued for well over five minutes, with Vogt repeatedly disappearing into a room behind the blackboards only to reappear for "curtain calls."

The succeeding five quarters were taught by five other faculty members: Edward Stone, a prominent cosmic-ray physicist; Barry Barish, a corecipient of the 2017 Nobel Prize in Physics; Robert Leighton, a coauthor of the *Feynman Lectures* and author of *Principles of Modern Physics*; Jerry Pine, a high-energy experimentalist turned biophysicist and science educator; and John Bahcall, a theorist who established the feasibility of the Bahcall–Davis solar-neutrino experiment. All were treated to warm rounds of applause at the conclusion of their respective quarters of instruction. I consider Feynman's physics lectures one of

the high points of my undergraduate days at Caltech.

Arden Steinbach
(ardensteinbach@gmail.com)
Sudbury, Massachusetts

Mavericks who failed

I enjoyed Tomasz Durakiewicz's commentary in the November 2022 issue of Physics Today (page 10) about the benefits of being a maverick. He gave some wonderful examples of mavericks who succeeded, but what about those who failed? Some failed for bad reasons, such as trying to create perpetual motion machines. But some—such as Albert Michelson and Edward Morley in their famous experiment—failed for good reasons, and the world learned something from their failure.

I spent the bulk of my career doing research in industry. A director of research at one lab used to say, "If we're succeeding all the time, we're not trying hard enough." The question then becomes how does one reward the "good" failures. I don't think he ever figured that out. Has physics?

Alan Karp
(alanhkarp@gmail.com)
Palo Alto, California

Hubble has more time

In the article "Electric propulsion of spacecraft" by Igor Levchenko, Dan Goebel, and Katia Bazaka (Physics Today, September 2022, page 38), the authors mistakenly refer to the *Hubble Space Telescope*'s "hydrazine thrusters."

As project scientist for *Hubble* from 1972 to 1983—the period of its creation as a real piece of hardware, its design, and its early phases of construction—I clearly recall that thrusters of any sort were not incorporated. That was because UV performance could potentially be lost through contamination by any gas used in thrusters.

Levchenko, Goebel, and Bazaka mention that "the telescope could potentially spiral back to Earth by 2028." Without a dedicated mission of another spacecraft to raise the orbital altitude of *Hubble*, the telescope will eventually decay into the upper atmosphere of Earth. That will cause *Hubble* to lose control of its pointing before finally making a fiery return. That is well in the future, with project leaders now estimating that there is a 10% chance that reentry will occur by October 2034, a 50% chance by July 2037, and a 90% chance by October 2045.

C. R. O'Dell
(cr.odell@vanderbilt.edu)
Vanderbilt University
Nashville, Tennessee

Superdeterministic loophole

In her excellent Physics Today report "Physics Nobel honors foundational quantum entanglement experiments" (December 2022, page 14), Heather Hill discusses how the laureates closed loopholes in the interpretation of entanglement. She rightly concludes that the freedom-of-choice loophole remains open, but she describes it incorrectly, writing, "Taken to an extreme, the loophole can suggest that every event in all spacetime was determined by the initial conditions at the Big Bang, an idea called superdeterminism."

Actually, that idea—that later events can be determined by earlier ones, and vice versa—is simply called determinism. There is a centuries-old philosophical tradition called compatibilism, which holds that even in a deterministic world we are free agents if we can do as we like without constraint. In the context of the Bell experiment, a compatibilist would say that experimenters are free to choose how to set their polarizers (for example, using the birthday of their grandparents or light from distant quasars), determinism notwithstanding.

Superdeterminism is much more subtle than that (and as a result is typically misunderstood or grossly oversimplified in the media). It is based around the following question: Do the laws of physics allow us to vary the Big Bang initial conditions in such a way that we could describe a hypothetical universe where the same pair of entangled particles—that is, with the same hidden variables—are measured with differently set polarizers? Such a universe is counterfactual, and superdeterminism describes an emergent restriction on such counterfactual measurements imposed by suitably formulated putative laws of quantum physics.[1,2]

No experiment to date has closed the superdeterministic "loophole." Indeed, we are still searching for a realistic experimental protocol that can test it. We will get there one day, hopefully in the not too distant future, but it will likely not be via a Bell experiment.

References

1. T. N. Palmer, *Proc. R. Soc. A* **476**, 20190350 (2020).
2. S. Hossenfelder, T. Palmer, *Front. Phys.* (2020), doi:10.3389/fphy.2020.00139.

Tim Palmer
(tim.palmer@physics.ox.ac.uk)
University of Oxford
Oxford, UK PT

CONTACT PHYSICS TODAY

Letters and commentary are encouraged and should be sent by email to **ptletters@aip.org** (using your surname as the Subject line), or by standard mail to Letters, Physics Today, American Center for Physics, One Physics Ellipse, College Park, MD 20740-3842. Please include your name, work affiliation, mailing address, email address, and daytime phone number on your letter and attachments. You can also contact us online at **https://contact.physicstoday.org**. We reserve the right to edit submissions.

A family of two-dimensional conductors comes into bloom

MXenes, a promising group of atomically thin materials, can now be fabricated without harsh acids and with little waste.

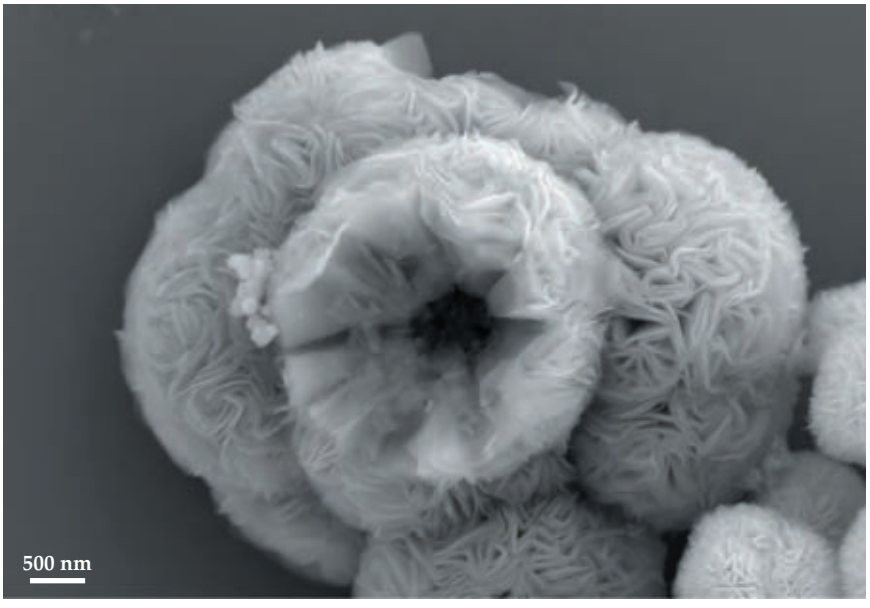


FIGURE 1. LAYERS of the material Ti_2CCl_2, synthesized through a new chemical vapor deposition reaction, form hierarchically structured, flowerlike spheres. Directly synthesizing Ti_2CCl_2 and other MXenes from their constituent elements could pave the way for a broader campaign of basic research on the two-dimensional conductive materials. (Courtesy of Di Wang.)

True metals are rare among two-dimensional materials. Ordinary metals such as gold, when shaved down to atomically thin dimensions, cease to conduct electricity: Their structures deform in a way that breaks the degeneracy of their valence and conduction bands. Even graphene, the electrical conductor of choice for 2D circuits and electrodes, is merely a semimetal, not a metal. The material lacks a bandgap, but its valence and conduction bands touch at only a few discrete points, so the quantum states that contribute to charge transport aren't as plentiful as they might be.

A notable exception is a class of materials called MXenes (pronounced "Maxines," like the name) with the general formula $M_{n+1}X_n$, where M is a transition metal and X is carbon or nitrogen. With their trellis-like structure of alternating M- and X-atom layers, MXenes are slightly thicker than the one-atom-thin graphene, but not so thick to disqualify them from behaving two-dimensionally. And their sturdy scaffold of covalent chemical bonds is robust enough to resist the conduction-destroying deformation that afflicts ordinary metals.

First synthesized in 2011, MXenes have some extraordinary properties, including an exceptional ability to block electromagnetic waves. And with their combination of electrical conductivity, high surface area, and chemical versatility, they're natural fits for applications in catalysis and energy storage. But despite their promise, they've been difficult to make cleanly and safely.

Now the University of Chicago's Dmitri Talapin and colleagues are working to change that. They've developed two new MXene synthesis routes that could help streamline basic research and open the door to more practical industrial manufacture.[1] Figure 1 shows one of their products.

"We're not saying that this is 'better' than the existing methods," says Talapin. "That's yet to be seen. But it opens up new ways of studying what's possible and what's not possible. It's a new way of thinking about MXenes."

Strange routes

When the right bulk precursor exists, making 2D materials is easy. Graphite, for example, consists of layers of graphene that weakly cling together through van der Waals forces. The layers are readily peeled apart: As Andre Geim and Konstantin Novoselov showed in 2004, isolating graphene monolayers takes nothing more than a piece of ordinary sticky tape.

And it's not just graphene. Other bulk van der Waals materials exist, and they, too, can be separated into their component layers using sticky tape or other tools that are nearly as simple. (See, for example, Physics Today, July 2017, page 16.)

But MXenes have allowed for no such treatment. They're made from bulk materials called MAX phases, in which MXene-structured layers are interspersed with layers of a third element A, often aluminum or silicon. The A atoms are bound to their neighbors more weakly than the M and X atoms are bound to each other, but they're still held in place by covalent or metallic chemical bonds, which are much stronger than van der Waals forces. The material preferentially fractures along the A-atom plane, but it can't be mechanically broken up into MXene monolayers.

The MAX phases have been known since the 1960s as interesting materials in their own right: soft, electrically conducting ceramics whose layered structure gives them anisotropic properties. In the early 2000s, Drexel University's Yury Gogotsi and colleagues showed that they could chemically remove the M and A atoms from a carbide MAX phase to obtain so-called carbide-derived car-

bon, which had useful patterns of porosity.[2] Then, in 2011, Gogotsi and colleagues found that bathing a MAX phase in hydrofluoric acid could remove just the A atoms.[3] Their result was flakes of Ti_3C_2, the first MXene.

"But the discovery came at the wrong time," says Gogotsi. Geim and Novoselov had just been awarded the Nobel Prize (see PHYSICS TODAY, December 2010, page 14), and graphene was the 2D material of the day, especially among physicists. Understandably, sticky-tape experiments had more appeal than working with HF, an acid so corrosive that it even dissolves glass.

The uptake of MXenes remained slow outside the materials science and chemical engineering communities. Even Talapin, a chemist, calls his group a "rare example" of nonengineers working on the materials. "We came by strange routes in the beginning," he says. His group's expertise is in colloidal nanoparticles, and in 2016 he and his colleagues showed that with a molten salt as a solvent, they could make colloidal materials that weren't possible in other liquids. "From there, it was an easy step to ask, 'Can you make colloids in liquid metals?'" he says. "We arrived at MXenes as a model system to study van der Waals interactions in liquid metals, and then we realized that there was a huge opportunity in synthesis."

Back to the future

For researchers unafraid of dangerous chemicals, the MAX-phase synthesis of MXenes is simple enough. "You just add hydrofluoric acid and stir," says Di Wang, a PhD student in Talapin's group and lead author on the new paper. But it's limited in which MXenes it can produce. With MAX phases that have weaker-than-average M–X bonds, including most of those whose X atom is nitrogen, the HF doesn't always stop at removing the A atoms: It breaks apart the M and X atoms too, leaving degraded MXenes or none at all.

Furthermore, the use of harsh acids makes it harder for MXenes to find their way out of the lab and into mass-produced consumer products. It's not that the chemical industry shies away from HF—it's used in producing Teflon, for example—but the hazard is a significant factor in any cost analysis.

Talapin and colleagues took the approach of synthesizing MXenes directly from their constituent atoms, rather than starting with a structure with too many atoms and etching away the excess. "There's nothing we did that couldn't have been discovered many years ago. The work that inspired us was published in 1986," says Talapin, referring to a paper by Iowa State University's John Corbett and colleagues, who created layered yttrium and zirconium compounds out of a few simple ingredients.[4]

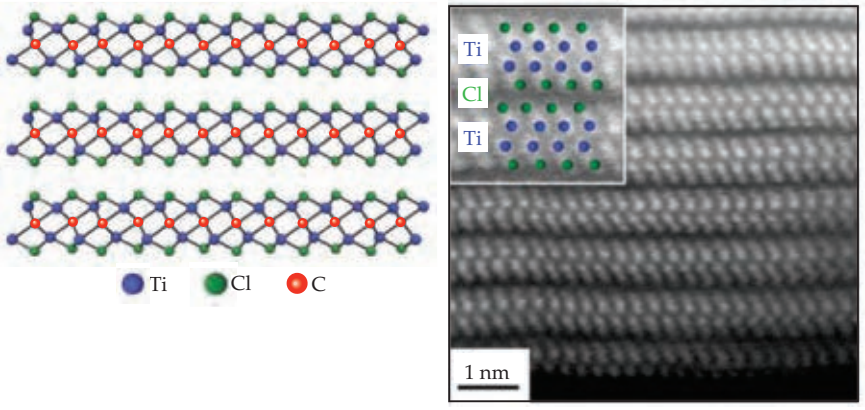


FIGURE 2. ATOMIC STRUCTURE of a MXene. On the left is a ball-and-stick diagram of three layers of Ti_2CCl_2. On the right is an electron micrograph of the same structure showing the positions of the titanium and chlorine atoms. (Adapted from ref. 1.)

"We wanted to study the zirconium and yttrium reactions," Talapin continues. "But the titanium MXenes are the most studied, so there's the most information out there about whether we're making them the right way or not." In analogy with Corbett's formulation, the researchers combined titanium metal, titanium tetrachloride, and graphite and baked them together at high temperature. The result was a van der Waals layered material with the formula Ti_2CCl_2, as shown in figure 2.

The presence of Cl atoms doesn't mean that the structures aren't MXenes. To the contrary, MXenes are almost always covered on both sides with some other atom or molecule, called a surface termination. In contrast to most other 2D materials, whose properties are radically disrupted by surface reactions, MXene surface terminations gently tune the MXene properties by adjusting the energy of the conduction-band electrons.

In fact, it's notable that the synthesis produces Cl as the only surface termination. When HF etches away the A atoms from MAX phases, it leaves MXenes covered with an unpredictable mix of fluorine atoms, oxygen atoms, and hydroxyl groups. "From the MAX phases, we get MXenes with poorly controlled surface terminations when using aqueous chemistry," says Gogotsi. "Talapin and colleagues' direct synthesis is much cleaner in that regard."

Runaway carpets

Two ingredients in the direct synthesis, titanium metal and graphite, are both solid at room temperature. (The third, $TiCl_4$, is a liquid with a low boiling point.) Talapin and colleagues realized that they could make MXenes in a way that's more compatible with device manufacture if they swapped graphite for methane as their carbon source, left Ti as the only solid reactant, and thereby gave the MXenes a single solid support on which to grow.

That type of process, called chemical vapor deposition (CVD), is widely used to produce materials in both two and three dimensions. But CVD synthesis of MXenes had never been demonstrated before. "So there weren't many papers to help us or tell us what to expect," says Wang.

Intuition would suggest that a CVD reaction should be self-limiting: When the reactants run out of available surface, the reaction should stop. But that's not what happened. The MXenes first grew perpendicularly up from the Ti surface like a carpet, not flat on top of it like a laminate floor. Once the carpet covered the whole surface, it buckled upward, and the reaction kept going. The result was the spherical flowerlike structures shown in figure 1, with MXene petals

emanating out in all directions.

The flowers aren't just nice to look at. Because the MXene sheets are oriented perpendicular to the outer surface, they're also ideal for applications in energy storage. To store and release energy quickly, batteries and electrochemical capacitors need high-surface-area electrodes that can hold large numbers of lithium and other ions. (See the article by Héctor Abruña, Yasuyuki Kiya, and Jay Henderson, Physics Today, December 2008, page 43.) With the help of Chong Liu and her electrochemistry research group (also at the University of Chicago), Talapin and colleagues showed that the CVD-synthesized MXenes worked well.

Strength in diversity

The sheer number of MXene structures is often touted as one of the family's greatest advantages.[5] Between all the possible M elements, X elements, sheet thicknesses, and surface terminations, there are hundreds of possible MXenes. For MXenes that are solid solutions of two or more metal elements, there are countless more options.

The titanium–carbon MXenes are by far the most studied, so that's what Talapin and colleagues focused on for their demonstration. But the researchers also showed that their synthesis schemes can produce many more MXene types, including several that have never been seen before, such as nitride MXenes that can't survive the HF etching method.

What does the world need with so many MXenes? One answer that's already been explored has to do with MXenes' use as solid-state catalysts. When a surface facilitates a chemical reaction between atoms or molecules adsorbed onto it, the specific surface properties, such as the spacing between atoms and the availability of electron states, matter a lot. The more MXenes there are, the more reactions they can possibly catalyze.

Beyond that, both Talapin and Gogotsi opine that a large part of MXenes' potential remains undiscovered, and the exploration could benefit from new scientific perspectives. In particular, the role of the surface terminations in tuning MXene properties creates an unusual interface between solid-state physics and molecular chemistry, with room for input from researchers in both fields.

"MXenes are metals that behave like semiconductors," says Gogotsi, referring to their combination of conductivity and tunability. "By chemically modifying the surface, you can modulate the optical and electronic properties. There's an exciting demand for the physics community to come explore, to check the existing predictions and make new predictions."

"The engineering side is well on track," says Talapin. "There are brilliant people working in this space, with lots of ideas of what MXenes can be used for. But as the field switches from simpler applications to more complicated ones, the diversity of properties will be more important. The next wave of discoveries will surely come from making MXenes more familiar to physicists and chemists, who can add chemical and physical rigor and deep physical insights. I see huge opportunities here."

Johanna Miller

References

1. D. Wang et al., *Science* **379**, 1242 (2023).
2. Y. Gogotsi et al., *Nat. Mater.* **2**, 591 (2003).
3. M. Naguib et al., *Adv. Mater.* **23**, 4248 (2011).
4. S. J. Hwu et al., *Inorg. Chem.* **25**, 283 (1986).
5. A. VahidMohammadi, J. Rosen, Y. Gogotsi, *Science* **372**, 1165 (2021).

Theory and experiment disagree on alpha particles

Electron-scattering experiments on excited helium nuclei open questions about the accuracy and sensitivity of state-of-the-art nuclear models.

Although the helium nucleus has just four nucleons—two neutrons and two protons—theoretical models fail to replicate some of its properties. Or so Sonia Bacca, now at the Johannes Gutenberg University Mainz in Germany, and her colleagues discovered in their 2013 calculations.[1] Helium nuclei, also known as alpha particles, are a popular testing ground for nuclear models because they are relatively simple while still capturing essential nuclear phenomena, and theory replicates their ground state pretty well.

But excited states were another matter. The researchers' calculations of a quantity related to how the nucleons are arranged in the alpha particle's first excited state didn't match the values inferred from electron-scattering experiments. The experiments were primarily from the 1970s, however, and the uncertainties were large.[2] In the intervening decades, the techniques and technologies—particularly detector sensitivity—had improved dramatically, but that property of the humble helium nucleus hadn't been explored experimentally since 1983.

"There are many things which experimentalists can look at," says Concettina Sfienti, a fellow faculty member of Bacca's at Johannes Gutenberg University Mainz, "and if you don't have a theory available or a hint that it might be interesting to look again, then you don't." But in light of the 2013 calculations that seemed to show a disagreement between theory and experiment, Sfienti and her colleagues decided that a new and improved experimental investigation was warranted. Now they and their theory collaborators have confirmed the disagreement and charted theoretical and experimental paths to suss out its origin.[3]

An effective method

The bulk of a nucleus's properties, including size and binding energy, arise from interactions among nucleons, which are themselves derived from the complicated web of strong interactions between constituent quarks and gluons. Early nuclear models were phenomenological, and their uncertainties were hard to assess. But that changed with the introduction of effective field theories.

Effective field theories show up in many topics—including particle physics, statistical mechanics, condensed-matter

physics, and general relativity—and are written to capture the given system's behaviors at a certain length or energy scale while ignoring or approximating those at other scales. Such theories transform burdensome calculations into expansions in a set of dimensionless parameters. Many of those expansions are perturbative and can be truncated reasonably at some point.

Introduced in the early 1990s, chiral effective field theory (ChEFT) deals with low-energy quantum chromodynamics, the theory behind the strong interaction. ChEFT creates a hierarchy of nuclear interactions in which those between two nucleons are stronger than those between three, which are stronger than those between four, and so on. In their 2013 paper, Bacca and her colleagues applied a ChEFT that included two-body and three-body interactions to the alpha particle's first excited state, which had been calculated just once before about a decade earlier using a phenomenological Hamiltonian.[4]

ChEFT correctly predicted the helium nucleus's ground-state properties to within 1%, but the theory team realized that wasn't the case for the excited state. The transition from the ground state to an excited state is described by what's known as a transition form factor, which captures information about the shape of the nucleus. The alpha particle's form factor turned out to be highly dependent on the choice of Hamiltonian, and although the older, phenomenological Hamiltonian's form factor nearly fell within the wide error bars of the measured ones, the state-of-the-art ChEFT didn't come close. The form factor could thus serve to distinguish the quality and accuracy of different models—if the experimental uncertainties could be reduced.

FIGURE 1. THE MAINZ MICROTRON, a particle accelerator at the Johannes Gutenberg University Mainz in Germany, includes this experimental hall that features a trio of high-precision spectrometers in red, blue, and green. The setup recently provided improved electron-scattering measurements of the alpha particle's cross section when in its excited state. Those results disagree with theoretical calculations, which opens questions for the nuclear-physics community. (Photo by Alexander Sell, JGU.)

Scattered results

Shortly after Bacca's paper was published, Sfienti and her colleagues in the Mainz Microtron's A1 collaboration decided to tackle the experimental problem using the equipment shown in figure 1. "The issue was to develop the target" for the electron-scattering measurement, says Sfienti. Helium is a gas, so holding it requires a container. But adding another material introduces many other nuclei for electrons to bounce off. The researchers crafted an aluminum cell with walls that were as thin as possible while still able to handle the pressure difference between the cryogenic gas inside and the surrounding vacuum.

Day and night for three weeks about five years ago, the A1 team shot electrons at the helium target. At a range of angles, they detected the number of scattered electrons, as shown in figure 2a, as a function of the so-called missing mass, a quantity that captures the electron's change in energy and momentum relative to elastic scattering from a helium nucleus. As indicated by the large left peak, many of the measured electrons ricocheted off the aluminum container. And many elastically scattered off helium nuclei to produce the large peak around 0 MeV.

Only one in every 10 000 electrons that hit helium excited the nucleus, and that signal, near 20 MeV in figure 2a, needed to be distinguished from the large background—a difficult task. To measure the background signal on its own, the researchers shot electrons at a nearly empty aluminum cell. (There had to be some helium gas, or else the thermal stress on its walls would've broken the cell.) Those measurements were paired with simulations and phenomenological models for elastic and inelastic scattering off aluminum nuclei. Over several years, Sfienti and her

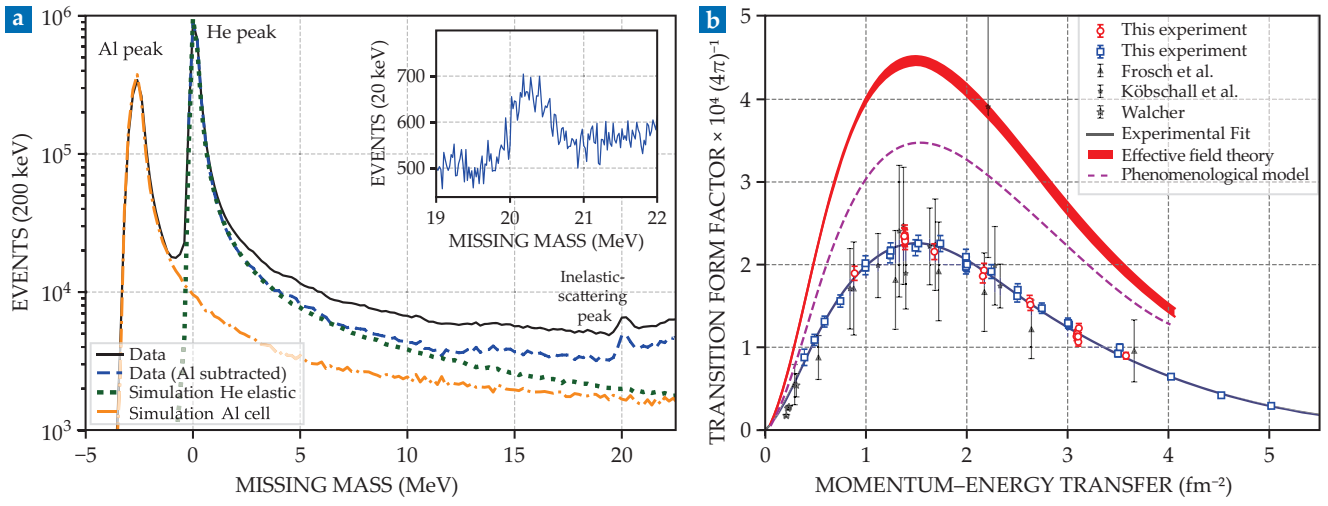


FIGURE 2. ELECTRON-SCATTERING DATA yield information about the helium nucleus's first excited state that conflicts with theory. **(a)** Given in terms of the missing mass, which captures the electron's change in energy and momentum, the two strong peaks at left arise from electrons that bounce off an aluminum container and that elastically scatter off helium nuclei. The inelastic scattering peak from electrons exciting helium nuclei is shown in the inset. **(b)** The associated experimental transition form factor (red and blue data points), which is related to the nucleus's shape, agrees with older experimental data (gray) but with improved error bars. State-of-the-art theoretical models (red and purple curves), on the other hand, predict values as much as twofold greater than those observed. (Adapted from ref. 3.)

colleagues meticulously processed the data to track the fate of the scattered electrons and painstakingly subtract out the unwanted signal.

The measured scattering cross section of the excited state was then converted to the transition form factor. The results, the blue and red data points in figure 2b, agree with older experiments (gray data and error bars) but with dramatically reduced uncertainty. But theoretical calculations (red curve) predict a form factor as much as twofold larger than is observed. "Such a strong disagreement was unexpected," says Sfienti, "and it remains unexplained at this point."

Uncertain future

"It's possible that we missed some piece of the nuclear force," says Bacca, "or that this observable is so sensitive to some detail of the nuclear force, that it's almost impossible to get it right." The wide range of predicted form factors supports the idea that the helium transition is sensitive. Compare, for example, the values predicted by ChEFT (red curve in figure 2b) with those predicted by the older, phenomenological Hamiltonian (dashed purple curve).

"If the form factor is super sensitive to a tiny part of the nuclear force, we would like to know which part," says Bacca, "and we would like to calibrate it to see if we screw up any other observables of the many other nuclei that we can accurately calculate these days." Those nuclei include elements as heavy as lead, although fewer studies have looked at excited states.

The ChEFT calculation has around 25 parameters, none of which were varied in the current study. "We just have to find the knob that allows you to agree with the experiment," says Bacca. The first ones Bacca will tweak are two parameters associated with the three-body contributions. Two-body interactions are well constrained by experiments on two-nucleon systems, but with four nucleons, alpha particles have plenty of three-body interactions at play.

On the experimental side, the Mainz team is constructing a new facility that can perform electron-scattering measurements on gases without the aluminum cell—and its pesky background—by instead using a continuous flow of gas. Reducing the background will reveal more of the lower-energy side of the form factor, which is more sensitive to the state's spatial structure and is thus a better test for the disagreement between the models and experiment. Called the Mainz Energy-Recovering Superconducting Accelerator, the new facility should be built by the end of the year, with the first experiments scheduled for 2025.

Understanding the disagreement between ChEFT and electron-scattering experiments could have implications beyond the field of nuclear physics. Neutron stars, for example, have hot, dense nuclear matter at their cores that prevents their collapse into a black hole (see the article by Jorge Piekarewicz and Farrukh Fattoyev, Physics Today, July 2019, page 30). ChEFT is extensively used to predict and understand the nature of that exotic stellar matter.

Heather M. Hill

References

1. S. Bacca et al., *Phys. Rev. Lett.* **110**, 042503 (2013).
2. R. F. Frosch et al., *Nucl. Phys. A* **110**, 657 (1968); T. Walcher, *Phys. Lett. B* **31**, 442 (1970); G. Köbschall et al., *Nucl. Phys. A* **405**, 648 (1983).
3. S. Kegel et al., *Phys. Rev. Lett.* **130**, 152502 (2023).
4. E. Hiyama, B. F. Gibson, M. Kamimura, *Phys. Rev. C* **70**, 031001(R) (2004). PT

Ultra-stable *DC Voltage Source*

DC205 ... $1995 (U.S. list)

- ±100 VDC range
- True 6-digit resolution
- 1 ppm/°C stability
- 0.0025 % accuracy (1 yr)
- Triggerable voltage scans
- Low-noise design
- Linear power supply

When you need a quiet, stable, high-resolution bias voltage, the DC205 is the right tool. Its bipolar, four-quadrant output delivers up to 100 volts with microvolt resolution and up to 50 mA of current. In 4-wire mode (remote sense), the instrument corrects for lead resistance delivering accurate potential to your load. The DC205's output stability is a remarkable ±1 ppm over 24 hours. With its linear power supply, there is no need to worry about high-frequency noise.

The DC205 can generate triggerable scans when voltage ramping is required. It is also fully programmable over RS-232 and USB, and there's a fiber optic interface for use with the SX199 Optical Interface Controller.

thinkSRS.com/DC205

SRS Stanford Research Systems
Tel: (408)744-9040 • www.thinkSRS.com

Urgent measures are needed to shore up NIST's crumbling facilities

Researchers must cope with flooding, power surges, and other difficulties.

THE LENGTH-SCALE INTERFEROMETER at NIST remains one of the most accurate length-measurement instruments in the world after almost 60 years in use. Since 1983 the SI meter has been defined by fixing the speed of light in a vacuum, and it can be realized independently anywhere. The world's national metrology institutes compare the accuracy of their dimensional measurements about once a decade. The NIST lab in Gaithersburg, Maryland, houses the venerable instrument but lacks modern environmental controls.

In 2019 the definition of the kilogram was changed by international consensus from a cylindrical platinum–iridium object held in a Paris vault to a formula based on the Planck constant. (See "An atomic physics perspective on the kilogram's new definition," by Wolfgang Ketterle and Alan Jamison, PHYSICS TODAY, May 2020, page 32.) In the US, a scale called a Kibble balance is used to precisely calibrate objects, known as artifacts, that represent the kilogram. There the gravitational force exerted on a mass is exactly offset by a force produced when an electrical current is run through a coil of wire immersed in a magnetic field.

To help define the kilogram value with a precision of one part in 10^9—one-fifth the mass of an eyelash, according to NIST scientist Darine El Haddad—NIST's Kibble balance is kept in a Faraday cage located three stories underground on the Gaithersburg, Maryland, campus. Housed inside a vacuum chamber, the instrument is mounted on a floating block to dampen vibration. In 2018 a combination of heavy downpours and a burst pipe overwhelmed the sump pumps and flooded the chamber. It took until March of this year to complete repairs and allow researchers to refloat the floor.

Since the flooding incident, NIST has been unable to investigate a mystery: why the uncertainty of its kilogram measurements nearly doubled from 13 micrograms that researchers had established on solid ground to the 25 micrograms El Haddad and colleagues obtained on the floating block before the flood. "We saw in 2018 that there was a systematic shift in the calibrated mass when the block is floated versus when the block was down," she says.

The next comparison of kilogram values among the world's national standards institutes will be made this fall at the International Bureau of Weights and Measures in Paris. The wider the uncertainty, the less weight is given to each individual nation's contribution to the consensus. El Haddad is hopeful that by that time NIST will be able to halve its uncertainty range back to 13 micrograms.

Flooding isn't the only facilities-related problem El Haddad has to cope with. "Every month we have to deal with something," she says. "If it gets too warm in here, we're going to have to break vacuum and bring fans to ventilate the lab. That happens a few times a year."

Hazardous conditions

Just down the hall from the Kibble balance, a different flood event destroyed a cesium clock in the lab where voltage standards are set. David Newell, group leader of the fundamental electrical measurements group, says the deluge also drenched racks of servers and capacitor banks, creating electrical hazards for personnel. "How do you not step on a land mine when you are going into the lab and powering everything down?" he says.

Newell's group, which includes El Haddad, employs superconducting magnets to establish the quantum Hall resistance standard. Repeated power surges have led to cryostat compressors shutting down and causing 15-tesla magnets to quench and suddenly stop superconducting. "Sometimes the magnets are okay, sometimes they're not," says Newell. On at least two occasions, magnets had to be sent to the manufacturer for repair, a process that can take up to a year.

In the Gaithersburg lab where an almost 60-year-old length-scale interferometer is used to calibrate lengths up to a meter to an uncertainty of only 50 nanometers, inadequate temperature and humidity controls can make such precision impossible, says John Kramar, deputy division chief of the micro-

systems and nanotechnology division of NIST's Physical Measurement Laboratory. A 1 °C temperature change will alter by 1 micrometer the measured length of a meter-long artifact made of Invar, a nickel–steel alloy often used in metrology because of its low coefficient of thermal expansion. "Every time the temperature control goes out, you can't make a measurement," says J. Alexander Liddle, scientific director of the microsystems and nanotechnology division.

Humid conditions can cause rusting of the artifacts that NIST uses to ensure the long-term stability and consistency of its calibrations, and high humidity also shifts the effective wavelength of the laser light used for interferometry. Portable dehumidifiers have been installed in the lab as a stopgap measure.

Deferred maintenance

Over an 11-month period ending in February 2022, 13 failures occurred in the vertical hot water pipes at the 10-story NIST headquarters building in Gaithersburg, flooding 40% of the offices and affecting 85% of staff. "It got to a point where I had to stop playing whack-a-mole and, out of my emergency reserve, fund a project for $5–6 million to replace all the hot water risers," says Skip Vaughn, chief facilities management officer. Buckets to catch dripping water are not an uncommon sight in lab hallways. A four-inch strainer in the high-pressure steam pipe at NIST's central utilities plant failed catastrophically in 2018. "If someone had been there at the time, they would have been severely injured or killed," Vaughn says.

Other mishaps caused by deficient facilities are detailed in a February report by a committee of the National Academies of Sciences, Engineering, and Medicine (NASEM). At NIST's campus in Boulder, Colorado, leaks in a 20-year-old roof destroyed a transmission electron microscope that will cost $2.5 million to replace. The delivery to national laboratories of radiation sensors important to homeland security was delayed by months due to the lack of humidity controls in a Boulder lab. Flooding caused by a corroded fitting in the hydronic system in a Gaithersburg lab building destroyed instrumentation valued at $5.2 million. That doesn't count the massive amount of research time that was lost, says Vaughn.

Scientists from "lots of other metrology institutes come and visit," says Vaughn. "We hear on a recurring basis that they can't believe the incredible results NIST produces, given how bad the facilities are. How many years of that before they start questioning our results?"

"What's happened at our facilities hasn't happened over a short period of time," Vaughn says. Most of the buildings at NIST's Gaithersburg campus date to the early to mid 1960s, when the institute, then known as the National Bureau of Standards, was relocated from Washington, DC.

The infrastructure problems were expected to be discussed at a House Science, Space, and Technology Committee hearing on NIST's fiscal year 2024 budget request. That hearing was scheduled for 10 May, after Physics Today went to press.

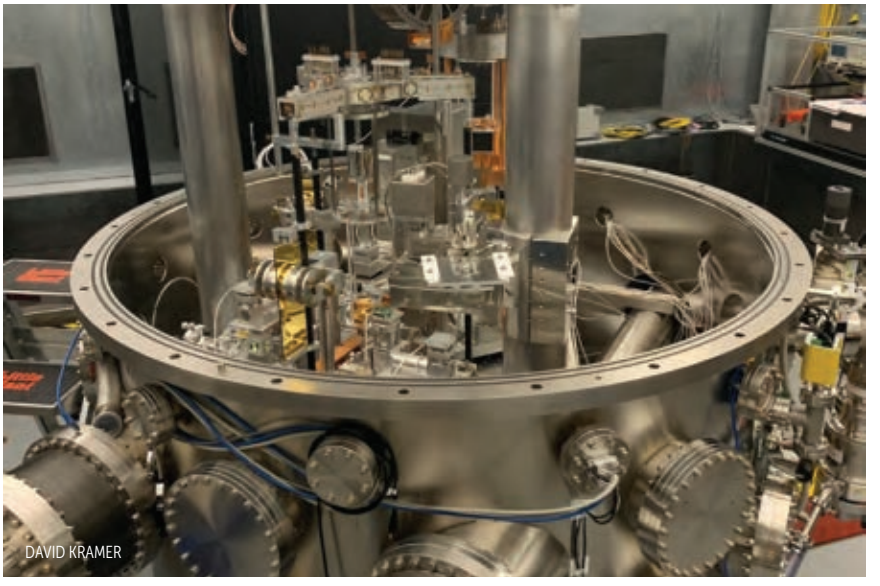
NIST's Boulder campus was completed in the 1950s. But it's far smaller than the Maryland campus, and it doesn't have nearly the number of issues, Vaughn says. Boulder also received funds from the 2009 American Recovery and Reinvestment Act to build a new central utility plant.

Vaughn says the design lifetimes of complex research buildings and central utility plants such as those at NIST are generally considered to be around 30 years. The vast majority of NIST's labs haven't been renovated since they were built.

The original 1962 lab buildings all have single-pane glass, uninsulated exterior walls, and original ductwork. "It's incredibly hard to do things like replacing air handlers and fixing those environmental control issues," Vaughn says.

Maintenance can only fix so much; some issues require full renovations. "The bigger the project, the cheaper the cost," says Vaughn. "Doing a lot of projects piecemeal costs more than doing a whole building, and you still haven't fixed everything."

For the past 20 years, NIST's Visiting Committee on Advanced Technology has warned Congress about "the poor and worsening physical condition and functionality of NIST's facilities, and the impact on its mission," according to the February NASEM report. More than two decades ago, the committee labeled the state of NIST labs alarming and said more funding was critical.



NIST'S KIBBLE BALANCE in Gaithersburg, Maryland, is used to define the SI kilogram. Housed in a vacuum vessel in a lab deep underground, the instrument can be floated to isolate it from vibration. Damage to the flotation mechanism caused by a 2018 flood was repaired in March 2023, allowing researchers to compare the mass values with and without flotation.

The NASEM report warns that deficient facilities "are preventing NIST from achieving its mission, that valuable researcher time is being wasted due to inadequate facilities, and that in many cases NIST facilities are no longer world class." Even if refurbished to their original condition, the report says, they wouldn't be capable of providing the dramatically increased environmental control requirements for metrology that have emerged since the buildings were constructed.

The NASEM report concludes that bringing NIST facilities to acceptable standards will require $300 million–400 million annually for major construction projects for at least 12 years. It recommends another $120 million–150 million each year over the same period for facility maintenance and major repairs.

In FY 2023, NIST received $130 million for maintenance and major repairs but nothing for major construction. President Biden's FY 2024 budget request pending before Congress would double the total for facilities to $260 million, including $50 million for a major renovation of the central utilities plant, $30 million to replace air handling systems in three Gaithersburg buildings, and $49 million for a building expansion in Boulder.

In addition to NIST's budget line for facilities maintenance and construction, a portion of the maintenance expense comes from an institutional support fund, into which NIST's lab programs pay 31% of their budgets. The fund also pays for administrative functions, such as human resources, finance, procurement, safety, and security. The scale of NIST's facility needs is so large that increasing the institutional support rate enough to make meaningful progress on NIST's deferred maintenance "would significantly reduce NIST's scientific and programmatic output to unacceptable levels," says Jason Boehm, NIST's chief of staff.

Construction costs soar

After Congress provided $60 million in both 2016 and 2017 for the modernization of NIST's radiation physics building, Vaughn commissioned an analysis of what else might be accomplished with that amount for annual major construction funding. The study showed that completing his office's top 11 priority projects alone would take "35 years to infinity," he says. That analysis assumed no inflation for five years, followed by 3% annually. If the inflation rate experienced between 2014 and 2019 was used instead, the 11 projects would never be completely funded, he says. In fact, construction costs generally have leapt nearly 50% just in the past two years.

Vaughn concedes that every federal agency could justifiably plead its case for inadequate facilities funding. "But what it really boils down to is what the impact is on your mission as an agency." While office staff can work from home if need be, that's not an option for scientists who conduct research that requires extreme controls and is mission critical. Around 80% of NIST's structures were built for that purpose, he says.

NIST's deteriorating infrastructure has caused a significant loss of productivity, with employees forced to devote much of their time and resources dealing with and designing workarounds to outages, leaks, and other deficient systems. "Everyone spends their research dollars to protect themselves," Newell laments. Using the salaries of affected staff and the amount of time they spend dealing with facilities issues, Vaughn calculates that $138 million worth of R&D is being lost annually. Based on that inefficiency, the funding needed for a complete renovation would be paid back in less than five years.

The situation also affects employee morale. Some researchers have left; others are threatening to quit. "The private sector has all nice new facilities. We're already hearing stories of people at NIST saying don't bother applying here, our facilities suck," says Vaughn.

Congressional staffers whom Vaughn has shown around the NIST campus are sympathetic, but they haven't been encouraging. They have suggested that he explore alternative funding sources, such as public–private partnerships and leasing modern lab facilities. But NIST's leasing authority requires the agency to pay for the entire lease term up front, making that option unaffordable.

The tiny agency's obscurity doesn't help. NIST's budget for lab programs this fiscal year is just under $953 million. "It's very easy for something to get lost in the huge federal bureaucracy," says Vaughn. Even the Department of Commerce, of which NIST is a part, has lots of other bureaus with different needs. "How do you make sure you're not lost in the noise?"

But the functions NIST performs are vital to industry, health care, consumers, and national defense. "NIST is the federal agency you've never heard of that probably has the most impact on your life," Vaughn says. "Pretty much anything you use goes back to NIST."

David Kramer

World-leading rare isotope facility is on line in Michigan

Ion beams from oxygen to uranium contribute to research for applications and fundamental nuclear science at a new DOE user facility.

THE FACILITY FOR RARE ISOTOPE BEAMS at Michigan State University is used for basic science and development of applications. The Department of Energy's 28th user facility, it opened in May 2022 and is ramping up to full power over the next few years.

How many neutrons can you squeeze into a nucleus before it falls apart? What can compressed atomic nuclei in the lab reveal about gravitational-wave sources? What is responsible for the relative abundances of elements in the universe? Can physics beyond the standard model be observed by studying pear-shaped nuclei? Those are some of the questions that researchers hope to explore with radioactive isotopes of unprecedented variety, intensity, and manipulability at the new Facility for Rare Isotope Beams (FRIB). (See the article by Filomena Nunes, PHYSICS TODAY, May 2021, page 34.)

Located at and operated by Michigan State University, the $730 million Department of Energy user facility broke ground about a decade ago and celebrated its on-budget, early completion with a ribbon-cutting ceremony in May 2022.

Bob Laxdal, who is head of the superconducting-RF department and deputy director for accelerators at TRIUMF, Canada's particle accelerator center in Vancouver, British Columbia, chairs the FRIB Technical Systems Advisory Committee. Once FRIB has ramped up to full power, he says, it "will eclipse other rare-isotope facilities. It will allow you to reach low-probability exotic isotopes. And it will produce rare isotopes in larger amounts than has yet been possible."

Research at FRIB is divided into four categories: properties of rare isotopes, nuclear astrophysics, fundamental interactions, and applications for society.

Fast, stopped, reaccelerated

FRIB produces radioactive isotopes through fragmentation. Beams of stable and very long-lived ions are accelerated in a paperclip-shaped 457-meter linear accelerator. As the ions progress through a total of 324 superconducting resonators, they traverse a liquid lithium curtain, which strips the ions of more electrons. The more charged the ions, the easier they are to accelerate. In using a flowing lithium film, says FRIB scientific director Brad Sherrill, "the stripper regenerates constantly, so there's no damaging it." A conventional solid carbon foil couldn't withstand FRIB's high-power beams, he says.

The initial beam can consist of ions ranging from oxygen to uranium. Flying at 10–60% the speed of light, the ions pass through a target, and collisions in the target material produce a cocktail of isotopes in the emerging beam. "You can't determine what isotopes you make, but you can select which ones you want to use," says Sherrill.

Rare-isotope facilities in China, Japan, and Germany also use the fragmentation technique. So did FRIB's predecessor at Michigan State, NSF's National Superconducting Cyclotron Laboratory (NSCL), which was a workhorse for 40 years starting in 1982. FRIB ups the game in terms of beam power, energy, and available isotopes. "For lighter ions the beam power will be 1000 times higher than at NSCL, and for heavier ones it could be up to a million times better," Sherrill says. FRIB will produce about 4500 distinct isotopes, compared with the NSCL's roughly 1000. One of the NSCL cyclotrons is being converted into a chip-testing center; some of the lab's detectors and other equipment are being used at FRIB.

Other facilities, including TRIUMF and CERN's ISOLDE, use isotope separation on line (ISOL). In that approach, protons smash into a thick target, and resulting rare isotopes are thermalized, ionized, and extracted as a low-energy beam. With ISOL, says Laxdal, "it's easier to control the beam quality" through acceleration after the isotopes have been extracted. With fragmentation facilities, he says, "because they create beams at high energy, they can measure things that have a shorter half-life. They can access isotopes that are more exotic. The two methods are very complementary." TRIUMF and other older facilities remain relevant, he adds. "There are more than enough experiments to go around."

A unique feature of FRIB is that it can provide isotopes in fast, stopped, and reaccelerated modes. The fast, high-energy beams exiting the target are a source for in-line experiments with short-lived isotopes and for studies in which protons or neutrons are knocked out of nucleons or that otherwise simulate astrophysical reactions. Trapping nuclei allows for precision measurements of fundamental and symmetry-violating nuclear properties and nuclear decay. And reaccelerating


SZOMBAT78/WIKIMEDIA COMMONS/PUBLIC DOMAIN

SUNFLOWERS absorb arsenic and so could be used to detoxify soil. That's one of many horticultural and other potential applications for harvested isotopes at the Facility for Rare Isotope Beams.

slowed isotopes produces high-quality beams that can be used, for example, to simulate lower-energy reactions that occur in stars.

For now, FRIB is running with beam intensities of 5–10 kilowatts. Increasing to the design intensity of 400 kilowatts will be done in steps over time, says FRIB director Thomas Glasmacher. "We need to balance supporting the user community in making discoveries and ramping up power deliberately and carefully," he says. "You have to worry about many things, make sure everything works, and be mindful of radiological hazards." If it were clear from the outset what parts of the setup might have to change to avoid damage at higher power, he says, "we would have built that way. The development of a higher-power accelerator is a science project in itself."

"Waste to wealth"

Gregory Severin, a radiochemist at Michigan State, spearheads an isotope-harvesting initiative at FRIB. At most 20% of the initial beam reacts in the target; the remainder is dumped. That's because the target has to be thin, on the order of 1–20 millimeters, in order to create short-lived exotic isotopes that retain forward momentum, he explains. Severin has his eye on the huge dumped portion of isotopes; he wants to "convert waste to wealth."

The dumped isotopes will land in a 7000-liter tank of water. From there, they'll be extracted with an ion exchanger and be put in hot cells for separation and delivery to researchers. Severin hopes the process will be efficient enough to use isotopes that have half-lives down to two hours.

DOE is investing $13 million over four years to build up the harvesting capability, with the aim of facilitating development of applications that benefit society. Planned applications so far include medical therapies and diagnostics, stewardship of the nuclear weapons arsenal, astrophysics, and horticulture. Severin leads the effort to identify potential users and, often, to help them get started. "Part of my job is to make people aware of what they might be able to do with radiotracing," he says.

MIT physicist Ronald Garcia Ruiz and colleagues are working out details on how they might use harvested isotopes. Garcia Ruiz also hopes to do in-line fast-isotope experiments at FRIB, he says, but the team "won't get more than a week or two a year." With harvesting, "we can collect isotopes in a parasitic way from the beam dump and have them almost all the time. Unprecedented access to rare isotopes, especially actinides with pear-shaped nuclei, is going to revolutionize our field." Pear-shaped and other deformed, nonspherical nuclei have unusual shell structures.

One beauty of FRIB, says Garcia Ruiz, is that it can create rare nuclei that enhance symmetry-breaking properties. Using harvested isotopes, he and a large international team of colleagues want to insert pear-shaped nuclei into trapped molecules and perform high-precision measurements. "Because these are molecules that have never before been created," Garcia Ruiz says, the team has a lot to figure out, including what lasers, molecules, and experimental techniques to use. Molecules with an unstable, heavy,


TOBY KING

THE FIRST EXPERIMENT at the Facility for Rare Isotope Beams measured decay times for exotic nuclei. The research team assembled the detector, known as the FRIB Decay Station initiator, using subsystems from many of the dozen collaborating institutions. The arc on the right is a neutron time-of-flight detector, at left is an array of high-purity germanium and lanthanum bromide gamma-ray detectors, and the yellow device in back is a total-absorption spectrometer. The experiment was led by scientists at Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Florida State University, Mississippi State University, and the University of Tennessee, Knoxville.

asymmetric nucleus would be "extremely sensitive" to time-reversal violation, he explains. "If we find something that the standard model doesn't predict, it would be a sign of new physics."

More generally, notes Severin, isotopes could be harvested and then fed back into FRIB's secondary accelerators for experiments that require isotopes at a precise beam energy.

High demand

FRIB has 11 experimental stations. Some are outfitted with general-purpose instruments, and some allow for scientists to install custom detectors. So far, the facility is oversubscribed about threefold.

Heather Crawford of Lawrence Berkeley National Laboratory was a principal investigator on the first FRIB experiment, a multi-institution collaboration conducted in May last year. "We looked at beta-decay properties of neutron-rich nuclei from sodium through phosphorus," she says. The researchers obtained half-lives of exotic nuclei and reconstructed energy excitation levels within the nuclei. The data are important for testing models of nuclei far from stability, she says, and for understanding the shape of the nucleus and how neutrons and protons exist in asymmetric nuclei. "The strong and weak forces that govern the nuclear system are not well known. The ultimate goal is a truly predictive model of nuclei to eventually understand nuclear decay and synthesis."

Michigan State nuclear astrophysicist Chris Wrede is keen to gain insights into x-ray bursts from FRIB experiments. He led the development of a detector to look at decay pathways of certain isotopes. For example, by studying beta decay of gallium-60 to excited states of zinc-60, which can emit protons or alpha particles, the researchers can learn about reaction rates and competition between copper-59 reactions in x-ray bursts: proton capture to form zinc-60 and proton capture followed by alpha emission, resulting in nickel-56. Wrede and his colleagues ran an experiment last November and are gearing up for more. The nuclear-reaction rates they obtain provide input to refine comparisons between computer models and x-ray observations from space telescopes.

Nuclear-reaction rates are important for modeling many astrophysical events, says Filomena Nunes, a theoretical physicist at Michigan State. For example, in 1998 she and others used NSCL data on the breaking of boron-8 into a proton plus beryllium-7 to validate a model and extract a critical reaction rate for the solar neutrino puzzle. (See, for example, the article by John Bahcall and coauthors, Physics Today, July 1996, page 30.) She says she hopes to learn about many nuclei with FRIB. "I'm particularly interested in heavy tin isotopes and neutron capture," she says. "I'd like to go all the way to tin-132. This is a region where models have a lot of uncertainty." Understanding the reaction rates and the competition with other processes are steps to understanding the abundances of elements, she says. "How much you get of each element depends on how you get there."

FRIB will discover new isotopes. And any predictive model of the nucleus should be able to say how many neutrons you can add before the nucleus falls apart, says Nunes. FRIB will help with all of those things, partly through improved statistics. "It will replace the little dribble of exotic isotopes by a fire hose."

Toni Feder PT

NANOPHOTONICS for a sustainable future

ISTOCK.COM/ZHAODONGFANG

Jennifer Dionne is an associate professor of materials science and engineering and, by courtesy, of radiology, and **Sahil Dagli** is a graduate research assistant, both at Stanford University in California. **Vladimir M. Shalaev** is the Bob and Anne Burnett Distinguished Professor of Electrical and Computer Engineering at Purdue University in West Lafayette, Indiana.



Jennifer A. Dionne, Sahil Dagli, and Vladimir M. Shalaev

As the field matures, its researchers are finding practical applications in solar-energy harvesting, chemical manufacturing, optical refrigeration, and energy-efficient computing.

In the field of nanophotonics, researchers strive to precisely control light and its interaction with matter. A few successes include record-setting photovoltaic efficiencies, sensors capable of detecting single molecules and trace amounts of viruses and bacteria, and therapies that can kill tumors noninvasively. Futuristic technologies, such as solar sails for near light-speed space propulsion, quantum photonic computers, and sensors for deep-sea ocean exploration, are also in the works.

How do those technologies work? Nanophotonics researchers have devised methods to control the amplitude, phase, polarization, and localization of light. Some of the unique principles underpinning nanophotonics have been exploited for centuries. Artisans during the Middle Ages commonly used metal nanoparticles to tune the color of stained glass in windows. A more ancient example, dating from the fourth century CE, is the famous Lycurgus cup, whose glass appears green in reflected light but red in transmitted light. In both examples, the metal nanoparticles dispersed inside exhibit resonant absorption or scattering of visible light at specific wavelengths, which gives rise to the vivid color.

Yet the field of nanophotonics has grown rapidly only in the past two decades. A recent explosion of new materials—including two-dimensional compounds and their heterostructures and metallic, dielectric, and semiconducting nanoparticles—fueled the growth. Each of those materials can be assembled in all dimensions with near atomic-scale precision. Moreover, improved computation, machine learning, and sophisticated classical and quantum simulations have accelerated their design. Nanophotonics researchers can also leverage the same manufacturing techniques used to make computer chips with nodes that are just a few atoms long and other nanoscale devices at low cost.

Imagine a future with plentiful clean-energy harvesting to phase out fossil fuels, chemical manufacturing that does not emit harmful pollutants or produce wasteful byproducts, point-of-care diagnostics and sensors, and computers that operate at light speed and consume little energy. Advances in nanophotonics are poised to usher in that future, and in this article we describe the underlying physics.

Materials palette

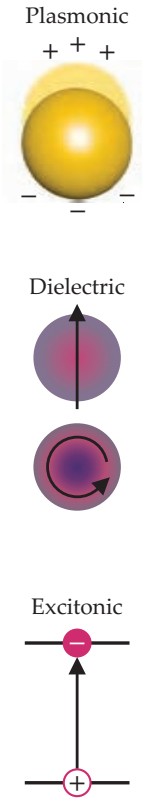
A material's optical response is directly linked to its electronic behavior. Metals and semimetals have free conduction electrons and exhibit different optical responses than do semiconducting and insulating dielectric materials, whose electrons are bound. Nanophotonics researchers tailor the shape and composition of nanostructures made of those materials to precisely control their optical response (see figure 1).

In the case of metallic nanostructures, a light field causes free electrons in the nanoparticle to oscillate in resonances called surface plasmons. The field of study focused on the fundamentals and applications of surface plasmon resonances is known as plasmonics (see the article by Mark Stockman, Physics Today, February 2011, page 39). The oscillating free electrons create an electric dipole that confines and amplifies electric fields in extremely small volumes called hot spots that are incredibly sensitive to the surrounding environment. Plasmonic behavior is also observed in metallic thin films, whose extended dimensions allow a surface plasmon to propagate along the interface between the film and its surroundings.

Doped semiconductors are also a common plasmonic material. As in metals, those plasmons rely on free conduction electrons, whose concentration and mobility can be tuned based on the material and its dopants. Because of their lower free-

carrier concentration, compared with metals, many doped semiconductors exhibit lower-energy IR resonances and absorb less light.[1] Recent advances include creating robust and refractory plasmonic ceramic materials, such as titanium nitride and zirconium nitride. They have a high melting point and are chemically stable at temperatures above 2000 °C. That makes them capable of operating in extreme environments and enduring shock and exposure to contaminants. And they are well suited to being used as durable plasmon catalysts and compact sensors.

Dielectric resonances share many of the exciting properties of plasmon modes—they confine light to small volumes and strongly amplify electromagnetic fields. Light still induces a dipole moment in dielectrics, causing bound charges (rather than free electrons) to oscillate in the material. Yet dielectric nanostructures also possess unique features. For example, because of their positive permittivity values, they support strong electric and magnetic fields localized inside the dielectric rather than at its interface. In the presence of light that is not energetic enough to excite electrons over the bandgap of the material, dielectrics are also lossless. Therefore, unlike metals, their nanophotonic structures do not locally heat and can exhibit longer-lived resonances with sharper spectral linewidths, known as high quality-factor resonances.[2]



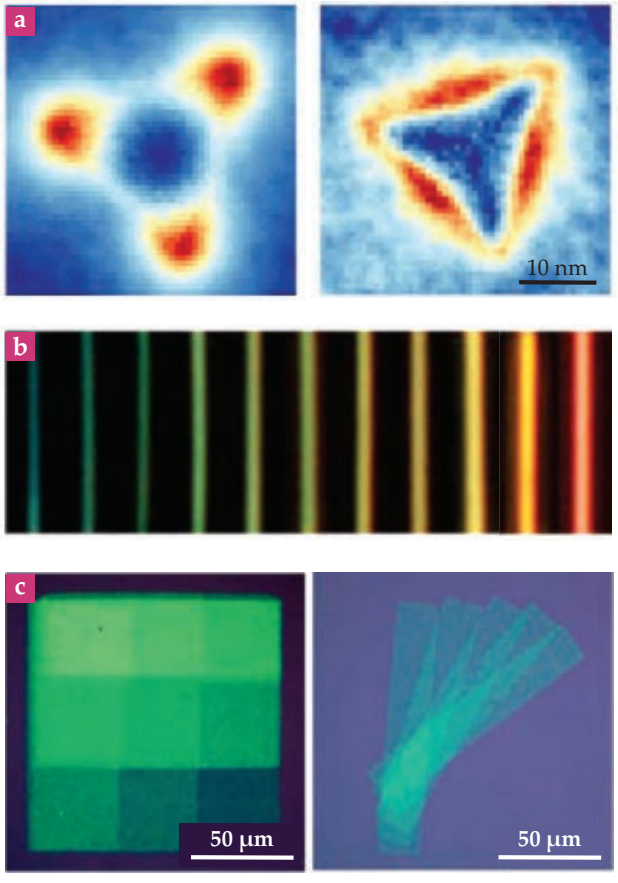


FIGURE 1. OPTICAL RESONANCES. At left (from top), a nanostructure can experience plasmonic resonances—charge-density oscillations—if it has free electrons, dielectric resonances if it has bound electrons, or excitonic resonances if it has bound electron–hole pairs. The resonances create an electric dipole that confines and amplifies the electric field in a tiny volume. **(a)** Experimental maps of the plasmonic modes in silver–palladium nanoprisms reveal the electric field's confinement at a prism's tips (left) and at its edges (right). (Courtesy of Daniel Angell and Jennifer Dionne.) **(b)** The colors on vertical strips of silicon dielectric nanorods change vividly as their radii in successive strips increase from 30 to 180 nm. (Adapted from L. Cao et al., *Nano Lett.* **10**, 2649, 2010.) **(c)** These photographs show the excitonic white-light reflectance of two-dimensional materials (left) and their stacked and twisted heterostructures (right). (Adapted from ref. 4.)

Atomically thin 2D materials are also emerging as an important class of nanophotonic components. They can span the entire range of electronic behavior. Transition metal carbides and nitrides—known as MXenes (see page 12 of this issue)—and graphene can act like semiconductors or metals and can support plasmons. Transition-metal dichalcogenides, such as molybdenum disulfide and tungsten diselenide, exhibit semiconducting behavior in the plane of the material and host excitons (bound electron–hole pairs). Wider bandgap 2D materials, such as hexagonal boron nitride, generally exhibit insulating, dielectric behavior.

Several of those materials can also host color centers—defects in the crystal lattice that serve as single-photon emitters.[3] Importantly, they can be exfoliated over large areas and stacked to form 3D heterostructures and so-called atomic metamaterials.[4] In thicknesses of up to a few nanometers, 2D materials can exhibit near-unity absorption and reflection, and their refractive indices are strongly tunable with applied voltage or light intensity. They also have electronic spins that can be directly excited by the photon spin and behave as optically addressable spin qubits and quantum sensors.

Periodic arrangements of subwavelength-sized nanoparticles from any of the above materials can give rise to collective optical responses distinct from the bulk material. Metasurfaces and metamaterials leverage that behavior to sculpt wavefronts of light. (See the article by Martin Wegener and Stefan Linden, Physics Today, October 2010, page 32.) By tuning the geometry of a nanoscale antenna unit cell, researchers have produced a host of flat optical devices, such as lenses, beam steerers, holograms, and lasers in ultrathin (submicron) and ultralightweight (milligram-scale) platforms.[5] Their 3D analogs—metamaterials—have produced sci-fi-like phenomena, such as negative refraction and invisibility cloaking, thanks to their complete control over the dispersion and propagation of light, from molecular to macroscopic length scales. (See Physics Today, February 2007, page 19.)

Plasmon catalysis

Metal nanoparticles are common catalysts for producing the fertilizers, fuels, and materials that support modern society. For example, the iron-based catalysts of the Haber–Bosch process produce ammonia; platinum nanoparticles catalyze the

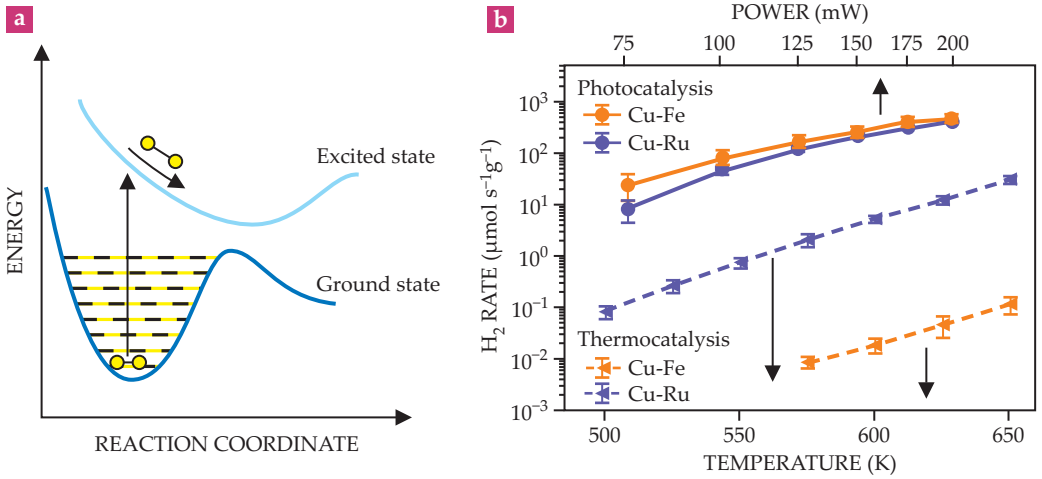


FIGURE 2. PLASMON CATALYSIS. (a) A molecular adsorbate on a catalyst initially sits at the equilibrium position on a ground-state potential-energy surface and requires a certain activation energy to dissociate. Photoexcitation of the catalyst (a plasmonic particle) deposits energy into the adsorbate and elevates it to an excited state, where it can react. (Adapted from ref. 6.) **(b)** Such processes can increase the reaction rates and product selectivity, as compared with thermocatalysis. In the case of hydrogen production from ammonia, the plasmonic element copper facilitates light absorption, whereas iron or ruthenium enables chemical conversion. (Adapted from ref. 7.)

reforming of naphtha for gasoline; palladium nanoparticles catalyze the formation of plastics and pharmaceutical intermediates; and gold nanoparticles catalyze solar-fuel generation and carbon dioxide reduction. To overcome the activation barriers of various reaction steps, metal-nanoparticle-catalyzed reactions generally operate at high temperatures that are typically achieved by burning petroleum fuels. But such thermal processes can form undesirable byproducts that require additional energy to separate and purify them.

Compared with thermal catalysis, plasmonic catalysis promises precision chemistry, in which reactions are simultaneously high yield, product selective, and free of greenhouse gas emissions.[6] Surface plasmons generate nanoscopically controlled distributions of electrons, photons, and phonons. They provide a chemical scalpel for sculpting reaction dynamics with a precision that is orders of magnitude higher than can be achieved using conventional thermo-, electro-, and photocatalysis. The plasmons offer such control through three main mechanisms.

First, strong electromagnetic fields at the surface of plasmonic metallic nanoparticles locally amplify the photon flux and can be used to improve the yields of countless chemical reactions. Second, localized heating associated with plasmonic near fields can increase chemical reaction rates and modify the products that are formed. And third, illuminating the surface can raise electron temperatures to several thousand degrees kelvin because electrons have a much smaller heat capacity than their host lattice.

Such hot electrons or holes, which are generated on plasmon decay, dissipate their energy using either molecular surface adsorbates or the catalyst lattice itself to heat the system to a few hundred kelvin. That feature of plasmon catalysis can not only influence the dissociation and desorption of small molecules but also open new, excited-state reaction pathways under optical excitation, as outlined in figure 2a.

Traditional transition-metal catalysts, such as iron, palladium, platinum, and nickel, have weak visible-frequency plasmon resonances. But they can be combined with plasmonic metals, such as silver, gold, and copper, to bolster the absorption of light while maintaining high chemical activity. Such bimetallic plasmonic systems generate catalytic activity that is highly dependent on the excitation wavelength and polarization state and on the particle's shape, size, and surface chemistry. Bimetallic systems can be created as a multinanoparticle antenna-reactor complex or as an alloy of the catalytic and plasmonic metals.

The many recent and exciting advances in plasmon catalysis are now bringing within reach sustainable hydrogen production, water splitting, ammonia synthesis, carbon capture, and CO_2 reduction. For example, Rice University doctoral student Yigao Yuan and his colleagues demonstrated the production of hydrogen gas from ammonia using an LED (see figure 2b); they employed earth-abundant iron as a catalyst rather than the more commonly used but less abundant ruthenium.[7]

Other exciting catalysis work is the exploration of selective reactions, including in producing the plastic (poly)ethylene from acetylene and in developing large-scale photoreactors for industrial materials, such as steel, whose manufacturing is responsible for 8% of all greenhouse gas emissions. A key challenge for the future will be developing reactors for efficient illumination of such catalysts, although several startup companies are making exciting progress.

Solar-energy harvesting, storage, and cooling

In various parts of the world, the low cost and increasing efficiency of silicon and silicon-tandem solar cells make photovoltaic (PV) energy more economical than fossil fuels. As the use of solar PV technologies grows, researchers strive to increase the efficiency of solar cells to the Shockley–Queisser limit and beyond—ultimately to the thermodynamic, so-called Landsberg limit. Various plasmonic systems can trap incident light and concentrate it in or guide it across the solar cell. Such systems can also increase the efficiency of solar concentrators and solar upconverters, which convert photons whose energy may be below the bandgap of the solar cell to higher energy photons that can be absorbed.

What's more, nanopatterning the PV material itself to support dielectric resonances that trap light can help prevent nonradiative recombination. Some nanophotonic materials systems can even break the equivalence between emission and absorption—a principle known as Lorentz reciprocity—which further boosts solar PV efficiencies. Several of those fundamental discoveries are now commercialized; for details, see the review in reference 8.

The Sun does not shine around the clock, and societies will need scalable energy storage devices to fully move away from fossil fuels. Although battery technologies are rapidly advancing, they are not always cost-effective or practical. Fortunately, other options exist. A thermal storage medium, such as graphite, stores electricity through Joule heating. The heat can then be converted back into electricity using thermophotovoltaic (TPV) cells. Such cells are made of semiconductors with lower bandgap energies than silicon, such as indium gallium arsenide, which can absorb low-energy photons emitted from the thermal storage medium.

Ultrareflective mirrors placed on the rear of the TPV cell improve its efficiency by sending photons that were not absorbed by the semiconductor back to the thermal battery to be reabsorbed as heat. When such highly reflective mirrors are combined with semiconducting materials optimized for temperatures of 1900–2400 °C, the TPV devices can reach efficiencies[9] of 40%.

Beyond thermal storage, nanophotonic design can offer novel approaches to cooling. Air conditioning amounts to 15% of the electricity consumed by buildings in the US. To ameliorate that load, hot objects can transfer energy to colder objects until their temperatures equilibrate. Think of the universe as a heat sink. Heat gets transferred from Earth to the cold of outer space as blackbody radiation through the atmosphere's transparency window of 8–13 μm (see figure 3a). An ideal thermal emitter maximizes emissivity in that wavelength range to avoid trapping the heat in the atmosphere. That process becomes more challenging during the daytime, however, when Earth is heated by absorbed sunlight.

Nanophotonic devices cool an area using systems that reflect the visible range of sunlight but emit thermal radiation in the mid-IR. They do not heat up in direct sunlight and are able to cool down well below the ambient temperature. In initial demonstrations, researchers used a 1D photonic crystal composed of oxide thin films on a silver mirror, creating a Fabry–Perot cavity that maximizes emission from 8 to 13 μm. They then integrated a thinner set of films into the device to maximize the reflection of sunlight.[10]

Practically implementing such a passive radiative cooling device requires isolating it from the surrounding environment to reduce heat exchange through conduction and convection. Apparatuses with insulating materials or air gaps surrounding the radiative cooler can usually do the job. As the technology scales to rooftop installations to improve cooling inside buildings, materials such as paints and polymer films are being used to improve durability and reduce costs.

Those radiative cooling techniques can also be repurposed for energy harvesting.[11] As the device cools, it experiences a spatially varying temperature gradient that can be combined with a thermoelectric generator to produce electricity. Researchers recently powered an LED in a demonstration of the idea, sketched in figure 3b. Impressively, the demonstration took place at night and used the thermal gradient between Earth and outer space. Such technologies are opening opportunities for off-grid lighting in resource-limited areas.

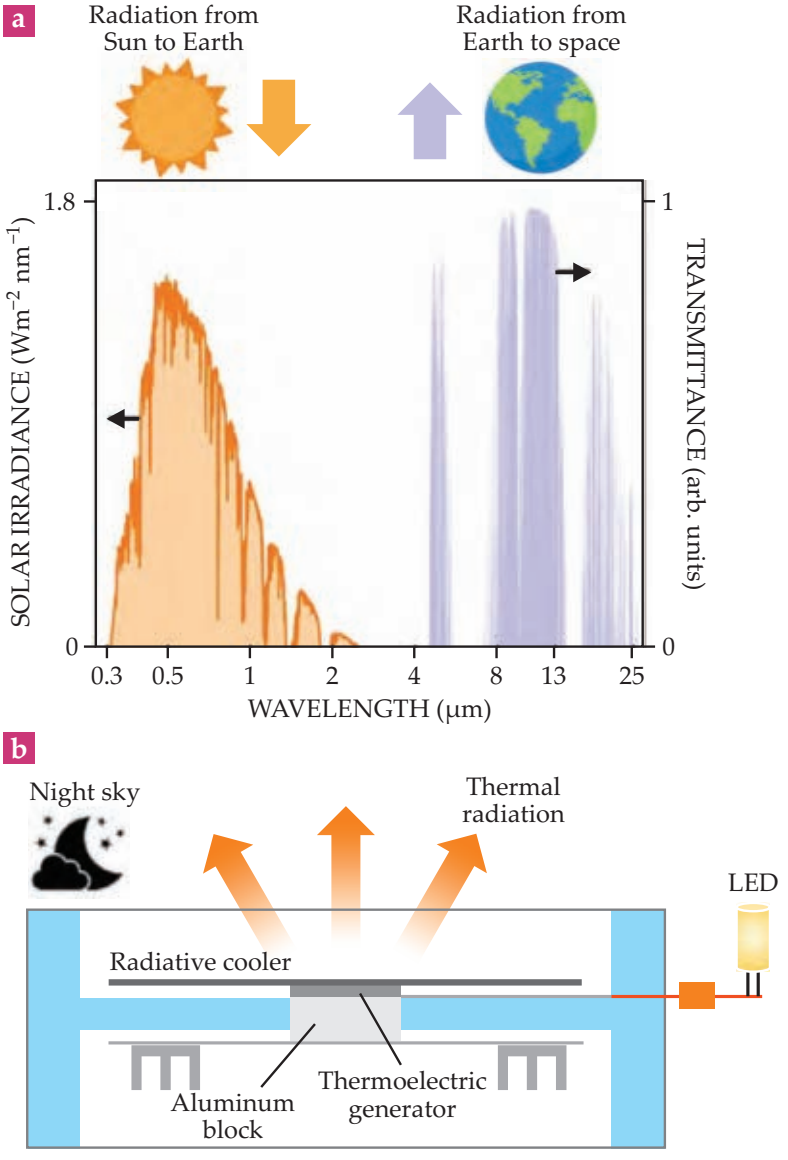


FIGURE 3. NANOPHOTONIC SYSTEMS can control optical absorption and thermal emissivity for various applications. **(a)** At left, the spectral energy intensity of solar radiation is plotted per unit area and per unit wavelength; at right, the thermal radiation from Earth is plotted. For photovoltaic applications, absorption should be maximized in the range of solar radiation. For radiative cooling, absorption should be minimized in the same range while simultaneously maximizing emissivity in the range of atmospheric transparency. (Adapted from ref. 10.) **(b)** Radiative cooling can be used to generate electricity when combined with a thermoelectric generator. Such systems produce electricity off the grid. (Adapted from ref. 11.)

Environmental monitoring

Climate change threatens ecosystem health, food security, and quality of life. Nanophotonics provides a way to monitor that threat. For example, sensors of environmental DNA—the genetic material released by organisms into the environment—

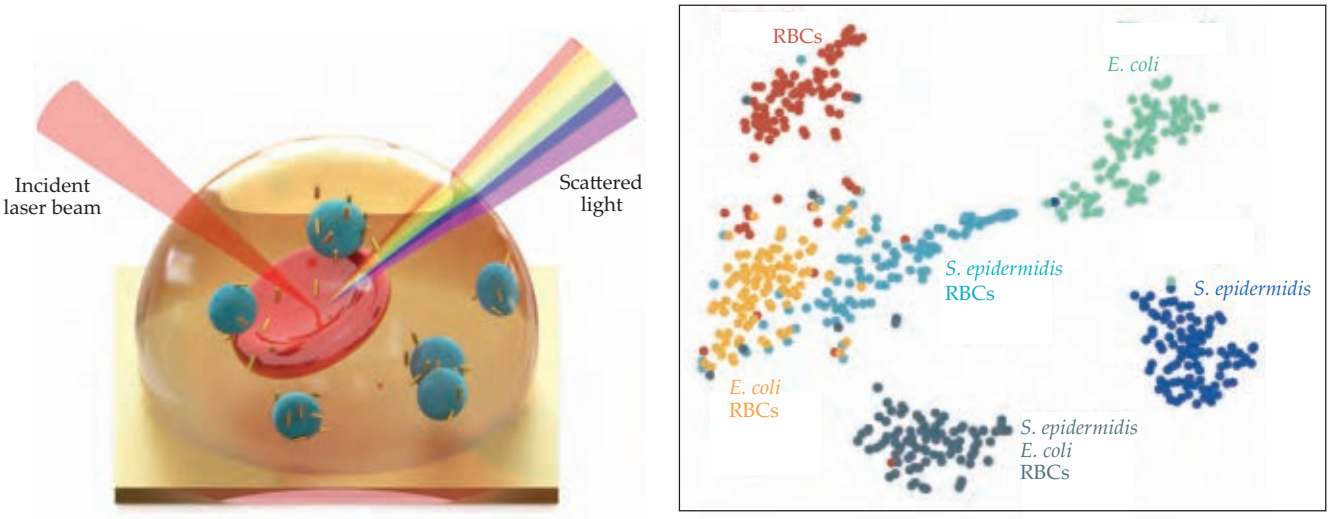


FIGURE 4. NANOPHOTONIC SENSORS can monitor the environment in real time at high resolution. Surface-enhanced Raman scattering (SERS) can amplify weak vibrational signals to detect the presence of molecules. A schematic (left) illustrates the scattering of laser light into a liquid droplet composed of red blood cells (RBCs; red), bacteria (blue), and plasmonic nanorods (gold). Combined with machine learning, SERS can detect *Escherichia coli*, *Staphylococcus epidermidis*, and other pathogens (right, in a two-dimensional projection of the data) in complex liquid samples, such as blood and wastewater. (Adapted from ref. 13.)

reveal details about the abundance and distribution of species and thus can provide an early indication of how invasive they may be. Such sensors can also detect toxins in the soil, air, rivers, and oceans, and they can survey areas for such extreme environmental conditions as wildfires and tsunamis so authorities can warn of threats to nearby communities.

The ability of nanophotonic materials to strongly concentrate electromagnetic fields allows them to behave as sensitive molecular detectors. In certain sensor designs, nanophotonic resonators are decorated with molecules that are specific to the analyte of interest. Binding those molecules to a target analyte modifies the optical signal because of subtle changes in the polarizability or refractive index of the resonator environment.

Recent studies have developed both plasmonic- and dielectric-based sensors of DNA, RNA, proteins, and metabolites. Indeed, SARS-CoV-2 rapid antigen tests rely on plasmonics principles—in particular, the color change that gold nanoparticles experience when antigens bind to antibodies. The tests' sensitivity can even be boosted to the single-molecule level when high-quality-factor structures, such as those hosting guided-mode resonances, are used.

Gas-phase molecules can be detected as well. For example, palladium nanoparticles in a hydrogen-rich environment can undergo hydrogenation; the resulting palladium hydride has a refractive index and thus resonant frequency that's distinct from pure palladium. Researchers have designed metasurface arrays of palladium nanoparticles that experience a large electric field amplification and yet have a narrow spectral linewidth. Sensors with that design can pick up hydrogen at parts-per-billion concentrations.[12]

That sensitivity is critical for rapidly detecting hydrogen embrittlement in materials used for hydrogen storage. Expanding the capabilities for gas-phase sensing could also lead to remote sensing, optical "e-noses" that pick up various gases and flavors, and sensitive atmospheric gas spectroscopy.

Beyond approaches that rely on surface functionalization, nanophotonics can detect, label-free, molecules and cells using vibrational spectroscopy. Techniques such as surface-enhanced Raman scattering (SERS) and surface-enhanced IR absorption do just that (see the article by Katrin Kneipp, PHYSICS TODAY, November 2007, page 40). The analyte's specific structural information is encoded in photons that are inelastically scattered by symmetry-dependent phonons.

Although those vibrational spectroscopies have been limited historically by poor efficiencies, the inclusion of plasmonic and dielectric materials boosts their sensitivity to the single-cell and single-molecule level. SERS can amplify the optical signal by a factor of $|E(\omega)|^4/|E_0|^4$, where E_0 is the incident electromagnetic field, and ω, the optical frequency. Such enhancements are routinely as high as 10^6.

Unlike approaches that rely on fluorescent tags, the label-free techniques maintain high temporal resolution and do not interfere with molecular or cellular integrity. They can be combined with machine learning to identify dozens of bacterial cell species and strains, including their drug susceptibility—even in complex liquid samples, such as blood and wastewater (see figure 4).[13] Metasurfaces[14] are especially valuable in under-resourced settings for such applications as single-cell analysis and the detection of pesticides or plastics when a dedicated spectrometer is not available.

Nanophotonics is also making significant strides in larger-scale environmental monitoring, particularly in lidar technology. Lidar is a scanning and sensing tool that uses time-of-flight measurements of light pulses to map a surrounding area—similar to radar but with higher resolution. Not only has the technology found a home on air, space, and ground vehicles, but it is also increasingly crucial for autonomous systems, such as self-driving cars, robotics, and unmanned aerial vehicles. Additionally, it can be used to survey areas for hurricanes, wildfires, and other environmental threats to local communities.

Lidar is typically a bulky technology with limited mobility, largely because its laser light sources and detectors are configured on mechanically rotating mounts. Flat optical components

based on metasurfaces are now capable of completing a number of tasks needed for lidar, such as beam deflection and point-cloud generation.[15]

Electrically reconfigurable metasurfaces are being developed for solid-state devices capable of full wavefront control. They require constituent materials whose refractive index is tunable with an applied stimulus, such as voltage. Liquid crystals, phase-change materials, epsilon-near-zero materials, quantum-well structures, and electro-optical polymers and crystals are all promising options.

Liquid crystals and phase-change materials offer a wider range of refractive-index tuning but can be limited in switching speeds. Electro-optical polymers and crystals generally have a narrower tuning range because of their weaker electro-optical coefficients, but they can operate at faster speeds. Metasurfaces having a high quality factor increase the field enhancement in the tuning medium, which in turn reduces the required voltage and improves device efficiency.

Recent advances in the field include the development of electro-optical and thermal metasurface devices capable of tunable beam steering and lensing. That work focuses on increasing the devices' field of view and switching speed and efficiency. By improving the systems' integration, researchers will also improve nanophotonic lidar's ability to extract information from the environment for such applications as remote gas sensing and high-resolution mapping.

Energy-efficient computing

It's estimated that data centers consume 1.5% of the world's electricity. The energy cost for a single operation in a standard von Neumann architecture is bounded by kT ln(2), the so-called Landauer limit. Yet existing computing systems far exceed that thermodynamic limit and consume a million times more energy per operation; the dominant cost comes from the transmission of the signal through electronic interconnects. Nanophotonics researchers are exploring novel computing architectures that can reduce the power consumption without sacrificing computational complexity or speed.

Advanced computational tasks, such as image processing, often require analog-to-digital conversion in signal processing systems. That conversion requires power and time, but wave-based analog computing can bypass the need for it. Metasurfaces can perform mathematical operations on beams of light, which expedites computation in a relatively small footprint and with the capability of highly parallel operations. What's more, passive metasurfaces require no power consumption to operate.

For example, several metasurface platforms have been developed to detect edges—a critical step in defining features for image processing and computer vision. Near the edges of an object in a differentiated image, sharp changes in brightness are highlighted, while areas with more constant brightness are filtered out (see figure 5). Current metasurface processors detect those brightness changes in real time without relying on digital electronic computing.[16] And their compact size, or form factor, allows them to be integrated into many existing imaging systems.

More sophisticated metasurface designs are capable of also solving equations. The Fredholm integral equations, for example, were recently solved using a metasurface and a semi-

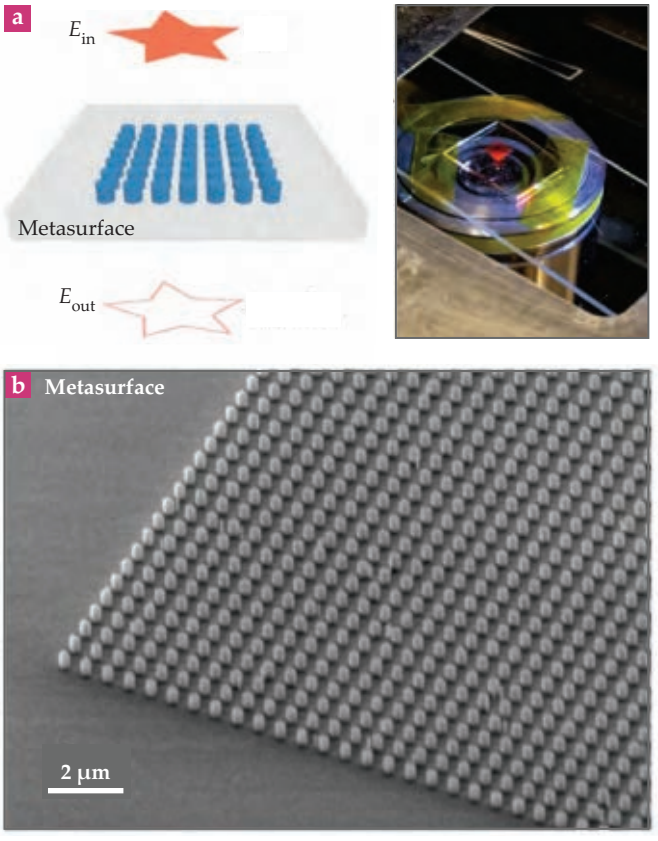


FIGURE 5. METASURFACES can enable energy-efficient computing. **(a)** They are engineered to detect the edges in an image, a star in this case. By taking a second-order spatial derivative of an incident electric field E_{in}, the metasurface—an array of silicon nanorods, each one effectively a dipole antenna—generates an output image whose edges are enhanced, and the rest of the image is filtered out. The adjacent photograph shows a fabricated metasurface on a glass slide, atop a microscope objective. **(b)** This scanning electron micrograph shows the structure of the edge-detecting metasurface. (Adapted from ref. 16.)

transparent reflecting plate. The device performed an iterative Neumann series to converge to a solution by reflecting off a semitransparent mirror and interacting repeatedly with the metasurface. The total time for the solution to converge was 349 fs—much faster than the speed of a conventional processor. Operating at visible wavelengths, the form factor of that nanophotonic device opens opportunities for chip-scale integration with other computing elements.[17]

Beyond analog computing, nanophotonics is paving the way for breakthroughs in quantum information systems. Optical resonators magnify the interaction between light and the materials used for quantum information by an amount proportional to the ratio of the resonator's quality factor Q and the mode volume V. For instance, various plasmonic nanoantennas and metasurfaces have been used to enhance and direct the emission from 2D transition-metal-dichalcogenide excitons at different valleys in the band structure and in different directions. The spatial separation of that emission is helpful for reading out the valley information as a quantum state.

Metasurfaces have also been used to enhance valley-specific photoluminescence and retain the valley polarization, even at

room temperature. High-*Q* resonators can enhance the light–matter interactions with longer resonance lifetimes. Low-*Q* plasmonic nanoresonators, by contrast, have a different set of advantages: They offer broadband operation at much faster speeds.

Intriguingly, the spontaneous decay rates of quantum emitters coupled to broadband and ultrafast plasmonic nanocavities can be sped up and potentially outpace room-temperature quantum decoherence rates in matter.[18] That feature is especially critical for generating indistinguishable photons and entangled states. Plasmonics can therefore increase the rates of quantum processes to the extent that they become immune to decoherence. Furthermore, it promises to bring the operation of quantum photonic systems to the terahertz range by offering variable bit rates.

On the horizon

Leveraging advances in materials science and machine learning, researchers continue to develop ways to advance chemical manufacturing, solar energy, environmental monitoring, computing, and communications. An ever-growing suite of new materials is expanding the realm of possibilities, based on unique light–matter interactions. In parallel, new algorithms and machine-learning models keep improving researchers' abilities to design better optical systems.

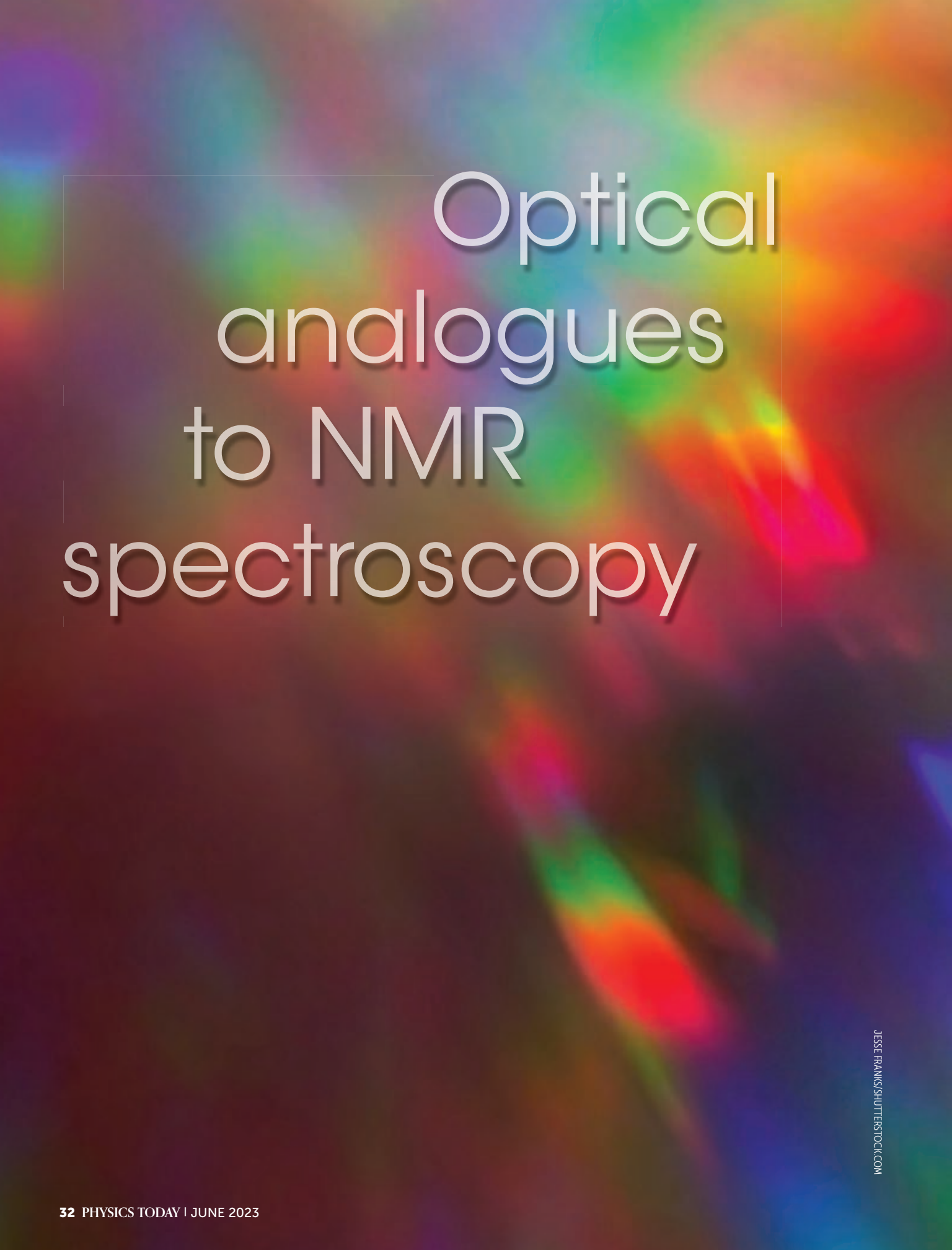
The advantages from those nanophotonic advances abound: Plasmonic photocatalysis is likely to improve the selectivity of chemical production and facilitate reactions that would be energetically unfavorable otherwise. Nanophotonic-enhanced PVs could be integrated directly into buildings and windows, while radiative cooling devices revolutionize our cooling infrastructure. Nanophotonic-enhanced vibrational spectroscopy, meanwhile, will rapidly detect viruses, bacteria, and toxins and will monitor our air, water, and soil in real time. Computing will be greatly advanced and far more energy efficient. In short, the physics of light provides almost countless benefits for the world we imagine in our future.

REFERENCES

1. G. V. Naik, V. M. Shalaev, A. Boltasseva, *Adv. Mater.* **25**, 3264 (2013).
2. A. I. Kuznetsov et al., *Science* **354**, aag2472 (2016).
3. A. Reserbat-Plantey et al., *ACS Photonics* **8**, 85 (2021).
4. A. J. Mannix et al., *Nat. Nanotechnol.* **17**, 361 (2022).
5. N. Yu, F. Capasso, *Nat. Mater.* **13**, 139 (2014).
6. U. Aslam et al., *Nat. Catal.* **1**, 656 (2018).
7. Y. Yuan et al., *Science* **378**, 889 (2022).
8. H. A. Atwater, A. Polman, *Nat. Mater.* **9**, 205 (2010).
9. A. LaPotin et al., *Nature* **604**, 287 (2022).
10. Z. Li et al., *Adv. Mater. Technol.* **5**, 1901007 (2020).
11. A. P. Raman, W. Li, S. Fan, *Joule* **3**, 2679 (2019).
12. F. A. A. Nugroho et al., *Nat. Commun.* **13**, 5737 (2022).
13. F. Safir et al., *Nano Lett.* **23**, 2065 (2023).
14. A. Tittl et al., *Science* **360**, 1105 (2018).
15. I. Kim et al., *Nat. Nanotechnol.* **16**, 508 (2021).
16. Y. Zhou et al., *Nat. Photonics* **14**, 316 (2020).
17. A. Cordaro et al., *Nat. Nanotechnol.* **18**, 365 (2023).
18. S. I. Bogdanov et al., *Optica* **7**, 463 (2020).

PT

Optical analogues to NMR spectroscopy



JESSE FRANKS/SHUTTERSTOCK.COM

John Wright is the Andreas C. Albrecht professor in the chemistry department at the University of Wisconsin–Madison. **Peter Chen** is a professor in the department of chemistry and biochemistry at Spelman College in Atlanta, Georgia.

John C. Wright and Peter C. Chen

By using tunable lasers to entangle rotational, vibrational, and electronic states, researchers are learning more about molecules and their properties than from previous methods.

Every element and molecule absorbs or emits light in a unique pattern or spectrum. That makes spectroscopy one of the most widely used and effective methods for studying matter. Raman and IR absorption spectroscopies, for example, are used to identify specific molecules and reveal their structural information. Visible, UV, and fluorescence spectroscopies work similarly and can sometimes even measure single molecules.

NMR spectroscopy measures the absorption of electromagnetic radiation at radio frequencies. It's increasingly being used in the biological and medical sciences because of its extraordinary ability to determine the structure and behavior of proteins and other exceptionally complex molecules. NMR spectroscopy uses a very different approach that's based on forming coherences.[1] A coherence is a quantum mechanical superposition state that consists simultaneously of two states, just like Erwin Schrödinger's famous cat. Although it may seem strange, such a situation is possible in quantum mechanics, where things are described by waves and those waves can oscillate coherently at multiple frequencies with well-defined phases.

For proteins and other complex molecules containing carbon-13 and hydrogen-1 atoms, it has become common to use multiple-quantum-coherence (MQC) NMR spectroscopy to determine their three-dimensional molecular structure. The strong magnetic field used in NMR preferentially orients the nuclear spin states of ^{1}H, ^{13}C, and other atoms. Microwave pulses are then used to create quantum mechanical superposition states that are mixtures of the up and down spins of the ^{1}H and ^{13}C and that oscillate at the frequencies of both nuclear spins. The result is a Floquet state—a periodically driven nonequilibrium state in which the oscillations of the up–down spins have well-defined phase relationships that are maintained indefinitely by the microwave driving field.[2] When the driving field is turned off, the Floquet state still remains coherent for a long time (about 0.1–1 seconds) until interactions with the thermal environment eventually force it back to equilibrium. The loss of the coherent phase oscillations is exponential in time and is characterized by a dephasing time.

Before dephasing occurs, however, MQC NMR spectroscopy manipulates the Floquet state by introducing additional pulses, and a Fourier transform (FT) converts the time between pulses to the frequencies in a multidimensional spectrum. The pulses are designed to manipulate dipole–dipole interactions between the magnetic moments of the ^{1}H and ^{13}C nuclear spin states. For example, since the energy of a ^{1}H atom depends on whether its neighboring ^{13}C atom's spin is up or down, it becomes possible for an additional pulse to flip the spin alignment of the ^{13}C and change the frequency and phase of the ^{1}H spin. As a result, MQC NMR spectroscopy is now a large family of techniques that uses different pulse orderings to engineer the Floquet state and embed the phase information of the ^{13}C oscillations on the ^{1}H oscillations.

Photon echoes

Ever since the invention of the laser, researchers have envisioned using a laser's coherence to enable optical analogues of NMR and expand coherent methods to all quantum states.[2] Now that laser systems cover the entire electromagnetic spectrum, that vision is being realized. The first such effort, similar to NMR's spin echo, was photon echo.[3] In that technique, three optical pulses sequentially created a coherence between two electronic states, a static population in the excited states, and the conjugate, oppositely evolving coherence that generated the output signal. Since its discovery, photon echo has been widely used for measuring the ultrafast dynamics of excited populations in chemical systems. It is particularly important for inhomogeneous samples in which different environments create a broadened distribution of quantum-state frequencies. Photon echo removes the frequency broadening in inhomogeneous samples because the conjugate coherence reverses the phase drift caused by different environments, which brings the signal components into phase with one another.

Since NMR spins oscillate at high frequencies, an additional microwave pulse—called the local oscillator—is used to create a measurable beat between itself and the output signal. The phase oscillations are converted to frequencies using a Fourier transform. In 1998 David Jonas and coworkers added a fourth light pulse to a photon-echo experiment to create a beat with the photon-echo signal; the beat could be used to measure the

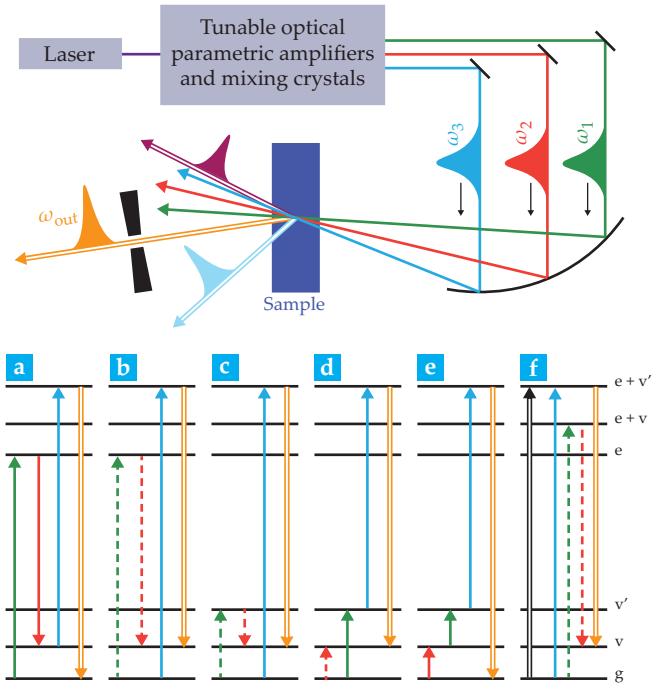


FIGURE 1. FLOQUET STATES are created in molecules when three tunable excitation pulses entangle the ground state (g) with vibrational (v), electronic (e), and vibronic (e + v′) states. A Floquet state emits beams at new frequencies and directions. Selecting one of the output beams and measuring its resonant enhancements as a function of input frequencies, researchers can collect three-dimensional spectral information of the targeted molecule. **(a–f)** The energy level diagrams show the various ways of accessing ground-state and electronic-state resonances, and each provides unique capabilities. The time in which interactions occur relative to one another is ordered from left to right in the diagrams. Solid arrows define the paths that create the initial states of the output transition ω_{out}, and dashed arrows, the final states.

first and last coherences' phase oscillations.[4] That optical analogue of 2D FT-NMR spectroscopy can resolve the underlying spectral features of inhomogeneous materials and is used extensively in physical chemistry to study the ultrafast dynamics of vibrational and electronic quantum states. (For more on 2D spectroscopy, see the article by Steven Cundiff and Shaul Mukamel, PHYSICS TODAY, July 2013, page 44.)

But the FT time-domain approach has its limitations. Dephasing times in optical spectroscopy are many orders of magnitude shorter than those for NMR: picoseconds for vibrational states and femtoseconds for electronic states. That's too short to create multiple quantum coherences that can be engineered the same way as MQC NMR. Time-domain methods are, therefore, constrained to creating sequential single quantum coherences over narrow frequency ranges.

Frequency-domain spectroscopy

An alternative approach that avoids those constraints is frequency-domain spectroscopy. Indeed, NMR spectroscopy was primarily a frequency-domain technique from 1945 until the 1970s, when laboratory computers became available. Frequency-domain multidimensional spectroscopy uses excitation pulses with different frequencies to create resonances with rotational, vibrational, and electronic states. The Floquet states that result from those resonances remain coherent for the duration of the pulses.

The approach was guided by work from 1965, which formed the foundations for nonlinear and coherent Raman spectroscopies.[5] The methods were initially constrained to single Raman resonances because of the limited availability and wavelength range of tunable lasers.[6] When tunable dye lasers became more readily available in the mid 1980s, one of us (Wright) built a system with three nanosecond, tunable dye lasers to create fully coherent Floquet states containing electronic, vibrational, and vibronic (combined electronic and vibrational transitions) coherences in pentacene molecules.[7] When tunable optical parametric-amplifier systems became readily available, the method was expanded to include multiple IR and UV excitation pulses.[8]

Figure 1 sketches several different Floquet-state spectroscopy techniques. A set of three temporally overlapped and tunable excitation pulses are focused into a sample at controlled angles where they establish resonances with different states in the sample. The pulses are intense, so a state's excitation rate becomes comparable to its dephasing rate. If multiple states are coupled, their interactions with each other create nonlinearities that distort the oscillations induced by the electromagnetic fields.

The dipole moments of the Floquet state launch multiple output beams with frequencies $\omega_{out} = \sum\pm\omega_i$ defined by energy conservation and directions $\mathbf{k}_{out} = \sum\pm\mathbf{k}_i$ defined by momentum conservation, where ω_i and $\mathbf{k}_i$ are the angular frequency and wavevector of pulse i, respectively. New output beams are produced because the phase oscillations of molecules emit light throughout the sample that constructively interferes in specific directions, so the beams can be more intense than incoherently emitted light. Spectra are recorded by scanning the excitation frequencies across resonances while monitoring the intensity of a particular output beam with a monochromator and detector. The resonance enhancements are multiplicative, so the intensity increases by orders of magnitude when the transitions are fully resonant.

Using the fully coherent, frequency-domain Floquet state for multidimensional spectroscopy offers many key advantages. First, having three independently controllable input pulses to generate a fourth output pulse can entangle states across the entire electromagnetic spectrum to form a Floquet state. For example, one beam can probe the mid-IR region, one can probe the near-IR region, and the other two can be used for the visible and UV regions.[9] Second, the experimental system is less rigid than FT methods because the coherent phases in a Floquet state are established entirely within each pulse set and are less susceptible to interference from competing effects. Third, a Floquet state creates an instantaneous snapshot of the coupled coherent states that avoids the complications created by changing state populations. Because dynamic effects change and collapse the Floquet state, they do not contribute to the output signal. Dynamics can, however, still be measured by a pump-probe pathway similar to that shown in figure 1f.

The fourth advantage is that the numerous ways to mix and scan the three input beam frequencies provide researchers with multiple methods that can be tailored to the needs and goals of an experiment. Fifth, the quantization of molecular states and the coupling between them creates patterns that link the features in multidimensional spectra, and that quantization clarifies the relationships between states. Sixth, the only fea-

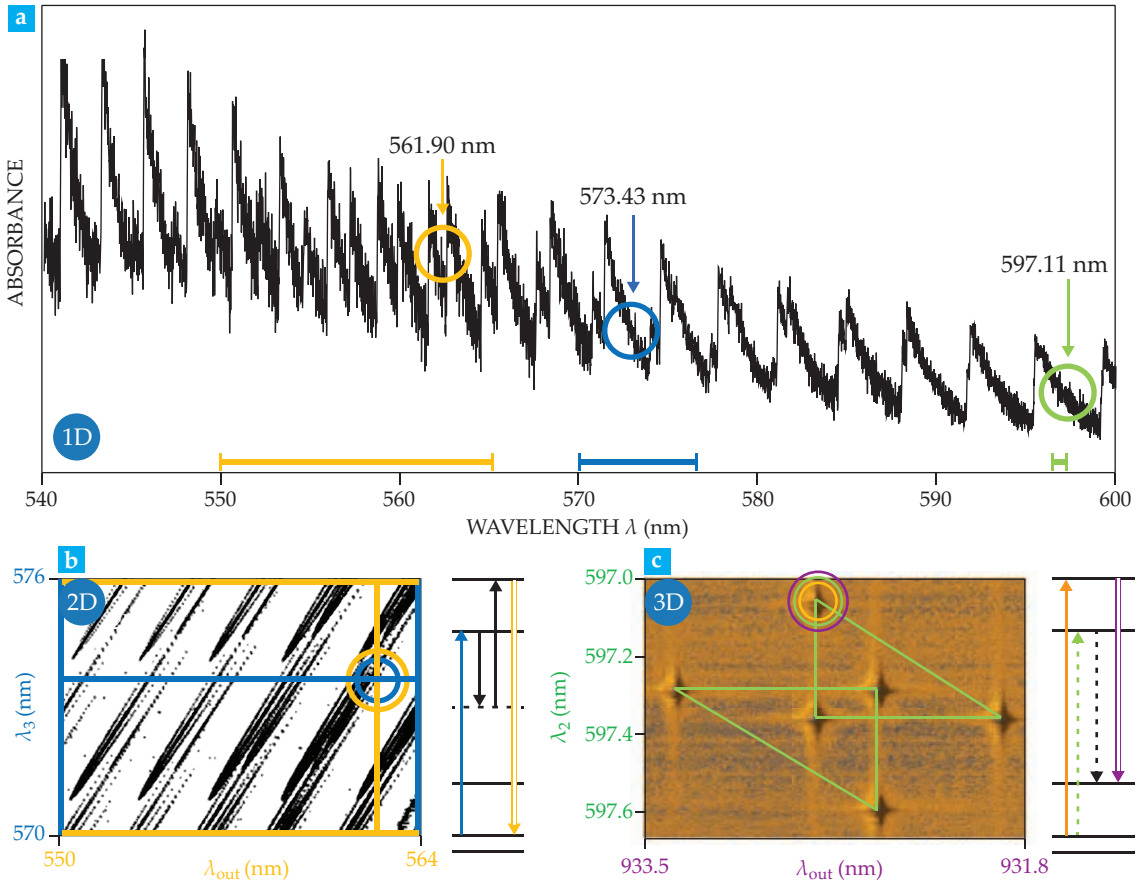


FIGURE 2. IODINE VAPOR has many broad spectral peaks. **(a)** In a one-dimensional spectrum, rotational–vibrational peaks are unresolvable. **(b)** In contrast, a 2D spectrum created using Floquet-state spectroscopy from two heavily congested regions (550–564 nm and 570–576 nm) shows 2D parabolic patterns of peaks. Each of the peaks is represented by a dot, and they are arranged by rotational and vibrational quantum number. The rows of parabolas resolve the v′ quantum numbers for each v″ ground-state vibration. To the right of the figure, the black arrows indicate a Raman transition, and the blue and yellow arrows represent excited electronic-state transitions. **(c)** For peaks that are still not fully resolved, a 3D spectrum that includes at least one axis from the 2D spectrum can be generated. This 3D slice—created using an input wavelength of 561.902 nm and two other input laser wavelengths—shows triangular patterns (green) that clearly resolve all I_2 peaks. The black and green arrows to the right of the figure indicate a resonance Raman transition. Colors correlate to specific spectral peaks (circles), scanned regions along the *x* and *y* axes, wavelengths (lines), and transitions (arrows) across the 1D, 2D, and 3D spectra.

tures that appear in multidimensional spectra are those that are coupled, which allows researchers to eliminate uninteresting features in congested spectra. Finally, the technique can easily create higher-dimensional spectra, which can better characterize complex samples.

Both MQC NMR and frequency-domain Floquet-state spectroscopy consist of a family of versatile techniques. The six diagrams in figure 1 show different ways to create a molecular Floquet state. For coherent anti-Stokes Raman spectroscopy (CARS), shown in figure 1a, most experiments use a single fixed-frequency laser for both the first (green arrow) and third (blue arrow) pulse while a tunable pulse (red arrow) probes a Raman-active vibration (v). As a result, the frequencies are usually not resonant with the two top participating levels (e and e+v′). Making all the pulses independently tunable creates fully resonant 3D CARS, which can probe vibronic and vibrational states.

To resolve features existing beneath the broadened spectral bands found in inhomogeneous samples, it is important to use photon-echo methods and other similar approaches that have conjugate coherences. Although fully resonant CARS provides the high selectivity required for congested spectra, it lacks conjugate coherences. But the dashed arrows in figure 1b, which depicts multiply enhanced nonparametric spectroscopy (MENS), create coherences that are conjugate to those of the last two interactions (blue and orange arrows), so that method can be used in samples with inhomogeneous broadening.[9]

Gas phase

Gas-phase spectroscopy can probe the detailed structure and behavior of molecules and is useful for various applications such as the satellite monitoring of greenhouse gases and the search for possible life on exoplanets. Gaseous molecules have huge numbers of energy levels because of many different possible combinations of quantized rotational, vibrational, and electronic motions. The resulting spectra are congested by thousands or even millions of overlapping peaks and often lack any recognizable patterns that researchers need in order to assign those peaks. That problem can be addressed by creating Floquet states in gases in the same way that 2D MQC NMR does for large biomolecules.

One reason that Floquet-state spectroscopy is useful for exploring relationships among rotational, vibrational, and electronic states is that different kinds of motions produce distinct patterns in multidimensional frequency-domain spectra.[10]

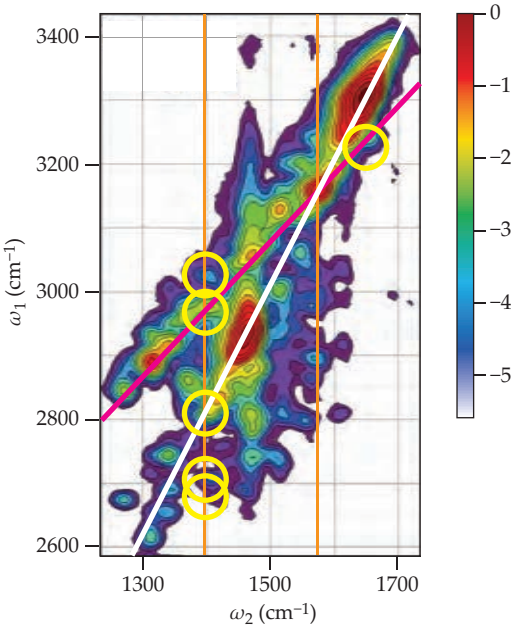


FIGURE 3. DRUG–PROTEIN INTERACTIONS that were previously unseen (circles) can be resolved with two-dimensional Floquet-state spectroscopy. This 2D spectrum of a protein–drug complex was recorded using the transitions in figure 1d. The color bar is the normalized logarithm of the output intensity. The orange lines mark the frequency of fundamental vibrations (*x*-axis) and run through combination-band frequencies (*y*-axis) containing those fundamentals. The white line runs through fundamental vibrations and their overtones. The other peaks along the orange lines are a result of combination bands that are coupled to the fundamental. The magenta line simultaneously intersects the white and orange lines at the 3144 cm^{-1} overtone of the amide (NH_2) fundamental mode at 1572 cm^{-1}. Other features along that magenta line correspond to the combination bands that are coupled to that fundamental. (Adapted from ref. 11.)

Rotational patterns, for example, have easily recognizable shapes—collections of rectangles, trapezoids, and triangles that form X's, asterisks, and other shapes—whereas vibration patterns show how the rotational patterns align in multidimensional space to form grids composed of columns, rows, and diagonal lines. The detailed shape of the patterns depends on quantization, technique, selection rules, molecular shape, and molecular behavior.

The peaks in the rotational and vibrational patterns are automatically sorted by a molecule's rotational and vibrational quantum numbers. Assigning peaks by quantum number is necessary for researchers to develop accurate molecular models and use spectroscopy to measure molecular temperature. Furthermore, if the sample is a mixture of molecules, the spectral peaks can also be sorted by species because all the peaks that make up a given pattern will come from the same species. Floquet-state spectroscopy can also explore the coupling between peaks in different regions of the electromagnetic spectrum, even if the 1D spectra of those regions appear heavily congested and lack patterns. The resulting multidimensional patterns can then be used with little or no prior knowledge to extract immediate information on molecular structure, molecular behavior, and the relationship between peaks in those regions.

Figure 2 shows the 1D absorption spectrum of a simple model system of iodine vapor, where overlapping peaks cause a loss of detectable patterns even when recorded at higher spectral resolution. Each broad peak consists of a high density of fine unresolved rotational–vibrational peaks, which are produced by transitions from $v'' = 0$, 1, or 2 of the ground electronic state to the many v' vibrational states of the excited electronic state. (Here, v denotes the quantized amplitude of a vibrational mode.) As v' increases, the wavelength decreases, and peaks grow closer together until v' becomes so large that the molecule dissociates. Transitions from $v'' = 0$ dominate at shorter wavelengths, whereas transitions from $v'' = 2$ dominate at longer wavelengths. From 550 to 570 nm, for example, the peaks from $v'' = 1$ gradually become more intense than the peaks from $v'' = 0$. Within each broad peak, however, numerous rovibrational peaks from multiple v'' and v' states overlap.

A 2D Floquet spectrum of iodine vapor was recorded by scanning one input pulse over a wavelength range of 570–576 nm and the detection wavelength over 550–594 nm. The spectrum shows rotational–vibrational peaks that are distributed into parabolic patterns, which are automatically grouped by their ground state's rotational quantum number J''. The smallest J'' values appear near the vertex of a parabola, and J'' increases toward the parabola's tail.

If needed, the resolution can be improved by several orders of magnitude by using a fully resonant process to record a 3D spectrum, which shows peaks as a function of three orthogonal wavelength or frequency axes. In fact, the density of peaks is so low in 3D space that finding them can be difficult. An easy solution is to use one of the wavelength coordinates from a peak in the molecule's 2D spectrum as one of the three wavelengths in the 3D spectrum. Scanning the wavelengths for the two other axes creates a slice through the 3D data that includes that selected peak as well as two additional related peaks with similar quantum numbers, all of which together form triangles and other easily recognizable patterns. Once one triangle is located, additional ones on parallel planes become relatively easy to find and can be used to calculate rotational quantum numbers and molecular constants.

Molecular systems more complex than iodine vapor also benefit from the use of conventional 1D spectra to design 2D and 3D Floquet experiments. Larger molecules, and systems in which perturbations hamper the ability to apply traditional molecular models, would benefit from improved spectral resolution, easy pattern recognition, and automatic peak sorting. Using multidimensional patterns is especially robust because of the high level of redundancy.

Condensed phases

The bonding that links molecules together is at the heart of understanding the properties and mechanisms of materials in almost all areas of science and technology. Floquet-state spectroscopy has the capability to directly probe bonding interactions. Vibrational spectra serve as fingerprints of specific molecules because the many vibrational modes create sharp spectral features sensitive to their structure. If two molecules are connected by a bond, for example, the 2D spectrum will contain cross peaks that depend on the shared bond. Those cross peaks provide direct access to the bonding interactions and can guide the development of new materials and materials properties.

One example of such a capability is the binding of drugs to proteins.[11] Figure 3 shows the 2D vibrational spectrum of a complex formed by bonding a cancer drug to a target protein. It contains about 200 features that would be unresolvable with a 1D spectrum. The six yellow circles show the features that appear only when the drug is attached to the protein. Experimentally, the spectrum was obtained by scanning the frequencies

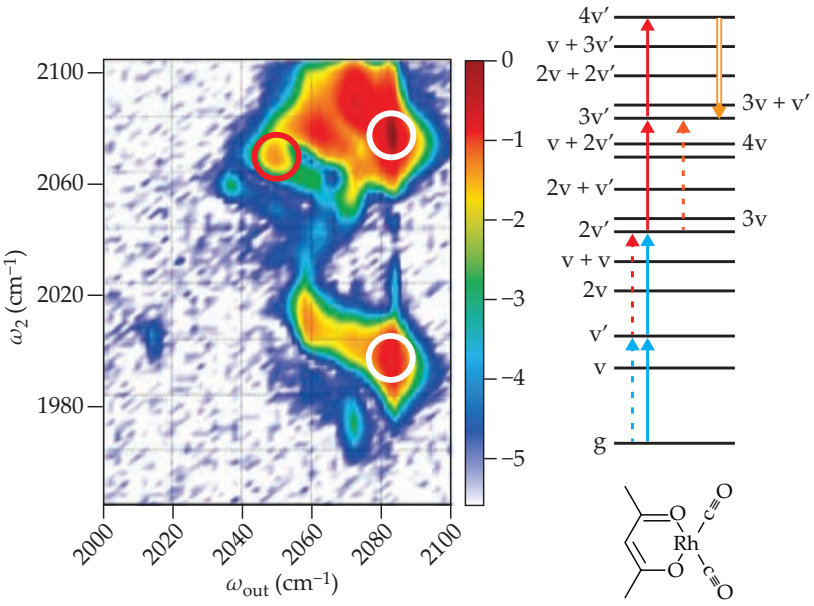


FIGURE 4. THE SPECTRUM of rhodium dicarbonyl in two dimensions was produced with high-intensity excitation pulses that interact multiple times. The color bar is the normalized logarithm of the output intensity. Compared with other types of spectroscopy, Floquet-state methods can reveal more information about a molecule and its properties. For example, the white circles show the diagonal C≡O symmetric v′ peak (top white circle) and the symmetric–asymmetric v + v′ cross peak (bottom white circle). The red circle denotes the 4v′, 3v′ overtone coherence created by the energy-level transitions summarized on the right. (Adapted from ref. 12.)

of the red (x-axis) and green (y-axis) excitation pulses shown in figure 1d across the vibrational resonances of the complex.

The lines in figure 3 identify patterns that relate the six new features to the vibrations associated with structural changes to the protein caused by the drug. The combination band's cross peak marked by the yellow circle at (1660 cm^{-1}, 3240 cm^{-1}), for example, shows that the 3240 cm^{-1} amine (NH_2) stretch mode of the drug is coupled to the 1660 cm^{-1} stretch mode of a protein carbon–oxygen double bond. That coupling is a signature of the hydrogen bonding of the drug to the protein.

Another combination cross peak, at (1400 cm^{-1}, 2980 cm^{-1}), corresponds to a coherence that involves the NH_2 group with another mode on the drug and appears only when the drug is attached to the protein. Similar combination bands and overtones caused by other drug–protein interactions can be found along the left vertical orange line. The ability to discover protein–drug binding interactions offers researchers a new tool to gather atomic-level structural information to support more intelligent drug design.[11]

Chemical reaction mechanisms

Among the many laser applications that its pioneers envisioned is the coherent control of chemical reactions.[2] The peak intensities of focused lasers are high enough to soften and even break bonds. When ultrafast lasers became popular in the 1980s, so did researchers' interest in coherently controlling reactions. Experiments aimed to optimize reactions focused largely on shaping ultrafast laser pulses by measuring the reaction product as a function of the pulse shape and controlling the shape with genetic learning algorithms.[12]

A different and more productive approach is to identify how chemical reactions occur by exciting the vibrational modes that control them. Bending, twisting, and stretching an object will eventually break it, and chemical reactions work the same way. Many vibrational motions are instigated by a chemical species' thermal and chaotic environment, but only a few are strong enough to break molecular bonds. Floquet-state spectroscopy can discover those modes and provide the mechanistic insights to guide chemists in intelligently discovering new reactions. The many overtone transitions shown in figure 2 are the simplest example of a reaction mechanism. The I_2 molecule dissociates when the amplitude of the I–I stretch mode is sufficiently large. The energy difference between the overtone vibrational modes declines at higher overtones, and when it reaches zero, the bond breaks.

For more complicated reactions, the Floquet methods shown in figures 1c–1f can replace the thermal environment with coherent excitations, which create mixtures of the vibrational overtones, combination bands, and electronic states that are responsible for bonding. The multidimensional cross peaks identify the states that are coupled and cause reactions. One of us (Wright) used a rhodium dicarbonyl chelate to demonstrate how Floquet-state spectroscopy can identify how chemical reactions occur.[13] The rhodium dicarbonyl has symmetric and asymmetric C≡O modes at 2015 cm^{-1} and 2082 cm^{-1}, respectively. The C≡O groups can disassociate and make carbon monoxide.

Figure 4 shows the 2D IR spectrum of the C≡O modes when the IR frequencies are changed. At low intensities, the spectrum has just two peaks, circled in white. At higher pulse intensities, the spectrum becomes exceptionally complex because each pulse can create multiple transitions and form the more energetic overtones and combination bands that break bonds. The red circled feature in figure 4, for example, was excited by three simultaneous interactions with ω_1 (blue arrows), three transitions with ω_2 (solid red arrows), and one transition with ω'_2 (dashed red arrow). The difference in the frequencies of the overtone and combination bands declines as the stretching becomes larger, just like in the I_2 molecule. By measuring the frequency changes of the higher energy overtones and combination bands, chemists can experimentally determine the reaction's potential energy surface and consequently how bonds break.

Beyond physical chemistry

Few laboratories in the world are involved in the development of fully coherent Floquet-state methods. Progress has been constrained by the experimental sophistication required to scan the frequencies of ultrafast laser systems. Excitation pulses in nanosecond systems are long enough that changes in frequency don't affect the temporal and spatial overlap that's required to measure nonlinear interactions. But scans of picosecond and femtosecond systems undergo substantial changes in overlap and directionality that must be corrected for, especially for spectral scans over long ranges.

Many of the opportunities envisioned in the early development of the methodology have yet to be fully realized.[14] An

MQC Floquet state could, for example, provide native, multidimensional contrast for highlighting specific molecules in a microscopic image without requiring fluorescent tags that perturb the sample. The spatial resolution can also be 3D and much higher than the IR diffraction limit because the highest-frequency excitation determines the resolution. The spectral resolution can be increased by using larger numbers of entangled vibrational states, as illustrated in figure 4.

Another example concerns semiconductor spectra, which are highly congested because of the many degrees of freedom for charge carriers that are delocalized within a lattice. Creating a Floquet state constrains the charge-carrier states to those that share the same momentum because of conservation laws that apply when transitions occur. Normally, only angularly resolved photoelectron spectroscopy is able to resolve the complex electronic structure of semiconductors, but that type of spectroscopy requires tunable x-ray sources, such as those at national laboratories.

An exciting application would be to use coherent x rays or extreme UV excitations of a Floquet state to entangle a valence core hole with vibrational or electronic states. That methodology would provide atomic and chemical selectivity. And the coupling between the states creates a nonequilibrium Floquet state for quantum computing and quantum information science. Currently, Floquet-state engineering is based on time-domain methods in which single quantum coherences can be controlled by other nonresonant pulses. Frequency-domain control of the multiple states within a Floquet state is potentially a new frontier for quantum applications.

Coherent multidimensional spectroscopy has remained almost exclusively in the field of physical chemistry, but its expansion beyond may provide a wealth of opportunities for the physics community. The development of Floquet-state spectroscopy will also be enhanced by the availability of the ytterbium-based laser systems that have now been engineered to avoid the problems of scanning the frequencies of ultrafast lasers. That advance and other new technologies will empower future experiments with multiple quantum coherences.

The development of Floquet-state spectroscopy has been made possible by NSF grants awarded to the Wright and Chen research programs.

REFERENCES

1. M. Munowitz, A. Pines, *Science* **233**, 525 (1986).
2. S.-I. Chu, D. A. Telnov, *Phys. Rep.* **390**, 1 (2004).
3. N. A. Kurnit, I. D. Abella, S. R. Hartmann, *Phys. Rev. Lett.* **13**, 567 (1964).
4. J. D. Hybl et al., *Chem. Phys. Lett.* **297**, 307 (1998).
5. P. D. Maker, R. W. Terhune, *Phys. Rev.* **137**, A801 (1965).
6. W. M. Tolles et al., *Appl. Spectrosc.* **31**, 253 (1977).
7. S. H. Lee et al., *Appl. Spectrosc.* **39**, 243 (1985).
8. J. C. Wright et al., *Appl. Spectrosc.* **51**, 949 (1997).
9. D. A. Daniels, T. A. Wells, P. C. Chen, *J. Chem. Phys.* **157**, 184201 (2022).
10. P. C. Chen, *Acc. Chem. Res.* (2023), doi:10.1021/acs.accounts.2c00637.
11. H. Sowley et al., *J. Phys. Chem. B* **123**, 3598 (2019).
12. D. J. Tannor, S. A. Rice, *Adv. Chem. Phys.* **70**, 441 (1988).
13. N. A. Mathew et al., *J. Phys. Chem. A* **114**, 817 (2010).
14. J. C. Wright, *Int. Rev. Phys. Chem.* **21**, 185 (2002).

PT

South Carolina State University

Orangeburg, SC
www.scsu.edu

Assistant/Associate Professor of Radiation Science

The Department of Biological and Physicals Sciences at South Carolina State University seeking to hire an Assistant/Associate professor of Radiation Science to teach undergraduate courses for the radiation concentrations for the Bachelor of Science in Chemistry and Physics at SC State on the main campus located in Orangeburg, South Carolina. These will be both in-person and online courses. In addition, the candidate will be expected to advise and recruit students, develop and improve programs, develop and administer online courses, conduct scholarly research and participate in committee assignments.

Apply Here

Job No: 492526

Minimum Requirements

BS and MS degree in Chemistry or Physics

Preferred Requirements

Doctorate degree preferred. The candidate must have a research base in the area of radiation science area. Must have a solid commitment to undergraduate teaching and student recruitment, program improvement and development, scholarly research activity, excellent communication skills, and personal concern for the student.

Stephen Case is a professor in the department of chemistry and geosciences at Olivet Nazarene University in Bourbonnais, Illinois. A historian of astronomy, he is the author of *Making Stars Physical: The Astronomy of Sir John Herschel* (2018) and coeditor of the forthcoming *Cambridge Companion to John Herschel*.

John Herschel's REFORM OF SCIENCE

Stephen Case

The son of the world's most famous astronomer, Herschel helped liberate science from the realm of aristocratic privilege.

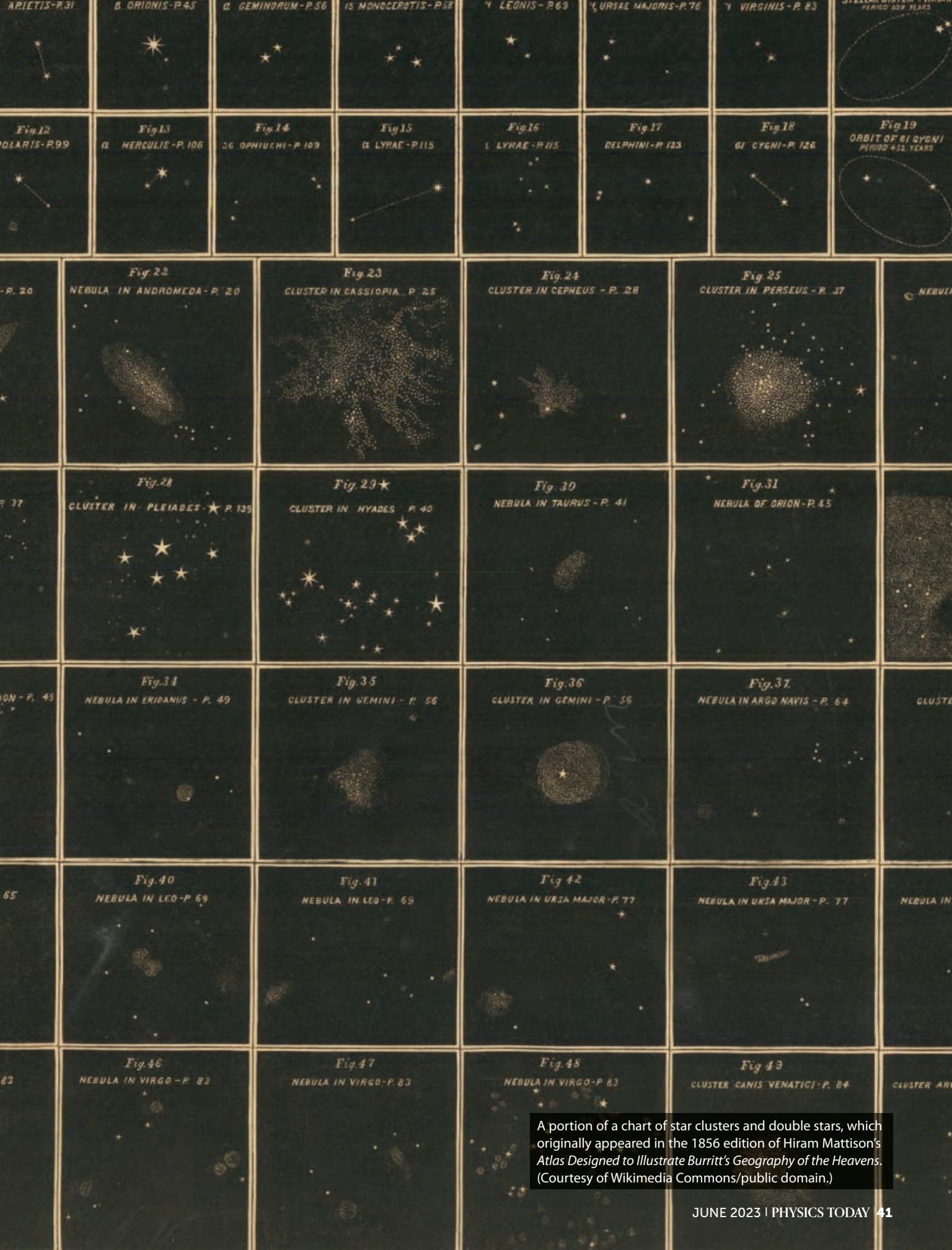
William Herschel had doubts about Saturn. Viewed through his large reflecting telescope, the ringed planet had a curious shape: The northern pole was flattened and the southern was "curved or bulged outwards." William was already known for pushing the observational limits of astronomy, whether it was because of his claims of telescope magnification or his speculations regarding life on the Sun. But his observations had also brought entire new classes of objects into astronomy: nebulae, star clusters, binary stars, and, most famously, the solar system's first new planet—Uranus, discovered in 1781.

On the night of 16 June 1807, however, William wanted confirmation of Saturn's strange shape. His sister, Caroline, had often assisted with and added to his observations. She typically recorded what he called out from the observing platform of the large telescope, but sometimes she even composed William's scientific papers for him. But on that particular evening, William called on a new set of eyes, those of his 15-year-old son, John Herschel. As William recorded, John also saw Saturn's strange curvature, marking a shape down on slate that "exactly delineated the appearance" William saw.[1] It was Herschel's first recorded astronomical observation. William no doubt hoped his son would continue his legacy but could not have predicted that Herschel would go on to help reform science itself.

Herschel (see figure 1) was born on 7 March 1792, the only child of William and his wife, Mary Baldwin Pitt. By the time of Herschel's birth in Slough, England, his father had rocketed to fame from a musician who had emigrated from Hannover in Germany to Europe's best-known astronomer. What had begun as a hobby with homemade telescopes became something more after William's discovery of Uranus, which he originally named after King George III. As a result, he was appointed the "King's astronomer," which gave William the chance to pursue stargazing full time and funds to build a massive 40-foot telescope. William was best known for his method of telescopic "sweeps," by which he discovered hundreds of new celestial objects. What he lacked, however, was the advanced mathematical training to turn his observations into coherent physical theories.[2]

The mathematical revolutionary

Things would be different for Herschel. William made sure that his son received the mathematical training he had lacked. By the time Herschel enrolled at the University of Cambridge, he had been privately tutored in the advanced techniques developed by continental mathematicians like Pierre Simon Laplace, Joseph Louis Lagrange, and Sylvestre François Lacroix, whose work connected algebraic



A portion of a chart of star clusters and double stars, which originally appeared in the 1856 edition of Hiram Mattison's *Atlas Designed to Illustrate Burritt's Geography of the Heavens*. (Courtesy of Wikimedia Commons/public domain.)

analysis with descriptions of the physical world in such areas as heat, vibrations, wave motion, and celestial mechanics. Yet that training simply set Herschel up for disappointment.

At Cambridge, Herschel found to his dismay an institution with little interest in mathematical developments outside of the UK. Like the University of Oxford—the only other university in England at that time—Cambridge was less an institution of research and discovery than a facility for training in law or the church and a place where young aristocrats learned the cultural polish needed to take their place among the landed elite. Instruction at Cambridge remained devoted to the "dot-age" of Newton's calculus—namely, his notation of dots over variables—and geometrical representation. For many Cambridge scholars, that representational aspect was essential to a view of mathematics as reason mapped onto the cosmos.

Continental—and in particular French—mathematics had, by contrast, developed along lines forged by German polymath Gottfried Wilhelm Leibniz and used the "d-ism" of differential notation (which is still used today). Not only did French mathematics carry political baggage in a UK that had been at war with France for decades, but it was also seen as a mere manipulation of logical symbols that was disconnected from the geometrical representation that many Cambridge scholars believed gave mathematics its epistemological grounding.

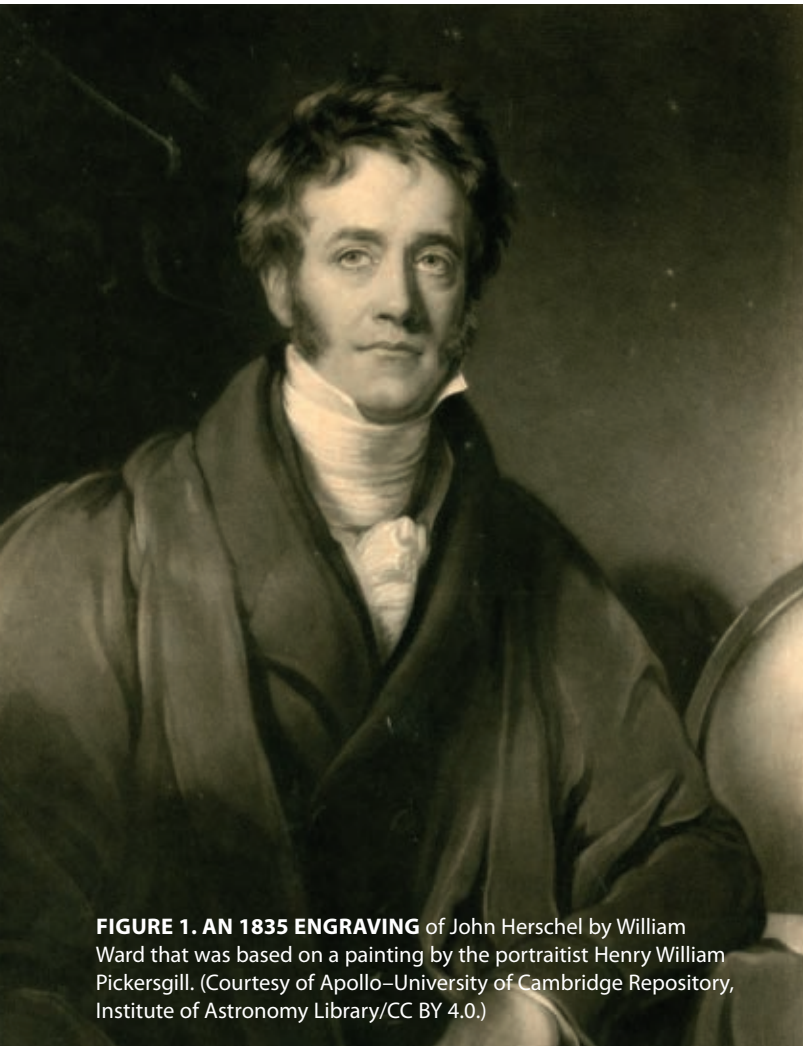


FIGURE 1. AN 1835 ENGRAVING of John Herschel by William Ward that was based on a painting by the portraitist Henry William Pickersgill. (Courtesy of Apollo–University of Cambridge Repository, Institute of Astronomy Library/CC BY 4.0.)

To Herschel, however, and to other like-minded students that included Charles Babbage, the logical methods of analysis were necessary to restore the UK's prominence in mathematics. When a controversy arose at Cambridge over whether the dons would support a Bible society that wanted to distribute copies of the Bible without accompanying commentary from the Book of Common Prayer, the opportunity for spoof was too much for Babbage. He proposed an analytical society that would promote the gospel of the d-ism of analysis instead of the conservative dot-age of the university.

The group convened, and the spoof became a revolutionary reality. Herschel, even as he completed his university course of study, reserved his real intellectual efforts for the Analytical Society. He wrote papers for the members that showed how trigonometric functions could be transformed into series expansions, defined functional operators, and taxed the limits of the day's typesetting technology with equations that marched across multiple pages. In the meantime, he passed his exams with top marks and received highest honors at graduation in 1813.

After producing a volume of mathematical memoirs with the Analytical Society, Herschel published a series of mathematical papers[3] in the *Philosophical Transactions of the Royal Society*, a venue with a history of resistance to pure mathematics.[4] He became one of the youngest fellows inducted into the Royal Society and was awarded its most prestigious prize, the Copley Medal, in 1821 for his contributions to mathematics. (He would win the award again in 1847 for his astronomical work at the Cape of Good Hope.) In those early publications, Herschel showed little interest in applying analysis to the natural world. Instead, his analysis illustrated the functioning of reason itself, divorced from geometrical restraint.

But at the time, Herschel's initial efforts to use the Analytical Society to stimulate the reform of mathematics instruction at Cambridge seemed to have failed. Herschel's friend William Whewell, who would eventually become master of Trinity College, complained, for example, that Herschel's allies at the university had stripped "analysis of its application & turned it naked" among the students.[5] Things were improved somewhat when Herschel (along with George Peacock and Babbage) published *Elementary Treatise on the Differential and Integral Calculus*, a translation of Lacroix's 1802 influential work, but it was some time before the seeds of the analytical revolution would bear fruit and transform Cambridge into a mathematical powerhouse.

Natural philosophy in London

Herschel was disappointed by the short-term failure of the Analytical Society to transform British mathematics, but he learned an important lesson. The hidebound university was not the place to institute reform. London, rather than Cambridge, was the center of the UK scientific world. If change were to occur, it would be there, where it could flourish alongside the growing influence and wealth of a new mercantile class. But like mathematics at Cambridge, the practice of science in London remained a conservative, hierarchical endeavor. Under the long presidency of naturalist Joseph Banks, the Royal Society—which functioned as a clearinghouse for dis-

FIGURE 2. THE ARISTOCRATIC CHARACTER of the Royal Society during the early 19th century is readily apparent in this 1844 engraving by Harden Sidney Melville, which was based on a similar 1843 engraving by Frederick William Fairholt. It depicts a meeting of the society in Somerset House, the large governmental complex where it was headquartered until 1857. (Courtesy of the Wellcome Collection/public domain.)

coveries in astronomy, natural history, and botany—enshrined science as a privileged, gentlemanly pursuit (see figure 2).

At the same time, a growing middle class and new technologies, such as the steam press, created a new audience with the access, means, and leisure to pursue science. As the drive for political reform gained momentum in the 1820s, there was a parallel push to make science more egalitarian. Herschel was at the center of that effort, which helped transform natural philosophy into modern science and the natural philosopher into the modern scientist.

In London, Herschel moved from pure to applied mathematics and explored a science that still had no firm disciplinary boundaries. He became interested in chemistry, mineralogy, and optics. He built a laboratory, and he filled notebooks with the records of hundreds of experiments. During that time, he discovered the properties of sodium thiosulfate solution and set the foundation for what would become the primary method of fixing images in photography (see the box on page 44). During visits to Paris in 1819 and 1821, Herschel worked with Jean Baptiste Biot and François Arago, who helped him realize how mathematical equations were embodied in the interactions between crystals and polarized light. Later, when he became known as an astronomer, he would tell his wife, Margaret, that "light was my first love."

In France, Herschel was also exposed to a new way of organizing science in which privilege was replaced by professionalization. In the French Academy of Sciences, natural philosophers were employees of the state and paid for full-time research. Positions were highly sought after, limited in number, and required scientific output. By contrast, London's Royal Society had only an advisory role to the government and was open to anyone recommended and approved by the society's fellows. By the time Herschel joined, membership had ballooned to hundreds, of which only a small minority contributed scientifically. Like mathematics at Cambridge, Herschel found the scientific institutions of London moribund and in need of reform. And as at Cambridge, Herschel's strategy involved a group of scientific rebels.

A sidereal revolution

After an abortive return to Cambridge as a tutor, Herschel finally acquiesced to become his aging father's apprentice and take up his observational program. But Herschel was not content to remain observing at his family's home in quiet Slough, 20 miles outside of London. Instead, astronomy became Herschel's means of combining his mathematical agenda with the reform of science. Along with Babbage, he helped found the new Astronomical Society of London in 1820 to challenge the hegemony of the Royal Society.

Not only did the Astronomical Society (renamed the Royal Astronomical Society in 1831) provide a vehicle for applying new mathematics to the practice, but its members were primarily bankers, stockbrokers, and schoolmasters—namely, members of the new professional classes whose membership was resisted in the Royal Society. As foreign secretary of the nascent society, Herschel built a correspondence network with astronomers across Europe. London was becoming the commercial and banking capital of the world, and the Astronomical Society aimed to likewise become the clearinghouse for the world's astronomical data.[6]

By taking up William's observations, Herschel also inherited a unique astronomical legacy. Prior to William and Caroline's work, astronomy had been primarily positional and concerned with establishing star positions as a background for measuring the Moon (for navigation and especially determining longitude)

Herschel and photography

After moving from Cambridge to London in 1814, John Herschel embarked on a series of chemical experiments. One of his early investigations was analyzing the properties of hyposulfurous acids. Herschel discovered a way to produce what he referred to as hyposulfite of soda, or what is today known as sodium thiosulfate ($Na_2S_2O_3$). In a series of papers in 1819 and 1820, Herschel outlined its properties, including its dissolving powers.[14] His discovery that $Na_2S_2O_3$ in solution dissolved silver halides would be critical for the development of photography.

Twenty years later, in early 1839, Herschel learned of Louis Daguerre's method for producing images on plates coated with light-sensitive material. Although the details of Daguerre's process were not published, Herschel realized that Daguerre had used light-sensitive silver halides, such as silver chloride and silver iodide. Within days Herschel had created a similar process that could be used on paper. The crucial step, however, was to "fix" the image by deactivating the photosensitivity of the coating. Otherwise, the image would continue to darken.

Initially, Daguerre used a heated solution of sodium chloride to halt the exposure. Herschel, however, realized $Na_2S_2O_3$ would provide a better method of dissolving the silver halide. His experimental notebook records that he "tried hyposulfite of soda to arrest the action of light" and found that it succeeded.[15] Because $Na_2S_2O_3$ was referred to as hyposulfite at the time, the fixing agent became known as "hypo." Herschel's hypo became the standard fixer for modern film photography. Fittingly, Herschel's first image was the frame of his father's massive 40-foot telescope.

A few months later, Herschel presented a paper on his photographic process, along with an album of example images, to the Royal Society.[16] Although the word "photography" had been used prior to his work, Herschel's paper popularized the term. Herschel also pioneered what he initially referred to as "transfers" or "reversals"—making a permanent photographic template of an image or engraving that allowed the image to be produced over and over. Eventually he dubbed those "negatives" and "positives," terms that are also still used today.[17]

The photograph shown here, attributed to Herschel in 1842, depicts a model of the Moon's Copernicus Crater. (Courtesy of the Getty Open Content Program/public domain.)

and planets and comets (for refining the application of Newtonian gravity to the solar system). With his large reflecting telescopes, William expanded the scope of astronomy to include objects beyond the solar system.

But despite his exciting discoveries, William's pursuit remained the domain of an eccentric amateur. His observing program was suited to his own unique instruments. Although his catalogs included hundreds of new nebulae and double stars, they did not provide the accuracy or organization for other observers to find them easily—which became a necessity as larger telescopes were constructed that rivaled William's 40-foot one. In addition, William's catalogs lacked standardized descriptions that would allow later observers to measure signs of change in those newly discovered objects, which was important if observations of nebulae and star clusters were to provide evidence for dynamic change in the universe beyond the solar system. Herschel's career in astronomy would be built around addressing those requirements.

Herschel began with double stars, which were particularly important objects because they provided a possible method for determining stellar parallax. If two stars were line-of-sight doubles—namely, stars that happened to appear close together along a line of sight from Earth but were actually distant from each other—measuring the annual variation in their apparent separation could provide the first means of directly determining stellar distances. But William's discovery that some double stars were in fact gravitationally bound pairs, or binary stars, complicated that picture because there was no easy method to determine whether any star pair was a line-of-sight double or a binary. The only way to know for sure was to carefully observe star pairs over years and decades.

Herschel decided to do just that. Along with James South, a London surgeon, he began revisiting all the double stars his father had cataloged. With the new catalogs, astronomers could determine which doubles were truly binary. Herschel would go on to publish double-star catalogs that included hundreds of additional doubles of his own discovery. His observations made double stars an active field for observers, and

the data he gathered allowed mathematicians to calculate the orbits of those bodies and make the first-ever measurements of stellar masses. Binary stars were so important that Herschel felt they were his father's true astronomical legacy, compared with which the discovery of Uranus was "but a trifle."[7]

Herschel also revisited the nebulae his father discovered, and again he created catalogs that provided both a means of locating those objects and a standardized empirical baseline from which to measure apparent changes over time. It was still an open question whether nebulae were formed of some luminous fluid that condensed to form stars or were merely collections of stars too distant to be clearly resolved. Before spectroscopy and astronomical photography, only painstakingly sketching nebulae against a background of precisely measured stars provided a means of confirming any potential change. Herschel's catalogs included such drawings, some of which were completed over years and contained hundreds of stars[8] (see figure 3). Measurements of nebulae and double stars were the observational frontier of astronomy, and Herschel worked meticulously to bring uniformity and standardization to those difficult objects.

At the Cape

By 1833 Herschel had revisited all his father's targets in the northern sky. But there was an entire hemisphere not yet swept by telescope. Herschel had already begun considering extending his astronomical surveys to that new frontier, and after his mother's death in 1832—his aunt Caroline had moved back to her childhood home in Germany following William's death in 1822—Herschel decided the time had come. Because of a large inheritance, Herschel was able to relocate his wife and three young children, along with their nurse and a workman to help him with his large reflecting telescope, to the UK colony at the Cape of Good Hope, at the southern tip of Africa, where they arrived in January 1834 (see figure 4).

The UK's Royal Navy offered him passage aboard a warship, but he refused. The entire endeavor would be, as he told a friend, "an entirely irresponsible private adventure."[9] Herschel wanted freedom to pursue his astronomical observations on his own terms. He ultimately spent four years at the Cape, where he continued his systematic sweeps and discovered and mapped new nebulae and double stars, and he became the first—and perhaps only—person in history to closely survey the entire visible sky by telescope. He also observed sunspots, variable stars, the moons of Saturn, and the return of Halley's comet in 1835. The product of that stay was the immense *Results of Astronomical Observations*—often referred to as the *Cape Results*—a massive volume published in 1847 that brought the wonders of the southern skies to view and which was distributed to observatories around the world.[10]

Upon his return to England in 1838, Herschel took his place at the head of the pantheon of UK science. He was given the title of baronet by Queen Victoria for his services to science, and a gala was thrown in London to welcome him home. By that point, Herschel's observing days were largely behind him, but he continued to write popular works that encouraged natural philosophers to apply his methods to the physical world. After spending 1850–55 as master of the mint, a post also held

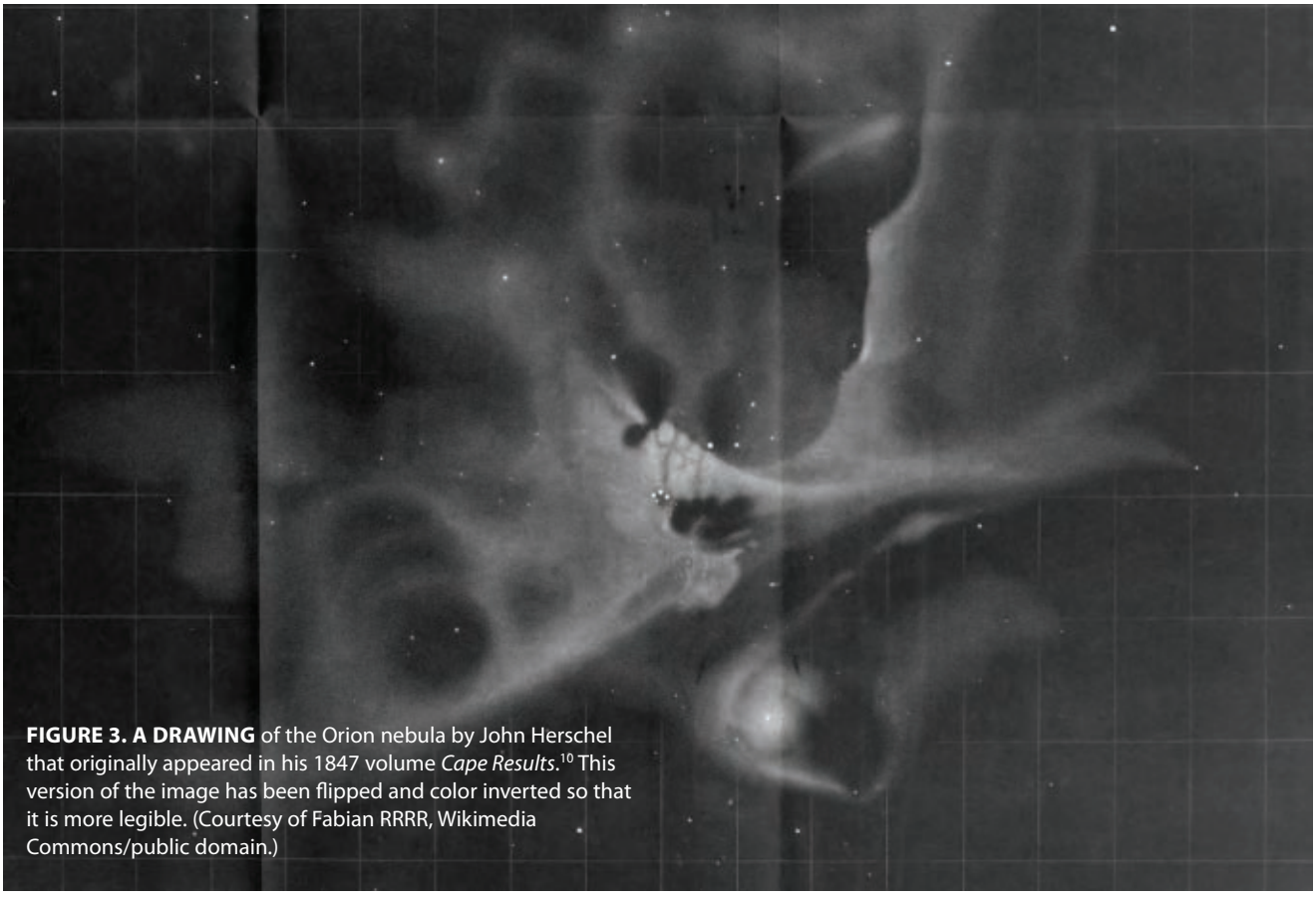


FIGURE 3. A DRAWING of the Orion nebula by John Herschel that originally appeared in his 1847 volume *Cape Results*.[10] This version of the image has been flipped and color inverted so that it is more legible. (Courtesy of Fabian RRRR, Wikimedia Commons/public domain.)

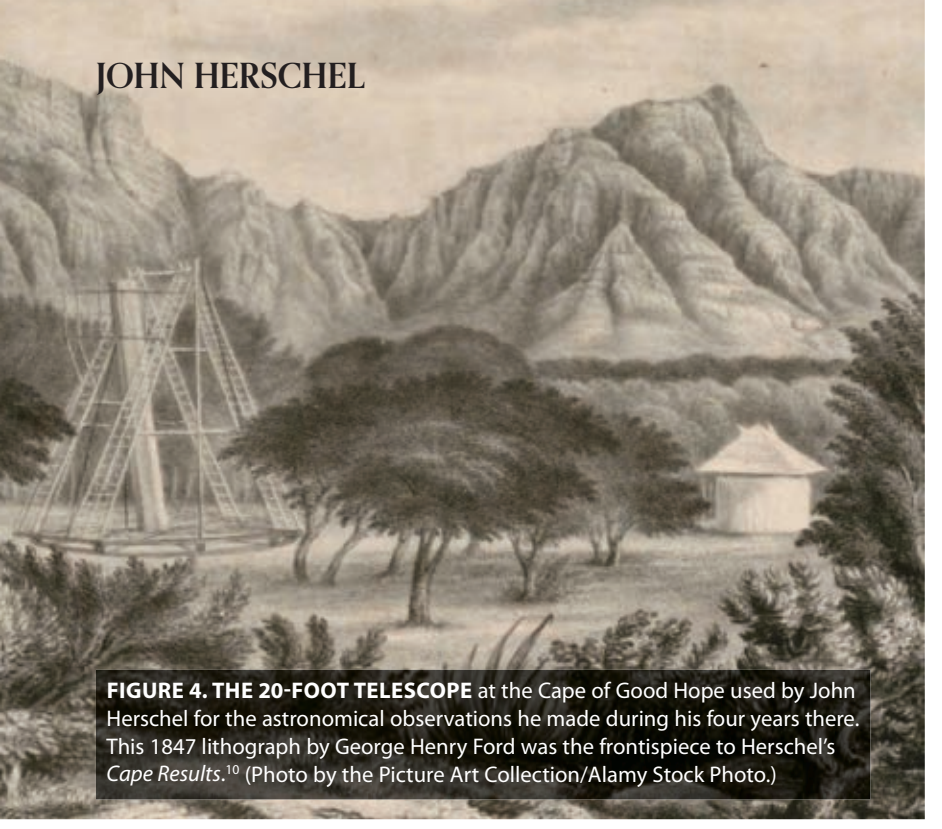


FIGURE 4. THE 20-FOOT TELESCOPE at the Cape of Good Hope used by John Herschel for the astronomical observations he made during his four years there. This 1847 lithograph by George Henry Ford was the frontispiece to Herschel's *Cape Results*.[10] (Photo by the Picture Art Collection/Alamy Stock Photo.)

by Isaac Newton, Herschel retired so he could spend his days preparing a general catalog of all the nebulae he had discovered. The object numbers in that catalog, which was revised posthumously into the New General Catalogue of Nebulae and Clusters of Stars, remain the primary label by which astronomers refer to deep-sky objects. At the time of Herschel's death on 11 May 1871, he was held in high-enough esteem that he was buried in Westminster Abbey near Newton.

But Herschel was not simply celebrated as an astronomer. He was recognized by an entire generation of scientific practitioners—who were at the time of Herschel's death only beginning to be referred to as scientists—for helping define the practice of science itself. To understand how requires a return to the years before his self-imposed exile to the Cape.

The reformation of science

Although his early work with the Astronomical Society threatened the Royal Society's control over UK science, Herschel was active in both societies before his South African expedition. Whereas his colleagues Babbage and South thundered publicly that the Royal Society was stifling science, Herschel worked in the 1820s to reform the venerable society from within. The culmination of those efforts came in an 1830 confrontation between the reforming and conservative parties of the Royal Society over who would be its next president.

That year, the aristocratic wing of the society pushed for the election of King William IV's brother Augustus Frederick, Duke of Sussex. For the conservative leadership of the society, the duke was an ideal candidate: He was interested in science and, as an aristocrat, had beneficial social connections. For Herschel, those attributes were antithetical to the scientific endeavor. How could science progress on a meritocratic basis with a president who was royalty and whose mere suggestions could be construed as commands?

So radical were Herschel's views on the egalitarian nature of science that he suggested the bookish Francis Baily—a stockbroker who had gained recognition through his recalculation of old star catalogs and who had risen to leadership in the Astronomical Society—as an opposing candidate. In a confrontation that mirrored the larger political landscape leading up to the parliamentary reforms of 1832, not only would Herschel not support the king's brother, but he supported a merchant commoner against him.

Herschel's reforming colleagues knew that Baily would not do. There was only one person whose scientific accomplishments and esteem could unify opposition to the duke: Herschel himself. At a meeting in October 1830, Herschel's colleagues urged him to allow his name to stand. He protested. He had no desire for leadership; he wanted the freedom to pursue his own scientific projects, not the responsibility of leading the Royal Society. Yet he agreed that the conservatives in the society should not be allowed to hand over the presidency through backroom dealings. Herschel ultimately allowed his colleagues to put his name forward, and soon the London newspapers were relishing in the scandal of the duke, son of the late King George III, being publicly opposed by the son of George's personal astronomer.

Although it was a close race, the reforming coup failed. The Duke of Sussex was elected and the aristocratic party retained its grip on the society. But the crisis reaffirmed in Herschel his belief that change must happen, and he channeled his efforts at reform into a new direction. If he could not transform the practice of science in the Royal Society, he would take his methods to the broader public.

The book that invented science

In the days leading up to his failed bid for the presidency, Herschel was approached by science writer and editor Dionysius Lardner to author the preliminary volume of a new encyclopedia series focused on science. Eager to capitalize on the booming market among the middle class for popularizations of science, Lardner was looking for someone who could write with authority for a wide audience. Herschel, already well known for his writings, was the perfect candidate.

For Herschel, that book—first published in 1831 and titled *A Preliminary Discourse on the Study of Natural Philosophy*—was an opportunity to set out his vision of science. It did not matter if his reforming tendencies had been stymied in both Cambridge and London. Science, he argued, was bigger than what took place in the halls of the privileged elite. More than a static body of knowledge or aristocratic pastime, science was a matter of social and personal virtue. In addition to the practical benefits it provided, which were clear to his readers because of the Industrial Revolution unfolding around them, understanding science allowed people to reason clearly and cultivate character. Herschel went on in *A Preliminary Discourse* to outline what many consider to be the earliest modern formulation of the laws of scientific reasoning, thus providing a template for how investigators should search for lawlike behavior in nature.[11]

A Preliminary Discourse articulated the relationship between mathematics and natural philosophy and showed how scien-

tific discoveries were made. It was both a defense of the scientific life and a manual for how to construct scientific theories. Apart from becoming a popular bestseller, it was read by those who would become the leading scientists of the next generation. Michael Faraday, for instance, wrote that he "continually endeavored to think of that book and to reason & investigate according to the principles there laid down."[12] It convinced a certain young Cambridge naturalist to pursue the scientific vocation. And when that naturalist, Charles Darwin, began to create his own theory of the origin of species, he structured it—consciously or subconsciously—along the framework outlined by his scientific role model in *A Preliminary Discourse*.[13]

In all of Herschel's pursuits—chemistry, astronomy, optics, and more—he pushed science toward standardization and mathematical analysis and away from traditions of prestige and privilege. Yet that effort bore most fruit through his *Preliminary Discourse*, which brought the ideals of science to the general public and articulated scientific methodology for a new generation. Although no theorem or discovery bears Herschel's name, his work molded the contours of an age and helped shape the ideals of modern science.

REFERENCES

1. W. Herschel, *Philos. Trans. R. Soc.* **98**, 145 (1808), pp. 160, 161.
2. For background on William's life and work, see M. Hoskin, *Discoverers of the Universe: William and Caroline Herschel*, Princeton U. Press (2011); C. J. Cunningham, ed., *The Scientific Legacy of William Herschel*, Springer (2018).
3. J. F. W. Herschel, *Philos. Trans. R. Soc.* **103**, 8 (1813); **104**, 440 (1814); **106**, 25 (1816); **108**, 144 (1818).
4. J. L. Heilbron, in *World Changes: Thomas Kuhn and the Nature of Science*, P. Horwich, ed., MIT Press (1993), p. 81.
5. W. Whewell to J. F. W. Herschel (6 March 1817), vol. 18, letter no. 158, Herschel Papers, Royal Society Library and Archives, London.
6. W. J. Ashworth, *Br. J. Hist. Sci.* **27**, 409 (1994), p. 419.
7. J. F. W. Herschel to C. Herschel (22 May 1831), ID no. L0576.3, Herschel Family Papers, Harry Ransom Center, U. Texas at Austin; J. F. W. Herschel, J. South, *Philos. Trans. R. Soc.* **114**, 1 (pt. 3, astron. obs.; 1824).
8. J. F. W. Herschel, *Philos. Trans. R. Soc.* **123**, 359 (1833); O. W. Nasim, *Observing by Hand: Sketching the Nebulae in the Nineteenth Century*, U. Chicago Press (2013).
9. J. F. W. Herschel to F. Baily (24 April 1832), vol. 21, letter no. 106, Herschel Papers, in ref. 5.
10. J. F. W. Herschel, *Results of Astronomical Observations Made During the Years 1834, 5, 6, 7, 8, at the Cape of Good Hope; Being the Completion of a Telescopic Survey of the Whole Surface of the Visible Heavens, Commenced in 1825*, Smith, Elder (1847); S. Ruskin, *John Herschel's Cape Voyage: Private Science, Public Imagination and the Ambitions of Empire*, Ashgate (2004).
11. J. A. Secord, *Visions of Science: Books and Readers at the Dawn of the Victorian Age*, U. Chicago Press (2014), chap. 3.
12. M. Faraday to J. F. W. Herschel (10 November 1832), rec. no. Faraday0623, Epsilon: The Michael Faraday Collection, https://epsilon.ac.uk/view/faraday/letters/Faraday0623.
13. C. H. Pence, *Hopos* **8**, 108 (2018).
14. J. F. W. Herschel, *Edinb. Philos. J.* **1**, 8 (1819); **1**, 396 (1819); **2**, 154 (1820).
15. S. Ross, *Nineteenth-Century Attitudes: Men of Science*, Kluwer Academic (1991), chap. 5.
16. L. Schaaf, *Hist. Photogr.* **3**, 47 (1979).
17. J. F. W. Herschel, *Philos. Trans. R. Soc.* **130**, 1 (1840).

PT

CHARLES O. PERRY/RAUL654/WIKIMEDIA COMMONS/CC BY-SA 3.0

Charles O. Perry's 1976 sculpture *Continuum* was inspired by the Möbius strip.

A synthesis of physical connectedness

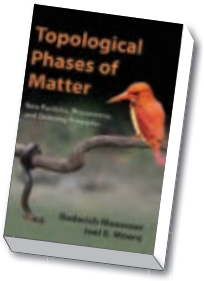
Topology is the study of connectedness. It addresses the question: Given two objects, can one be smoothly deformed into the other? Two objects that do not fit that criterion are said to be topologically distinct. Think of an ordinary rubber band. It cannot be stretched into a Möbius strip unless it is cut, twisted, and glued back together. Topology has broad applications in the physical sciences, and perhaps the most well-known is the theory of topological defects: large-scale structures such as vortices and domain walls that describe stable, twisted configurations of classical fields that cannot be deformed away.

A more subtle application of topology began to emerge in the 1980s with the discovery of the quantum Hall effect. Topologically speaking, it arises from the twisting not of classical fields but of electronic wavefunctions, or of collections of them that are called bands. Remarkably, the degree of their twisting—a topological invariant called the Hall conductivity—is characterized by an integer that can be directly measured in units of e^2/h, where e is the electron charge and h is Planck's constant. In other words, a combination of fundamental constants defines a quantum of conductance.

The subsequent discovery of the fractional quantum Hall effect, in which the Hall conductivity was found to be a rational fraction of e^2/h, led to the notions that many-body wavefunctions could be twisted and that quasiparticles may exist and behave like fractions of electrons. Those eventually led to the modern concept of topological order, which provides a way to organize phases of matter that is complementary to the conventional one based on symmetry and order parameters.

Topological Phases of Matter

Roderich Moessner and Joel E. Moore
Cambridge U. Press, 2021. $69.99



Although they were appreciated for their beauty, topological applications in physics remained largely limited to the esoteric realm of ultrahigh magnetic fields in artificial structures until the 2000s, when it was discovered that the concepts applied much more generally. Today they are the bread and butter of theoretical condensed-matter physics. There are now databases of topological characteristics of materials, corporate efforts to build topological quantum computers, and much more. The theory is much more evolved, and its mathematical treatment is more sophisticated and has been applied to such topics as band structure, exotic quantum magnets, and unconventional superconductors.

Roderich Moessner and Joel Moore's recent book, *Topological Phases of Matter*, provides a synthesis of the vast subject. The authors begin with an introduction before delving into a compact summary of background material including the Berry phase, Landau levels, tight-binding models, and Landau theory. They also include a succinct section on the mathematics of topology, which readers will benefit from because it summarizes material often found in disparate sources in one place. Subsequent chapters discuss the integer quantum Hall effect, quantum pumps, and the Chern number; examples of fractionalization including the fractional quantum Hall effect, spin liquids, gauge theories, and topology in conductors and superconductors; and even topological ideas in quantum computing and nonequilibrium-driven systems.

It became clear to me only after reading the book just how ambitious and challenging it is to cover all that material. Moessner and Moore generally chose to illustrate through examples instead of presenting a systematic overview of the topic. That makes the book more accessible, but at the same time it can be limiting. Moreover, the choice of examples may sometimes reflect the authors' predispositions rather than being entirely representative. I found it strange, for example, that although disorder and localization are discussed in chapter 8, there's no discussion of them when the integer quantum Hall effect is introduced in chapter 3, nor any mention of the Kubo formula. Both are essential to understanding the exactness of quantization and the existence of plateaus in the Hall effect.

Analogously, the chapter on gauge theory contains a thorough yet concise discussion of Ising gauge theory, but it presents without explanation Alexander Polyakov's famous result that proved the instability of $U(1)$ gauge theory in two spatial dimensions. I also was frustrated that the presentation of spin liquids in several chapters completely avoids the concepts of Gutzwiller projection and general parton constructions, both of which are central to the subject. Finally, tensor networks and matrix product states, which provide a powerful tool to understand many topological phases, are essentially absent.

But Moessner and Moore are clear about the choices they make, and in the preface, they explain their reasons for being less than encyclopedic. On balance, *Topological Phases of Matter* is an enjoyable read and a particularly broad introduction to diverse aspects of topological ideas in quantum theory. Its main weaknesses are ones of omission: Many results aren't derived in the text, and some topics—such as those mentioned above—are left out entirely. That means that the level of detail is probably less than one would want to present in a graduate physics course, but a knowledgeable instructor could fill in the gaps and rely on the book as a resource to guide the order of topics presented in the class. The volume should be a helpful resource for anyone wanting to learn more about a topic that has become increasingly central to modern physics.

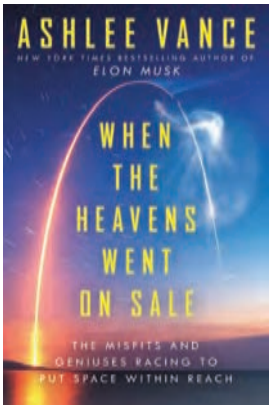
Leon Balents
University of California, Santa Barbara

NEW BOOKS & MEDIA

When the Heavens Went on Sale

The Misfits and Geniuses Racing to Put Space Within Reach

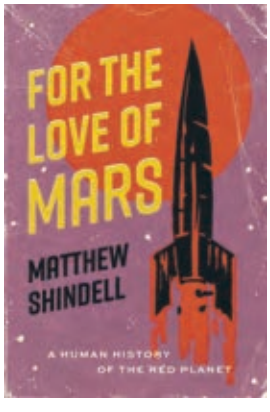
Ashlee Vance
Ecco, 2023. $35.00



Although space tourism and the efforts of billionaire entrepreneurs such as Elon Musk have tended to dominate public perceptions of the private space industry, a host of startup companies have been proliferating to cash in on another burgeoning market—smaller, faster, and cheaper satellite launches. In *When the Heavens Went on Sale*, writer Ashlee Vance focuses on four of the leading pioneers in that field: Planet Labs, Rocket Lab, Astra, and Firefly Aerospace. Having gained exclusive access to the companies and their founders, Vance provides a firsthand account of their race to build new types of satellites and rockets, and the many adventures and misadventures along the way. —CC

For the Love of Mars

A Human History of the Red Planet



Matthew Shindell
U. Chicago Press, 2023. $27.50

What is it about Mars that has captivated humanity for centuries? In this new book, Matthew Shindell, a curator at the Smithsonian's National Air and Space Museum, investigates why the red planet has cast a spell on societies from antiquity to the present. Early portions of the book, including a section on the depiction of Mars in Dante Alighieri's *Divine Comedy*, are highly intriguing. But the meat of the book focuses on 19th- and 20th-century conceptions of Mars. It interrogates the key tension of modern Martian "history": Missions searching for signs of life on the planet have had both scientific and geopolitical motivations. As with so many other fields during the 20th and 21st centuries, advances in planetary science have often been linked to superpower rivalries. —RD

The Short Story of the Universe

A Pocket Guide to the History, Structure, Theories and Building Blocks of the Cosmos

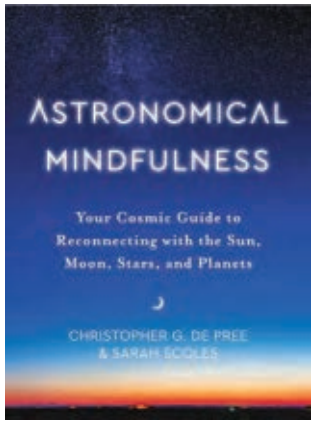
Gemma Lavender
Laurence King, 2022. $19.99

With the beautiful illustrations of a coffee-table book and the conciseness of a primer, *The Short Story of the Universe* aims to provide an easily digestible overview of current astronomy knowledge. Divided into four parts—structure, history and future, components, and theories—the book comprises some 100 two-page spreads featuring encyclopedic entries on such subjects as spacetime, the origins of our solar system, individual planets and their moons, and special and general relativity. Color and black-and-white images, callouts of notable scientists involved in or notable examples of the phenomena in question, lists of key publications or developments, and cross-references round out the entries. —CC

Astronomical Mindfulness

Your Cosmic Guide to Reconnecting with the Sun, Moon, Stars, and Planets

Christopher G. De Pree and Sarah Scoles
HarperOne, 2022. $24.99

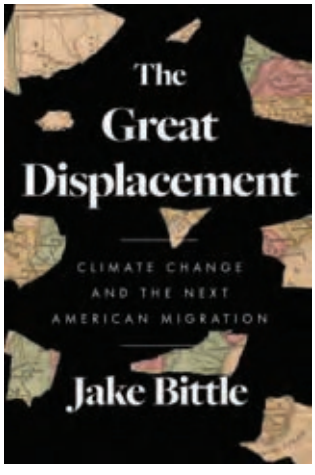


A starlit sky can inspire awe and wonder, yet how often do we take the time to stargaze? In *Astronomical Mindfulness*, the astronomer Christopher G. De Pree and the science writer Sarah Scoles focus on the value of becoming better acquainted with the stars and planets as a means of pursuing a heightened awareness of oneself and one's place in the cosmos. They achieve that through a combination of practical astronomical instruction and homework interspersed with mindfulness exercises, which involve such activities as observation, breathing, and visualization. The book is a timely reminder for people caught up in their daily jobs and routines to take a moment and see the bigger picture. —CC

The Great Displacement

Climate Change and the Next American Migration

Jake Bittle
Simon & Schuster, 2023. $28.99



One potential effect of climate change will be the forced relocation of individuals and entire communities as extreme temperatures, droughts, flooding, and forest fires occur more frequently and become more widespread. In *The Great Displacement*, the journalist Jake Bittle focuses on the US, where climatological events are already driving people to abandon their homes and move elsewhere. He discusses the havoc wreaked by several 21st-century catastrophes, such as Hurricane Irma in Florida and the Tubbs fire in California; the loss of community and history that results from such tragic events; and the need for improvement in economic and government programs to help those most affected, who tend to be minorities and the less affluent. —CC

"You Are Not Expected to Understand This"

How 26 Lines of Code Changed the World

Torie Bosch, ed.
Princeton U. Press, 2022. $19.95 (paper)

Contrary to the book's title—a comment made in 1975 by a Unix programmer—this collection of 26 essays aims to enlighten readers, programmers and nonprogrammers alike, about the history of computers and coding. Written by leading technology experts and journalists, the essays cover diverse topics: Some focus on actual lines of code, while others discuss software, coding languages, and the very act of coding. As editor Torie Bosch writes in her introduction, by revealing both moments of genius and major mistakes, she aims to tell the stories of the people behind the programming and convey the complexity of the technical environment in which we live. —CC PT

NEW PRODUCTS

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

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

Andreas Mandelis

EMI test receiver

The R&S EPL1000 from Rohde & Schwarz is a compact, complete, and CISPR 16-1-1 compliant test receiver for quick, precise electromagnetic interference (EMI) measurements of up to 30 MHz. For seamless measurements over extended periods of time, the very fast time-domain scan lets the R&S EPL1000 check all frequencies in CISPR bands A or B in a single shot. A user-friendly graphical user interface helps electromagnetic compatibility engineers quickly find infrequent emissions and gain a good overview. The R&S EPL1000 has a pulse-protected input; an autoranging function prevents the overloading of the signal-processing chain. Built-in preselection ensures a high dynamic range and enables the acquisition of short pulses, and spectrogram and intermediate frequency-analysis functions facilitate detailed signal analysis. Automation simplifies measurements and ensures exact reproducibility of test sequences. An integrated CW signal generator with a tracking generator function is optional. ***Rohde & Schwarz GmbH & Co KG**, Mühldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Inline gas analyzer

MKS Instruments has announced additional measurement capabilities for its T-Series inline gas analyzer. The instrument now provides simultaneous measurement of silicon tetrafluoride and carbon dioxide found in by-products of semiconductor processes. The gas analyzer uses the company's tunable filter spectroscopy, a scanning technique capable of generating spectra in the IR region. By subtracting spectra from interferent gases in the same IR regions, the technology improves gas-identification accuracy and measurement compared with traditional methods. It also enables multicomponent measurement. The T-Series inline gas analyzer is suitable for end-point detection in advanced semiconductor processing and etch-process monitoring in a clean chamber. ***MKS Instruments Inc**, 2 Tech Dr, Ste 201, Andover, MA 01810, www.mks.com*

Multipurpose power amplifier

AR RF/Microwave Instrumentation designed its model 800W1000 solid-state broadband power amplifier for applications that require instantaneous bandwidth, high gain, and linearity. Those include not only general-purpose testing but also testing of radiated and conducted electromagnetic compatibility (EMC), antennae, and components. The self-contained, air-cooled power amplifier delivers a minimum of 800 W across the 80–650 MHz frequency range and 750 W across 650–1000 MHz. The device is protected from input overdrive beyond 0 dBm and from various failure conditions, including high temperatures and power-supply faults. The low level of spurious signals and linearity make the amplifier suitable as a driver in testing wireless and communications components and subsystems; because it covers a wide bandwidth, it is suitable for 5G network testing. Its class A design makes it appropriate for EMC test applications that require continued operation into high-voltage standing-wave ratio loads, including open and short circuits. ***AR RF/Microwave Instrumentation**, 160 Schoolhouse Rd, Souderton, PA 18964, www.arworld.us*

Chip carrier for multiqubit processors

Quantum Machines has unveiled the QCage.64 from QDevil, the company's Quantum Electronics business unit. QCage is a microwave chip-packaging system for high-fidelity operation of superconducting processed and microwave-resonator-based quantum measurements. Designed for interconnecting superconducting quantum processors with up to 30 qubits, the QCage.64 chip carrier features a sample holder that suspends the chip in the microwave cavity to minimize losses and decoherence, a low-loss printed circuit board (PCB) with embedded coplanar transmission lines for signal integrity, and an electromagnetically compatible superconducting shielding enclosure. The cavity and PCB are optimized for resonance-free transmission. According to the company, data from leading quantum laboratories have shown that the QCage chip carrier offers a suitable low-loss environment for operating superconducting resonators with Q factors as high as 2×10^8 and transmon qubits with coherence times of longer than 200 μs. ***Quantum Machines**, Yigal Alon St 126, Tel Aviv-Yafo, Israel, www.quantum-machines.co*

Compact vacuum meters

Thyracont has improved the performance of its vacuum-meter product family and enhanced its intuitive handling. The new VD800 series measures absolute pressure in the range of 2000 mbar to 5×10^{-5} mbar and relative pressure from −1060 mbar to 1200 mbar. A big graphic display and 4×1 membrane keypad provide comfortable menu-driven operation, and an integrated data logger saves multiple measurement series with its real-time clock data. With sample rates from 50 ms to 60 s, the instruments are suitable for both fast vacuum processes and long-term monitoring in applications such as quality control and leakage testing via rate-of-rise measurement. The model VD800, designed to be used with an external Thyracont USB transducer, is suitable for reduced-space applications or for readout of permanently installed sensors. The VD810, with a resistant ceramic sensor, produces measurements independent of gas type in the rough vacuum range. The piezo/Pirani combination sensor of the VD850 covers a wide measuring range in rough and fine vacuum with high precision and accuracy. ***Thyracont Vacuum Instruments GmbH**, Max-Emanuel-Str 10, 94036 Passau, Germany, https://thyracont-vacuum.com*

Automated IR microscope for defect analysis

Shimadzu developed its AIMsight IR microscope to more efficiently identify and analyze micro contaminants, such as those that might adhere to pharmaceutical pills, dirt on electronic circuit boards, and microplastics. AIMsight offers easy determination of the measurement range via a wide-field camera and automatic identification of measurement targets, setting of measurement position, and contaminant analysis. The IR microscope needs to be connected to a Fourier-transform IR (FTIR) spectrophotometer, such as the company's IRXross model. Using the reflection and transmission of IR light, the microscope can measure microregions that cannot be measured by FTIR units alone. Out of concern for the environment, a type II superlattice detector has been adopted that does not use mercury or cadmium, which are restricted under the European Restriction of Hazardous Substances Directive. AIMsight can be used in various sectors, including drug manufacturing, materials science, electrical devices and electronics, machinery, transportation equipment, and the environment. ***Shimadzu Scientific Instruments Inc**, 7102 Riverwood Dr, Columbia, MD 21046, www.shimadzu.com*

Spectrum analysis for satellite communications

A real-time spectrum analysis (RTSA) solution from Keysight helps satellite operators perform rigorous, accurate signal-interference monitoring to identify anomalies and mitigate service degradation as they happen and thereby provide high-quality service to users. The RTSA solution was developed for use with the company's N9042B UXA signal analyzer. According to the company, the software-based RTSA solution reduces analysis time and improves the probability of intercept. It enables the N9042B UXA to conduct continuous, gapless capture and analysis of elusive and transient signals with optical-data-interface streaming up to 2 GHz. To minimize the time gap between processing and recapturing signals, Keysight's advanced field-programmable gate-array technology enables a multithreaded, parallelized RTSA measurement up to a bandwidth of 2 GHz. By using digital twins that speed the design and testing of satellite payloads, the RTSA test solution can accelerate innovation and lower prototyping costs. ***Keysight Technologies Inc**, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Software for Raman and correlative measurement control

WITec, an Oxford Instruments company, has released its Suite SIX software for Raman and correlative measurement control, data acquisition, and postprocessing. Developed to enhance the configurability of the company's alpha300 microscope series, the software offers a multiuser management capability that allows site administrators to determine the instrument functionalities and data-access rights associated with each system login. It assists in administrators' efforts to comply with good-practice guidelines, such as the US FDA's 21 CFR Part 11; that is especially important for pharmaceutical R&D. To streamline recurring experiments, the software can be used to develop a library of distinct hardware setups. TrueOrigin, Suite SIX's portable coordinate system, expedites the correlation of data acquired by multiple techniques from the same position, even when the sample is moved between instruments. To navigate to an area of interest or to conveniently document a project, it can also import images of a sample made with an external camera. ***WITec Instruments Corp**, 130G Market Place Blvd, Knoxville, TN 37922, https://raman.oxinst.com* PT

LOOKING FOR A JOB?

Job ads are now located throughout the magazine, alongside the editorial content you engage with each month. Also find hundreds of jobs online at physicstoday.org/jobs

LOOKING TO HIRE?

Enjoy the power of print plus online bundles any time as well as impactful exposure packages & discounts for our special Careers issue each October. Post online-only jobs anytime at physicstoday.org/jobs

Questions? Email us at ptjobs@aip.org

PHYSICS TODAY | JOBS

Omar Awartani is a research scientist at Meta Reality Labs and an adjunct assistant professor in the department of mechanical and aerospace engineering at North Carolina State University in Raleigh. **Michael Dickey** is the Camille and Henry Dreyfus Professor in the department of chemical and biomolecular engineering at North Carolina State University.

Making soft and reconfigurable electronics with liquid metals

Omar Awartani and Michael D. Dickey

Gallium-based alloys can change shape when an electric potential reversibly alters its surface tension.

Gallium has a melting point of 30 °C, which is low enough that body heat alone can melt it. The element's melting point can be lowered further by dissolving other metals to form gallium-based alloys—such as eutectic gallium indium (EGaIn)—which are liquid at room temperature. Those alloys are referred to as liquid metals, or simply LMs. (See the article by Michael Dickey, PHYSICS TODAY, April 2021, page 30.)

LMs are similar to water in some respects. For example, both water and EGaIn have similar viscosities, of 2.0 mPa·s and 1.0 mPa·s, respectively. They also both expand when they freeze. But water boils at 100 °C and has a vapor pressure of 2.33 kPa, whereas gallium boils at 2400 °C and has an extremely low vapor pressure, which practically eliminates inhalation concerns during its handling or processing. Additionally, EGaIn has metallic thermal and electrical conductivities that are orders of magnitude larger than water. Those attributes combined with EGaIn's low toxicity make the alloy an attractive material for soft, stretchable, and wearable electronics.

Advanced electronic applications such as interconnects, electrodes, and antennas require metals to be patterned into precise and stable structures. But controlling and stabilizing the shape of liquids is difficult because they tend to flow in response to force. Consider, for example, how difficult it is to create a stable cylinder of water without a container. Fortunately, gallium-containing LMs react spontaneously with oxygen in the air to form an oxide. That nanometers-thick oxide skin encases the LM and stops it from freely flowing, a fundamental difference compared with most other liquids. Water droplets in contact with each other simply merge into one larger droplet, but LM droplets can be patterned and stacked into three-dimensional structures, as shown in figure 1.

Another property of LMs is their ability to significantly change their interfacial energy by a simple electrochemical reaction. Whereas surface tension typically refers to the tension of a fluid relative to a surrounding vapor phase, interfacial tension broadly encompasses the tension of fluids in contact with other materials. Of the elements that are liquid near room temperature, Ga has the largest surface tension, at 708 mN/m. EGaIn's surface tension is slightly lower at 624 mN/m, still nearly nine times that of water. Such large tensions cause LMs to bead up into droplets in the absence of oxide. The most common way to lower tension is with surfactants, such as soap, but they're not very effective. And once such molecules diffuse to the interface of a liquid, they are hard to remove.

In contrast, the interfacial tension of metals can be controlled electrochemically in an aqueous electrolyte. A reducing potential of −1 V removes the surface oxide by converting it to metallic EGaIn. Once the oxide is removed, the metal is left bare and has a high interfacial tension. It therefore beads up to minimize its surface energy.

The effects of electrochemical reduction on the interfacial tension of LMs can be reversed with electrochemical oxidation. To demonstrate the effect, we applied a modest positive potential of 1 V on EGaIn immersed in a sodium hydroxide electrolyte. The potential drives the oxidation of the metal's surface and lowers the interfacial tension of the LM from 624 mN/m to nearly 0 mN/m.

Altering the tension of a metal droplet in an electrolyte by gathering charges at the interface is a widely known phenomenon called electrocapillarity. It can't, however, explain why the interfacial tension of LMs drops so much during electrochemical oxidation. Under those conditions, liquid

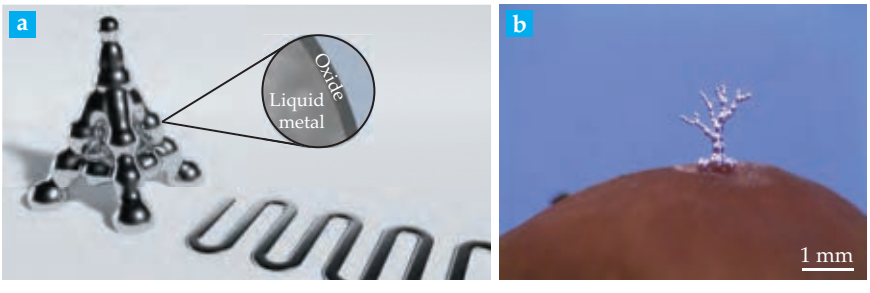


FIGURE 1. LIQUID-METAL STRUCTURES. **(a)** Two- and three-dimensional patterns are stabilized by a thin oxide skin that forms when gallium or gallium-based metal alloys react with air. (Courtesy of Luke Cunningham.) **(b)** Three-dimensionally printed droplets of liquid metal are stacked on the surface of a mushroom. (Courtesy of Collin Ladd.)

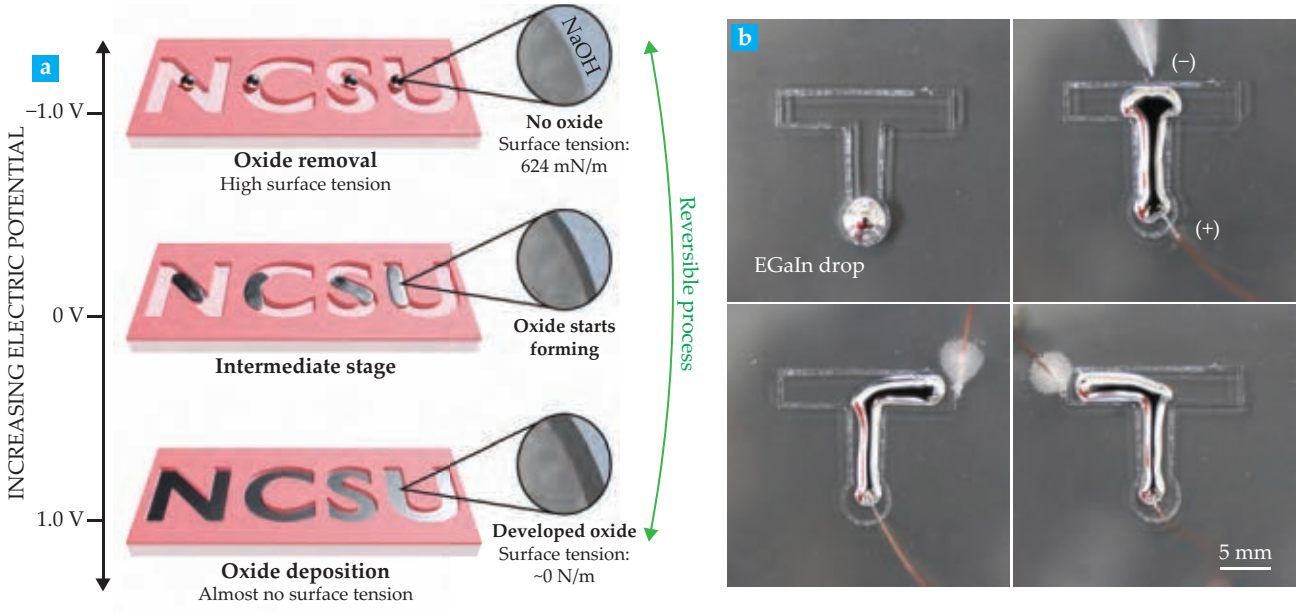


FIGURE 2. INTERFACIAL TENSION of liquid metals can be electrochemically controlled. **(a)** The tension of the liquid metal in a water-based solution increases with an applied reduction potential and is reversibly lowered with an applied oxidation potential. (Courtesy of Luke Cunningham.) **(b)** Variations in electric potential also control the shape and the direction of travel of metal droplets, as shown in this open T-shaped channel submerged in a sodium hydroxide solution. The different positions of the counter electrode—located outside of the T channel—dictate the flow direction of the metal droplet. (Adapted from M. R. Khan et al., *Proc. Natl. Acad. Sci. USA* **111**, 14047, 2014.)

streaming from a nozzle emerges as a wire rather than as the typical spherical droplet. One possibility is that the oxide species deposited electrochemically acts like a surfactant that resides between the metal and electrolyte. Another possibility is that the oxide itself exerts compressive stresses that counteract interfacial tension. The mechanism that lowers tension remains, for now at least, poorly understood.

By taking advantage of the ability to tune the tension of LMs using electrochemical reactions, we can manipulate the shape of the metal using modest electric potentials on the order of about 1 V. For instance, applying an oxidative potential causes the metal immersed in electrolyte to lower its interfacial tension, thus allowing the LMs to conform and fill a more complex geometry, as illustrated in figure 2a. The process is reversible: Applying a negative potential removes the oxide, and the metal retracts from the cavity. Figure 2b shows the LM's movement as it preferentially spreads toward the counter electrode. In both reduction and oxidation, the electrochemical modulation of LMs creates new, unique devices with reconfigurable shapes, including pumps, antennas, and thermal switches.

Researchers have many opportunities and challenges to explore in using LMs for soft and stretchable devices. The interfacial chemical reactivity and stability, for instance, are not fully characterized for gallium-based alloys with standard metal contacts, such as nickel, silver, gold, and copper. But that characterization is critical if manufacturers are to successfully integrate Ga-based alloys in consumer electronics and if researchers are to identify the right barrier materials for the required electrical performance.

Although tremendous strides have been made in high-resolution printing and patterning, little research has explored the high-density LM interconnects that are needed to join electrical components. Some initial research has shown that LMs can be mixed as particles within other materials, such as filler within elastomers, to create composites with unique thermal, mechanical, and electrical properties. Depending on the desired application, LM composites can be tailored to produce highly stretchable and electrically conductive materials or made into electrically insulating but highly thermally conductive materials. LM researchers are particularly excited by thermal-management and thermoelectric applications in soft electronics.

In yet another application, physicists and other scientists are exploring how to use LMs for promoting reactions, including using them as a source for producing thin oxide layers. Research groups focused on those emerging research areas are striving to elucidate the fundamentals that govern the unique behavior and characteristics of LMs. With that understanding, they can harness the remarkable properties of LMs to create novel functional materials and devices.

Additional resources

- S. Liu, D. S. Shah, R. Kramer-Bottiglio, "Highly stretchable multilayer electronic circuits using biphasic gallium-indium," *Nat. Mater.* **20**, 851 (2021).
- J. Ma et al., "Shaping a soft future: Patterning liquid metals," *Adv. Mater.* 2205196 (2023).
- M. R. Khan et al., "Giant and switchable surface activity of liquid metal via surface oxidation," *Proc. Natl. Acad. Sci. USA* **111**, 14047 (2014).
- N. Kazem, T. Hellebrekers, C. Majidi, "Soft multifunctional composites and emulsions with liquid metals," *Adv. Mater.* **29**, 1605985 (2017).
- A. Zavabeti et al., "A liquid metal reaction environment for the room-temperature synthesis of atomically thin metal oxides," *Science* **358**, 332 (2017).

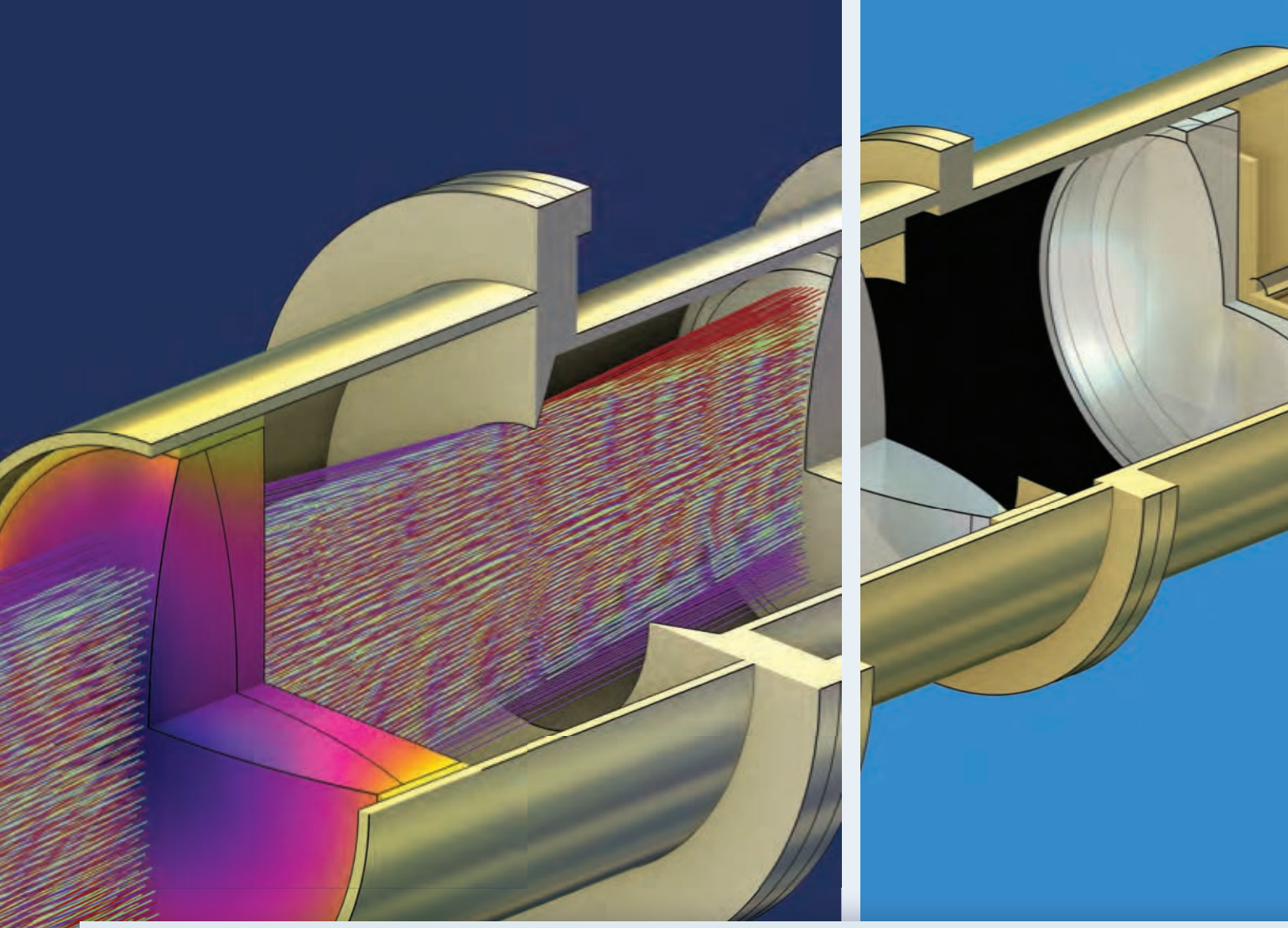
PT

Tied up in knots

It takes California blackworms—roughly 200 of which are pictured here—a few minutes to entangle themselves into a knotted ball to stay warm and moist but just milliseconds to untangle themselves and avoid danger. Georgia Tech's Saad Bhamla and his colleagues now think they understand how the few-centimeter-long animals tangle and untangle themselves at such different rates. From an active-matter point of view, the worms are analogous to autonomous filaments. As individuals, they behave differently from how they function when they self-assemble into a larger emergent structure. With ultrasound imaging, the researchers observed that the three-dimensional motion of each worm follows a loop-like pattern. They approximated the movement with just two parameters involving a worm's head: its turning speed and the rate at which it changes direction.

From those observations, the researchers developed a predictive model. In it, a dimensionless parameter called the chirality number describes the amount of right-handed or left-handed loops traced by a worm. When all the worms choose to make a large number of successive loops in one direction—a state characterized by large values of the chirality number—they yield a tangled ball. To untangle themselves, the worms make both right-handed and left-handed loops, a state described by low values. Although the time scales between tangling and untangling differ by orders of magnitude, the same underlying dynamics control the behavior. The authors suspect that the worms could be a model system to guide the design of topologically tunable active materials, such as smart adhesive bandages. (V. P. Patil et al., *Science* **380**, 392, 2023; image courtesy of Harry Tuazon, Georgia Tech.) —AL

TO SUBMIT CANDIDATE IMAGES FOR BACK SCATTER VISIT https://contact.physicstoday.org.



Shine Brighter in Optical Design

with COMSOL Multiphysics®

Multiphysics simulation drives the innovation of new light-based technologies and products. The power to build complete real-world models for accurate optical system simulations helps design engineers understand, predict, and optimize system performance.

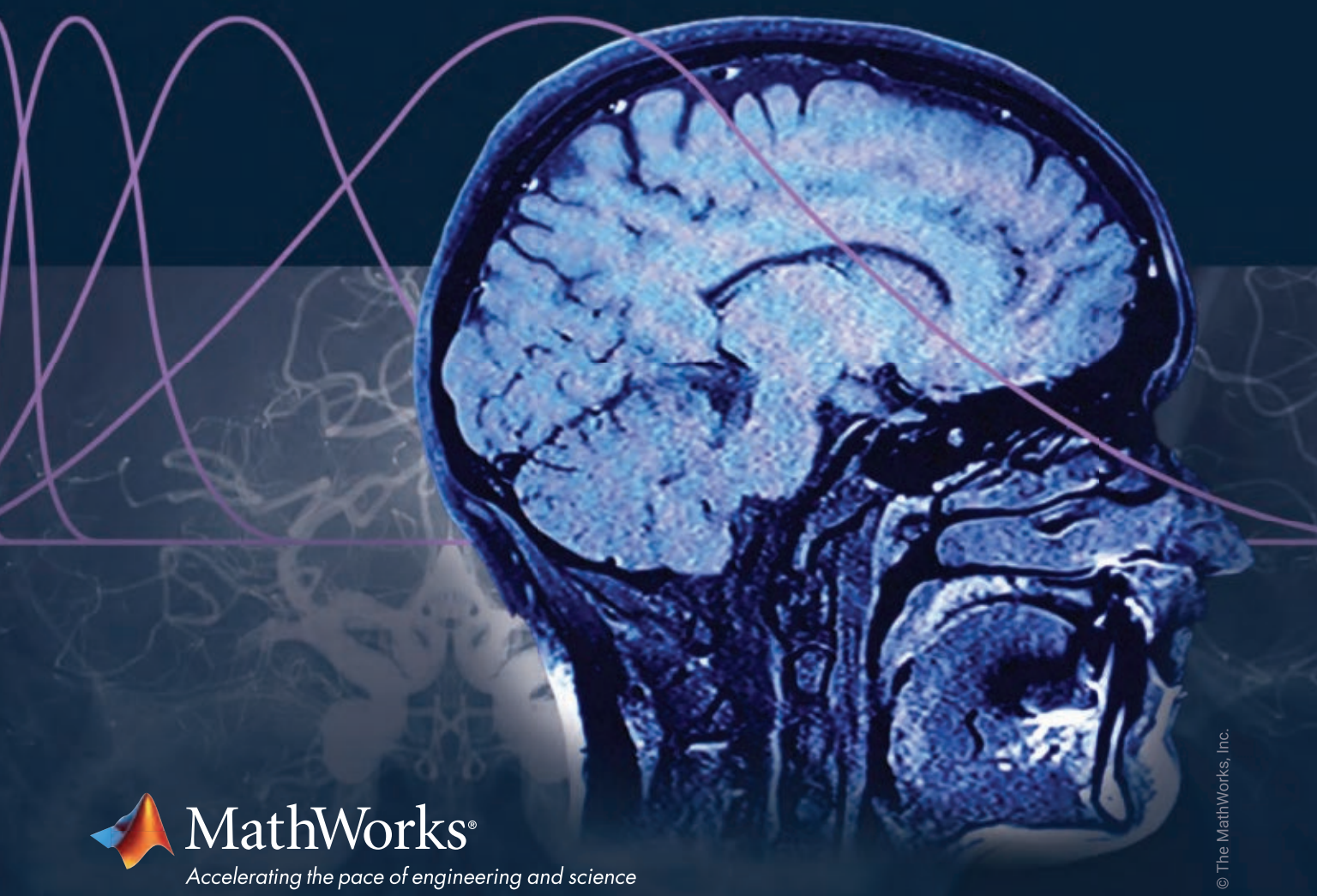
» *comsol.com/feature/optics-innovation*

COMSOL

MATLAB FOR AI

Accelerate scientific discovery with explainable and reproducible AI. With MATLAB low-code apps, you can train, validate, and deploy AI models.

mathworks.com/ai



MathWorks®

Accelerating the pace of engineering and science