PHYSICS TODAY

April 2021 • volume 74, number 4

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The chemistry of einsteinium

Medieval meteorology

A versatile liquid metal


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Sub-angstrom thickness sensitivity provides additional information about film nucleation, surface conditions and other process conditions
J.A. Woollam

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FEATURES

ON THE COVER: This image, *Geoprint V7010*, grew out of the patterns that visual artist and printmaker Ellen Karin Mæhlum saw when she joined biologists and geophysicists from the University of Oslo on two Arctic expeditions. Other scientists and artists are working together to improve data visualization and communication and for mutual inspiration. For more on the forms that such collaborations take and the value they bring to the interdisciplinary partnerships, see the news feature on **page 24**. (Image courtesy of Ellen Karin Mæhlum, www.ellenkarin.no.)

Recently on PHYSICS TODAY ONLINE

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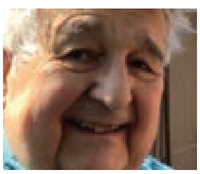
Scientific recipe

The book *Science and Cooking*, reviewed on page 53 of this issue, introduces the science behind cooking and baking. For a hands-on demonstration, try out an annotated recipe for molten chocolate cake adapted from the book. The commentary explains the rationale behind its ingredients and techniques.
physicstoday.org/Apr2021a



Community colleges

Physicist John Cise has spent nearly 50 years teaching at the community college he helped found in Texas. He talks to PHYSICS TODAY's Toni Feder about the process of starting a college and the importance of community colleges in the context of US higher education.
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LOS ALAMOS NATIONAL LABORATORY

Pit production

Congress requires that by 2030 the National Nuclear Security Administration create the capacity to produce 80 new cores for nuclear weapons per year. Scientists are skeptical of the necessity of replacing existing plutonium pits and of the safety of the new facility in South Carolina.
physicstoday.org/Apr2021c

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FROM THE EDITOR

Dangerous gadgets

Charles Day

Jim Hawkins came off shift from the nuclear research station DESY at 4:00 a.m. and headed his VW towards the dark suburbs of Hamburg. A peculiar traffic accident was his last memory before waking to champagne in an elegant country villa tucked away in the hills of the Black Forest. As Jim regained consciousness, a suave and elegant Herr Doktor explained that Jim was being "borrowed" by a sophisticated terrorist organization. Only in exchange for his nuclear expertise would the Doctor's organization return Jim, his wife Leora, and their daughters to freedom.

The quote comes from the dust jacket of the first US edition of Nicolas Freeling's 1977 novel *Gadget*. Freeling is best known for his series of books that feature Dutch detective Piet van der Valk. Although I'd heard of the novelist, I wouldn't have known about *Gadget* if PHYSICS TODAY reader Peter Zimmerman hadn't written to me.

Zimmerman had read my feature article "Novel appearances," which discussed the rare examples of physicists as main characters in novels (PHYSICS TODAY, October 2018, page 44). His email not only brought my attention to another example—Hawkins in *Gadget*—but also revealed his role in the novel:

> Nicolas was a good friend, and I was his coauthor on the project and wrote or outlined all of the technical parts. In addition, the opening scenes are based extremely closely on my commute from my lab at DESY in Hamburg (1969–71) to my home in Lokstedt. [The Hawkins] character is based on a mélange of other physicists.

Although *Gadget* is long out of print, you can still buy it on Amazon. Because it's a thriller, I'll refrain from disclosing the plot. However, it's not much of a spoiler to discuss the implications of what's hinted at on the dust jacket: The dangers of terrorists obtaining one of the principal ingredients of a nuclear weapon, highly enriched uranium (HEU).

When Freeling wrote *Gadget*, South Africa was on the brink of becoming a nuclear weapons state. One of the largest uranium mines in the world, Rössing, is in Namibia, a former German colony that had been granted to South Africa by the Treaty of Versailles. South Africa had also acquired the technology to enrich uranium to weapons grade. Plans for an underground test of a device in the Kalahari Desert in August 1977 were uncovered by Soviet espionage and verified by US aerial reconnaissance. South Africa abandoned the test but developed weapons anyway.

South Africa used the same basic design, gun-type fission, that the US used for Little Boy, the bomb dropped on Hiroshima. The terrorists in *Gadget* chose the same design. Whereas South Africa had the material and the technology to make HEU, *Gadget*'s terrorists simply stole enough to make a 1 kiloton weapon.[1] All the other methods and ingredients, readers are led to believe, are not beyond the ability of a nuclear physicist and the capability of a well-stocked garage-sized lab.

That last point is what makes *Gadget* both chilling and enduringly relevant. Enriching uranium or procuring HEU is the hardest step in making a nuclear weapon. That's why the US worked so diligently with the successor states of the Soviet Union to secure stockpiles of HEU and plutonium. It's why the American Physical Society is so worried about SILEX, a laser-based technique for enriching uranium, and why Princeton University's Frank von Hippel and others vigorously advocate replacing the use of HEU in reactors with low-enriched uranium.

In my 2018 feature I asked why a novelist chose to include a physicist as a main character. In the case of *Gadget*, it's clear: To build a nuclear weapon. I also explored how the physicist characters were portrayed. Perhaps because Hawkins was based on physicists whom Zimmerman knew, the portrayal is convincing. Hawkins would become so lost in thought at dinner that he'd forget his table manners, dip his finger in a puddle of sauce, and lick it.

Reference

1. For an estimate of the destruction wrought by a nuclear weapon of 1 kiloton or any other yield, use Alex Wellerstein's NUKEMAP simulator, https://nuclearsecrecy.com/nukemap/. PT

Einsteinian subtleties in Magritte's *Time Transfixed*

In his 1938 painting *La durée poignardé* (*Time Transfixed*; shown below), Belgian surrealist René Magritte presents a surprising and enigmatic juxtaposition of common and unrelated images—a smoke-belching locomotive charging out of a fireplace topped by a clock and two candlesticks, all beneath a large mirror in an otherwise typical interior space.

Albert Einstein was interested in clock synchronization, particularly as it pertained to time signals for railroad schedules and longitude determination.[1] One of his many *gedanken* experiments demonstrated the lack of timing agreement between two observers, one on a moving train and the other standing near the tracks.[2] Simultaneity—and hence time and space—is relative.

Magritte's fireplace finds a connection with Einstein through the 1930s fireplace (see next page) located in Common Room 202 of Jones Hall (formerly Fine Hall) at Princeton University. Einstein had an office there when he first came to Princeton from Germany. Inscribed on the fireplace is a remark Einstein had made during a 1921 visit to Princeton: "*Raffiniert ist der Herr Gott, aber boshaft ist er nicht,*" commonly translated as "Subtle is the Lord, but malicious He is not."[3] Magritte would probably prefer "surreal" to Einstein's "subtle."

And what of Magritte's mirror? Mirrors figure prominently in the Michelson interferometer that was used in the notably unsuccessful attempt to detect the putative luminiferous ether. Also, precision mirrors were used at the Laser Interferometer Gravitational-Wave Observatory to detect gravitational waves, 100 years after Einstein's 1915 general theory of relativity predicted them, from the merger of two black holes 1.3 billion light-years from Earth.[4]

Although there is no evidence that Magritte intended to represent those Einsteinian ideas in his painting, surrealists were nonetheless thoroughly engaged with modern physics; they referred repeatedly to relativity and quantum physics in their writings and often interpreted those new sciences through their work.[5]

The two candlesticks, one of which is mysteriously missing its mirror reflection, remain for now outside the bounds of even a coincidental relativistic connection to Magritte's famous painting. Nevertheless, the associations between

TIME TRANSFIXED, by René Magritte, oil on canvas (1938), Art Institute of Chicago. (Image from Peter Barritt/Alamy Stock Photo.)

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FIREPLACE IN JONES HALL at Princeton University. Albert Einstein had an office there in the 1930s. (Photo by Robert Fleck.)

Magritte's art and Einstein's science are striking and help to situate the painting in the broader intellectual and cultural compass of its transfixed time.

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Repulsive Casimir forces

The article "Science and technology of the Casimir effect" by Alex Stange, David Campbell, and David Bishop (Physics Today, January 2021, page 42) presents data from a 2009 experiment by Jeremy Munday and coworkers[1] that shows that Casimir forces can be repulsive. Sixteen years earlier we published similar results.[2]

As Stange and coauthors point out, the Casimir force is emerging as a technological tool to manipulate matter at small scales. Our earlier effort to create repulsive and nearly neutral Casimir and van der Waals interactions was motivated by an attempt to improve the imaging resolution of contact-mode atomic force microscopy (AFM). The idea was to eliminate the jump-to-contact instability associated with attractive Casimir interactions, which elastically deforms the AFM tip, sets a lower limit on its effective size, and reduces imaging resolution. Imaging with special fluids works to eliminate that instability, but the fluids we had to use, bromo- and methylnaphthalene, were not compatible with biological materials. Since our hope was to image molecules such as DNA, we did not pursue further the manipulation of Casimir forces.

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2. J. L. Hutter, J. Bechhoefer, *J. Appl. Phys.* **73**, 4123 (1993).

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Icebreakers and Arctic ice melt

Saara Matala's article "Finnish–Soviet nuclear icebreakers" (Physics Today, September 2020, page 38) gives an account of how the small Western country of Finland managed to maintain its neutrality and start a commercial collaboration with the Soviet Union based on icebreakers. What struck me most in the article was figure 1, which depicts the routes around the Arctic Ocean: the Northern Sea Route along Siberia and the Northwest Passage along Canada. Almost every article I have read regarding the early and accelerating melting of the Arctic ice stresses the importance of the albedo difference between intact ice and free ocean water (see, for example, "The thinning of Arctic sea ice," by Ron Kwok and Norbert Untersteiner, Physics Today, April 2011, page 36).

When I read that Finland's "five *Moskva*-class polar icebreakers" were "designed to cut through multiyear Arctic sea ice," my mind linked icebreakers with the premature Arctic melt. Icebreakers keep the routes in figure 1 open most of the year—if not year-round—for commercial shipping. Thus they initiate or at least aggravate the melting of multiyear sea ice: Breaking the ice allows the open waters to warm with respect to the surrounding ice due to the albedo difference, with probably a very small addition from the heat generated by the ships themselves. I therefore find it hard to believe that a Physics Today news story (September 2017, page 24), for example, advocates the use of new icebreakers "to gauge global effects of the polar region's diminishing ice cover." I have to wonder if the models regarding Arctic warming have taken the effect of icebreakers into consideration.

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▶ **Matala replies:** The question Peter Steur asks, whether it is reasonable to advocate the use of icebreakers "to gauge global effects of the polar region's diminishing ice cover," would be better answered by a climate change expert.

As a historian of technology, not a trained climate scientist, I consider what information the contemporary actors had. The Helsinki shipyard contracted for the first *Moskva*-class polar icebreakers in the mid 1950s, before climate change was seriously considered in ship design.

My article emphasized the ability of polar icebreakers to "cut through multiyear Arctic sea ice" because length constraints restricted discussion of other features that differentiated the polar icebreakers from the previous Finnish design. Getting through multiyear ice is a heavy task even for modern icebreakers. Most of the shipping activities in the Northern Sea Route take place during the summer season when sea-ice cover is lower.

Polar icebreakers also make the Arctic Sea accessible for research vessels gathering information essential to improving climate models. As historian Melvin Kranzberg famously put it, "Technology is neither good nor bad; nor is it neutral."

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Nine reactors beat ZEEP into service

David Kramer's article on nuclear developments in my native Canada (PHYSICS TODAY, January 2021, page 23) was an enjoyable read. However, his assertion that the Zero Energy Experimental Pile (ZEEP) was the world's second operating nuclear reactor after Enrico Fermi's Chicago Pile-1 (CP-1) is erroneous; at least nine other stateside piles achieved criticality before ZEEP did so in September 1945.

Those nine US piles were CP-2 and CP-3 at Argonne National Laboratory (March 1943 and May 1944; CP-3 was the first heavy-water pile); the X-10 pilot-scale pile at Oak Ridge National Laboratory (November 1943); the 305 fuel-testing pile and the B, D, and F plutonium production piles at the Hanford Site (1944 to early 1945); and two small aqueous enriched-uranium devices, LOPO and HYPO, at Los Alamos National Laboratory (1944). ZEEP was the first pile outside the US to achieve criticality.

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"But what is physics?"

I took my first physics class ever at Stanford University in January 1960. The professor was Leonard Schiff, then also the chairman of the physics department. The lecture hall was full of mostly freshmen, some excited and some terrified at the thought of calculus-based physics taught by one of the most distinguished members of the department.

Leonard began by talking about the difference between basic and applied research, perhaps not a topic calculated to excite the group. But one guy (not I, let me assure you) raised his hand to stop the lecturer for a question: "Yes, but what is *physics*?" Leonard stopped in his tracks. I doubt he had ever been asked that question that way.

After thinking for a few moments, he responded, "Why, physics is whatever physicists do." In the 61 years of my career as a physicist, I've never heard a definition I liked better. Physics isn't the manipulation of mass and energy and the measurement of ever-more-precise quantities. Instead, it's whatever the people trained in those arts decide to do.

That's a definition I've used more than once as I've wandered from MeV- to GeV-range nuclear and particle physics, to planetary orbital mechanics, to strategic arms control, and to diplomacy with Chinese and Soviet colleagues. As long as I'm using the mental attitudes of a physicist, I'm doing physics and need not apologize for my changing interests and skills.

And so, my thanks for the February 2021 issue, which demonstrates and encourages the enormous range of activities that we can collectively call "physics": from neutrinos to rare-earth magnets, lunar exploration, tech transfer, and measurable differences between whisky and whiskey. I think Leonard would have been charmed and delighted. I wish I had a hundred copies to give to high school seniors, mid-degree undergraduate physics majors, grad students, and physicists who have left the lab for other careers.

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Corrections

February 2021, page 23—The article erroneously reported a $1.8 million grant in 2020 to Ucore Rare Metals Inc from the US Army Research Laboratory. In fact, grants totaling $1.8 million were awarded in 2014–16 to Innovation Metals Corp to help fund development of its proprietary rare-earth separation technology. IMC was acquired by Ucore in 2020.

February 2021, page 27—The device in the photo is incorrectly identified as "the inside of an acoustic cytometer." It is actually a close-up image of a DNA fragment-sizing flow cytometer. PT

Einsteinium chemistry captured

The creation of a rare molecule offers a peek at how heavy atoms interact with other elements.

Where is the end of the periodic table? Although uranium, with an atomic number *Z* of 92, is the heaviest element found naturally on Earth, physicists have created dozens of synthetic transuranic elements. No one yet knows whether there's a limit to the elements that can possibly exist. But the ones that have been made so far extend up to $Z = 118$.

Not all of those elements are equally easy to synthesize or study. Kilograms of neptunium, plutonium, americium, and curium ($Z = 93$–96) are produced in U-burning nuclear reactors through neutron capture followed by beta decay, a process that increases an atom's *Z* by one. Berkelium, californium, einsteinium, and fermium ($Z = 97$–100) can also be made by neutron capture, but in drastically smaller quantities and only in specialized facilities such as the one at Oak Ridge National Laboratory (ORNL; see "The overlooked element makers," PHYSICS TODAY online, 30 September 2019). Mendelevium ($Z = 101$) and beyond can be made only one atom at a time.

There are ways to study the atomic properties of elements produced atom by atom (see, for example, PHYSICS TODAY, June 2015, page 14). But the traditional way of investigating how atoms behave—mixing them with other substances in solution to form chemical compounds—requires a bulk quantity of material. ORNL's two-year production cycle yields just a picogram of Fm, which has yet to be purified. So from the chemist's point of view, the periodic table effectively ends with Es, produced in microgram quantities.

Now Lawrence Berkeley National Laboratory's Rebecca Abergel and her colleagues (two of them shown in figure 1) have performed the most complicated and informative Es chemistry experiment to date.[1] With just a few hundred nanograms of the heavy element—a mere quadrillion atoms or so—the researchers probed both its chemical bonding geometry and its electron energetics. The results could point the way to a better understanding of heavy elements in general and perhaps the discovery of the next new one.

FIGURE 1. KOREY CARTER (left) and Katherine Shield study the chemistry of einsteinium (atomic number 99) in Rebecca Abergel's lab. (Photo by Marilyn Sargent, the Regents of the University of California, Lawrence Berkeley National Laboratory.)

Actinide complex

Abergel and her group are experts in the coordination chemistry of the actinides, the series of radioactive elements with atomic numbers 89–103, usually shown floating below the body of the periodic table, and they're especially interested in how those heavy elements behave inside the human body. They've been working to find new organic molecules that bind to actinide atoms—either to purge the radioactive material from the body in case of contamination or to deliver it to tumor cells for targeted radiotherapy.

Although Es is too scarce to serve as either poison or medicine, the researchers wanted to see if they could push their methods to the limit. They applied for a share of ORNL's most recent biennial Es supply. They got half of it.

When it comes to characterizing new molecules—and any organo-einsteinium molecule would be a new one—the gold standard is the x-ray crystal structure, a diffraction pattern that reveals each atom's position in exquisite detail. Because that technique requires milligrams of material, Abergel and colleagues' first idea was to encapsulate each Es atom in a large protein molecule to make a big enough sample without much of the heavy metal.

That didn't work. It would have been feasible except that what ORNL had delivered as Es was, in fact, almost half Cf. Unable to separate the elements any more cleanly than the ORNL scientists had done, Abergel and colleagues could only make a mixture of Es-bearing proteins and Cf-bearing proteins. The resulting diffraction pattern would have been a hopeless mess.

So instead of crystallography, the researchers turned to x-ray absorption spectroscopy, a technique that measures the energy needed to remove one of the

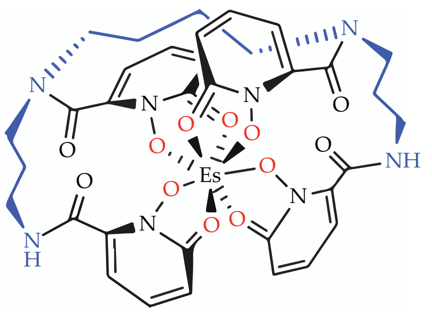

FIGURE 2. MOLECULAR STRUCTURE of an einsteinium complex. A single organic molecule, held together by the backbone shown in blue, wraps around the Es atom and binds to it from all sides. X-ray absorption spectroscopy measures the distance from the central Es atom to the oxygen atoms shown in red, and luminescence spectroscopy yields information about the Es's electronic states. (Adapted from ref. 1.)

tightly bound inner electrons from a high-Z atom. "Those energies are element specific," explains Abergel, "so it's straightforward to screen out the contaminants": Just zoom in on the part of the spectrum that corresponds to the Es excitation.

X-ray absorption spectroscopy doesn't yield a complete molecular structure the way x-ray crystallography does. But ripples in the spectrum form an interference pattern that gives some information about the distances to the atoms neighboring the heavy atom, and thus how the heavy atom forms chemical bonds.

Furthermore, it's possible to adapt x-ray absorption spectroscopy to analyze extremely small amounts of material. Freed from the requirement of using a large protein, Abergel and colleagues opted instead to react their Es with a so-called octadentate ligand—a single organic molecule that wraps around a central metal atom and binds to it from all sides—to create the complex shown in figure 2.

Among its other useful properties, the ligand acts as an antenna: It absorbs light in the UV and efficiently channels it to the central metal atom, which emits light at a range of longer wavelengths. That luminescence spectrum, which can be measured with an extremely small sample, carries information about the central atom's electronic energy levels that complements what x-ray absorption spectroscopy reveals about the spatial arrangement of atoms.

Abergel and colleagues had already studied complexes of the same ligand with several other metals, including lighter actinides. So they could directly compare Es's chemical behavior with that of other elements.

Pulling the thread

Across most of the periodic table, chemical behavior varies by column. Fluorine, for example, is much more like its downstairs neighbor chlorine than its left- and right-hand neighbors oxygen and neon. However, because the actinides' valence electrons lie in *f* orbitals that don't strongly influence chemical properties, they're all expected to behave much like one another.

That's not what Abergel and colleagues found. In complexes of the same organic ligand with the lighter actinides Am, Cm, and Cf, the metal–oxygen bond length is between 2.42 Å and 2.45 Å. The Es–O bonds, in contrast, are a considerably shorter 2.38 Å. Furthermore, the luminescence spectrum of the Es complex showed an electronic transition that's higher in energy than for the bare Es ion, whereas for the lighter actinides, the opposite is true.

Says Jenifer Shafer of the Colorado School of Mines, "The prevailing dogma has been that the actinides are just heavy versions of the lanthanides," the upper row of *f*-block elements, which all exhibit similar behavior to one another. "It's been hard to justify work on actinide chemistry without knowing that it will find anything interesting. But now the thread is starting to get pulled on the differences between them."

Chemical differences among the actinides aren't wholly unexpected, though, and the culprit is easily identified: relativity. The more highly charged an atomic nucleus, the faster the electrons whiz around it. When an electron's speed is a significant fraction of the speed of light, its effective mass increases, and all the atom's electronic orbitals shift in energy in a way that's extraordinarily difficult to model.

All actinides are affected by relativity, but the heavier ones especially so. The chemistry of Es, in other words, amplifies effects that are already present in lighter atoms, so it's a valuable benchmark for theorists seeking to model the lighter, more technologically relevant actinides. If a model works well for Am and Cm but not for Es, it may be on the wrong track.

It's also possible that Es is showing something not seen in other actinides: a transition to a new regime of spin–orbit coupling. Each electron in an atom has both spin and orbital angular momentum, and there are two distinct ways of representing the atom's total angular momentum: either as the sum of the total orbital angular momentum L and the total spin S or as the sum of each electron's combined angular momentum j. The two schemes give different answers and predict different behaviors. "We can compute the angular momentum in each of those schemes individually," says Valérie Vallet, a CNRS theorist at the University of Lille in France. "It's harder to predict which one we should use."

The former approach, called LS coupling, tends to apply when electrons aren't packed too closely together. It accurately describes most light atoms, and it even works well for molecules containing Am or Cm. The latter coupling scheme, jj coupling, is less commonly seen in atoms and molecules, but it could be behind some of Es's unusual behavior. "We don't know that that's what these photophysical measurements are showing," says Vallet, "but it calls for further investigation."

Not the end

With a half-life of less than a year, most of Abergel and colleagues' Es has decayed away by now. But they still have a little left, and they're continuing to experiment on it to glean whatever information they can about the chemical differences between Es and other actinides, particularly Cf. "We have a whole library of ligands we're working through," says Abergel.

Their ultimate goal is to identify an Es-containing molecule that's different enough from the analogous Cf molecule that the two can be efficiently separated. Such a find would enable the ORNL scientists to streamline the purification of their next batch of Es, which would make possible the x-ray crystallography experiments Abergel and colleagues had in mind from the start.

It could also lead to the discovery of a new element. The six most recent additions to the periodic table, from nihonium ($Z = 113$) to oganesson ($Z = 118$), were all made in the same way: by shooting a beam of calcium-48 into an actinide target. With so-called magic numbers of both protons (20) and neutrons (28), ^{48}Ca is unusually stable, and it combines readily enough with actinide nuclei of atomic number Z to yield a few superheavy atoms of atomic number $Z + 20$.

No new elements have been made in that way, or any other, since the 2010 discovery of element 117, now called tennessine after ORNL's home state. (See PHYSICS TODAY, June 2010, page 11.) It took longer to discover Ts than Og because the Bk target was harder to work with than the Cf one. Until a big enough Es target can be assembled to make element 119, the ^{48}Ca-fusion technique has seemingly reached the end of its road. Better Es purification through chemistry may help breathe new life into superheavy element research.

Johanna Miller

Reference

1. K. P. Carter et al., *Nature* **590**, 85 (2021).

Pauli crystals make their experimental debut

When a few ultracold atoms are repeatedly trapped and imaged tens of thousands of times, self-organized patterns emerge out of the quantum blue.

Whereas bosons can condense into a single quantum state, fermions, such as electrons in ordinary solids, are forbidden from doing so. Pauli exclusion is the best-known manifestation of Fermi–Dirac statistics, and it accounts for, among other things, the structure of the periodic table and electrical conductivity in metals.

Identical fermions do not even need to interact to behave as if they repel each other. Indeed, the mere presence of fermionic atoms near one another but unable to occupy the same locations produces an emergent Fermi pressure that prompts the atoms to rearrange themselves. The resulting correlations between atoms can be visualized in geometric structures known as Pauli crystals. Mariusz Gajda coined the name five years ago when he and his colleagues at the Polish Academy of Sciences in Warsaw predicted the phenomenon.[1]

Now doctoral student Marvin Holten, postdoc Luca Bayha, and their colleagues, under the direction of Selim Jochim at Heidelberg University, have directly observed Pauli crystals in the momentum correlations of a few lithium-6 atoms trapped in a two-dimensional plane.[2]

Simulating a solid

Theorists have long tried to account for the electronic behavior of strongly interacting many-body systems by using model Hamiltonians. But when researchers attempt to fabricate materials that embody such Hamiltonians, they often struggle to cope with imperfections, defects, and

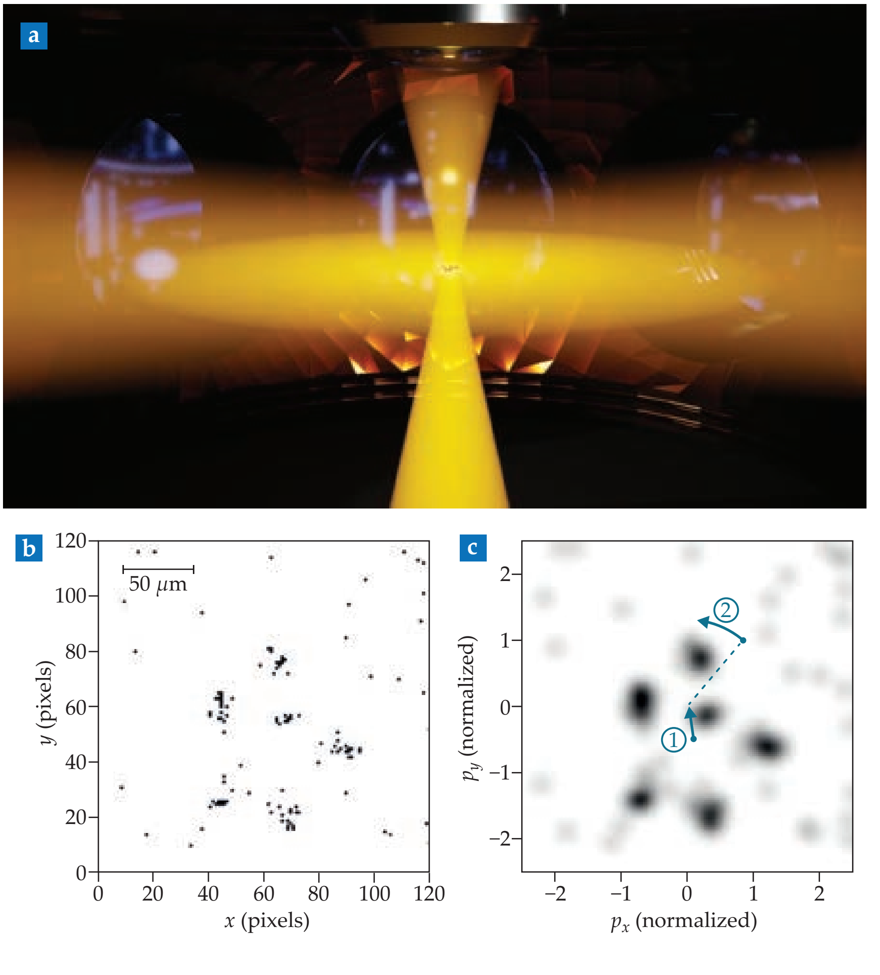

FIGURE 1. SIX ULTRACOLD lithium-6 atoms are trapped in the superposition **(a)** of a focused optical tweezer and a single layer of a one-dimensional optical lattice (yellow disk). The atoms can move in the two-dimensional plane but are frozen vertically. **(b)** When the tweezer is switched off, the atoms expand in the 2D plane until a laser pulse prompts them to fluoresce; photons from each atom are registered as momenta (dots) in a CCD detector. **(c)** To reveal correlations between the atoms, researchers subtract their center-of-mass motion (arrow 1) from each atom's momentum **p** (normalized to harmonic oscillator states) and then rotate each image to a common symmetry axis (arrow 2). (Adapted from ref. 2.)

other features of the real material world. A tantalizing alternative, developed about a decade ago, is to study the systems' complicated behavior by using small clouds of ultracold atoms.

To simulate the behavior of itinerant

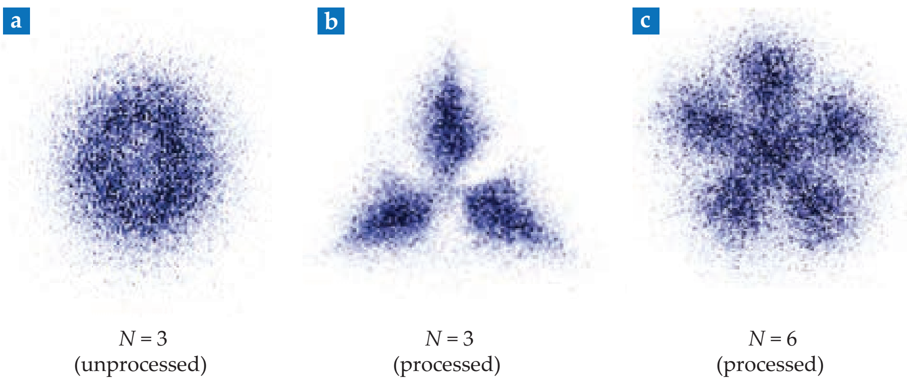

FIGURE 2. PAULI CRYSTALS unveiled. **(a)** This nearly featureless blob of fluorescence measurements is the momentum distribution—or, more precisely, the measured momenta of each lithium-6 atom minus the center-of-mass momentum—for $N = 3$ atoms. The reduced density in the center is due to the harmonic-oscillator eigenfunctions. **(b, c)** The strong correlations between atoms reveal themselves in the configuration probability densities for $N = 3$ and $N = 6$ only when each experimental run has been rotated separately to a common symmetry axis. (Adapted from ref. 2.)

electrons in a solid, researchers typically trap the gases in a 2D periodic array of optical potentials and then tune the atoms' interactions. (Because atoms are electrically neutral, those interactions can be turned on or off on demand using an applied magnetic field.) A separate laser then irradiates the atoms and snaps their photograph, which records the fluorescence they emit. (See PHYSICS TODAY, October 2010, page 18, and August 2017, page 17.)

The new Heidelberg experiment uses a similar kind of fluorescence microscope. Its ability to image the positions of single atoms makes the instrument ideal for capturing the shapes of different Pauli crystals. Those shapes, however, are hidden in the correlations in the atoms' relative positions or momenta. Observing them requires preparing noninteracting fermions in a well-defined quantum state at nearly zero temperature and then detecting the correlations. Holten and colleagues' choice of ^{6}Li is especially suitable for the job: The atoms can be precisely controlled from a regime in which they rethermalize and cool quickly in an optical trap to one in which they are noninteracting.

Rather than confine the ^{6}Li atoms in a periodic lattice—where they would be localized like eggs in a carton—the researchers hold them in the intersection of an optical tweezer and a single layer of a 1D optical lattice. They are thus frozen in the vertical direction but free to move in the 2D plane. Figure 1a outlines the experiment. The researchers loaded the tweezer's potential well with a few hundred Li atoms and then "spilled" the excess by bending one side of the well with a magnetic field gradient.[3]

The potential well filtered out all but the coldest atoms. In the 2D plane the atoms' energy states are arranged in shells, akin to electron orbitals around a nucleus. The shells are closed—as in noble gases—for one, three, and six atoms. In separate experiments the researchers chose to trap three and six of the ^{6}Li atoms to discern the different patterns that emerge. In both cases, the most desirable configuration for the atoms would be to sit exactly at the center of the potential well. Pauli exclusion forces them to adjust their positions to avoid stepping on one another.

Taking pictures

The group's optical tweezer confines the atoms within about a micron of one another. That's too close to be directly imaged. Instead, the team mapped the atoms' initial momenta onto position by turning off the tweezer—thereby loosening the harmonic trap—and allowing the atoms to expand two dimensionally. After a few milliseconds of free evolution, the distance an atom travels determines its velocity and hence its momentum. The expansion corresponds to an effective magnification of the wavefunction by a factor of 50.

To capture images of those momentum distributions, the researchers take snapshots. Beforehand, the atoms are in a quantum mechanical superposition, existing as delocalized wavepackets. A flash of laser light forces them to fluoresce, which enables their positions to be recorded by a CCD camera (see figure 1b), but collapses the many-body wavefunction's momentum probability distribution. With the fluorescence measurement, the structure of the wavefunction is lost. So to restore the complete, rotationally symmetric density distribution, the researchers perform some 20 000 experiments—starting each one with a bunch of freshly prepared identical fermions.

That collection of measurements alone cannot reveal the correlations between atoms. The nearly featureless blob of dots in figure 2a bears that out. Because of the random nature of the wavefunction's collapse, each snapshot differs from the last in angular orientation. So before averaging the images, the researchers performed two steps—they subtracted the center-of-mass momentum from each set of atom momenta and then they rotated each snapshot until the clusters of dots in each one match a theoretically predicted pattern. Only then are the Pauli crystals revealed, as shown in figures 2b and 2c.

The Heidelberg team studied the effect of temperature to assure themselves that the crystalline arrangements were not artifacts but a genuine quantum effect. They "melted" the six-atom crystal by shaking its atoms—modulating the confining potential at twice the harmonic trapping frequency. Reassuringly, the melting drastically reduced the contrast of the correlations even when small amounts of energy were added. Only very close to absolute zero temperature did Pauli exclusion remain visible.

The measurements set the stage for the researchers' next round of experiments: incorporating strong physical interactions between atoms. What will happen, for instance, to the self-organization in Pauli crystals that emerge in few-atom systems designed to mimic superconductors, whose electrons can pair up and condense?

R. Mark Wilson

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A tabletop waveguide delivers coherent x rays

The layered anode emits bright, directed beams without the need for mirrors or large-scale accelerators.

Tools for imaging the interior of solid objects have come a long way since Wilhelm Röntgen accidentally discovered x rays and captured an image of his wife's hand bones in 1895. Röntgen would likely be amazed by today's synchrotron light sources, in which coherent beams of x rays scattered by an object can be used to reconstruct nanoscale structures such as crystals and biological macromolecules.

Bright beams of x rays that are emitted in a single direction onto the target of interest are difficult to come by in a laboratory setting. Unlike large-scale accelerators, which emit highly collimated beams, small-scale laboratory sources generate x rays in all directions. Once they're emitted, x rays may be concentrated or redirected with mirrors, crystals, and lenses. However, collecting photons over a wide angular range and refocusing them onto a sample is hampered because, for x rays, the difference between the index of refraction of any two materials is tiny. Furthermore, filtering out incoherent light to improve the beam's coherence also has the detrimental effect of reducing the flux.

Malte Vassholz and Tim Salditt of the University of Göttingen have now developed and demonstrated an approach for generating coherent x-ray radiation directly within a waveguide structure.[1] The layered material that makes up the waveguide, depicted in an artist's impression in figure 1, emits x rays within a nanometers-wide channel. The resulting beam's brilliance—that is, the number of photons of a given wavelength and direction that are concentrated on a spot per unit time—exceeds that of a conventional x-ray tube by two to three orders of magnitude.

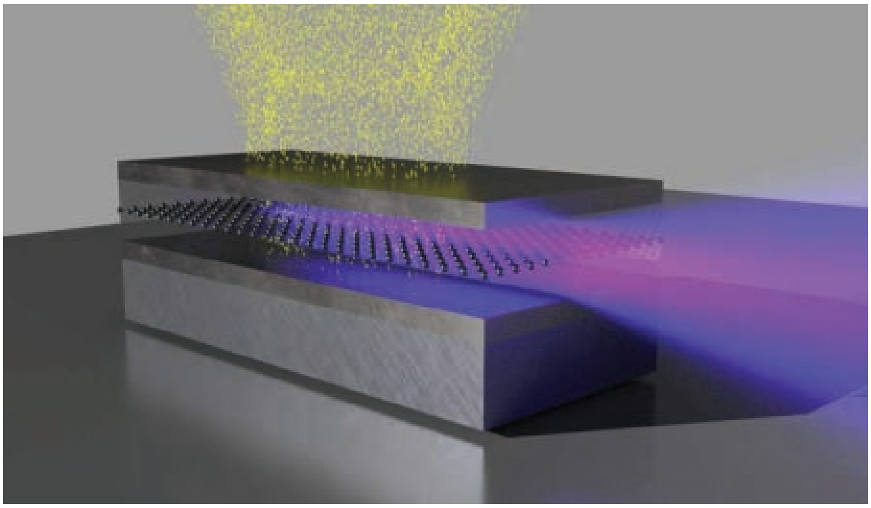

FIGURE 1. METAL ATOMS in a thin film become excited and generate x rays (purple) when electrons (yellow) bombard a layered waveguide structure (gray) in this artist's impression. The x rays emerge from the end of the structure in a beam of spatially coherent light. (Courtesy of University of Göttingen/Julius Hilbig.)

Seeking brilliance

The basic method by which laboratory-scale sources produce x rays is similar to the technique first used by Röntgen. Electrons, accelerated by a high voltage and focused into a beam microns in diameter, collide with a metal anode in a sealed vacuum tube. Radiation is emitted at all angles when the atoms in the metal deflect and slow those electrons and when the electrons excite the atoms.

One early way to boost brilliance was to swap out the stationary anode with a rotating one. Because the heat from the electron beam is dispersed evenly across the anode surface, the anode can tolerate higher beam current and power, and as a result can produce x rays with higher flux and energy, which depends on the acceleration voltage of the electrons. By the 1950s rotating anode tubes had become the standard design for diagnostic x-ray imaging.

The next major improvement in x-ray brilliance came in 2003, when researchers at Sweden's Royal Institute of Technology in Stockholm developed anodes based on jets of liquid metal.[2] In those setups, the anode is continuously regenerated by a stream of molten metal. That development offered an order-of-magnitude increase in brilliance over conventional x-ray tubes and enabled analytical applications, including phase-contrast imaging and high-resolution diffraction. Those sources have since become common tools for providing the 10 keV x rays, desirable for high-contrast imaging work.[3]

Today the brightest and most coherent known sources of x rays are synchrotrons and x-ray free electron lasers. (See the article by Phil Bucksbaum and Nora Berrah, PHYSICS TODAY, July 2015, page 26.) Those building-sized relativistic light sources emit radiation with brilliance more than 10 orders of magnitude greater than conventional x-ray tubes. When coupled into suitable waveguides, for example, the radiation can form a coherent beam that enables not just traditional x-ray and phase-contrast imaging but also tomography on nanoscale materials including liquids, single crystals, and thin films.

Salditt and his research group rely on x-ray imaging techniques to probe the structure of biological tissues. The researchers have carried out holographic imaging at synchrotron radiation sources and have performed phase-contrast tomography using in-house x-ray sources. "We could never quite bring the tomography in the lab to the resolution range necessary to resolve the structure of individual cells in the tissues," says Salditt. The sequential approach of first generating x rays and then coupling them to a waveguide to provide coherence is unsuited for low-brilliance laboratory x-ray sources: There simply aren't enough photons. But Salditt's familiarity with waveguide optics gave him an idea.

Layered solution

To harness the filtering power of a waveguide to improve the brilliance of a laboratory source, Salditt and his graduate student Vassholz proposed generating the x rays inside the waveguide itself. As illustrated in figure 2a, waveguiding becomes possible for x rays by total reflection within suitable thin-film structures or in two-dimensional channels.[4]

Vassholz and Salditt built a 5-mm-long sandwich-like structure made up of an iron or cobalt metal sheet embedded between guiding and cladding layers. A high-energy (15 kV to 50 kV) electron beam was generated by an instrument adapted from a microfocus x-ray tube. The beam excited the central metal layer, causing it to emit x rays that were funneled into the guiding layers.

The radiation propagated within the 10 nm channels of the guiding layers, and spatially coherent light was emitted either through the top of the waveguide at an angle, as shown in figure 2b—in the case of a leaky design based on a thin top cladding layer—or out the open end of the waveguide. The former produced a 100 μm source spot with small divergence; the latter, a smaller source spot with high divergence. Both emissions can be useful for different applications and adjusted by varying the layer thickness.

A silicon drift detector placed across from the waveguide exit showed sharp peaks in emission intensity as a function of spatial position. The peaks corresponded to the waveguide modes and indicated that the device had effectively channeled x rays onto a target. From the photon counts recorded under conditions of a low current that would not saturate the detector, the researchers extrapolated that the source could reach a brilliance of up to 10^{11} photons/(s mrad^2 mm^2) when fully powered. That value corresponds to an improvement over conventional sources of two orders of magnitude. “It’s not really difficult to build, once you know how it should be designed. It’s just that no one thought that changing from a bulk anode to a waveguide structure would make any difference,” says Salditt.

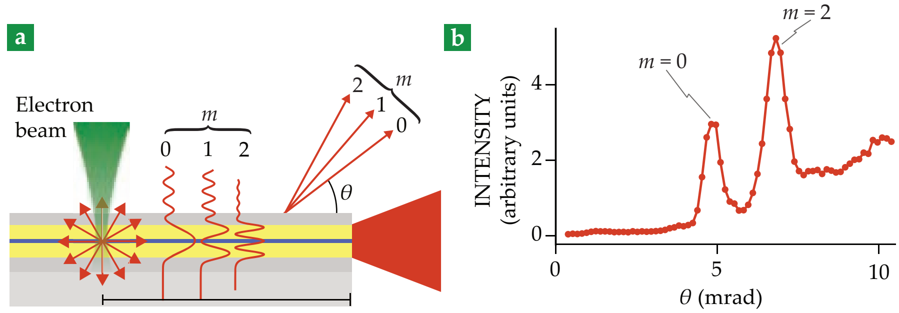

FIGURE 2. X-RAY GENERATION in waveguides produces spatially coherent light. **(a)** An electron beam (green) impinges upon a planar waveguide consisting of cladding (gray) and guiding (yellow) layers and a central fluorescent metal layer (blue). The electron impact excites metal atoms, which directly emit x rays (red arrows) into waveguide modes (red wavy lines) with mode numbers *m*. The x rays exit the channel through the cladding at angle θ with respect to the waveguide or out the end. **(b)** Detected far-field emission of the x rays that leave through the top of the waveguide at angle θ shows sharp peaks corresponding to the waveguide modes, *m*. (Adapted from ref. 1.)

Additional experiments and calculations suggested that the brilliance of the emitted x rays could be further increased—by up to several additional orders of magnitude—by using different metals or by varying the thickness of the layers. According to simulations and experiments, the distance between the spot of electron impact and the waveguide exit can be used to control the far-field emission pattern.

New directions

The improved coherence of x-ray radiation within a resonant cavity is an example of the quantum electrodynamic Purcell effect, in which a system’s spontaneous emission rate—in this case, of x rays—can be enhanced by its environment. Achieving the effect in a tabletop waveguide allows a glimpse of nanoscale structures that could otherwise only be seen with diffraction imaging that uses visible light lasers and with x rays in synchrotron experiments.

Claudio Pellegrini of Stanford University observes that the technique is similar to a much older proposal that uses channeling in a crystal to obtain x-ray emission in a well-defined direction instead of the full solid angle. But for the crystal, the channel size is a few angstroms and thus can only be used for extremely narrowband radiation.[5] The waveguide’s larger channel size of 10 nm offers a resonant-cavity approach that can be used with standard electron sources.

The new waveguide-based design could enable benchtop measurements of nanoscale structures that until now have only been accessible using large-scale instruments. Changing from a planar to a channeled waveguide could provide a beam that is both coherent and directed in two lateral dimensions—ideal for holographic imaging experiments, for example. Says Vassholz, “We’re driven by imaging tools, but the possibilities are really open-ended with the new design’s degree of freedom.”

Rachel Berkowitz

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Beating back the coronavirus requires a bigger arsenal

More than a year into the COVID-19 pandemic, researchers seek alternative targets to the spike protein, whose rapid mutations threaten the effectiveness of current vaccines.

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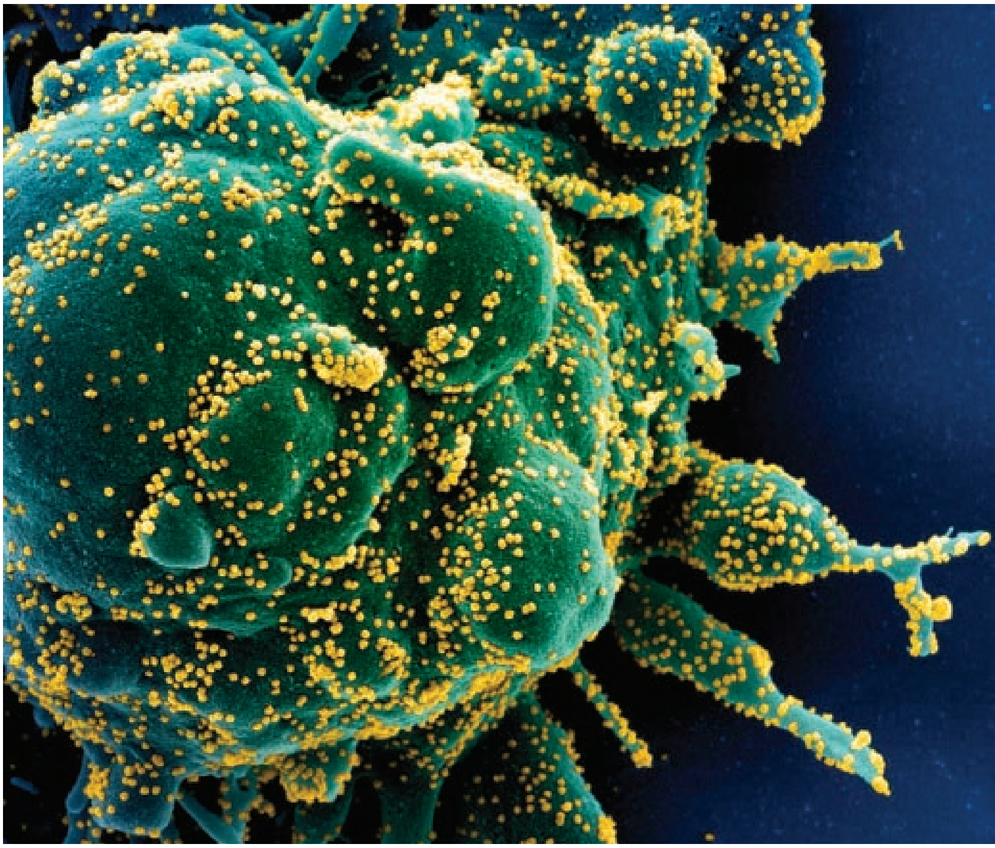


A COLORIZED scanning electron micrograph of a cell (green) heavily infected with SARS-CoV-2 virus particles (yellow), isolated from a patient sample.

Physics continues to be vital in the search for new antibodies and antivirals to fight the coronavirus. The powerful one-two combination of the world's high-performance computers sifting through hundreds of thousands of existing compounds and billions of potential ones and the world's battery of synchrotrons, neutron sources, and cryo-electron microscopes are providing new leads for neutralizing SARS-CoV-2.

But the inexorable mutations of the coronavirus threaten to block, or at least render less effective, the vaccines that are gaining widespread usage. Already, research is showing that the antibodies produced by the Pfizer–BioNTech and AstraZeneca vaccines are far less effective against the variant originating in South Africa than against earlier SARS-CoV-2 strains, says Dave Stuart, who heads the biosciences program at the UK's Diamond Light Source and is joint head of structural biology at the University of Oxford. As of early March, researchers had confirmed that the variant had broken through vaccine protection in some cases. "That is a genuine cause for concern," he says.

Providing a more comprehensive defense against the coronavirus will require not only vaccines that may target less mutagenic proteins but also therapeutics to treat infected individuals. "Tackling a virus requires a multipronged approach in the big-picture way of not only having an arsenal to respond with as the virus changes over time, but also recognizing that trying to kill something that's not really alive is a very hard task," says Marti Head of Oak Ridge National Laboratory (ORNL), who leads the molecular design project of the National Virtual Biotechnology Laboratory (NVBL). That consortium of nine national laboratories was formed last year by the Department of Energy to focus on COVID-19 research with funding from the Coronavirus Aid, Relief, and Economic Security (CARES) Act. (See "Q&A: DOE's Chris Fall," PHYSICS TODAY online, 28 April 2020.)

A moonshot

"If I look globally at what's happening with antivirals, it's really disappointing at the moment," says Stuart. "The most effective therapeutics have been things like steroids," which are used only for late-stage disease. After screening 12 000 compounds that have been tested in humans, researchers using Diamond have identified two molecules that look particularly promising. They are about to undergo tests in animal models at the Rega Institute for Medical Research in Belgium. "One of the lessons is that the basic science of making the protein, doing the experiments at the synchrotron, and getting structures has been much quicker than joining that up with the virology, the cellular work, and the animal work," Stuart says.

Other promising molecules discovered at Diamond have been made public. They provide leads for Covid Moonshot, a crowdsourced drug development effort by medicinal chemists around the world who work *pro bono* to optimize the compounds. Some have been synthesized by Enamine, a Ukrainian medicinal chemical company, and sent back to Diamond to crystallize and check for binding with their targets. "We haven't had the resources to do a large-scale screening, but we found a handful of compounds that do actually bind to the target molecule. It's a good start and an indication that the process is not just throwing out random noise," Stuart says.

The most potent antivirals are likely to be compounds that are specifically designed for SARS-CoV-2, he says, rather than repurposed drugs such as remdesivir, which has been approved or granted emergency use authorization in the US and other countries in Europe, Asia, and elsewhere for treatment of COVID-19.

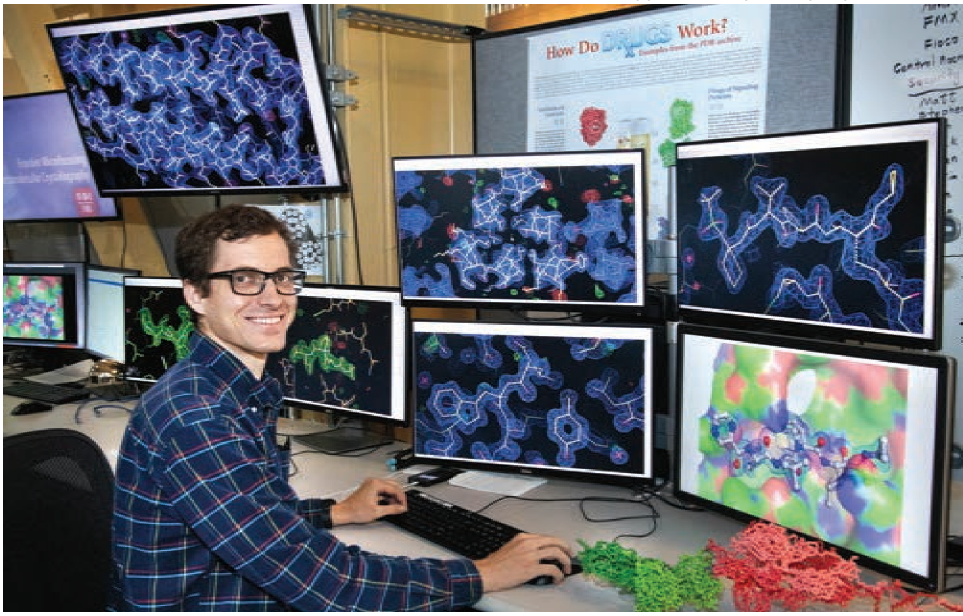
At ORNL, Head says the NVBL molecular design team was, as PHYSICS TODAY went to press, very close to publishing a preprint describing a potential antiviral molecule that was found in *in vitro* tests to block the function of the papain-like protease (PL^{pro}), one of two SARS-CoV-2 enzymes essential to processing the virus's polyproteins. The team hopes to move the compound outside the lab into a small animal trial. But she cautions that it's a long way from a compound to a drug that is stable, nontoxic, and bioavailable.

"One of my roles in the NVBL, since I came from pharma, is to occasionally break my team members' hearts by telling them that success rates in pharma are around 5–8%, starting from a target hypothesis," Head says. Nonetheless, she says she is "very excited" about the molecule.

The NVBL-funded design team identified three other compounds as potent inhibitors to viral infection, but it's unclear how they work. "We've made a computational prediction that it is through interactions with one or more of a set of eight proteins. We need to do experiments to confirm that," she says.

Those involved in the research acknowledge that development of new drugs will take a long time. "Particularly for small molecules [meaning most pharmaceuticals], the timelines are such that we are not going to have a major impact on the pandemic," says Jim Brase, a Lawrence Livermore National Laboratory (LLNL) deputy associate director who cochairs an industry–lab consortium for computational drug development. "But we would like to use the effort to make sure we have tools in place for future needs so we'll be in a better position next time around."

X-ray and neutron sources play a "huge role" in the molecular design efforts, Head says (see PHYSICS TODAY, May 2020, page 22). Structural biologists working at ORNL and Brookhaven National Laboratory have solved several structures of the coronavirus's main protease (M^{pro}) and provided input to the computational design of inhibitors. And since the hydrogen atoms in proteins are essentially invisible to x rays, neutron crystallography gives details of where those atoms are located, which is important to understanding the details of bond formation. For covalent bonds, such as the one formed with PL^{pro} and the lead antiviral candidate in NVBL's effort, "understanding where all of the hydrogens are moving around as you have a chemical reaction that forms a bond is very important," Head says.



DALE KREITLER from Brookhaven National Laboratory with some of the SARS-CoV-2 protein structures determined at the National Synchrotron Light Source II, including portions of the coronavirus spike and the main protease interacting with potential inhibitor drugs. The model on the desk shows the spike (red) bound to the ACE-2 receptor of a human cell (green).

A threat to vaccines

The spike is a powerful antigen and the standout vaccine target because the immune system immediately mounts a strong response to it. Of the coronavirus's 28 proteins, the spike also is the most prone to adapt via mutation. Vaccines can be readily altered to cover variants by changing a few amino acids in their messenger RNA (mRNA) or DNA code, says Jason McLellan, associate professor at the University of Texas at Austin. But as with influenza vaccines, annual boosters may be needed to keep pace.

Using blood taken from recovered COVID-19 patients, Diamond's Stuart and collaborators identified 19 antibodies that were potent neutralizers of the receptor-binding domain, the region on the spike that attaches to the host cell. Five of those are known as public antibodies because they are shared by most people. They mutate the most rapidly in response to an infection, and their nimbleness in reacting to the antigens in the vaccines helps to explain why the vaccines in use today are so highly effective against the initial variants, he says.

But the variants of SARS-CoV-2 that have originated in the UK, South Africa, and Manaus, Brazil, each have mutations in the receptor-binding domain. "From the biophysics of it, it appears that those mutations increase the affinity of the virus for the [cellular] receptor. That will allow the virus to enter cells more easily and might account in part for the transmissibility advantage of those mutant viruses," Stuart says. Antibodies, which also attach to the receptor-binding domain, are crowded out.

Stuart and colleagues found antibodies resulting from the Pfizer–BioNTech and AstraZeneca vaccines were somewhat less effective against the UK and Brazilian variants. But their effect on the South African variant was significantly reduced, he says. Some of the public antibodies were "knocked out" by the South African variant but notably not all. "I think the response can be rescued."

Researchers at Diamond evaluated the performance of monoclonal antibodies that are approved for use in COVID patients against the South African variant. They found one of the antibodies in Regeneron's two-antibody cocktail effective. But results for Eli Lilly's single antibody against the variant "were deeply disappointing," Stuart says. AstraZeneca's antibody cocktail, still in clinical trials, performed well.

As spike variants continue to crop up, researchers will have to move quickly to modify antibodies computationally, create physical versions, and validate them experimentally, Head says. The NVBL team has used computational approaches to sample a chemical space of more than 10^{40} possible antibody combinations and has identified two antibodies and one nanobody—a class of molecule that is one-tenth the size of an antibody—that potently prevented the spike from attaching to cell receptors (see PHYSICS TODAY, September 2020, page 22).

A different kind of vaccine

A vaccine that bypasses the spike altogether is the goal of a partnership announced in January between the UK company ConserV Bioscience and LLNL. The candidate targets two of the virus's other 27 proteins; their identities are considered proprietary. Because it will inhibit protein regions that are common to all coronaviruses, ConserV's vaccine should work against existing and future viruses of that type, says Kimbell Duncan, the company's CEO.

While development is still in the preclinical stage, the partnership calls for LLNL to contribute its nanolipoprotein particle technology as the delivery vehicle for ConserV's mRNA construct. Those water-soluble molecules, which resemble high-density lipoproteins, bind to and coat the genetic material.

Animal studies are scheduled to begin in the second quarter of this year, followed by human trials later in the year, says Duncan. He says he first learned of the nanolipoprotein technology serendipitously when he spent time at LLNL as a graduate student at Georgetown University.

LLNL is primarily a nuclear weapons laboratory. Its bioscience program was initiated in the early 1960s to study the effects on biological systems of fallout and other radioactive hazards and was refocused on bioterrorism after 9/11. The lab is also providing delivery platforms for other vaccines under development, says senior staff scientist Amy Rasley.

71 billion molecules

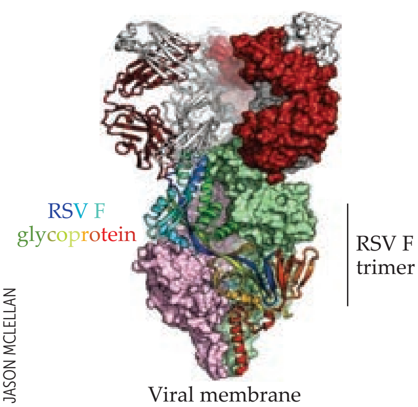
Large-scale computational screening of libraries of small molecules has turned up some hits as possible antivirals. Exscalate4CoV, a public–private consortium led by the Italian pharmaceutical

R&D on today's coronavirus vaccines started in 2013

The coronavirus vaccines made by Moderna, Pfizer–BioNTech, and Johnson & Johnson each deliver genetic information that codes for a stabilized form of the spike protein, the protrusions on the virus through which SARS-CoV-2 infects human cells. Depending on the vaccine, the messenger RNA (mRNA) or DNA instructs cells to produce copies of slightly altered versions of the spike, which stimulates the immune system to develop the antibodies to deactivate the viral spike, preventing infection. A vaccine by CureVac, now in clinical trials, includes the same mRNA coding, whereas the Novavax vaccine, which could be authorized in May, contains recombinant versions of the stabilized spike itself.

The research that led to those vaccines dates to 2013, when scientists at NIH's Vaccine Research Center were hunting for a vaccine to prevent respiratory syncytial virus (RSV), which can cause serious disease in infants and older adults. Jason McLellan, now associate professor of molecular biosciences at the University of Texas at Austin, and collaborators were targeting the RSV fusion (F) protein, which is ancestrally related to the SARS-CoV-2 spike protein.

The team knew that the F protein existed in two conformations, corresponding to before and after fusing to the human cell. Although human antibodies to the virus were known to act against the pre-fusion form, the researchers were unable to obtain stable pre-fusion F proteins in isolation because the molecules immediately refolded into the post-fusion state. Using a beamline at Argonne National Laboratory's Advanced Photon Source (APS), "we were able to get the crystal structure of post-fusion F," says McLellan. "That was a helpful reagent allowing us to characterize different antibodies, and we were eventually able to find pre-fusion-specific antibodies."



JASON MCLELLAN

After purifying and crystallizing the protein–antibody complex, McLellan and his team obtained its structure at APS. "I was able to eventually determine the structure of pre-fusion F [pictured here in green, pink, and multicolor] bound to a human monoclonal antibody [red and white] that was extremely potent," says McLellan. The researchers then slightly altered the protein's chemical structure to prevent it from refolding. "Ultimately we created a molecule stabilized in the pre-fusion form that we could express and purify in the absence of those antibodies, and we had in our hands pre-fusion F. We crystallized that and solved the structure at APS."

A similar process was used to develop stabilized pre-fusion versions of the spike proteins of coronaviruses that cause severe acute respiratory syndrome (SARS), Middle East respiratory syndrome (MERS), and in 2020, SARS-CoV-2. Because the spike of SARS-CoV-2 can't be crystallized, its structure was resolved using cryoelectron microscopy.

The RSV vaccine, which entered phase 3 clinical trials late last year, has followed the more typical 7- to 10-year timeline for vaccine development. The SARS-CoV-2 vaccines were developed and approved in about as many months. —DK company Dompé and partially funded by the European Commission, last fall combined the high-performance computing assets of the petroleum giant Eni and the publicly funded Italian supercomputing consortium Cineca to look for activity against SARS-CoV-2 in 400 000 molecules—including all compounds tested in humans, unregulated substances with physiological benefits, and substances used in traditional Chinese medicine.

The screening found that raloxifene, a low-cost generic drug used to treat osteoporosis, had potential in treating COVID in mildly symptomatic patients, and the drug is now undergoing clinical trials in Europe for coronavirus use. A second drug already on the market for another use has been found to be a potent viral inhibitor and is now in preclinical testing, says Andrea Beccari, the project's chief scientist. He declined to identify the drug pending experimental validation and publication.

Since last fall, Exscalate4CoV has screened 71 billion synthesizable molecules for activity against 15 active sites on 12 of the SARS-CoV-2 proteins. ORNL's supercomputer performed a similar exercise last summer involving 1 billion molecules on a single protein in two conformations. "We believe that 71 billion compounds among 15 targets is a huge chemical space that can be effective to use for training neural networks for a specific protein or for addressing the entire viral functional proteome," Beccari says. "The idea is to release the biggest possible profile of chemical space for this and future pandemics."

The consortium routinely interacts with European light sources, including Italy's Elettra Sincrotrone and FERMI. "Crystal structure information optimizes models," Beccari says. "We have molecules that are active on the papain-like protease and are moving to crystallization with these compounds."

In the US, funding for NVBL under last year's coronavirus relief legislation has mostly dried up, but the stronger links on coronavirus persist among the DOE labs. Labs with large computational assets and those having light sources and other imaging capabilities have strengthened collaborations, says LLNL's Brase. He coleads the consortium called Accelerating Therapeutics for Opportunities in Medicine (ATOM), which includes GlaxoSmithKline, the Frederick National Laboratory for Cancer Research, and the University of California, San Francisco (UCSF). Formed to search for cancer therapeutics, the partnership added infectious diseases to its mission last year, and ORNL, Brookhaven, and Argonne National Laboratory came aboard.

ATOM is contributing models it has developed to predict the safety of candidate molecules and whether they will travel through the body and be bioavailable, Brase says.

A nanobody inhaler

Researchers at UCSF are developing synthetic nanobodies against the coronavirus that they propose to be delivered via nasal spray or inhaler. Their technology, dubbed AeroNabs, is undergoing animal trials. After combing through databases containing 2 billion synthetic nanobody molecules, the scientists found three that neutralized the spike. At Lawrence Berkeley National Laboratory (LBNL), they were able to determine through cryoelectron microscopy and crystallography where two of the nanobodies bind to the spike. But they were unable to get structures of the third using either method.

The UCSF scientists turned to x-ray footprinting, a relatively new structural technique, performed on a synchrotron, that doesn't require crystals but instead uses molecules in solution. Corie Ralston, facility director for biological nanostructures at LBNL's Molecular Foundry, says the method infers the structure by whether a part of the biomolecule known as a residue and a water molecule are adjacent. "For instance, if in the process of folding, this residue has a water molecule next to it and then it doesn't, we figure that's where it's making contact with another part of the protein. Then we can figure out how it folded."

The structural work at LBNL provided information for researchers to optimize the potency of the nanobodies, using strategies such as linking two or three nanobodies together to attach to the spike at multiple points.

When the pandemic eases, it will be critical that governments not let up on developing broad-spectrum antivirals and therapeutics, says Duncan. "They need to extend the emergency work to focus on the next pandemic. They really need to stay on high alert."

David Kramer

Mingling art and science opens minds

Collaborations enrich science communication, visualization, and inspiration.

After viewing *Little Shop of Horrors*, Andrew Pelling and his research group wondered if they could create a plant with muscles. They were inspired by Audrey II, the monster plant that eats people in the 1986 film. They tried and failed to grow muscle tissue on a leaf, but the attempt sparked a research direction that has blossomed in Pelling's group over the past decade: plant- and polymer-based scaffolding for growing mammalian tissue. Recently, he says, they have shown that an asparagus-derived scaffold can guide the growth of neurons for use in treating spinal cord injuries. They have also been studying a new polymer scaffold developed by a textile artist in the lab.

From the start, Pelling's research group in the physics department at the University of Ottawa has included a mix of scientists and artists—sculptors, painters, digital media artists, and others; at present 3 of the roughly 15 members are artists. "Every artist I've known is busy questioning and investigating the world, just like scientists," Pelling says. He aims to generate questions that haven't been asked before. "For me, the best way to do that is by having diverse people around, sharing lunch, shooting the breeze." The interactions, he says, have led to both museum pieces and scientific advances.

Science and art often are compartmentalized—as is also the case for subdisciplines within science. But it hasn't always been like that—consider, for example, Leonardo da Vinci, who studied friction and other topics, or his 15th-century contemporary Piero della Francesca, a painter and author of mathematical treatises. Today, connections range from science-inspired art, to art as a vehicle to explain or illustrate science, to science explored by artists, to—perhaps most rare—collaborations that advance scientific understanding.

IN HIS PAINTINGS, structural biologist David Goodsell incorporates known information and best guesses to portray detailed views of molecular structures. This watercolor is titled *SARS-CoV-2 Fusion, 2020*. (Illustration by David S. Goodsell, RCSB Protein Data Bank; doi: 10.2210/rcsb_pdb/goodsell-gallery-026.)

Indirect inspiration

Ágnes Mócsy is a professor of physics and astronomy at the Pratt Institute, a school in Brooklyn, New York, that emphasizes art, design, and architecture. For her, Joseph Stella's paintings of the Brooklyn Bridge invite a discussion about the Doppler effect. Jackson Pollock's paintings suggest momentum and energy and fluid dynamics. Sculptures can be used to talk about mass and space, and from there general relativity. And comparing artworks from Eastern and Western cultures elucidates different senses of space and time. "When you are in front of a painting or a sculpture, there are no right or wrong answers, so people can feel more comfortable opening up," says Mócsy, who previously worked in heavy-ion theory at Brookhaven National Laboratory and now focuses on physics education with an emphasis on the intersection of physics and the arts. Physics often alienates people, she continues. "I am interested in enriching the narrative we tell about physics. Art, science, and social justice are interlinked in my work."

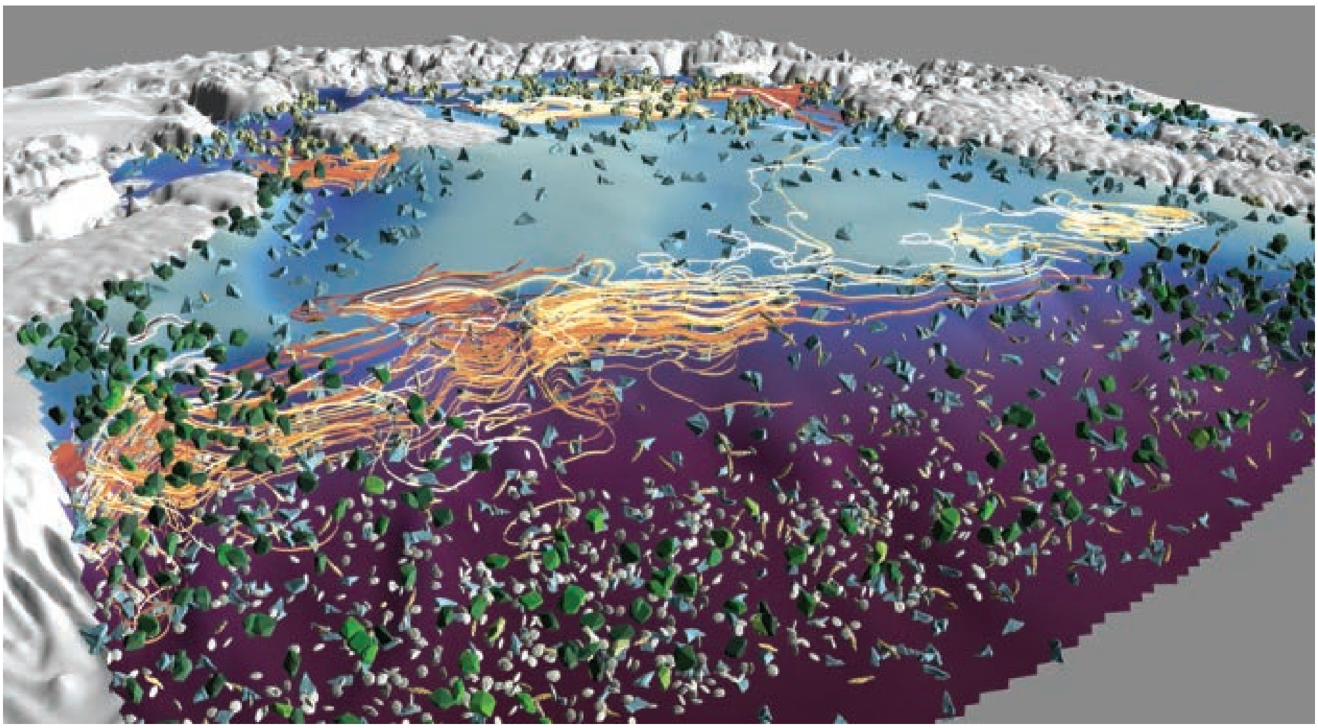
Like Mócsy, Kathryn Schaffer left a research-intensive career to teach physics to artists. (She describes her exit from a toxic physics culture and more about her life and career in an interview at https://physicstoday.org/schaffer.) Since 2009, she has overseen the science program at the School of the Art Institute of Chicago. She started a scientist-in-residence program there and frequently invites scientists to give lectures. Whereas science does not rely on art, she says, science is "integral in the art world"—from tools and techniques to the themes that artists address. Still, artist–scientist collaborations are valuable for scientists in ways that are hard to measure, she says. For example, creative cross-disciplinary collaborations can "refocus attention on who we are as curious, caring, and unique humans engaged in the practice of science."

In 2003, as a director of a new center in Oslo, Norway, on the physics of geological processes, Bjørn Jamtveit brought in painters, photographers, and other artists to collaborate with the center's scientists. A composer worked with a scientist who was studying stress in rock deformations to create works using geological sounds; one was a walk-in installation that surrounds visitors with the sounds of cracking rocks. (Examples of sound from art–science collaborations can be found at the online version of this story.) Scientists are supposed to be objective, but often they see what they are looking for or what they recognize as familiar, says Jamtveit, who originally pursued the collaborations to increase the chances of future funding by excelling in outreach. "I've become a better observer because of my interactions with artists," he says.

Early on in their long collaboration, recalls Harvard University's George Whitesides, photographer Felice Frankel told him that his picture of water spreading on a surface was "boring" and that she could do better. That challenge and her aesthetic interests led to insights into how fluids behave at small scales, says Whitesides. "Nothing captures attention like a good photograph. If you see an arresting photograph, you ask, Why is that happening? That is an asset to science."

For her part, Frankel says scientists often crowd figures with captions, scale bars, and more. "Compositionally, you don't know where to look." She asks scientists what they want viewers to see first. "I use design principles for the purpose of communicating science, not to create art," she says. "When people understand what they see, they become more engaged."

As scientists are increasingly pressed to justify their use of taxpayer money, outreach has expanded. It includes illustrations in journals, grant proposals, and activities with the public. Geraldine Cox is an artist—with an undergraduate degree in physics—who is embedded in the physics department at Imperial College London. (Cox's paintings appear on the cover and inside the March 2021 issue of PHYSICS TODAY.) She creates workshops for children, the public, and physicists. They explore the Sun, atomic spectra, and other phenomena using painting, light, and poetry. For example, in an activity based on sculptor Alexander Calder's



SIMULATING OCEAN CIRCULATION gives clues about climate change. This view toward the South Pole is a snapshot of the Antarctic ice sheet. The yellow and orange squiggles are currents, and light blue to purple represents increasing water depth, with the transition to purple indicating the continental slope. The tracers indicate parameters such as salinity and ice shelf water. The US Department of Energy's Energy Exascale Earth System Model incorporates hundreds of variables and has a resolution of 10 km. (Courtesy of the Sculpting Vis Collaborative, Daniel Keefe, and Francesca Samsel, funded by NSF #IIS 1704604 and 1704904.)

work, she had atomic physicists make mobiles out of items they found in their lab. "People made things about atoms and light, life and research, or set themselves practical goals like building a mobile upside down," Cox says. "It was an afternoon of playfulness and openness."

Denmark has a long tradition of public science outreach, says University of Aarhus quantum theorist Klaus Mølmer, and it's "exploded" since 2005, the World Year of Physics. (See the letter "Lessons learned from the World Year of Physics," by Laurence Lavelle, PHYSICS TODAY, December 2005, page 15.) When artists and scientists get to know each other, Mølmer notes, "you get collaborations."

Mølmer has teamed up with artists, including composer Kim Helweg. "We discuss quantum mechanics in detail, he asks me questions, and then he goes and does whatever he wants," says Mølmer. "The inspiration is indirect in both directions." The questions that artists ask him are "an eye-opener," he adds. "I don't think there is a big difference in the source of inspiration for physics and art."

Another quantum physicist–composer collaboration is that of Maciej Lewenstein and Reiko Yamada at the Institute of Photonic Sciences in Barcelona, Spain. Experimental musicians overlap in their aims with scientists, says composer Yamada. "We push boundaries, make discoveries, and experiment in new areas." In one project, she incorporates into musical timbres random nudges generated by quantum processes. "We compare the sounds with classical randomness. Is it different? Is it recognizable?" says Yamada. Early data suggest that timbres are distinguishable. "If people can hear the difference, it would lead to questions about cognition," says Lewenstein. "The quantum world is not intuitive, so it creates public interest and excitement," he adds.

Tools for science

Art plays two major roles in science, says David Goodsell, a structural biologist at the Scripps Research Institute in La Jolla, California. Visualization tools help scientists see their science, he says, and art is used to communicate science. "I've been working on a third aspect," he says. "I use art to generate scientific hypotheses. My art is focused on being a tool for science."

Goodsell has painted the coronavirus life cycle, the influenza vaccine, lipid droplets, and other subjects. He integrates current knowledge with informed guesses and aims to stretch scientists' intuition and understanding. The paintings involve many approximations and decisions. The SARS-CoV-2 spike protein, for example, undergoes complex conformational changes as it directs the fusion of the virus with a cell (see the figure on page 24). "Structural snapshots are available for the beginning and final states, but I use artistic license to speculate about intermediate states," he says. "I have to pick among hypotheses. I do these pictures in collaboration with specialists. It's often difficult to get them to pin down and commit without qualifiers." Yet the paintings lend freedom to the scientists because they are "artistic renditions," he says.

Francesca Samsel uses her skills and sensibility as an artist to help scientists extract more information from vast data sets. She has worked closely with several scientists from Los Alamos National Laboratory for nearly a decade on such topics as climate modeling, ocean biogeochemistry, and the waves created by asteroid impacts. A current project with ocean modeler Mark Petersen and others involves Antarctic ice melt and ocean circulation (see the image on page 25).

"In the arts we are trained to use visual elements—lines, shapes, color—to create relationships between variables, organize content, and direct attention," says Samsel. That can be done with color, she adds, "but you have to know how to use it." Traditional rainbow-colored maps can lead to visual artifacts, she notes. What's more, in such maps, fully saturated colors are adjacent, which causes visual vibration that tires viewers' eyes.

The key to artist–scientist collaborations is leaving assumptions at the door, says Samsel. "Scientists have to leave

Facing page (clockwise from top left):

CURVED THREE-DIMENSIONAL LATTICES are depicted here by artist Tony Robbin, who works closely with mathematicians. The braided lattices are color coded and identified by different polyhedra. In higher dimensions, the lattices flow over and under each other, he explains, but in projection they appear to intersect. The painting, *2006-6*, is acrylic on canvas, 56 × 70 inches, from the collection of the artist. (Courtesy of Tony Robbin.)

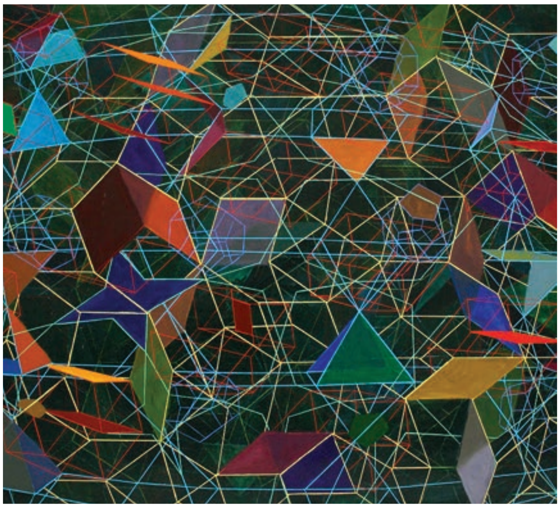
CHIXEL ARRAY is a light sculpture made of stuff bought from a dollar store and scavenged from the garbage. It started with the idea of lighting toy chickens with pixels, and involved designing a circuit and coding. "It's goofy and esoteric," says University of Ottawa biophysicist creator Andrew Pelling. But, he says, "it symbolizes how my lab works. Beneath it all, a scientific team is being cultivated to take on any project—a team that is comfortable with troubleshooting, iteration, and pivoting as a project proceeds." (Courtesy of Andrew Pelling.)

ENTANGLED WEBS in this image are woven by different species of spiders. It is from Arachnophilia, an interdisciplinary research project started by Berlin-based artist Tomás Saraceno that probes spider web architecture, vibrational signaling, and more. Saraceno developed a scanner to digitalize spider webs and has recorded the sounds of vibrating web threads. (Image from Photography by Andrea Rossetti, ©2013.)

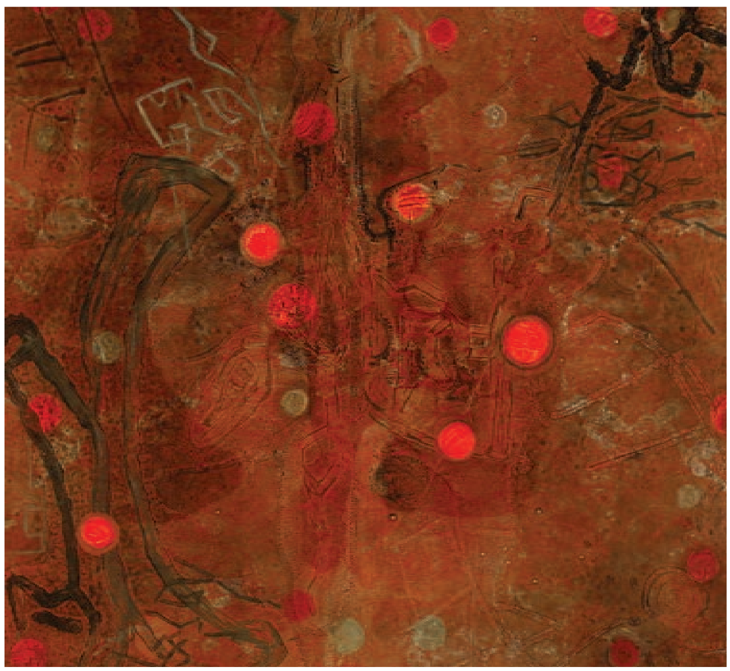
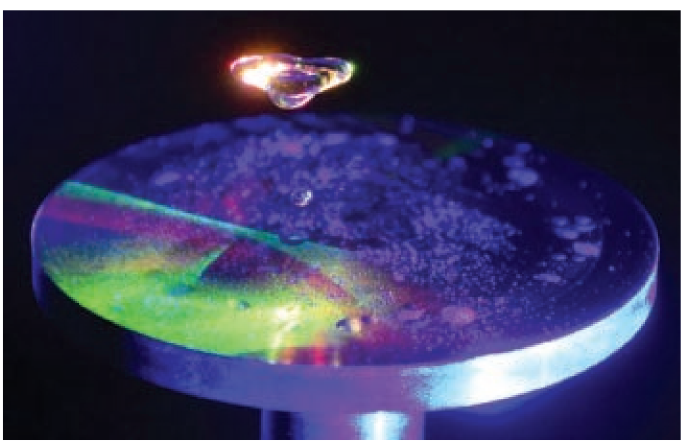
GEOPRINT is a series by artist Ellen Karin Mæhlum. She joined scientists from the University of Oslo's center on the physics of geological processes on an Arctic expedition in Svalbard to explore the relationship between rock and life forms in a Mars-like environment. Based on forms and patterns on different scales, the images, including *P0911* shown here and *V7010* on the cover, were formed in layers using printing plates, drypoint, and stencils. (Courtesy of Ellen Karin Mæhlum, www.ellenkarin.no.)

ACOUSTICALLY LEVITATED water droplets resonate, vaporize, and reassemble as they spin nearly devoid of shear. Creators Evelina Domnitch and Dmitry Gelfand describe *Force Field* (2016) as tapping into the three-dimensionality of sound, the elusive physicality of water, and the rotational dynamics of celestial and subatomic bodies. (Courtesy of Evelina Domnitch and Dmitry Gelfand.)

COFFEE BUBBLES move and burst. The photo was taken through a microscope that was fitted with a smartphone adapter. (Courtesy of Felice Frankel.)





aside the idea that I may be flaky. And I have to work to understand the science and the scientists and their needs." The process is iterative, she adds. "It's thematically rich and symbiotic." Petersen notes that "Francesca is deeply embedded—she is part of the team."

To depict simulations of the waters under the Antarctic ice shelves, Samsel introduced tracers based on hand-sculpted forms. Textured, shaped, and shadowed, different tracers allow the viewer to distinguish between multiple variables—temperature, salinity, currents, water depth, and more. Such an image can be digested more easily than when the variables are represented by colored spheres. In virtual reality, the scientists can swim up close or zoom out to study the data from a range of perspectives. "The goal is complexity without cacophony—a calm, clear environment of visual clues," says Samsel.


JESSICA SMOLINSKI

SUZANNE BROWN (right) discusses her painting *dis,oRdered* with Stephanie Wiles, director of the Yale University Art Gallery. The self-portrait explores entropy, heat transfer, and time, and makes an analogy with everyday feelings of disarray and stress. Brown painted it in 2019 during an undergraduate course, Physics Meets the Arts, taught by Ágnes Mócsy, who was a visiting professor in the Yale physics department from the Pratt Institute.

Different questions

Evelina Domnitch and Dmitry Gelfand are an artist couple based in the Netherlands who create performances and installations that are deeply rooted in science. "We are interested in art that prods uncharted perceptual physical and philosophical domains," says Gelfand. When they began working together more than two decades ago, he says, "we opted to work with gases, fluids, and wave phenomena. This was an unorthodox constraint in the arts. It was inspired by quantum theory."

The duo's explorations include sonoluminescence, acoustic levitation, black holes, and ion traps. Domnitch and Gelfand learn the relevant science. "One of our reasons for confronting these exotic physical phenomena is to come to terms with the nature of reality," says Domnitch.

In their piece *Camera Lucida*, the artists transmit sound waves into a 60-liter glass sphere containing gas-infused water to induce sonoluminescence. "High-frequency sounds form microbubbles. When they collapse, they reach temperatures as high as in the Sun and emit faint flashes," says Domnitch. Kyuichi

Yasui, a theorist at Japan's National Institute of Advanced Industrial Science and Technology in Nagoya, says that it was interesting to watch the bubbles and sonoluminescence in the work "because the container was much larger than in laboratories." Although there was not a direct connection to his research, he adds, "when I see art, my stress in research disappears, and my passion from the art is useful for my research."

Another artist whose work is steeped in science is Berlin-based Tomás Saraceno of Argentina. "We need to reinvent our modes of collaboration and to work across disciplines," he says, because of the scale of problems humanity is facing: global warming, mass extinctions, human suffering. Saraceno's projects include digitizing and reconstructing spider webs and recording the vibrations spiders make in their webs. "Now I think of the web as a musical instrument," he says. "A spider senses or locates prey by tuning its web; energy propagates through the web's threads." The three-dimensional reconstructed spider webs have been compared with cosmic webs, he notes. "You can scale up and think about the visual effects and the harmonics and musical scales."

Andrea Polli's installation *Particle Falls* is similarly science based. The University of New Mexico professor and environmental artist displayed particulate-matter concentrations on streets in Philadelphia and other cities. The data, updated every 15 seconds and projected onto a building, visualize unseen pollution.

Art can help science by opening doors to what needs to be understood, says Tommaso Calarco, director of the Institute of Quantum Control in Jülich, Germany. Artists ask different questions, inspiring new ways of thinking. And artists present ideas in ways that are "beautiful, appealing, exciting, and emotional." Domnitch and Gelfand, says Calarco, make science experiments "beautiful to behold and thought provoking. They create a sense of wonder, and that can inspire scientists to approach their research differently."

Calarco says interactions with art and artists "form a strong anchor and inspiration in shaping the direction" of his work in quantum thermodynamics. "If we forget that science is beautiful," he says, "we will have the innovation of tomorrow, but not of the day after tomorrow. It's wise to pursue the useless side of knowledge."

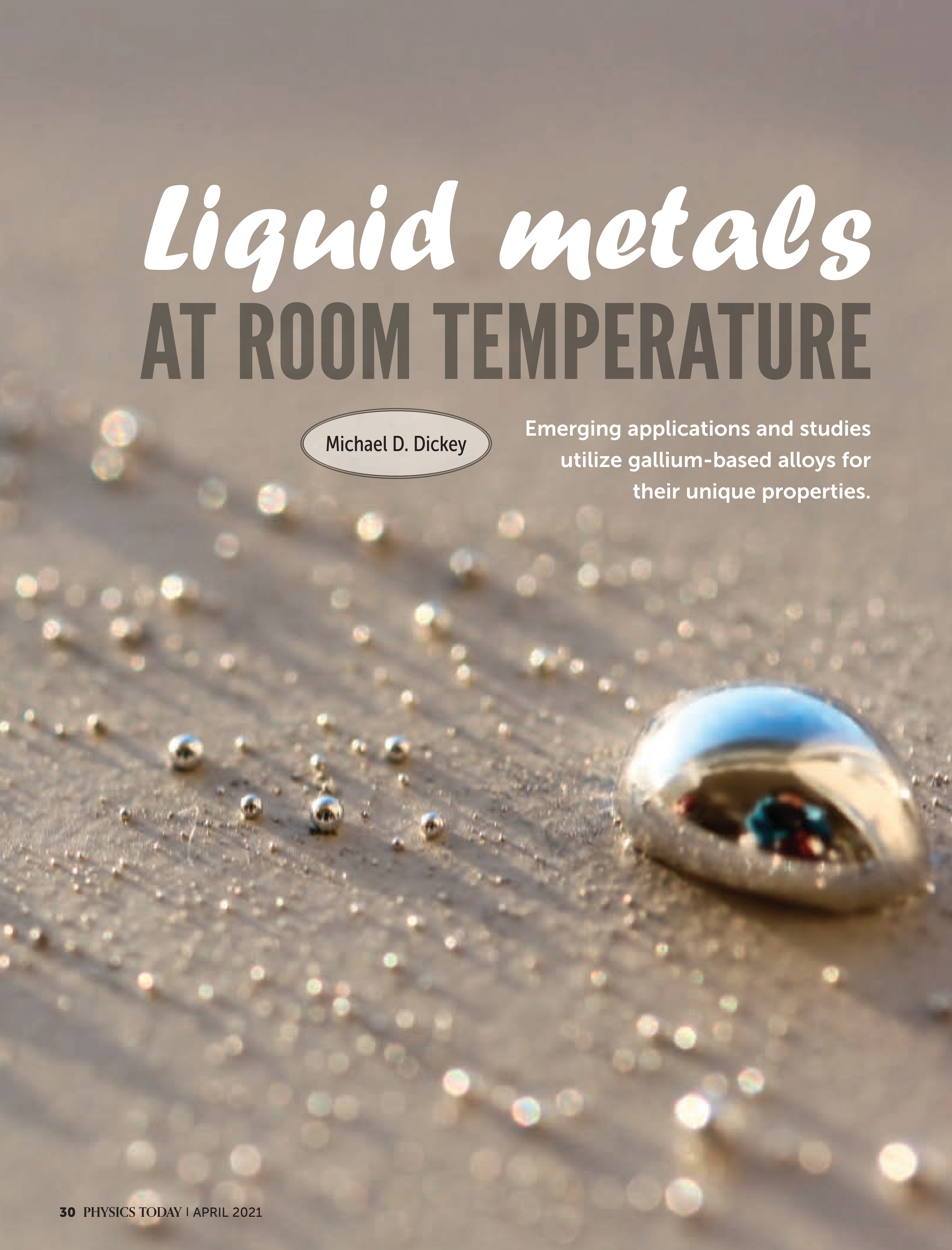
Art and science both value economy and intensity, says Roald Hoffmann, a chemistry Nobel laureate at Cornell University. "This is obvious in poetry, and in a different way, equations or explanations communicate best when they are concise." But a difference, he says, is emotion. "Artists, poets, musicians, dancers, are good at communicating with emotions. But science by and large rules out emotions." And that, he says, "is absolutely wrong." He notes that scientific lectures tend to be much more interesting than papers, "and it's because they [lecturers] are weaving together a story with emotional descriptors along the way." Communicating emotion is something science can learn from the arts. "I am interested in building an intellectual community. We need bridges between humanities and science."

Toni Feder PT

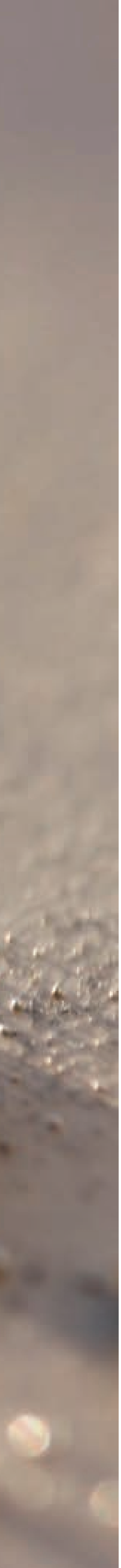
Liquid metals AT ROOM TEMPERATURE

Michael D. Dickey

Emerging applications and studies utilize gallium-based alloys for their unique properties.



Michael Dickey is the Alcoa Professor and a University Faculty Scholar in the department of chemical and biomolecular engineering at North Carolina State University in Raleigh.



COLLIN LADD

The phrase "liquid metal" readily evokes images of toxic mercury, mad hatters, and the menacing villain from the movie *Terminator 2*. (Incidentally, the villain's computer rendering was based on mercury.) Suffice it to say, the phrase often carries negative connotations.

However, there is hope for liquid metals: Gallium has a melting point near room temperature and doesn't share Hg's toxicity. When Ga was discovered in 1875, Hg had already been known for more than 1000 years and was being used in thermometers, electrochemical reactions, and dental fillings. But because Ga reacts readily with oxygen to form a thin oxide crust on its surface, it could not readily replace toxic Hg.

The formation of surface oxides is common. Noble metals such as platinum and gold are rare examples of metals that do not readily oxidize. In contrast, Ga oxidizes almost instantly—likely within microseconds in air—much like aluminum, its neighbor on the periodic table. Surface oxides can be beneficial: They protect the underlying metal from further oxidation. Known as passivation, the formation of thin surface oxides shields metals like Al and stainless steel from O in the air and thereby prevents rusting.

The surface oxide on Ga is problematic, however, for applications that require a free-flowing liquid. It can also impede electrochemical reactions, and that explains why chemists still opt for Hg rather than Ga as an electrode in certain experiments. Ga also corrodes in water, one of several reasons why dentists continued for many years to fill cavities with Hg amalgams. Despite its toxicity, Hg is not easy to replace.

Over the past decade, Ga and its liquid alloys have received renewed interest. They have a wide range of interesting properties that researchers are now exploring. Simply stated, Ga is a solution looking for the right problems.

The most interesting element?

The electrical and thermal properties of Ga are metallic, yet its melting temperature is just 30 °C—low enough that it would melt if you held it in your hand. That temperature can be lowered further by adding other metals, such as indium or tin. The two most popular options are eutectic gallium indium (EGaIn) and gallium indium tin (Galinstan).

Conceptually, the melting and freezing point of materials should be the same. One might thus expect Ga and its alloys to freeze on a cold day. Yet the liquids tend to become supercooled, meaning they freeze at temperatures well below their melting points. Consequently, once melted, Ga and many of its alloys remain liquid at or below room temperature. For example, for months researchers in my laboratory have left EGaIn in a freezer at −15 °C—a remarkable 30 °C below the material's melting point. It has yet to freeze. The supercooling effect becomes even more pronounced in small particles.

Like water, Ga is one of the few materials that expands in volume when frozen. It therefore becomes more electrically conductive in the liquid state, which is also unusual for metals. The remarkable phase behavior and low melting point can be attributed to Ga's unique bonding: Rather than form bonds between atoms, as other metals do, Ga forms bonds between covalently paired dimers.

Ga has effectively zero vapor pressure at room temperature. In fact, it must be heated to above 2400 °C before it will boil. Whereas water, ethanol, and other familiar liquids will evaporate at ambient conditions, Ga will not. Why does that matter? Ga can be handled openly outside a safety hood without fear of inhalation. It can even be placed in the very low-pressure vacuum environments that scientists often use to study materials. Normally those low pressures would cause liquids to evaporate, but not Ga.

Like most molten metals, Ga has a low bulk viscosity. In fact, its viscosity is just twice that of water. And at 500 mN/m, Ga's surface tension is the largest of any liquid at room temperature; for comparison, water's surface tension is 72 mN/m, and ethanol's is 22 mN/m. Thus, in the absence of a surface oxide layer, the metal flows like water due to its low viscosity and naturally forms spherical shapes due to its high surface tension.

Importantly, Ga has low toxicity. Its salts have been approved by the US Food and Drug Administration for human use in applications such as MRI contrast imaging. Although it should still be handled with care since it is not a regular dietary nutrient, Ga appears to be safe because the body has the ability to remove it.

Although Ga is relatively abundant in the earth, it is difficult to mine on its own. Instead, it is found as an impurity in alumina—the precursor to aluminum—which makes it expensive despite its abundance; one gram costs around \$0.25–\$1.00. Ga has industrial applications as a precursor for compound semiconductors such as Ga arsenide and Ga nitride. Researchers are exploring gallium (III) oxide (Ga_2O_3), a wide bandgap semiconductor, as a promising material for power electronics—that is, solid-state semiconductor devices that control electric power. Such devices are becoming increasingly important for electric vehicles and renewable energy. Commercial uses of liquid Ga are still in the early stages of development, but several companies are beginning to harness its unique properties. This article briefly explains some of these emerging applications.[1]

Printing and patterning

Perhaps Ga's most important property for applications is its ability to rapidly form an oxide skin on its surface.[2] The oxide layer is a few nanometers thick; for reference, the diameter of a human hair is about 30 000 times thicker. As mentioned above, the native oxide layer was historically found to be a nuisance. However, it enables patterning of liquid metal into shapes that would not be possible with conventional liquids, especially ones with low viscosity and high surface tension. The rapidly formed surface oxide shell is behind the shapes shown in figure 1.

Liquid metals can be printed and patterned in ways that simply are not possible with conventional solid metals.[3] Those that are liquid at room-temperature can be, for example, injected, painted, smeared, wetted, molded, and printed. (Figure 1 shows one example of printing.) Despite being thin, the oxide layer stabilizes the resulting structures. Above a critical surface stress, however, the oxide layer breaks and the low-viscosity metal flows readily.

The critical surface stress, a force per length, is a material property of the oxide that can be combined with the curvature of a surface to determine the critical stress—force per area—required to break the oxide. Gravitational forces can exceed the critical stress of a spherical structure when its diameter exceeds just a few millimeters, whereas a 100-μm-diameter vertical cylinder can grow to be several cm tall without collapsing.

In the absence of stress, an oxide layer forms rapidly and helps maintain the shape of the metal. It is similar to a scaled-down waterbed mattress—a thin, solid barrier contains the liquid. But a waterbed would leak if punctured, whereas the liquid Ga's shell can reseal when broken. The ability of the metal to flow by breaking the oxide combined with the ability of the oxide to re-form allows patterning of the liquid metal.

Perhaps the simplest way to pattern the metal is to inject it into tubing. If the tubing has a diameter smaller than about a millimeter, then it is considered a microchannel, which is useful for manipulating fluids for various applications. Among

FIGURE 1. LIQUID METALS based on gallium can be patterned into nonspherical shapes, such as wires, that remain stable due to a very thin oxide layer on their surface. Here, droplets of liquid metal have been 3D printed into self-supporting structures. The droplets are about 200 μm in diameter, about twice the diameter of a human hair. The structures are extremely soft, which makes them interesting candidates for soft and stretchable conductors. (Image courtesy of Collin Ladd, Dishit Parekh, and Jie Sun.)

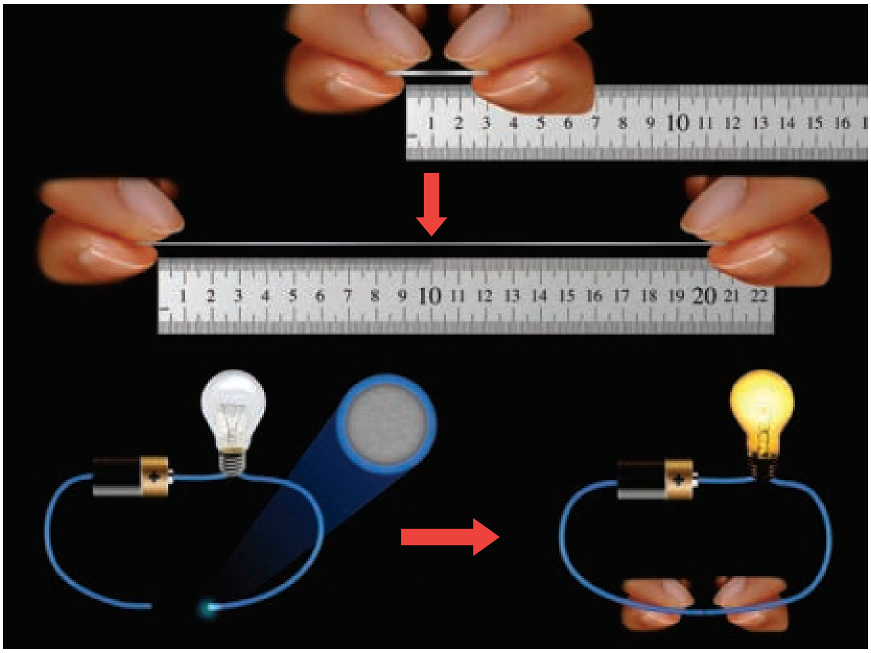


FIGURE 2. WIRES made from liquid metal can have the best of both worlds: the conductivity of a metal and the mechanical properties of rubber. A hollow elastomeric fiber filled with liquid metal (top) can be stretched to 10 times its original length. Its stretchiness is limited only by the properties of the polymer. Liquid metal can also form circuits (bottom) that electrically self-heal after being cut. The metal remains flush with the cut interface because it forms an oxide layer when exposed to air, and the interfaces merge when put in contact. Encasing the metal in an insulating shell of self-healing polymer (blue) allows the circuit to heal mechanically. (Image courtesy of Jie Sun.)

them are so-called lab-on-a-chip devices that can, for example, miniaturize assays of biological liquids. The ability to inject liquid metal into such channels is a simple way to create electrodes, pumps, valves, and other microfluidic components.[4]

Liquid metal can also be used in 3D printing, which is a popular technique for creating structures in an additive manner. Most commercial 3D printers utilize polymers, although the resulting polymeric structures' utility could potentially be increased through multimaterial printing. The ability to print liquid metals at room temperature is enticing because the metal can be incorporated into structures with plastics, elastomers, and other temperature-sensitive materials.

The surface oxide that forms on liquid metals causes the materials to adhere to most surfaces, a property that is necessary for maintaining a printed shape. In the absence of the oxide, the metal beads up to form spherical shapes that minimize surface energy. However, there are a few surfaces to which liquid Ga can adhere without its oxide layer. For example, it can reactively wet solid metal substrates by forming metal–metal bonds.

Soft and stretchable metal

Conductors made from liquid metal adopt the mechanical properties of the encasing material. In other words, placing liquid metal inside a rubber tube produces a wire that can maintain metallic conductivity while being stretched like a piece of rubber. That property is useful for creating soft, stretchable electronics.[5] It also eliminates a long-standing trade-off encountered in conductive composites: Adding solid conductors such as metallic or carbon particles to rubber increases its conductivity but changes its mechanical properties. Liquid metals, on the other hand, do not significantly alter the rubber's mechanical properties. That ability has been exploited to create wires that can stretch to nearly 10 times their original lengths while maintaining their metallic conductivity, as shown in figure 2.

Likewise, liquid metal has been utilized to form stretchable electric interconnects between small, rigid chips embedded in elastomer. The overall soft devices harness the sophistication and capabilities of microelectronics and maintain functionality during stretching. Liquid metal thus promises to advance technology such as wearable electronics, skin-mountable devices, and soft sensors that mimic skin's mechanical properties.

Liquid Ga conductors can be designed to heal themselves when damaged.[6] As illustrated in figure 2, when a liquid-metal wire is cut, it will rapidly form an oxide skin that keeps the material from leaking out of a circuit. When the broken wire ends are brought back together, the exposed interfaces merge—the thin oxide on each side breaks and the liquid reconnects—to re-form the electrical connection. If the metal wires are encased in a special self-healing polymer shell, the entire circuit can heal when brought into contact.

Soft electrodes for probing surfaces can also benefit from liquid metal.[7] Rather than depositing metal electrodes using expensive equipment that often requires high temperature and vacuum, the liquid metal is simply placed against a surface where it makes gentle contact. The electrode can then measure the electrical properties of molecules on the surface. That ability has helped advance the field of molecular electronics in which molecules are investigated as the smallest building blocks for electronic devices such as transistors.

Traditional wires, such as those made from copper, can move and bend when touched but do not change their cross-sectional geometries. Liquid-metal conductors, on the other hand, can change their geometries in response to deformation. Such changes can alter a device's capacitance or resistance, depending on the design, and can be used to detect touch, strain, and other modes of deformation. Antennas made from liquid metal can shift their resonant frequency in response to strain.

Recently, students in my research group harnessed touch-responsive circuitry to create soft materials that performed simple logic operations without the use of conventional transistors.[8] We were motivated by the octopus: The neurons distributed throughout the animals' arms eliminate the need for complex neuronal wiring to send signals back and forth between sensors (their arms) and a centralized processor such as the brain.

To demonstrate the concept of "materials logic," we created circuits composed of liquid-metal wires in which electricity can travel along multiple paths. Pressing a given path decreases the cross-sectional area of the wire and thus increases the local resistance. That change can divert current to other paths or alter the potential drops through parts of the circuit. With proper design, such a soft circuit can generate a response that depends uniquely on the location and number of touch points. The concept may be useful for designing smart materials that respond to tactile inputs in complex and appropriate ways. (For more about tactile circuits, see the Quick Study by Adam Fortais, PHYSICS TODAY, November 2020, page 62.)

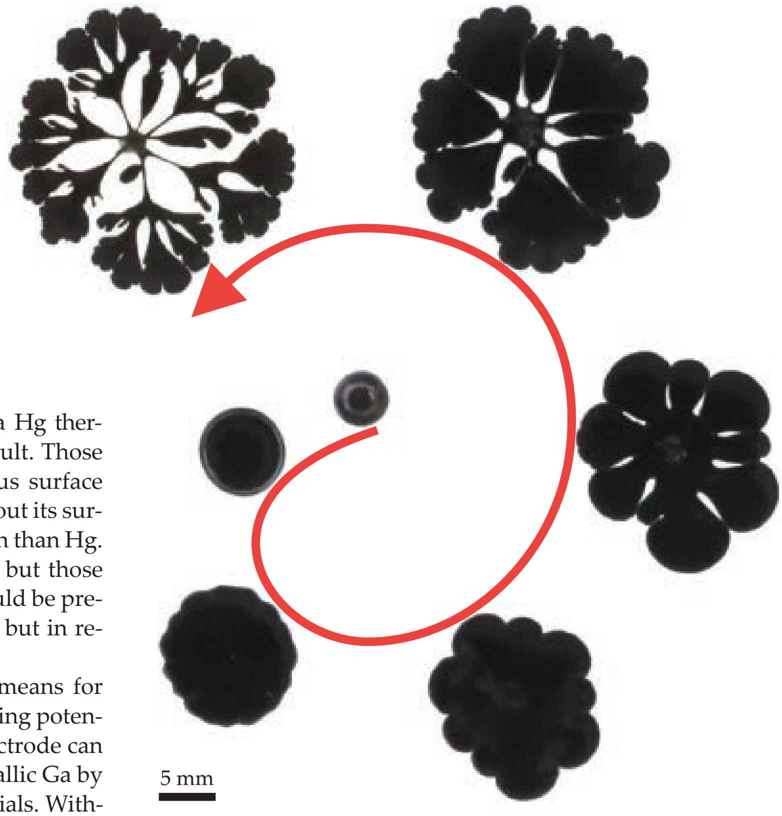


FIGURE 3. GALLIUM DROPLETS have enormous surface tension in the absence of a surface oxide layer and therefore form spheres (center). However, putting a droplet in an electrolyte and applying a positive potential drives surface oxidation. Here, a droplet is connected to a small wire from below (not shown) and submerged in 1 molar sodium hydroxide electrolyte; it is photographed from the top down and appears black because it is backlit. The oxidation process causes the metal to spread into fractals, which suggests that the effective tension is near zero under the conditions shown. (Image courtesy of Collin Eaker and Jie Sun.)

Surface tension modulation

Anyone who has had the misfortune of breaking a Hg thermometer knows about the spherical droplets that result. Those droplets form because liquid metals have enormous surface tensions in the absence of native oxides. In fact, without its surface oxide layer, Ga has an even larger surface tension than Hg. A native oxide can be removed by an acid or base, but those liquids are corrosive. In principle, the oxide layer could be prevented by working in an oxygen-free environment, but in reality oxygen is difficult to avoid.

Electrochemical reduction provides a practical means for removing Ga's oxide layer. Applying a modest reducing potential of, say, −1 V to the metal relative to a counter electrode can convert the Ga^{+3} on the oxidized surface back to metallic Ga by providing electrons at energetically favorable potentials. Without the oxide, the metal readily beads up (figure 3, center). The oxide spontaneously re-forms once the potential is turned off, although the metal can be kept oxide-free if the experiments are performed in acidic or basic electrolytes.

My research group discovered an unexpected phenomenon that occurs on applying a positive potential of, say, +1 V to a droplet of liquid Ga in a basic solution of 1 molar sodium hydroxide: The droplet spreads out into fractals,[9] as shown in figure 3. Snowflakes can form fractals of ice crystals, but when melted, they bead up into a droplet of water due to surface tension. How, then, is it possible to form a fractal with a liquid that has nearly 10 times the tension of water?

Applying a positive potential drives the formation of the surface oxide. One might expect the oxide layer to form a crust on the surface of the metal and restrict its flow. We found, however, that during electrochemical oxidation, the droplets behave as if their surface tension is very low.[10] The NaOH slowly but continuously dissolves the oxide being deposited on the droplet's surface, so the metal can flow despite the oxide formation. With the tension significantly lowered through electrochemical oxidation, gravity flattens the normally spherical drop and small gradients in surface tension cause so-called Marangoni flows that contribute to the unusual fractal patterns.

In a well-known phenomenon called electrocapillarity, charge that gathers across a metal–electrolyte interface can modestly lower a metal droplet's surface tension. However, the observed behavior cannot be explained by electrocapillarity alone for several reasons—most notably that the magnitude of the change in tension, from more than 500 mN/m to near zero, is too large to be caused by an approximately 1 V potential; such a small potential would only reduce the tension to about 400 mN/m. Our experiments establish that electrochemical oxidation lowers the metal's surface tension.[9] Understanding the complex behavior is an ongoing area of research.

Liquid-metal reactors

An intriguing recent discovery suggests that the thin oxide layer that forms on liquid metal can be removed by exfoliation.[11] The technique is an attractive way to deposit thin oxide films onto surfaces at room temperature, and it can be utilized for transferring thin insulators, conductors (including indium tin oxide), and semiconductors onto arbitrary surfaces, as illustrated in figure 4a.

Once deposited, the oxide layers can be chemically transformed into other species—for example, gallium oxide can become gallium sulfide. Another way to alter the composition of the surface oxide is by doping the liquid Ga droplet with small amounts of other metals prior to exfoliation. If the formation of the dopant metal's oxide is more energetically favorable, it can form preferentially over Ga_2O_3. For example, adding trace amounts of Al to Ga can produce Al_2O_3 on the surface of the metal (figure 4b). Liquid metals can also be used as substrates to grow two-dimensional materials, such as

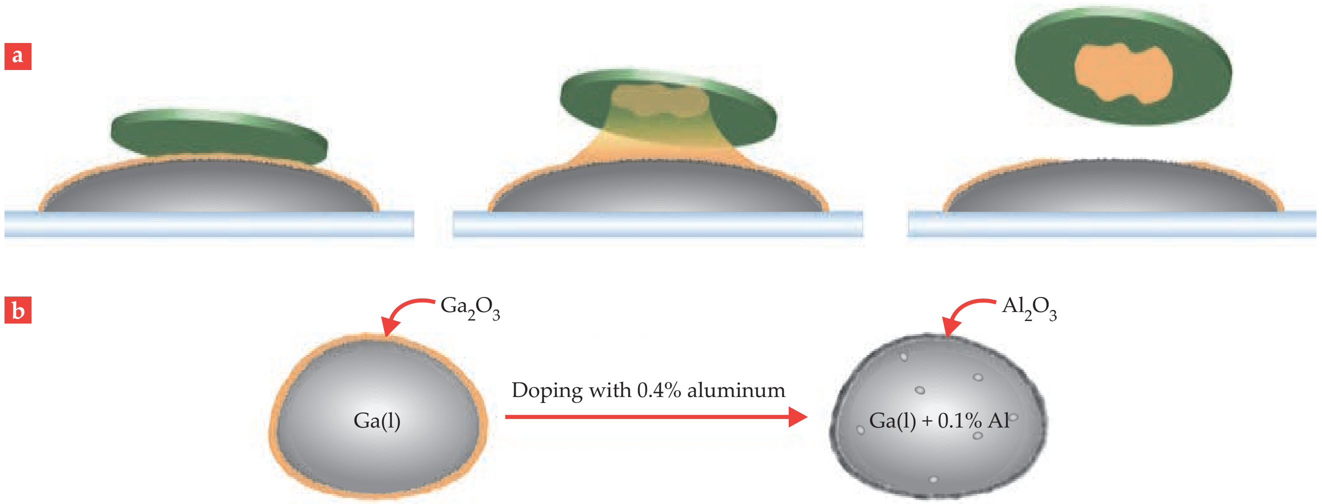


FIGURE 4. OXIDE SPECIES form when liquid metal reacts with air. **(a)** Those species can be transferred to other surfaces by exfoliation. The process offers a simple route for creating ultrathin oxide films at room temperature. **(b)** Adding small amounts of a reactive dopant to liquid gallium can transform the surface from the native oxide, Ga_2O_3, into a different chemical species. For example, adding 0.4% aluminum causes the surface to become Al_2O_3. (Images courtesy of Jie Sun.)

graphene, and may offer a facile way to transfer them to other surfaces.

The ability to alter the surface chemistry of liquid metal may be useful for catalysis or electrochemistry. For example, recent experiments show that trace amounts of cerium added to Ga naturally segregate to the surface of the liquid and lower the energy required to reduce carbon dioxide into solid carbonaceous species.[12] In addition, the carbon species do not adhere to the liquid metal, which prevents them from "coking," or building up on the droplets and blocking reaction sites. Improving the efficiency of CO_2 reduction is of great practical interest considering its impact as a greenhouse gas. Liquid-metal nanoparticles have also been shown recently to initiate polymerization—that is, to cause monomeric molecules to react and form polymers.

Droplets and composites

Liquid metals can be mixed into polymer matrices to form composites with new or enhanced properties.[13] It is well-known that adding solid particles to a polymer can significantly change the polymer's mechanical properties; for example, tire makers toughen rubber tires by adding carbon particles. Yet the same solid particles can make elastomers—rubbery materials—less stretchy. In contrast, liquid-metal particles have a minimal impact on rubber's extensibility because the particles themselves are liquid (see figure 5).

Depending on the particle loading and size, liquid-metal particles can have non-negligible effects on an elastomer's mechanics, and understanding those effects is an ongoing area of research. Interestingly, adding liquid metal can significantly increase an elastomer's tear strength by dulling cracks, which is where stress concentrates and leads to failure; consider how much easier it is to tear fabric if it is first nicked with scissors. (For more on how elastomers tear, see PHYSICS TODAY, February 2021, page 14.)

Adding liquid-metal particles to elastomers can increase the resulting composite's conductivity. Stretching rubbery composites loaded with solid particles, such as silver flakes, causes the particles to move apart and thereby increases the material's thermal and electrical resistance. In contrast, elongation of rubber loaded with liquid-metal particles causes the particles to elongate. The transition from spheres to ellipsoids generates anisotropic

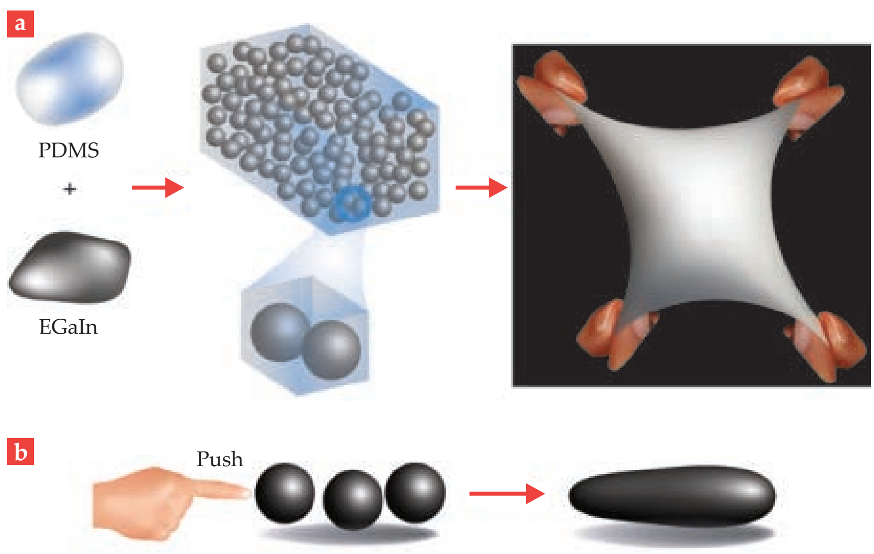


FIGURE 5. STABLE PARTICLES of liquid metals can be formed by simply stirring the metal in the presence of another liquid. **(a)** Mixing liquid metal (eutectic gallium indium; EGaIn) into silicone (polydimethylsiloxane; PDMS) creates a soft composite upon curing the silicone. Adding solid particles to a rubber normally makes it stiffer, but with liquid particles, the composite remains soft. **(b)** Liquid particles can easily be mechanically sintered by pushing them together (shown here in an oversimplified schematic). Likewise, straining or compressing composites that contain liquid metals can lead to unusual "piezo" properties—those that change when the material is squeezed—due to the particles' geometric changes within the elastomer. (Images courtesy of Jie Sun.)

thermal conductivity—that is, the ability to conduct heat in the direction of strain is enhanced.[14]

Recent studies show that adding magnetic particles such as iron to liquid-metal composites can result in piezoconductivity, meaning the material becomes more conductive when strained; most composites instead possess piezoresistivity. In addition, composites loaded with liquid-metal particles can self-heal electrically when cut because the metal particles smear across the damaged region.

Liquid-metal particles formed in liquid media can have diameters with length scales from tens of nanometers to hundreds of microns. Sonication—agitation by ultrasonic vibrations—can break the metal into smaller droplets that can be stabilized by an oxide layer or by polymers grafted to the surface. The many applications for such particles in nanotechnology include self-propelled particles, new types of phase behavior, dual liquid–solid particles, drug delivery, catalysis, and optics.[15]

A better reputation

Ga is one of the most interesting elements on the periodic table because of its low melting point, negligible vapor pressure, high surface tension, low viscosity, and metallic properties. Its reactivity has historically been considered a hindrance, since the liquid metal rapidly forms a thin surface oxide that precludes certain applications.

In the right context, however, both the oxide and the surface reactivity can be beneficial. The oxide skin that forms on liquid Ga allows for the assembly of soft and stretchable conductors that can maintain metallic conductivity at unprecedented levels of strain. It also enables 3D printing and other patterning methods that would be impossible with solid metals, and it stabilizes droplets inside composite materials to generate unique thermal, electrical, and mechanical properties. Furthermore, liquid Ga permits electrochemical reactions that dramatically modulate the material's interfacial tension. The metal can be used as a "reactor" that sheds thin oxide sheets and presents reactive species on its surface.

Physicists have many opportunities to contribute to the fundamental understanding of liquid Ga's interesting properties and the applications they enable. With such a bright future, the term "liquid metal" should shed its once-negative connotation.

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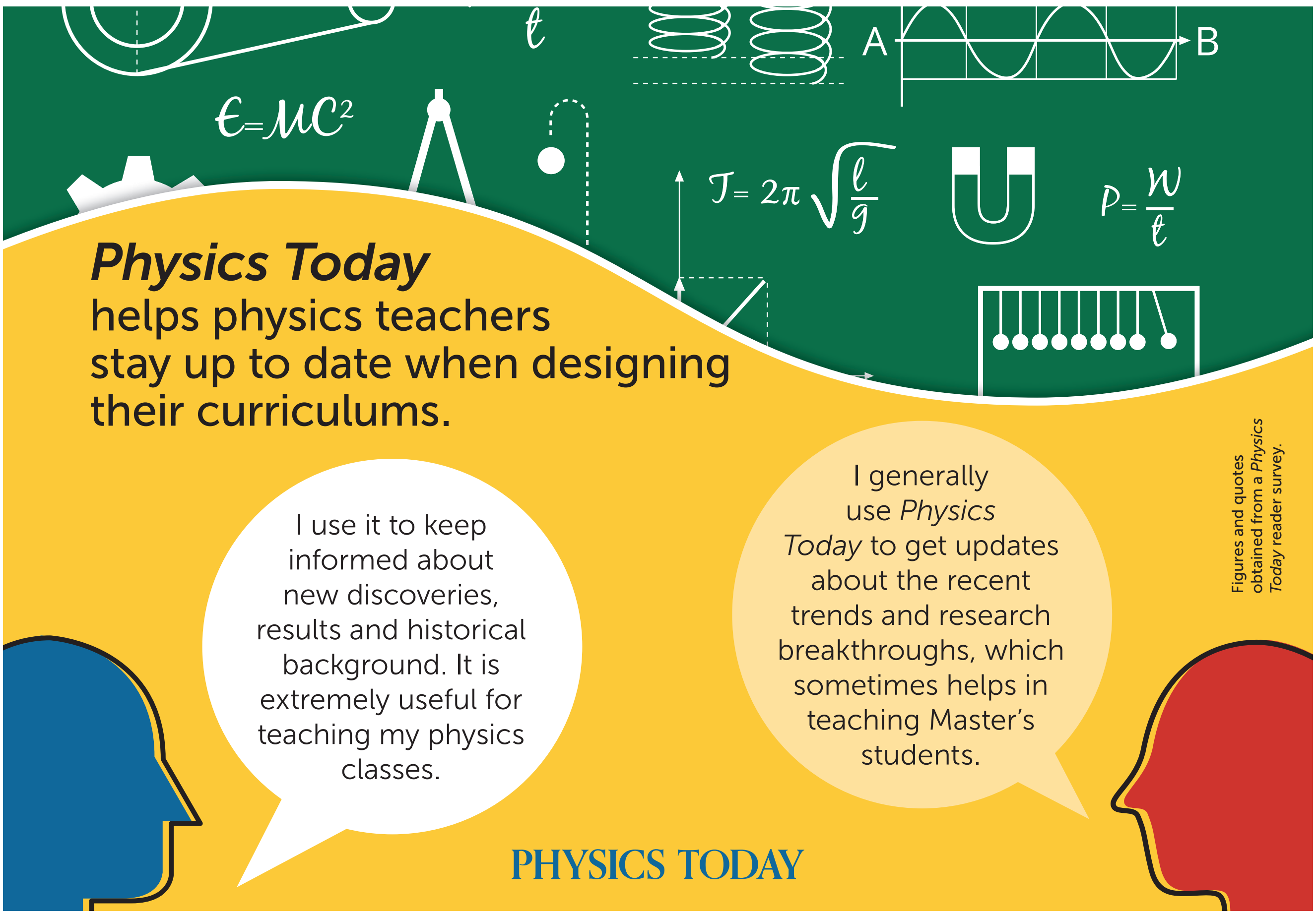
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Medieval weather prediction

Anne Lawrence-Mathers

Meteorological practices that developed in the first millennium did not die in the Middle Ages but were radically improved with an international science of weather forecasting.

Observations of clouds, sunbeams, and birds—like those seen in this photo taken in Salisbury, UK—were important elements of classical weather forecasting. (Image courtesy of Peter Lawrence.)

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In August 1861 the London-based newspaper *The Times* published the world's first "daily weather forecast." The term itself was created by the enterprising meteorologist Robert FitzRoy, who wanted to distance his work from astrological "prognostications." That story has led to a widespread assumption that weather forecasting is an entirely modern phenomenon and that in earlier periods only quackery or folklore-based weather signs were available.

However, more recent research has demonstrated that astronomers and astrologers in the medieval Islamic world drew widely on Greek, Indian, Persian, and Roman knowledge to create a new science termed astrometeorology. Central to the new science was the universal belief that the planets and their movements around Earth affected atmospheric conditions and weather. It was enthusiastically received in Christian Latin Europe and was further developed by Tycho Brahe, Johannes Kepler, and other astronomers. The drive to produce reliable weather forecasts led scientists to believe that astrometeorological forecasting could be more accurate if they used precise observations and records of weather to refine predictions for specific localities. Such records were kept across Europe beginning in the 13th century and were correlated with astronomical data, which paved the way for the data-driven forecasts produced by FitzRoy.[1]

Islamicate astrometeorologists were the first to replace the ancient practice of observing only short-term signs, such as clouds and the flight of birds, to predict weather. They based their action on the hypothesis that weather is caused by the movements of planets and mediated by regional and seasonal climate conditions. Improved calculations of planetary orbits and updated geographical and meteorological information made the new science possible and compelling.

The prospect of acquiring reliable weather forecasts, closely linked to predictions of coming trends in human health and agricultural production, made the new meteorology attractive in Christian Europe too. Considerable pride shines through medieval Christian accounts of the weather questions that they could now start to answer. Central among them was one that classical meteorologists had failed to figure out: How can weather vary so much from one year to the next when the seasons are caused by regular, repeating patterns produced by Earth's spherical shape and its interactions with the Sun?

Geoffrey of Anjou, father of King Henry II of England, posed that question to the 12th-century philosopher William of Conches.[2] Drawing on translations of works attributed to the 8th-century astronomer Māshā'allāh, the writings of 11th-century scholar Constantine the African, and contemporary discussions by Adelard of Bath, William answered by invoking Ptolemaic models of planetary movements and Islamicate theories of their impacts on local seasons and weather.

The body of scientific material being translated from Arabic continued to grow in the 12th and 13th centuries. During that time, rising populations spurred increases in urbanization, long-distance trade, and wealth. With improved forecasting, rulers were better able to address practical societal concerns, such as military strategy and food supply, both of which were heavily affected by weather. Bankers and traders were willing to pay for such valuable information. As a result, astrometeorology continued to develop during the 14th and 15th centuries and reached ever-growing audiences in the 16th and 17th centuries. It only fell from favor in the 18th century when forecasters began to view astrology with scorn.

How astrometeorology worked

Hellenistic scientists, particularly Ptolemy of Alexandria, made major advances in the field. Ptolemy produced geometrical and mathematical models of planetary movements based on observations recorded over centuries and new observations that he carried out himself. His fundamental works—generally known in the medieval period as the *Almagest* and *Tetrabiblos*—provided the means to calculate planetary positions and guidelines to interpret the data.

In astrometeorology, each planet had specific qualities that influenced related phenomena on Earth. Saturn—characterized as distant, slow-moving, and cold in color—was associated with the cold, dry element of earth. Mercury, being small, fast-moving, and usually close to Venus and the Moon, was associated with the warm, moist element of air. Exactly how planetary qualities influenced weather was disputed by philosopher–scientists, but the most widely accepted argument was that the planets emitted imperceptible rays that carried the qualities of the emitting planet to Earth.

The Sun and the Moon were the most significant astronomical bodies. The Sun's effect on weather and climate through its light and heat was long established, and the Moon's influence over ocean tides, bodily fluids, and plant growth was also widely recognized, at least by the educated. Astrometeorologists thought that the Sun and Moon were so powerful that they could even modulate the influences of weaker planets.[3]

The first step in making a forecast was for the astrometeorologist to calculate the positions of all the planets on a chosen date in relation to the zodiac belt and the ecliptic—the apparent path of the Sun around the heavens. Both were envisaged as circular, and the zodiac was divided into 12 equal sectors or signs, as shown in figure 1. Ptolemy systematized the portions of the heavens and explained that each had its own characteristics, which acted on any planet passing through the sectors.

Astrometeorologists noted that the angular relationships between planets were important for determining their mutual effects. Planets facing one another across the zodiac were negatively related; an angle of 45° was also problematic and likely to produce an atmospheric disturbance. However, planets at 60° or 120° would interact more positively and produce more moderate weather. When planets were close together, the intensity of their effects would increase depending on the natures and placements of the planets involved. Forecasters needed to also account for the climate zone of the chosen place and the current season. For example, an increase in atmospheric heat would have one set of effects in summer near the equator and another in winter near the Tropic of Cancer. An apparently simple set of principles required forecasters to make judgments as to the outcomes of all the factors at play.

The calculations for a forecast depended on the achievements of Islamicate astronomers, who had built accurate and updated models and tables of celestial structures and motions. That work in turn drew on advances in mathematics and the improvement in scientific tools and instruments. Astronomers tested and revised Ptolemy's instructions for making weather forecasts, and many of them produced their own treatises on the subject. Those specialist works not only provided guidance for the basic techniques but also drew on the updated planetary data and new cosmological models.[4] The result was a sophisticated, enticing, and complex body of material.

Rise of the expert forecaster

The scientific advances being made in the Islamicate world were first recognized in Latin Europe in the 11th century and stimulated curiosity and emulation rather than rejection. For example, figure 2 highlights an English astrolabe predicated on an Islamicate one. Territorial conquests by northern European forces in the Iberian peninsula of al-Andalus made librarians, scholars, and translators available to the new Christian rulers. Thus was born one of the greatest movements for scholarly translation and cultural assimilation in European history, and astrometeorology texts had an honorable place in that effort.

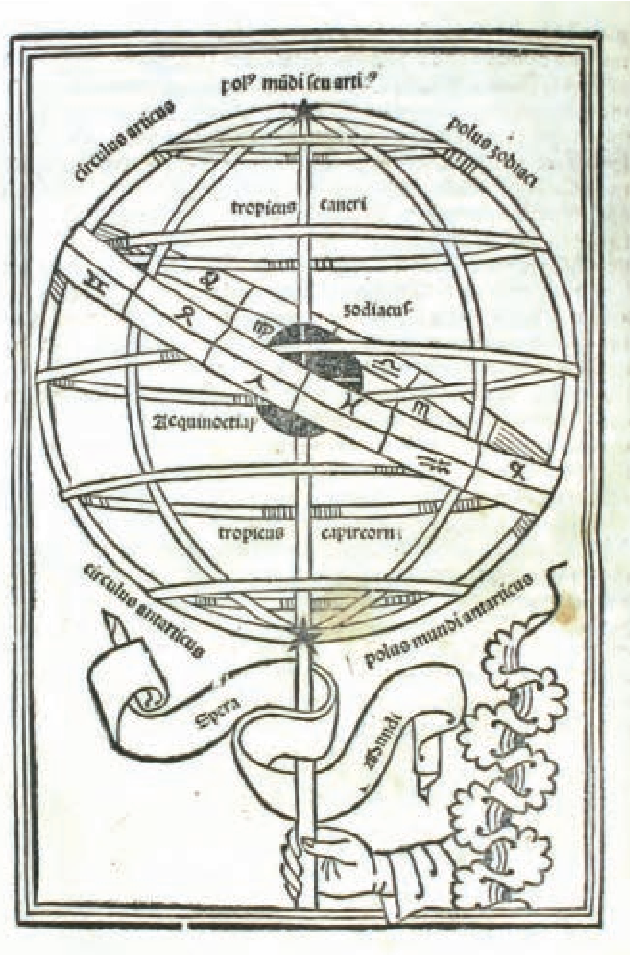

FIGURE 1. THE ZODIAC. This illustration from Johannes de Sacrobosco's *De sphaera*, printed in 1488, shows the circle of the zodiac and its various signs surrounding several latitudinal lines that demarcate the equator, tropics, and polar regions. For medieval scientist–philosophers, the climate zones and celestial divisions formed a basis for making astrometeorological predictions. (Courtesy of the History of Science Collections, University of Oklahoma Libraries.)

Scholars enthusiastically translated updated versions of Ptolemy's tables of planetary movements, for example. The translations were well received despite requiring users to grapple with a foreign calendar and dating system and with Hindu–Arabic numerals and the unfamiliar mathematical concepts underlying them.

Several Islamicate philosopher–scientists became established as authorities in Christian Europe, even if under Latinized versions of their names. One was Abu Ma'Shār—known in Latin as Albumasar—who spent most of his career in Baghdad, where he wrote a series of important works in the ninth century. Another was Māshā' allāh, or Messehalla; he also worked in Baghdad in the golden age of the science of the stars and wrote an influential survey of astronomy and astrology, which devoted 6 of its 12 chapters to astrometeorology.

Perhaps most celebrated for his meteorological expertise, at least in the Latin world, was al-Kindi. Treatises on weather forecasting, extracted from his longer works and circulated in Latin, remained popular in the Renaissance. They offered a

FIGURE 2. ASTROLABES, like the 14th-century English one pictured here and housed at the British Museum, were based on Islamicate models. It provides a map of stars and planets that's calibrated for a chosen latitude with pointers to named stars. (Photo by Marie-Lan Nguyen, Wikimedia Commons, CC BY 2.5.)

clear explanation of the specific causes of heat, cold, drought, and rain and how their interactions in the atmosphere produce weather.

Al-Kindi's conceptual framework and the central idea in his treatises, that the driving force for weather is heat generated by planetary movements, was Aristotelian. The concept was linked to the idea of four elements that compose the sublunar zone—earth, air, fire, and water—and their intrinsic connections to the primary qualities of hot, cold, dry, and moist.[5] Astrologers believed that the planets and the fixed stars, including those making up the constellations to which the houses of the zodiac were linked, had special affinities with individual elements and qualities. Those qualities determined the nature of the effects each planet would have on the terrestrial world as it moved through the heavens.[6]

The first step in al-Kindi's forecasting method, as typical in astrometeorology, was to calculate the relevant planetary positions and directions. Next, forecasters would start their interpretation of the weather with the position and strength of the Sun. In al-Kindi's model, the Moon had particular power over the elements of earth and water, both of which would be modulated on any given day by its position relative to the Sun.[6] Forecasters needed to assess that interaction to predict winds because they believed the joint influence of the Sun and Moon determined whether the air in a particular region would be hot or cold. They then considered the other five known planets and calculated the factors affecting each one individually before incorporating the planetary groupings and interactions.

The techniques in al-Kindi's method required that forecasters confidently judge which factors would have the greatest effects and for how long, and they accepted that experience was crucial in making a successful prediction. Experts put their trusted methods on record for the benefit of others. Especially influential was al-Kindi's application of the concept known as "opening of the doors." The treatises do not explain the phrase, but it hints that rain was caused by an almost physical change in the atmosphere, driven by specific combinations of planets and their movements in relation to one another.

The timing and extent of rainfall was sufficiently important in the Islamicate world that treatises on weather forecasting were frequently referred to as "books of rain." Another valuable addition to the basic Ptolemaic model was the concept of "mansions of the Moon." Credited to Indian astrologers, they were based on 28 fixed stars or star groupings, each of which occupied a sector of the Moon's path through the zodiac. Each mansion was characterized in terms of its degree of humidity, which would affect the Moon.

The effect of the mansion currently occupied by the Moon was especially influential for the weather four times per month. The general monthly pattern of weather could be forecast by drawing up charts for each of the four occasions. If the Moon was in or moving into a wet mansion, for example, then the outcome would normally be rain. However, a significant interaction of the Moon and Saturn would modify the outcome considerably. Similarly, the disruptive influence of Mars would make storms, thunder, and hail more likely. The factors would diminish in power as the Moon traveled in its orbit and would be supplanted when the next key point was reached.

The spread of astrometeorology

Interest in Latin treatises on astrometeorology continued to grow after the 13th century and was unaffected by religious concerns. Theologians viewed weather forecasting differently from the making of personal astrological predictions for individual clients. The latter was fraudulent at best and heretical and dangerous at worst because of its clash with important teachings on free will. But an important endorsement for weather forecasting came from the great 13th-century theologian Thomas Aquinas. In his *Summa Theologiae*, he wrote of the power of the stars over earthly things and cited St Augustine's statement that the heavenly bodies can cause physical effects on Earth.[7] Because Aquinas viewed weather forecasting as an application of knowledge drawn from observation and experience, many theologians didn't condemn it as demonic or divinatory.

For students, especially in Paris, the authoritative, contemporary survey of all forms of astrology was *Speculum astronomiae* (*Mirror of Astronomy*). The work by 13th-century theologian Albert the Great praised the value of knowing how variations in heavenly bodies can cause changes in earthly things, including the weather. Rather than rejecting astronomical weather forecasting as foreign and suspect, *Speculum astronomiae* endorsed the practice.[8] Technological developments helped disseminate the new science. Most notably, the printing press, which arrived in northern Europe in the 15th century, made it possible for long-term weather forecasts, calendars, and predictions of health and political trends to be published as annual almanacs.

Almanacs grew out of the predictions and forecasts privately commissioned from renowned scientists and holders of university chairs in astronomy. Demand appeared almost as soon as the new meteorology reached Latin Europe. An early example was that of the astrologer Guido Bonatti, who advised Guido da Montefeltro, ruler of Urbino, and other leaders in the 13th century. Bonatti recorded his trusted techniques for weather forecasting in a long section of a book that was widely copied for the next two centuries and later printed when the technology was available.

Rulers made impressive investments in universities across Europe in the 13th and 14th centuries in no small part because of astronomy, astrology, and meteorology. The demand for expert astronomers and astrologers is illustrated by the career of Georg Peurbach, who studied in Italy, France, and Germany before becoming a professor of astronomy at the University of Vienna. He worked for Ladislaus V of Hungary and Bohemia and the Holy Roman Emperor Frederick III. Forecasts and predictions for powerful rulers were private, but university department chairs were often required to provide public guidance. Those predictions were given to university members and patrons in the form of annual prognostications, which included forecasts of seasonal weather. Examples survive from the early 15th century, and they were likely a matter of civic pride because the custom quickly spread.

The prognostications of Peter of Monte Alciano, who lived in Pavia, Italy, seem to have been especially sought after. His forecasts for 1419, 1421, 1430, and 1448 survive and reached not only the Holy Roman Empire but also France and England. Perhaps the most influential forecaster was Joannes Vesalius—the great-grandfather of the more famous Andreas Vesalius, the physician and author of the famous anatomy book *De humani corporis fabrica* (*The Structure of the Human Body*). Joannes Vesalius took a position at the University of Louvain in 1429 before becoming an adviser to Duke Philip the Good of Burgundy. The city council of Louvain commissioned a prognostication for 1431, which Vesalius duly read to an invited audience at the end of 1430. When Louvain's first printer, Jan van Westfalen, arrived, he promptly issued annual prognostications modeled on those of Vesalius.

Strikingly, the University of Bologna employed two professors of astronomy and astrology in the 15th century. One was required to compile an annual almanac that showed the positions of all seven planets on a daily basis for the coming year and tabulate the angles of the planets to the Moon and to one another. The other professor was to use the data to produce a prognostication.[9] Printed almanacs today continue to follow the same formula.

Much of the time-consuming work of calculating the planetary positions was alleviated by the contribution of the astronomer Regiomontanus, pictured in figure 3. He produced a calendar and *Ephemerides*, or book of astronomical tables, both of which were made available in print beginning in 1476. The large volumes provided not only full planetary data but also guidelines for their interpretation and a table of corrections to apply when adjusting the coordinates for a particular city or region in Europe. The powers of the planets in each sign and each aspect were tabulated in numerical form, and the lunar mansions were included in a table.

Regiomontanus provided rules for producing prognostications, with the first section addressing weather forecasting. The rules applied standard procedures of the time and appear to be how Regiomontanus conducted his own practice. He identified specific planetary occurrences as especially influential. For example, an opposition of the Moon and Jupiter, when occupying the fire sign of Aries and the water sign of Scorpio, will generate clouds. If the Moon is moving toward Mercury, the forecast will include what Regiomontanus called an opening of the doors of the winds. But for traditionalists, he appended a section after his rules that offered the ever-popular weather forecasting according to al-Kindi.

FIGURE 3. REGIOMONTANUS, the Latin name of Johannes Müller, created *Ephemerides* to document the trajectory of astronomical objects. Along with other guidelines, the work advanced early-modern astrometeorology, the precursor to modern weather prediction. (Portrait from the Austrian National Library, public domain.)

In the time of scientific revolution

High demand for Regiomontanus's works meant that multiple printed versions rapidly appeared, many of them pirated. He was acclaimed as the greatest astrologer of his time: Cardinal Bessarion and King Matthias Corvinus of Hungary employed him, and his work was used by Christopher Columbus to calculate the dates of coming storms.[10,11] Besides Regiomontanus, several well-known early-modern scientists espoused astrometeorology, including Tycho Brahe and Johannes Kepler. The growing acceptance of a heliocentric universe failed to shake the belief that celestial bodies affected the atmosphere, Earth's weather, and the health of the human body. Indeed, the ongoing refinements to the rules for making weather forecasts by practitioners reinforced astrometeorology's place in scientific and popular culture.

The supporting trend for astrometeorology appeared in several locations beginning in the mid 14th century. From about 1340, astronomers and scientists working at Merton College in Oxford, England, including the prominent John of Ashenden, showed a particular interest in the practice. Ashenden composed an enormous summa on astrology, and astrometeorology dominated its long second section. He became famous for having predicted the Black Death of 1348–49, and his weather forecasts for 1368–74 emphasized the major planetary conjunctions of 1365 and 1369. The conjunctions suggested that a period of heavy rain and floods would be followed by three years of drought and, consequently, crop failures and food shortages.

Parallel with Ashenden's work were more local studies of weather, and predictions were recorded in treatises and presented to Merton College by William Reed, the bishop of Chichester from 1369 to 1385 and a fellow of the school. One treatise was entitled *Rules for the Forecasting of Weather* by Master William Merle. The rules were accompanied by detailed weather observations for 1337–44, made mostly in Lincolnshire but also in Oxford. The central aim seems to have been to correlate astrometeorological factors with actual weather notes to establish which factors proved most significant for making predictions.[12] The research was perhaps inspired by the pioneering work of the Franciscan friar Roger Bacon, who conducted his studies in Oxford in the late 13th century. Among a collection of his scientific treatises is a calendar with daily planetary positions and weather notes.

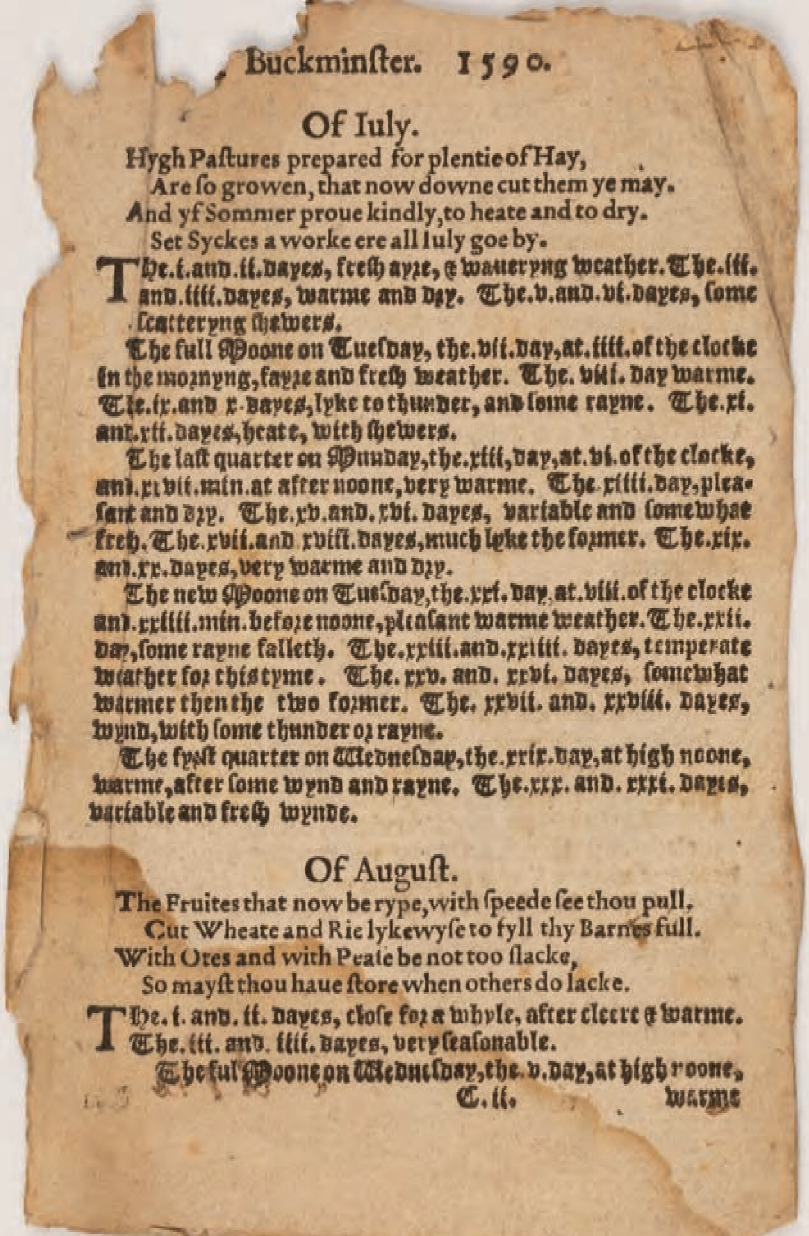

FIGURE 4. ALMANAC FORECAST. This page from Thomas Buckminster's almanac for 1590 records his weather predictions for southern England in July and August. (Image from the University of Reading, Special Collections.)

A similar, separate project to the Bacon one was undertaken by Eyno of Würzburg, whose treatise on astrometeorology was supported by the inclusion of weather notes from 1331 to 1355. Like the Oxford group, Eyno placed a special emphasis on predicting advance warning of damaging weather; he records with some pride, for example, that he successfully forecast heavy snow on three separate occasions.

A volume of uncertain origin belonging to the Dominicans of Basel records comparable work from 1399 to 1406. The volume includes rules for astrometeorological prediction accompanied by sets of weather records and observations. The notes identify which astrometeorological factors would match the recorded weather. For example, 7 April 1400 was reported as cloudy with short sunny intervals and a strong west wind. A note indicates that the Moon moved away from the beneficent planet Jupiter, out of an air sign, and toward Mercury, a planet that was thought to cause air disturbances.[13]

The argument that weather research was intended to improve and sharpen astrometeorology rather than to challenge it is supported by the expansion of science in the 15th and 16th centuries. The 16th century, for example, saw the production of treatises that amateur scientists could use to carry out their own forecasts and the publication of an ever-increasing number of annual almanacs and prognostications.

Books for nonexperts were published in local languages rather than the Latin found in theoretical works. Those in English are striking for the long-lived vocabulary they deployed. For instance, Thomas Buckminster's *An Almanacke and Prognostication for the Year 1598* indicates that the start of April would see "fair" and "fresh" weather. The Moon's first quarter on 3 April saw a change to cloudy, cold weather that would become "raw" on 6 April. At the full Moon on 11 April, the weather was predicted to become "clear" and "fair." A page from Buckminster's almanac of 1590 is shown in figure 4.

Tycho's work provides further evidence for the ongoing value placed on astrometeorology. He devoted a surprising amount of space to the subject in his 1572 treatise on a new star that appeared in Cassiopeia. Tycho gave his own observations and calculations on meteorology and supported the publication of daily weather forecasts. He acknowledged the inaccuracy of the predictions, but he argued that keeping weather records would strengthen astrometeorological practice.[14] Tycho's pupil, Kepler, followed his advice and made daily records of weather. His published *Ephemerides* and calendars included his weather observations and forecasts. Like other practitioners before him, Kepler identified what he believed to be the most important factors for weather prediction—in his case, planetary aspects.

Such distinguished support for medieval meteorology shows that it was hardly the result of superstition and ignorance. The updated and corrected observations of planetary movements that scientists like Tycho and Kepler produced made it possible to improve the planetary tables used by astrometeorologists. The accurate recording of the weather and its strengthening of forecasting techniques was perhaps the greatest legacy of astrometeorology to its modern successor.

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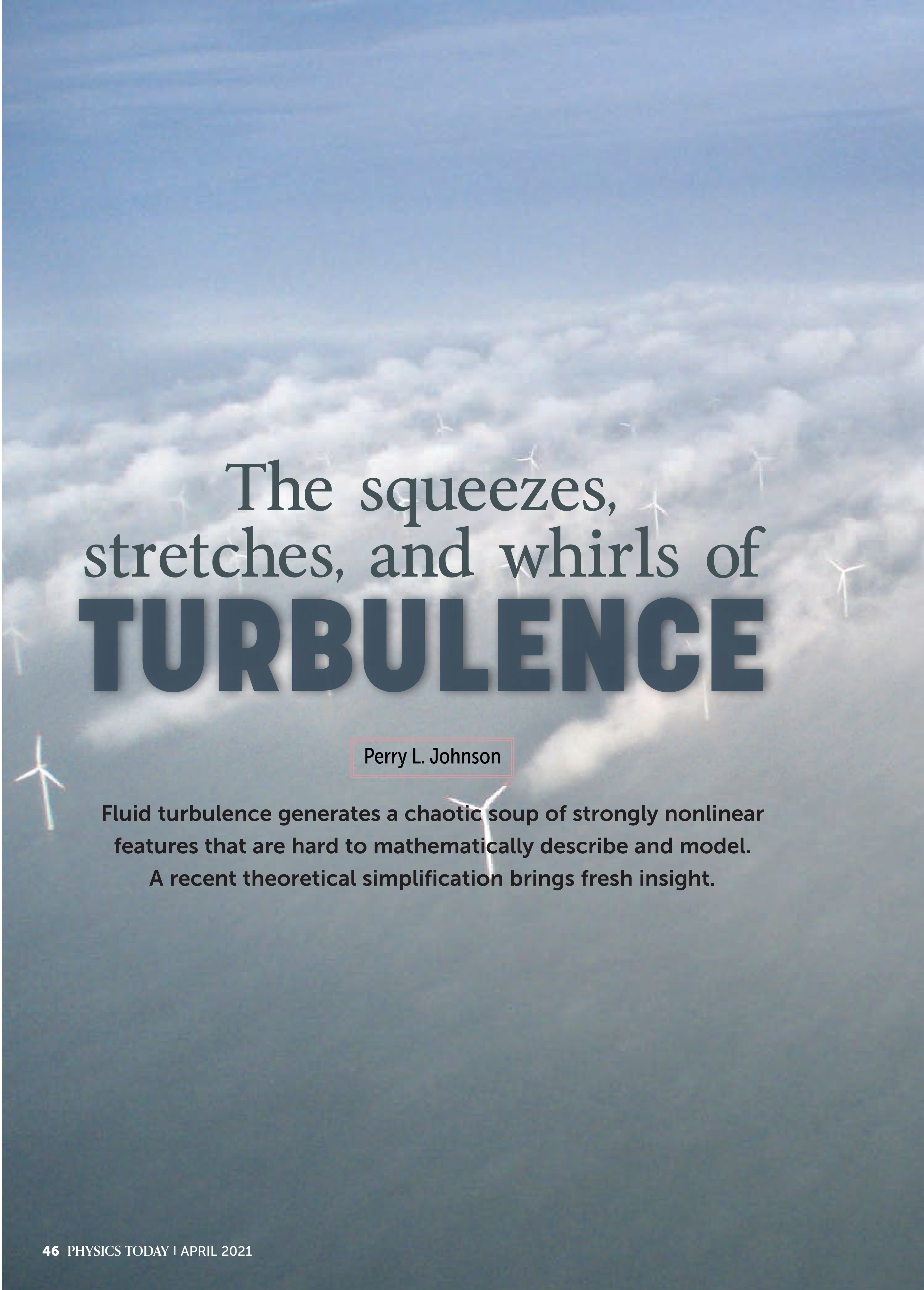

The squeezes, stretches, and whirls of TURBULENCE

Perry L. Johnson

Fluid turbulence generates a chaotic soup of strongly nonlinear features that are hard to mathematically describe and model. A recent theoretical simplification brings fresh insight.

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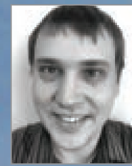

In his famous *Lectures on Physics*, Richard Feynman reflected on a "physical problem that is common to many fields, that is very old, and that has not been solved. It is not the problem of finding new fundamental particles, but something left over from a long time ago—over a hundred years. . . . It is the analysis of *circulating or turbulent fluids*."[1] Even today in the age of supercomputers, the need for understanding, modeling, and predicting aspects of turbulent flows has, if anything, increased. Reliably simulating turbulent flows still requires more theoretical advances, and Feynman's vision of "solving the problem of turbulence" remains elusive.

Turbulent flows are characterized by apparently random, chaotic motions. And they are everywhere: They govern the efficiency of gas turbine engines, the workhorses of modern power generation and aerospace propulsion, and of large-scale wind farms, a key technology for renewable energy (see the article by John Dabiri, PHYSICS TODAY, October 2014, page 66). In the past year, turbulent flows produced by coughs and sneezes, as shown in figure 1a, have come to the forefront because of the COVID-19 pandemic.[2] What's more, turbulence physics is vital for estimating and mitigating the impact of deep-sea oil spills, informing parameterizations for weather prediction and global climate models, and quantifying the turbulence-induced damage on red blood cells in artificial heart valves and blood pumps. Turbulence is at work even in our leisure; it alters the aerodynamic behavior of, for example, race cars, golf balls, baseballs, and soccer balls—as illustrated by the irregular motion of the controversial Jabulani soccer balls specially designed for the 2010 World Cup. (For more on soccer-ball dynamics, see the article by John Eric Goff, PHYSICS TODAY, July 2010, page 62.)

For many turbulent scenarios, analytical solutions to the equations of motion aren't possible, and the computational cost of simulations is unwieldy. For example, in large arrays of wind turbines, such as the ones shown here, a turbulent wake of lower-speed air forms behind each turbine and diminishes the power output of downwind ones caught in the wake.[3] The smallest turbulent motions in that flow are less than a millimeter, whereas

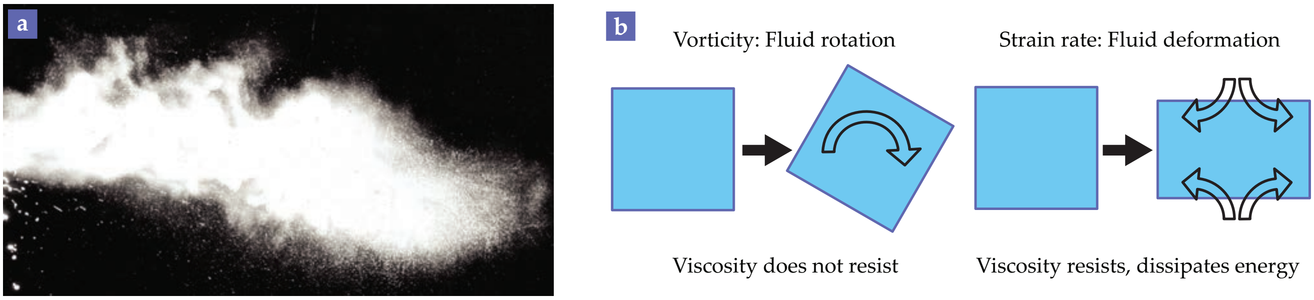

FIGURE 1. TURBULENT FLOWS, which occur in various systems, share two forms of motion. From the wind turbines seen in the opening image to **(a)** the sneeze droplets pictured here (reproduced from ref. 2), turbulence contains strong coherent regions where **(b)** fluid (blue square) is subjected to rotations, which are quantified by the vorticity, or to deformations, which are quantified by the strain rate. Viscosity does not resist rotations, but it does resist deformations. As a result, the strain rate results in energy dissipation.

the farm extends for kilometers. A brute-force simulation with millimeter resolution over a kilometer range is not currently possible, nor will it be in the foreseeable future. A similar combination of small and large scales holds true for many important turbulent flows, such as the aerodynamic flow over a car or airplane[4] and the complex flow through airplane engines.

Despite emerging in such disparate physical systems, turbulent flows tend to display remarkably similar characteristics—although different types of turbulent flows have enough unique qualities and behaviors to warrant discipline-specific specialized research. However, the emergence of universal attributes motivates cross-disciplinary effort to analyze and compute turbulence. One such attribute is the enhancement of energy dissipation through the production of motion on a progressively smaller scale. Understanding the physical mechanisms behind that dissipation is vital for constructing accurate theories and computational models of turbulence.

Energy cascade

A detailed description of a turbulent flow involves a three-dimensional field of velocity vectors **u**, which vary erratically in space and time. Turbulent velocity fluctuations are not completely unorganized in space and time; on closer inspection, they have a degree of coherence not on a set of discrete length scales or frequencies but in an intrinsically broadband manner. The faster or larger the overall flow or the lower the fluid viscosity, the wider the range of length scales and frequencies dynamically active in a turbulent flow. The low viscosities of common fluids such as air and water ($\nu_{air} = 10^{-5}$ m^2/s and $\nu_{water} = 10^{-6}$ m^2/s) explain why turbulent flows with a wide range of scales are encountered frequently in science and engineering.

The multiscale nature of turbulence can be thought of as a superposition of motions with spatial coherence of a given length scale. The wide range of scales in a turbulent flow results from one of the most fundamental and universal aspects of turbulence: the energy cascade. It is the process by which kinetic energy generated at large scales is passed successively from smaller scale to smaller scale until the motions are so small that viscosity prevents the formation of even smaller motions because it dissipates the energy into heat. The process occurs rapidly and enhances the overall rate of energy dissipation far above that of smooth laminar flows.

The energy cascade is an important consideration for computer simulations in scientific discovery and engineering design. For the wind-farm example discussed earlier, any attempt at simulation must use coarser-grain resolution than a millimeter and thus end up severely underresolved. To compensate for that lack of resolution, kinetic energy is artificially removed from simulations to mimic the cascade of energy from resolved scales to unresolved

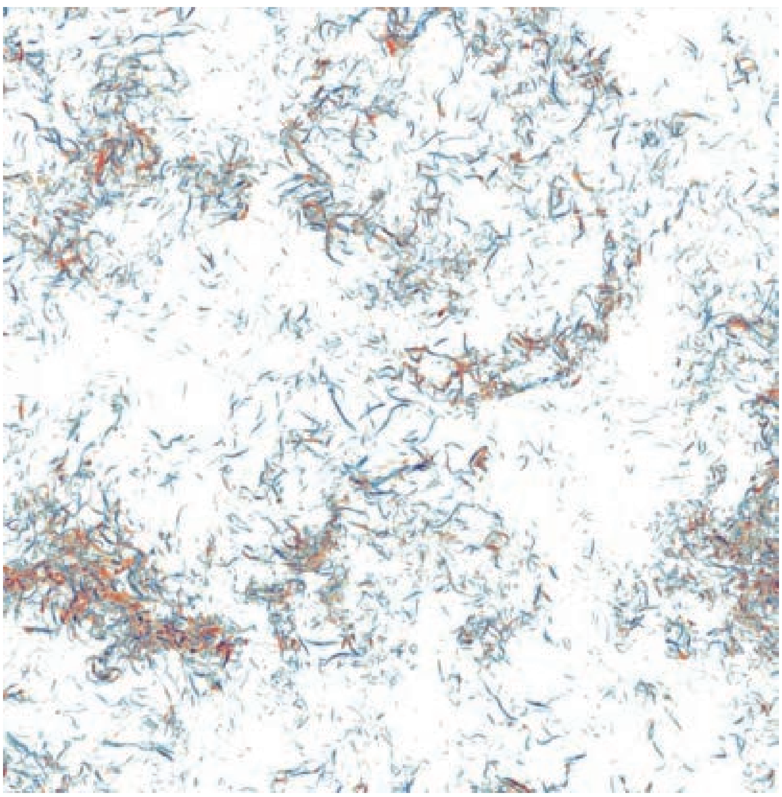

FIGURE 2. STRETCHING AND ROTATING regions. In this turbulence visualization, most of the fluid has low activity, but certain regions are characterized by large-magnitude vorticity (blue) and large-magnitude strain rate (red). (From ref. 6.)

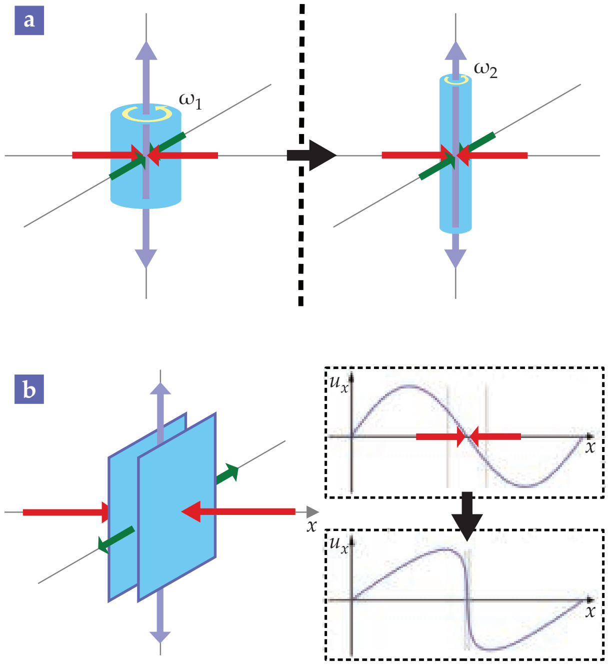

FIGURE 3. ENERGY DISSIPATES at an enhanced rate from a combination of two mechanisms. **(a)** When under strain (red, green, and violet arrows), a fluid vortex rotating at a rate ω_1 gets stretched out, and the result is a higher rotation rate ω_2. Energy passes to successively smaller and smaller vortices, a phenomenon known as vortex stretching. **(b)** Regions of strong strain rate can also self-amplify. In that mechanism, a sheet-like region of high compression naturally tends to grow thinner as the strain rate gets steeper because faster-moving fluid (peaks in graphs of u_x as a function of position x) overtakes slower fluid ahead of it and squeezes the fluid particle.

ones. Doing so accurately requires understanding the mechanisms behind the energy cascade.

Stretches and whirls

In a 1922 rhyming verse, British meteorologist Lewis Richardson was the first to describe the energy cascade in turbulent flows: "Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity."[5] The dynamics of "whirls" or eddies—that is, localized rotations in a flow—has since proven key to the phenomenology of the energy cascade.

In the continuum approximation of fluid dynamics, a fluid particle is defined as an effectively infinitesimal volume of fluid at a specific location. In addition to the particle's velocity, its dynamics is described by two quantities: the vorticity and the strain rate. The vorticity gives the rate at which a fluid particle at a given position is rotating. The strain-rate tensor describes the local rate at which a fluid particle is getting stretched and squeezed. In figure 1b, for example, strain deforms an initially square fluid particle into a rectangle. Pressure forces keep a fluid particle's volume constant in flows with velocities well below the speed of sound, so a particle that is stretched in one direction will necessarily be squeezed in another.

Mathematically, the vorticity and the strain rate involve the gradient of the velocity vector, $\nabla \mathbf{u}$, a 3 × 3 rank-2 tensor that describes the local variation of the three components of velocity in each of the three coordinate directions. The strain rate $\mathbf{S}$ is defined as $\mathbf{S} = \frac{1}{2}[\nabla \mathbf{u} + (\nabla \mathbf{u})^T]$, in terms of the gradient tensor and its transpose, and the vorticity vector $\boldsymbol{\omega}$ is defined as $\boldsymbol{\omega} = \nabla \times \mathbf{u}$. The magnitude squared of the velocity gradient tensor, measured using the square root of the sum of the absolute squares of the tensor elements, is the sum of the strain-rate and vorticity magnitudes, $\|\nabla \mathbf{u}\|^2 = \|\mathbf{S}\|^2 + \frac{1}{2}|\boldsymbol{\omega}|^2$.

But those two components are physically distinct, as highlighted by their relationship to viscosity. A fluid's viscosity ν quantifies how much the fluid resists deformation by the strain rate. That resistance dissipates kinetic energy into heat at a rate $\epsilon = 2\nu\|\mathbf{S}\|^2$. Viscous forces do not resist rotation, so vorticity incurs no similar energy dissipation.

Figure 2 shows regions with large-magnitude vorticity and strain rate in a simulation of a stirred fluid in a periodic box.[6] The soup of turbulence contains mostly regions with low activity intermittently dispersed with coherent regions of high vorticity and high strain rate.

Vortex stretching

In the years after the publication of Richardson's verse, the dynamics of vorticity has commonly been associated with the energy cascade, even though vorticity doesn't directly cause energy dissipation. A phenomenon known as vortex stretching is widely used to explain the connection. When a vortex—a compact tube-like region of vorticity—is pulled by the fluid's straining motion along the axis of rotation, as depicted in figure 3a, the cross section of the vortex shrinks. Conservation of angular momentum dictates that the rotation rate must increase, similar to when spinning figure skaters pull in their arms to rotate faster. The result is a larger-magnitude vorticity in a smaller vortex. The region of coherent strain rate typically spans a slightly larger scale than the vortex and, through the work involved in stretching the vortex, passes energy from larger to smaller scales.

The historical explanation for the energy cascade was successive vortex-stretching events,[7] an idea introduced in a 1938 paper by G. I. Taylor. After careful measurements of a model turbulent air system—produced by placing a square grid of cylindrical bars in a wind tunnel—he wrote, "It seems that the stretching of vortex filaments must be regarded as the principal mechanical cause of the high rate of dissipation which is associated with turbulent motion."[8] A decade later Lars Onsager echoed that assessment in his theoretical treatment of turbulence: "Since the circulation of a vortex tube is conserved, the vorticity will increase whenever a vortex tube is stretched. . . . This process tends to make the texture of the motion ever finer, and greatly accelerates the viscous dissipation."[9] Despite the prevailing belief that the energy cascade is driven by vortex stretching, a precise connection between the two has remained elusive until recently, as will be discussed below.

Work in the past few decades has suggested an alternative mechanism called strain self-amplification to explain how energy passes from larger to smaller motions.[10] In strain self-amplification, shown schematically in figure 3b, a strong compressive strain rate naturally steepens as faster-moving fluid (peaks in the graphs of velocity) overtakes slower-moving fluid in its path. The effect is analogous to an ocean wave steepening before it breaks. Physically, strain self-amplification reduces the size of the region being squeezed and distributes the associated

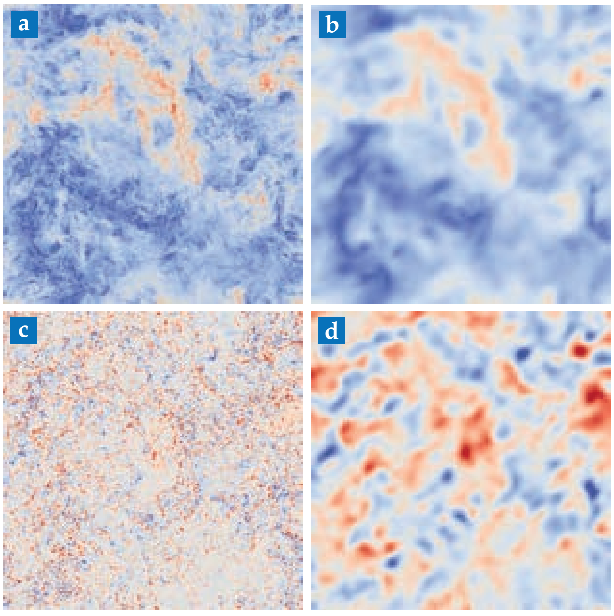

FIGURE 4. A STIRRED FLUID simulated in a periodic box displays turbulence in its three-dimensional flow. **(a)** A 2D slice showing the magnitude of the flow's velocity (red, high velocity; blue, low velocity) includes coherent motions of various sizes, including very small-scale features. **(b)** A technique called spatial filtering makes the simulation easier by sacrificing the resolution of small-scale motions. **(c)** The velocity gradient, typified by the vorticity seen here, reveals the smallest-scale motions in turbulence. **(d)** Spatially filtered vorticity, and by extension filtered velocity gradients, highlight motions at a chosen length scale. Filtered velocity gradients thus provide a basis for quantifying how energy passes between different scales.

kinetic energy toward smaller scales of motion. Similar to vortex stretching, successive self-amplification events can explain the energy cascade.

Navier–Stokes equation

To move from simplified descriptions of vortex stretching and strain self-amplification to the chaotic reality of turbulent flow requires a quantitative description. The Navier–Stokes equation encapsulates the law of momentum conservation for a fluid flow. In the simplest form, it can be written as a partial differential equation of the velocity vector field:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} .$$

On the right side of the equation, forces due to pressure gradients ∇p and viscosity ν accelerate a fluid of mass density ρ.

Acoustic waves and electromagnetic radiation propagate at speeds set by either the medium or physical constants, such as the vacuum permittivity. As a result, excitation at a single frequency typically results in a single-frequency field. The momentum of a fluid particle, on the other hand, propagates at the local fluid velocity, which in turn is proportional to the momentum. That property generates the nonlinear term in the Navier–Stokes equation $\mathbf{u} \cdot \nabla \mathbf{u}$, which leads to vortex stretching and strain self-amplification.

Analytical solutions aren't possible in the Navier–Stokes equation for turbulent flows. But insights into the flow's nonlinear dynamics are possible if the equation is reframed in terms of the velocity gradient field $\nabla \mathbf{u}$ instead of the velocity field $\mathbf{u}$ and if the fluid particles are treated as independent of the influence of neighboring particles. Although that autonomous-particle assumption is a severe simplification, it enables exact analytical solutions. The result, called the restricted Euler equation, is drastically simplified with only a few degrees of freedom.

In 1982 Patrick Vieillefosse demonstrated that for all initial conditions, the restricted Euler equation leads to a singularity in finite time—that is, the velocity gradient magnitude $\|\nabla \mathbf{u}\|$ becomes infinite at some specific time.[11] The underlying cause of that singularity is clear from the equation for the growth in velocity gradient magnitude,

$$\frac{d}{dt}\left(\frac{1}{2}\|\nabla \mathbf{u}\|^2\right) = \underbrace{-\mathrm{Tr}\,(\mathbf{S} \cdot \mathbf{S} \cdot \mathbf{S})}_{P_S} + \underbrace{\frac{1}{4}\,\omega^T \cdot \mathbf{S} \cdot \omega}_{P_\omega} .$$

The velocity gradient's growth is driven by strain self-amplification, which happens at the rate P_S, and vortex stretching, which happens at the rate P_ω. When unopposed by the pressure and viscous forces of neighboring fluid particles, those two processes, which represent the autonomous dynamics of individual fluid particles, produce the singularity in the restricted Euler equation. Physically, the pressure and viscous forces of the Navier–Stokes equation restrain the autonomous dynamics and avert such singularities.

But along the path to the singularity, restricted Euler solutions display many traits that are observed in turbulent flow experiments and computer simulations of the full Navier–Stokes equations.[12] Those features account for why P_S and P_ω are positive on average for full Navier–Stokes solutions. In fact, only specially constructed configurations of the interactions with neighboring fluid particles can prevent nonlinear effects from establishing the statistical bias toward positive P_S and P_ω and the affiliated growth of the velocity gradient.[13]

Spatial filtering

A route to make the simulation of turbulence computationally tractable is a simplification known as spatial filtering, which is akin to changing the resolution of an image. A low-pass spatial filter operation is a weighted average over a subregion with characteristic size ℓ. Applying the filter to a 3D turbulent velocity field removes motions smaller than ℓ—for example, the velocity field in figure 4a becomes the image in figure 4b after spatial filtering.

The Navier–Stokes equation can be filtered to obtain a dynamical equation for the smoothed field shown in figure 4b. In the filtered Navier–Stokes equation, kinetic energy dissipates either through viscosity directly acting on the large-scale motions and thus dissipating energy into heat, as it does in an unfiltered field, or through energy passing to small-scale motions not represented in the filtered field. At sufficiently large filter sizes, energy removal results primarily from the latter. The field Π quantifies the rate at which that energy transfer happens.[14]

The gradient of the velocity field highlights the smallest-scale activity in a turbulent flow, as shown by the detailed features in figure 4c. That small-scale activity—namely, the vorticity and strain rate—predominantly organizes into small

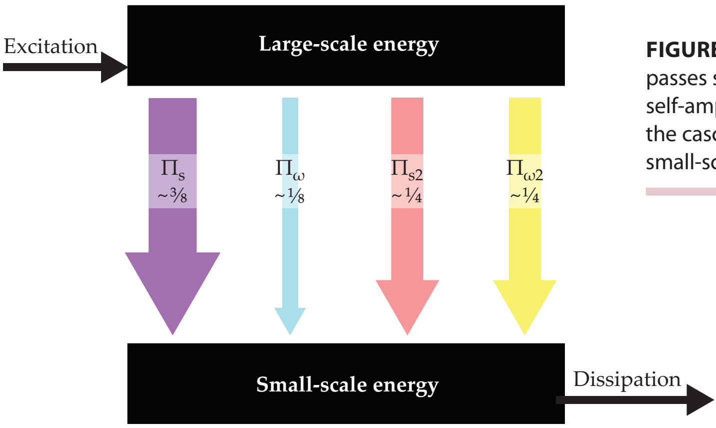

FIGURE 5. KINETIC ENERGY introduced at large scales in turbulent flows passes successively through intermediate scales at different rates due to strain self-amplification (Π_S and Π_{S2}) and vortex stretching (Π_ω and $\Pi_{\omega 2}$). At the end of the cascade, energy dissipates as heat because of viscosity's resistance to small-scale motion.

coherent regions, which resemble a chaotic soup of miniature tornadoes that swirl and stretch the participating fluid particles. The gradient of the filtered velocity field, however, accentuates organized motions of size ℓ, whatever filter size is chosen, as illustrated in figure 4d. Filtered velocity gradients thus provide a convenient definition for the scales of motion in turbulence.

A quantitative description of how turbulent motions at scale ℓ drive the cascade of energy from scales larger than ℓ to those smaller than ℓ becomes possible only if Π can be related to P_S, P_ω, and similar terms—that is, the mechanism behind turbulence cascade becomes clear if the local cascade rate can be written in terms of filtered vorticity and strain rate. Whereas previous work demonstrated a connection only in terms of truncating an infinite series, with no clear explanation as to the role of truncated terms, recent work has provided an exact relation.[15]

Cascade rate

The energy cascade rate can be written as a sum of five contributions: $\Pi = \Pi_S + \Pi_\omega + \Pi_{S2} + \Pi_{\omega 2} + \Pi_{c2}$. The first two parts, $\Pi_S = \tfrac{1}{2}\ell^2 P_S$ and $\Pi_\omega = \tfrac{1}{2}\ell^2 P_\omega$, are proportional to the strain self-amplification and vortex stretching at scale ℓ. The filtered velocity gradients tend to strongly self-amplify, just as in the restricted Euler equations, due to biases toward $P_S > 0$ and $P_\omega > 0$. Robert Betchov derived an exact relation for velocity gradients[16] that when rephrased for filtered fields states that the average contribution of Π_S to the energy cascade is three times that of Π_ω. The first two rate terms, Π_S and Π_ω, were independently identified by Maurizio Carbone and Andrew Bragg using a truncated series.[17] But solidifying a set of cascade mechanisms relied on the identification of the remaining three terms.

The next two contributions to the energy cascade, Π_{S2} and $\Pi_{\omega 2}$, have interpretations analogous to the first two terms. They arise from the amplification of smaller-scale strain rate by larger-scale strain rate and the stretching of smaller-scale vorticity by larger-scale strain rate, respectively. The final term, Π_{c2}, results from the distortion of small-scale strain–vorticity covariance by larger-scale strain rate. Whereas the first two terms represent the contribution of velocity gradient dynamics at one scale, the final three terms describe multiscale interactions. Numerical simulations have revealed that the final term contributes little, so the energy cascade rate is in practice a sum of the first four terms. Those terms precisely quantify strain self-amplification and vortex stretching along with their respective multiscale generalizations.

Figure 5 shows the fractional contribution of each term as numerically computed from turbulent solutions to the Navier–Stokes equation for a stirred fluid in a periodic box. Contrary to the theories of Taylor[8] and Onsager,[9] strain self-amplification is a bigger contribution to the energy cascade than vortex stretching, and previously unidentified multiscale interactions are a vital part of the picture. The results provide invaluable insights for improving approximation methods for computing an artificially smoothed version of turbulent flows, such as the coarse-grained simulation of a wind farm described earlier. Those methods depend on models that accurately represent the energy cascade to know how energy must be removed from the simulation in a point-wise manner. And a precise understanding of multiscale strain self-amplification and vortex stretching can lead directly to more accurate models.[15]

Vortex stretching and strain self-amplification are universal aspects of turbulent flows, so results in simple flows should illuminate modeling efforts for a wide range of complex flows, including wind farms, gas turbine engines, and aerodynamic vehicles. For the time being, experimental measurements of both scaled-down replicas and expensive full-scale systems remain indispensable to scientific discovery and engineering design. But developments in turbulence theory and modeling will help propel computer simulation into a more central role in design and analysis. Many applications will require extending the current models to include additional physical phenomena such as heat and mass transport in combustion engines, flows with density stratification in oceans, compressible flows for high-speed flight, flows in a magnetic field in astrophysics, and flows with small particles and drops.

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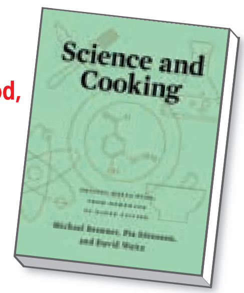
A PLATTER OF "thousand-year-old eggs," a traditional Chinese delicacy made by preserving quail or duck eggs in a brine made with lye, tea, and zinc.

A taste of soft-matter physics

Science and Cooking
Physics Meets Food, from Homemade to Haute Cuisine
Michael Brenner, Pia Sörensen, and David Weitz
W. W. Norton, 2020. $35.00



Ten years after launching their highly successful course on science and cooking, Harvard University professors Michael Brenner, Pia Sörensen, and David Weitz have followed up with a book of the same title. It has the same objective as the course: To use cooking to teach the underlying concepts of soft-matter science.

Although *Science and Cooking: Physics Meets Food, from Homemade to Haute Cuisine* is obviously of interest to physicists and chemists, its use of recipes by world-famous chefs and its focus on molecular gastronomy give the book a broader appeal. By describing the science in simple terms and adding detailed recipes, the authors have cooked up an interesting read for PHYSICS TODAY's more technically oriented audience and the general public alike.

The first three of the book's seven chapters cover topics commonly associated with cooking: the science of food ingredients and how changing pH or temperature can induce phase transformations in food molecules. *Science and Cooking*'s uniqueness lies in the three subsequent chapters, which are devoted to ideas from soft-matter science, including diffusion, viscosity and elasticity, and emulsions and foams. The last chapter takes an unexpected detour and focuses on the biology and chemistry of fermentation.

The authors do an excellent job of integrating underlying topics from physics and chemistry into the book's narrative. They discuss, for example, the structure of different types of biomolecules in food and describe how changes in temperature and pH induced by cooking cause phase transitions in those molecules. Food properties such as taste, texture, and flavor are explained in terms of the basic chemistry and related to concepts of rheology and mechanics from soft-matter physics. Diffusion and elasticity are examined in considerable detail; the former is explained using random walks, and the latter is outlined by a simple quantitative calculation.

Surprisingly, the authors did not include a simplified description of the intermolecular interactions that lead to thermal phase transitions in simple substances like water. That would have helped clarify the important distinction between the conformational phase transitions of proteins and the melting and freezing of water. The treatment of thermal physics and phase transitions in chapter 2 would have also benefited from a simplified overview of kinetic theory explaining how temperature relates to kinetic energy. In general, readers with a basic knowledge of physics and chemistry will understand and appreciate the underlying science of the topics covered in the book, but those who do not have such a background may find some of the material challenging.

The numerous recipes included in every chapter—more than a hundred in total—are a high point of *Science and Cooking* and serve to illustrate the scientific concepts. Many of them instruct readers on how to make simple yet delicious items, including ceviche, cheese, cookies, cakes, sauces, and beverages, that require only ingredients and tools found in most kitchens.

More exotic and complicated dishes, such as chocolate eggs, black truffle gel, and suckling pig with Riesling Pfalz, require rare ingredients and specialized equipment. However, they could be useful for restaurant chefs or demonstrations in a laboratory classroom equipped with liquid nitrogen, rotary evaporators, and temperature-controlled baths. Some of the far-out recipes like "old book essence" and "thousand-year-old eggs" are probably more fun to read than to eat, unless you have an adventurous palette.

Science and Cooking is neither a science *of* cooking book nor a textbook for teaching an undergraduate science and cooking course like the one taught by the authors. For those interested in learning about the physics and chemistry of cooking, there are more detailed books like *On Food and Cooking: The Science and Lore of the Kitchen* by Harold McGee (1984, rev. 2004), *The Food Lab: Better Home Cooking Through Science* by J. Kenji López-Alt (2015), and *The Science of Good Cooking: Master 50 Simple Concepts to Enjoy a Lifetime of Success in the Kitchen* by the editors at *America's Test Kitchen* and Guy Crosby (2012).

For an undergraduate class, *Science and Cooking* could be complemented by the videos from the authors' online edX course and its electronic supplement, *Course Companion: For the Science and Cooking Course at Harvard* (also written by Brenner, Sörensen, and Weitz), to provide a more quantitative approach to the underlying physics.

Science and Cooking provides an entertaining introduction to the fascinating science behind gastronomy and is likely to appeal to a broad audience. Those seeking to experiment with novel cooking methods and interested in analyzing recipes scientifically with the goal of improving or modifying them will find plenty to chew on here.

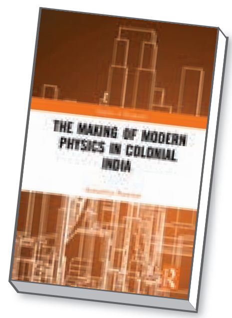
Rama Bansil
Boston University
Boston, Massachusetts

AIP ESVA, MARGRETHE BOHR COLLECTION

CHANDRASEKHARA VENKATA RAMAN (second from right), with Niels Bohr (third from left), George Gamow (far left), and others at Bohr's institute in Copenhagen, likely sometime in the 1930s.

Quantum physics and colonialism

The Making of Modern Physics in Colonial India
Somaditya Banerjee
Routledge, 2020. $160.00



The history of 20th-century physics is usually told from a Western perspective, but anyone familiar with Bose–Einstein statistics, the Raman effect, or the Saha ionization equation is at least implicitly aware that it was not exclusively Euro-American. In *The Making of Modern Physics in Colonial India*, Somaditya Banerjee, a historian of science at Austin Peay State University, examines the lives of the three Indian physicists who gave their names to those discoveries: Satyendra Nath Bose, Chandrasekhara Venkata Raman, and Meghnad Saha.

Serving as a corrective to the standard Eurocentric story, Banerjee's book demonstrates that the three scientists not only laid the foundation for modern physics in India but also earned international renown for their significant contributions to the then-emerging field of quantum physics. Indeed, despite their location on the scientific periphery, Bose, Raman, and Saha engaged with the leading scientists of their time, most of whom were based in Europe or the US. But their international outlook never blinded the three to political struggles at home, which drove them to use science as a weapon in the nationalist fight against colonialism.

Bose, for example, opposed the Raj and wanted to avoid associating with it as much as possible. That anticolonial sentiment is part of why he chose to correspond with Albert Einstein—a foreign scientist who was not a subject of the British Empire—even though British scientists and administrators supported Bose's work.

Raman had a robust network of international correspondents, although he remained very much rooted in his land and culture. Like Bose, he was close to many leading non-British scientists, including Niels Bohr, Arnold Sommerfeld, and Max

Born. At a time when it was unheard of for a non-Western scientist to receive the Nobel Prize in Physics, he was repeatedly nominated for the award by some of the most important scientists of his time, including Bohr, Ernest Rutherford, and Charles Thomson Rees Wilson. Thanks in part to his network of international scientific connections, Raman eventually received the prize in 1930—the first time it was awarded to a physicist from the non-Western world.

Saha, the third scientist discussed in the book, differed from Bose and Raman in that he came from a lower-caste background; unlike his upper-caste compatriots, he had to deal with everyday discrimination and inequality. Banerjee argues, however, that Saha was accepted alongside Bose and Raman as a *bhadralok*—a member of the educated upper elite in Bengali society—because he excelled in his studies, went to the best educational institutions, and worked with some of the top professors of his day.

Given their backgrounds, neither the lower-caste Saha nor Raman, whose Tamil Brahmin upbringing provided him with cultural and caste privileges, would seem to fall into the bhadralok category. Nevertheless, Banerjee attempts to show that the bhadralok identity was not tied to geographic origin and caste background but instead linked with education level, intellectual pursuits, and the choice of a modern profession. He argues that a distinct practice of bhadralok physics emerged in early-20th-century India—one embodied by Bose, Raman, and Saha.

Although *The Making of Modern Physics in Colonial India* is about three leading Indian physicists, it serves as an invitation for scholars to examine other non-Western scientists who did important work under colonial rule but often remain overlooked in traditional narratives. It also urges historians to transcend the binary of the West and the East and to analyze multiple geographic contexts and individuals in their work. Banerjee's book will be of interest not only to historians and anthropologists of science but also to scientists who want to go beyond Western narratives of quantum physics and related fields.

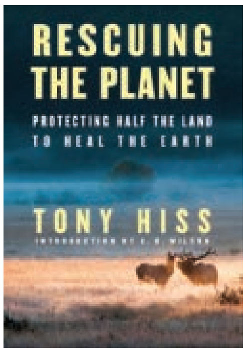
Renny Thomas
Indian Institute of Science Education and Research Bhopal
Bhopal, India

NEW BOOKS & MEDIA

My Nuclear Life

Shelly Lesher, host
2020 (Season 1)

Nuclear physicist Shelly Lesher, a professor at the University of Wisconsin–La Crosse, hosts the podcast *My Nuclear Life*, which examines the intersection of atomic science and broader society. Its six-episode first season, which premiered in fall 2020, discusses such wide-ranging topics as startup companies building generation IV nuclear reactors; the Iran nuclear agreement, which the Trump administration withdrew from and which the Biden administration is considering rejoining; and the Manhattan Project. A particular highlight is the second episode, with nonfiction author Dan O'Neill covering the history of Project Chariot, the early 1960s plan to "excavate" a harbor in Alaska by detonating atomic bombs. The podcast's second season began in March 2021. –RD

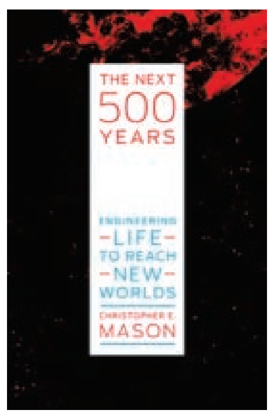


Rescuing the Planet
Protecting Half the Land to Heal the Earth

Tony Hiss
Knopf, 2021. $27.95

To counter the mass-extinction threat caused by humanity's impact on the environment, a plan has been proposed to protect 50% of Earth's natural land by 2050. In *Rescuing the Planet*, former *New Yorker* staff writer Tony Hiss focuses on efforts being made in North America to further that goal. A blend of biography, history, science, and travel, the book takes the reader on a journey to such wilderness areas as Canada's Boreal Forest, the Appalachian Trail, the Southeast's Piney Woods, and Yellowstone National Park. Hiss discusses their evolution, the plants and wildlife that live there, and some of the people who have worked over the years to conserve them. –CC

The Next 500 Years
Engineering Life to Reach New Worlds



Christopher E. Mason
MIT Press, 2021. $29.95

Traveling into space and colonizing new planets is a necessary duty for humanity, writes geneticist and computational biologist Christopher E. Mason. Humans, alone among Earth's species, understand that Earth's life span is finite. Moreover, we have the technological capability to preserve life by transporting it elsewhere in the universe. But to do that, he says, we need to bioengineer it to survive in alien environments. In *The Next 500 Years*, Mason lays out a timeline for accomplishing such engineering on a genetic, cellular, planetary, and interstellar scale. His vision is ambitious, and his detailed descriptions of current science and what we have achieved so far bolster his expectations for the future. –CC PT

Focus on cryogenics, vacuum, materials, and semiconductors

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

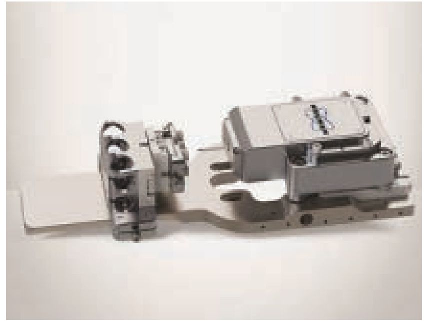
Andreas Mandelis

Compact, quiet vacuum pumps

Leybold has expanded its Ecodry Plus product family of dry multistage Roots vacuum pumps for laboratory, R&D, and analytical applications. The compact Ecodry 25 Plus and 35 Plus, which achieve high pumping speeds with relatively little footprint, complete the company's range of low-maintenance, economical fore-vacuum pumps. They are also particularly quiet, with a noise level of 52 dB(A). The Ecodry 25 Plus and 35 Plus emit neither oil vapor nor particles, which is important in research institutes and laboratories where a clean working environment is essential. The pumps are equipped with an integrated pump controller and are suitable for all voltage ranges. Users can also connect a pressure gauge directly to the vacuum pump and adapt the pump's performance to specific requirements, which can potentially make it more energy efficient. ***Leybold GmbH**, Bonner Str 498, 50968 Cologne, Germany, www.leybold.com*

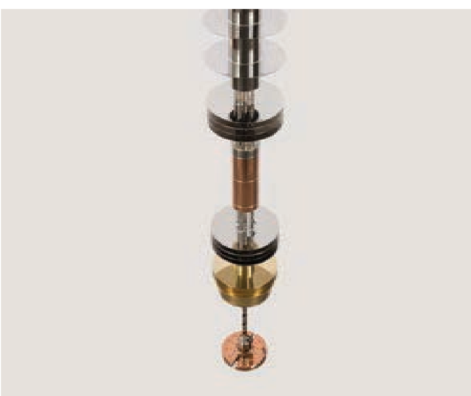
Leak detectors

Busch Vacuum Solutions has unveiled two leak detectors suitable for testing the tightness of vacuum systems and individual vacuum components, locating possible leaks, and quantifying their leakage rate. The smaller TAPIR HL 1102 A is for mobile applications, and the larger, multipurpose TAPIR HL 2216 A is for stationary applications. Both operate with helium or hydrogen as a tracer gas and can detect leaks with a leakage rate of up to 5×10^{-13} Pa m^3/s, depending on the test method used. Two methods are possible with the TAPIR HL leak detectors. The spray test, in which the tracer gas is sprayed onto the surface of a component under vacuum, has the highest sensitivity. The sniffing leak detection method, in which a vacuum component is pressurized with the tracer gas, reveals the exact location of the leak. ***Busch LLC**, 516 Viking Dr, Virginia Beach, VA 23452, www.buschvacuum.com*



Nanomechanical SEM materials analysis *in situ*

Bruker Nanomechanical Testing designed its Hysitron PI 89 SEM PicoIndenter to expand understanding of the deformation mechanisms of high-strength materials. According to the company, the device provides a scanning electron microscope (SEM) with nanomechanical testing capabilities at higher loads and in more extreme environments than previously possible. Combined with novel capacitive transducer and intrinsic displacement technologies, Bruker's high-performance controller enables wide force and displacement ranges. The versatile tool also features an electrical characterization module and two rotation and tilt stage configurations, among other capabilities. It is suitable for use in such areas as accelerated mechanical property mapping, fatigue testing, and nanotribology. For analytical imaging, it is compatible with electron backscattered, convergent beam, and transmission Kikuchi diffraction detectors and with energy-dispersive and scanning transmission electron microscopy detectors. ***Bruker Nano Surfaces Division**, 3400 E Britannia Dr, Ste 150, Tucson, AZ 85706, www.bruker.com*



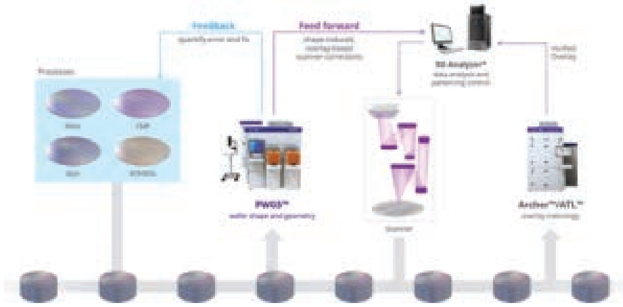
Cryostat with fast cool-down times

The Dry Ice 1.5K 100 mm closed-loop cryostat from ICE Oxford lets users carry out experiments in the 1.3–325 K temperature range. It ensures tight tolerance on temperature stability (±10 mK below 10 K), fast cool-down times (less than 30 min to 1.4 K), and minimal vibration in the sample space (as little as ±100 nm). The option exists to add helium-3 and dilution-fridge inserts to achieve even lower temperatures—300 mK and 15 mK, respectively. According to the company, the large 100-mm-diameter sample space and the cryostat's high cooling power of greater than 30 mW at 1.75 K are the best available for a variable-temperature-insert cryostat. Variants are offered with 30-, 50-, or 70-mm-diameter sample spaces. Using LabVIEW-based software, the cryostat can be highly automated to reduce system setup and turnaround time. ***ICE Oxford**, Ave 4, Station Lane, Witney, Oxford OX28 4BN, UK, www.iceoxford.com*

Diaphragm pumps for vacuum and compressor use

KNF's N 630 diaphragm vacuum/compressor pump series delivers high pressure and gas tightness. It offers vacuum down to 0.74 inHg (25 mbar abs), positive pressure up to 174 psig (12 bar rel), and a flow rate up to 2.4 cfm (68 L/min). Four models of the N 630 pumps are available: one- or two-headed and connected in series or parallel; each can be used as either a vacuum pump or a compressor. To ensure durability, all models come with long-lasting diaphragms coated with ethylene propylene diene monomer rubber or chemically resistant polytetrafluoroethylene. The N 630 series handles ambient and media temperatures down to 5 °C and, because of head water-cooling systems, up to 60 °C. The pumps are suitable for use in industrial coolant systems, gas recycling, gas and emissions measurement and analysis, and leak detection in applications ranging from chemical processing and energy to physics research. ***KNF Neuberger Inc****, 2 Black Forest Rd, Trenton, NJ 08691-1810, https://knf.com*

Patterned semiconductor wafer metrology



The PWG5 patterned wafer geometry system from KLA addresses difficult issues in the manufacture of leading-edge memory and logic integrated circuits. The most capable flash memory is built in an architecture called 3D NAND constructed of 128 thin layers. Manufacturing those structures requires depositing hundreds of thin films of multiple materials and then creating memory cells by etching and filling holes several microns deep and one-hundredth of a micron across. As the film stacks grow higher, they can distort the surface planarity of the wafer and ultimately affect device performance and yield. To identify and correct patterned wafer distortion at the source, the PWG5 metrology system can measure minute distortions of the wafer's geometry on the front and back sides simultaneously. According to the company, the system accomplishes that with inline speed and exceptional resolution that support not only 3D NAND but also advanced dynamic random-access memory and logic applications. ***KLA Corporation****, Three Technology Dr, Milpitas, CA 95035, www.kla-tencor.com*

Capacitance diaphragm gauge

InstruTech's CDM900 Micro Bee capacitance diaphragm vacuum gauge has a ceramic sensor and a cost-effective design. According to the company, the temperature-compensated CDM900 provides highly accurate pressure measurements with full-scale ranges of 10–1000 torr. Pressure measurement is independent of gas type. Models are available with 0.5% and 1% of reading accuracy and with various fittings, including ½-inch tube (O-ring compression), NW16KF, NW25KF, and 1⅓-inch Mini-Conflat types. No span adjustment is required, and in clean applications, no zero adjustment is needed. The CDM900 provides 0–10 V_{dc} linear analog output. It does not require a controller to operate; it provides an analog output signal that can be directly interfaced with users' control systems. The company's AGC302 controller can be used for panel- or rack-mount-display installation and when setpoint relays or serial communications are required. ***InstruTech****, 1475 S Fordham St, Longmont, CO 80503, www.instrutechinc.com*

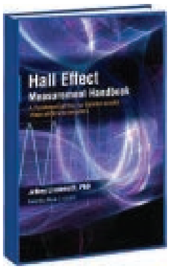
Gifford–McMahon cryocoolers

ULVAC Cryogenics—a joint venture of Japan-based ULVAC and US-based Helix Technology Corporation, currently doing business as Edwards Vacuum—has upgraded its Gifford–McMahon cryocooler product line so researchers and industrial users can select the system best suited to their need for second-stage wattage. Three new 4 K models are offered: the UHE10F (1.0 W at 4.2 K), the UHE12F (1.25 W at 4.2 K), and the UHE15F (1.5 W at 4.2 K). The cryocoolers feature high cooling capacities and are orientation-free and UL/CE certified. ***ULVAC Cryogenics Inc****, 1222-1 Yabata, Chigasaki, Kanagawa, 253-0085, Japan, www.ulvac-cryo.com*

Fast-setting two-component epoxy

When the white and black parts of Master Bond's EP51CC color-coded epoxy are combined, they form a uniform gray paste that indicates proper mixing. The nondrip compound is electrically insulative and suitable for bonding and sealing applications. It sets up quickly at room temperature, with a working life of 3–5 min for a mixed 50 g batch. The exact fixture time can vary from a few minutes to several hours, depending on various factors. Those include curing temperature, component size, substrates being bonded, and amount of adhesive applied. The cure schedule plays a role in bond strength. For example, when cured at room temperature for 24 h, EP51CC offers a lap shear strength of 700–800 psi; cured at room temperature for 8 h followed by 3 h at 250 °F, its strength increases to 2300–2500 psi. The epoxy bonds to various substrates, including metals, composites, glass, ceramics, vulcanized rubbers, and many plastics. Formulated for temperatures from −452 °F to 250 °F, EP51CC is also suitable for challenging cryogenic applications. ***Master Bond Inc****, 154 Hobart St, Hackensack, NJ 07601-3922, www.masterbond.com*

NEW LITERATURE



Hall effect measurement handbook

Lake Shore Cryotronics's 88-page *Hall Effect Measurement Handbook: A Fundamental Tool for Semiconductor Material Characterization* is a comprehensive resource for both new and experienced materials researchers. Written by Jeffrey Lindemuth, the handbook covers topics such as the theory of Hall effect measurements; how to measure the resistivity and Hall coefficient of materials; the major sources of measurement errors, both intrinsic and geometric; and ways to minimize the effects of those errors. The handbook is available both electronically and in print. US and Canadian customers can receive a print copy by mail at no charge. ***Lake Shore Cryotronics Inc****, 575 McCorkle Blvd, Westerville, OH 43082, www.lakeshore.com* PT

Vittorio Degiorgio

Vittorio Degiorgio, a professor emeritus of physics at the University of Pavia in Italy, died at his home in Milan on 17 January 2021 after a long battle with cancer. Possessed of a remarkably curious and independent mind, he made numerous achievements in radiation–matter interaction, statistical physics, soft-matter science, and photonics. He investigated those sundry topics with a unifying and distinctive personal style.

Milan, where Vittorio was born on 5 January 1939, was the social and cultural stage of his youth, education, and early career. Childhood was not kind to him. His mother, a high school teacher of Jewish origin, had been expelled from her public school job because of Italy's racial laws. In 1943, because of the heavy bombing of Milan, Vittorio had to find shelter in the countryside, where he taught himself to read and write.

Vittorio described himself as "a good high school student, but not a top one," who was particularly fond of the British empiricist philosophers. In 1957 he entered the Polytechnic University of Milan's new MS program in nuclear engineering, which was limited at the time to 10 carefully selected students.

Vittorio graduated in 1963 after an experimental thesis done under the direction of Emilio Gatti, a trailblazer in the field of nuclear instrumentation. Gatti was also a director at CISE, a research center that was regarded as the Italian counterpart of Bell Labs. In 1964 Tito Arecchi, a young CISE scientist just back from Stanford University, proposed that Vittorio, on a fellowship at CISE, work on a "new light source with promising application": the laser. Together with Bruno Querzoli, they published a successful 1967 paper on the statistical properties of coherent radiation. That work prompted Vittorio to try a US adventure, and in 1968 a Fulbright fellowship brought him to MIT.

Vittorio Degiorgio

In this photo, taken at the MIT entrance, Vittorio sits at the left of his best friend Marzio Giglio, with whom he shared an apartment—a feat in itself, for although Marzio was (and is) a bright scientist, he also was a rather messy guy.

At MIT, Vittorio was supposed to work in George Benedek's group, but he soon started an independent research line and in just a year produced two scientific gems. The first, with Marlan Scully, pointed out the analogy between laser threshold and a second-order phase transition. The second, with John Lastovka, posed the basis for the optimal design of correlators for dynamic light scattering (DLS). Working at MIT was demanding and time-consuming, but Vittorio still made time to listen to the jazz piano concerts of his friend Ran Blake; the two last met in 2015 at an "aperitif in concert" in Milan.

Light scattering was Vittorio's "gateway" to the investigation of complex fluids, which he worked on when he returned to Italy in 1970, first at CISE and since 1980 as a full professor at the University of Pavia. With Mario Corti, he studied interactions and phase transitions in surfactant solutions. His heyday in the field of soft matter was surely the 1990s, when his research interests broadened to encompass a wide class of systems ranging from model colloids to polyelectrolytes and liquid crystals. Those investigations led Vittorio to obtain seminal results about depolarized DLS, rotational Brownian dynamics, charge renormalization in macroions, and sedimentation of colloidal fluids.

Vittorio never neglected his youthful passion for nonlinear optics. In the late 1990s, he started a fruitful collaboration with Gianpiero Banfi on nonlinear properties of semiconductors and organic crystals and on cascaded nonlinear phenomena. Vittorio's overwhelming and genuine scientific curiosity also led him toward the field of integrated photonics and optical communications. He focused on nonlinear waveguides for signal processing and on microstructured fibers, and he achieved key results on soliton dynamics and supercontinuum generation.

Gifted with an ability to organize and lead with remarkable poise, Vittorio was involved in several commissions of trust. He served on the physics panel of the European Union, the liquids board of the European Physical Society, and the Scientific Council of the European Laboratory for Non-Linear Spectroscopy, among others, and was vice president of the Italian Institute for the Physics of Matter. He fulfilled his duties with generosity and spirit of service.

Working with Vittorio for many years, we had the chance to appreciate and admire his superb skills in scrutinizing experimental evidence, dissecting arguments, and rejecting hasty conclusions. In addition to being a first-class scientist, he was an outstanding teacher; although he was rigorous, he was clear and descriptive. The book on photonics he published with one of us (Cristiani) in 2014 testifies to his dedication to the education of young scientists. Above all, Vittorio was fair and a man of principle, gifted with intellectual honesty and strengthened by a vast literary culture. His colleagues and friends miss him greatly.

Roberto Piazza
Polytechnic University of Milan
Milan, Italy
Ilaria Cristiani
University of Pavia
Pavia, Italy

Roddam Narasimha

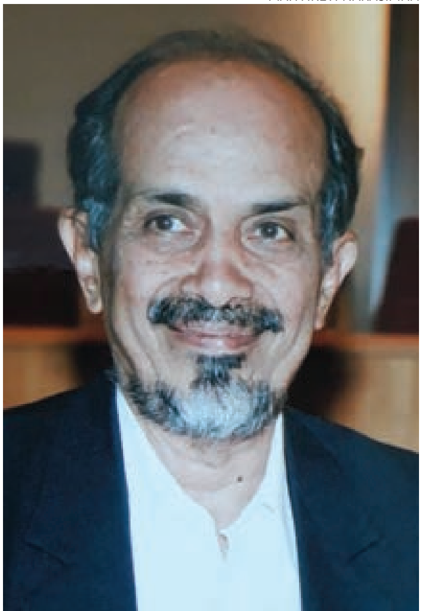
Roddam Narasimha, known to his students as RN, was one of the most influential scientists in India and a world-renowned expert in fluid dynamics and aeronautical engineering. He died in Bangalore on 14 December 2020. He remained scientifically productive until a few weeks before he succumbed to a brain hemorrhage following an unrelated surgery. Those who met him knew him as a person of great depth and dignity. He left an enormous footprint on the scientific subjects and national projects on which he worked.

Born on 20 July 1933 in Bangalore, RN picked up his scientific interests and attitude from his father, who taught physics at the Central College in the city. RN thus naturally was drawn to physics. However, he got caught up in the heady days after India's independence in 1947 and the fervor of nation building that ensued. In 1949 he decided to study mechanical engineering, rather than physics, at the Government Engineering College at Bangalore, and he graduated with distinction in 1953.

During an informal visit RN made to the Indian Institute of Science (IISc), the sight of a lovely World War II Spitfire standing in a quadrangle resulted in his decision to pursue a master's degree in aeronautical engineering at the IISc. There he was mentored by Satish Dhawan, a stalwart in the country's science and technology development. RN's very first work, with Dhawan, on boundary-layer transition catapulted him to fame and continues to be cited and used today.

RN then went to Caltech for his PhD; Hans Liepmann, his adviser, remained a lasting influence on his scientific development. The year RN started his doctorate, 1957, was a turning point for US aerospace research because the Soviet Union launched *Sputnik 1* that year. RN was impressed by the rapidity with which the US scientific establishment organized itself on both budgetary and academic fronts to start a space program. He was also quickly drawn into fundamental problems of free molecular flow and the structure of shock waves.

MAITHREYI NARASIMHA



Roddam Narasimha

RN returned to the IISc as an assistant professor in 1962 and rose quickly through the ranks. He continued his exceptional research in rarefied gas dynamics, the transition to turbulence, and turbulent boundary layers. One of his abiding interests was relaminarization, which subsumes a host of mechanisms by which an initially turbulent flow can be rendered laminar. He built a first-rate fluid-dynamics research group, part of which in 1982 went on to create what is now the Centre for Atmospheric and Oceanic Sciences. Among his group's achievements there were the novel laboratory simulation of clouds and their direct numerical simulations. RN conceived the Monsoon Trough Boundary Layer Experiment, carried out in the Indo-Gangetic Plain in 1990, to measure the atmospheric boundary-layer properties and derive flux relations relevant to monsoons. He conceptualized the Indo–French atmospheric research satellite *Megha–Tropiques*, launched in 2011 to study tropical clouds.

Amidst all that intellectual activity, RN served for 10 years as director of the National Aerospace Laboratories, where he focused on civil aviation, particularly trainer and light transport aircraft. He then spent about seven years as director of the National Institute of Advanced Studies, building a multidisciplinary research group of leaders from industry, academia, and government. He also created and chaired a new unit on engineering mechanics at the Jawaharlal Nehru Centre for Advanced Scientific Research. He never sought out leadership roles, although many came his way, including the presidency of the Indian Academy of Sciences; in each of his positions, he engaged in new initiatives that left the institutions better than they had been.

As a member of the Scientific Advisory Council to prime ministers Rajiv Gandhi and Manmohan Singh, RN was instrumental in establishing a major parallel computing initiative in the country and the Ministry of Earth Sciences. He served a critical role on the Indian Space Commission and was its longest-serving member.

RN was a highly cultured and scholarly person who combined the best from the East and the West and achieved an excellent balance between "building" and "doing." Rather than advising his students to follow fashionable research areas, he taught them to work on questions that excited them and emphasized quality over quantity. He was well versed in Indic philosophy and scientific heritage; his awareness of the complexity of the country only enhanced his keen love for it. He was progressive on social issues and was free from prejudices against region, religion, gender, and age.

Many honors and recognitions came RN's way, both in India and abroad. But he did not allow them to affect the personal qualities that endeared him to so many in the first place: his easy accessibility and openness to people of all walks of life; his intellect and his love for truth, scientific culture, and scholarship; his unprejudiced and disciplined advice; his clarity of thought in spoken and written words; his genuine curiosity; and the inspiration he provided to numerous younger colleagues. His legacy will remain far into the future.

K. R. Sreenivasan
New York University
New York City

Pietro Gambardella is a professor of magnetism and interface physics, **Zhaochu Luo** is a postdoctoral researcher in magnetic logic, and **Laura Heyderman** is a professor of mesoscopic systems–all at ETH Zürich in Switzerland.



Magnetic logic driven by electric current

Pietro Gambardella, Zhaochu Luo, and Laura J. Heyderman

Spin-based logic gates consume no power when idle, are compatible with CMOS circuitry, and can be seamlessly integrated with memory.

A hundred years ago, Heinrich Barkhausen heard the crackling sounds produced by magnetic domains expanding and contracting in an iron bar. Those clicks were the first experimental evidence of the jumpy processes associated with the displacements of the domain walls. The movements determine many of the useful properties of ferromagnets, including how readily they respond to an applied magnetic field in transformers and electric motors.

But controlling domain propagation is difficult. Microscopic magnetization processes are stochastic, and disorder is inevitably present. In this Quick Study, we discuss how domain walls can nevertheless be manipulated by an electric current in order to move, store, and process digital information encoded in their magnetizations.

Driving domains

Early proposals for manipulating magnetic domains date back to the 1960s. Memory devices based on the propagation of cylindrical domains, or bubbles, in perpendicularly magnetized thin films reached a remarkable level of circuit integration and speed for their time. Although they were eventually abandoned in favor of cheaper semiconductor memories, magnetic bubble memories spearheaded the application of lithography techniques to fabricate magnetic devices. Moreover, they revealed the possibility of combining digital memory and logic functions in the same medium. Unfortunately, the domains were manipulated by magnetic fields produced by a maze of metal wires, which are neither scalable nor energy efficient. That scenario has changed in recent years. Spin–orbit torques have emerged as the most effective tool to push domain walls around via direct current in magnetic nanowires, now rebranded as domain-wall racetracks.

A spin–orbit torque is an effect by which an electric current transfers orbital angular momentum from electrons flowing in a conductor to the spins of a magnet. The transfer is mediated by the spin–orbit interaction, which couples the electrons' orbital and spin moments. And its overall effect is a change in the magnetization's orientation, which depends on the strength and sign of the current. In the most common devices, the electric current flows in a heavy metal, such as platinum, deposited next to a magnetic layer. Spin–orbit torques offer a way to electrically manipulate the magnetization of different materials, including metals and insulators, without the need for external magnetic fields. The action of the spin–orbit torque on the spins inside a domain wall is equivalent to that of a magnetic field that drives the domain wall forward. At high enough current density in properly designed racetracks, spin–orbit torques can move domain walls at record speeds of 0.5–5 km/s.

Coupling domains

Whereas the spin–orbit torques can transfer magnetic information by displacing domain walls between different parts of a

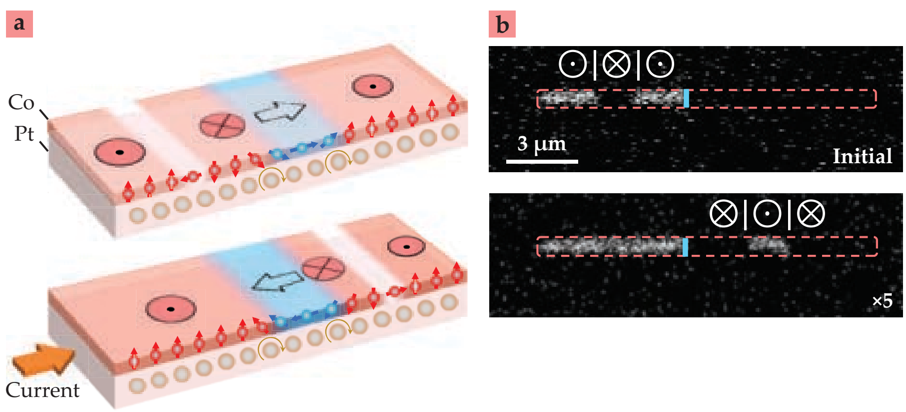


FIGURE 1. DOMAIN WALLS atop a strip of magnetic cobalt and platinum metal can be driven by an electric current. **(a)** Red regions signify up (⊙) and down (⊗) magnetization, white is the domain wall, and blue is the domain-wall inverter, or NOT gate, magnetized in-plane along the arrow. The illustrations show the initial state (top panel) and the current-driven inverter in action (bottom panel): Here the ⊙|⊗ domain wall propagates across the strip and changes to a ⊗|⊙ domain wall. **(b)** Kerr-effect images of a train of two domain walls, shown before and after 5 current pulses are applied. The inverter is shown as a blue line. (Adapted from Z. Luo et al., *Nature* **579**, 214, 2020.)

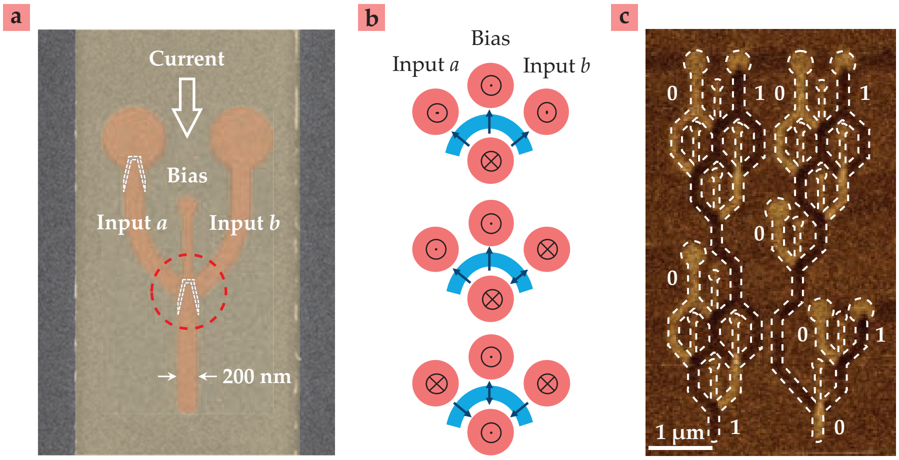


FIGURE 2. MAJORITY RULES. (a) In this scanning electron micrograph of a reconfigurable NAND/NOR logic gate, the current-carrying strip is tan colored. **(b)** In red and blue are circuit regions whose magnetizations are out of plane and in plane, respectively. The magnetization is shown for the two logic inputs, the bias, and the logic output for the gate. **(c)** Magnetic force microscopy image of a full adder gate, showing the sum (left) and carry (right) circuits. The light and dark regions in the device correspond to ⊙ and ⊗ magnetization, respectively. (Adapted from Z. Luo et al., *Nature* **579**, 214, 2020.)

multilayered wire, something more is needed to process that information and build a logic circuit. For a start, we need a coupling mechanism to perform combinatorial operations with domain walls. Our racetracks are made from a 1-nm-thick cobalt layer deposited on a 5-nm-thick platinum track and capped with aluminum oxide. That stack of materials produces the so-called Dzyaloshinskii–Moriya interaction (DMI), an unusual form of magnetic coupling between atomic spins—also mediated by the spin–orbit interaction—that occurs naturally in systems with broken inversion symmetry.

Unlike the usual magnetic exchange interaction, which causes the spins to align parallel or antiparallel to each other in ferromagnets and antiferromagnets, the DMI favors the orthogonal alignment of adjacent spins with a unique sense of rotation, or chirality. As shown in figure 1a, the alignment produces chiral domain walls with a left-handed rotation of the spins between up (⊙) and down (⊗) domains. That left-handed rotation is found in Pt/Co/AlO_x, and it is those chiral domain walls that can be moved under the action of a spin–orbit torque.

We have also exploited the DMI to induce coupling between different sections of a magnetic racetrack. More specifically, we have built devices in which different parts of a continuous Pt/Co/AlO_x racetrack have different orientations of magnetization. We built them by oxidizing selected regions of the Al cap layer; regions that are oxidized have out-of-plane (OOP), or perpendicular, magnetization, and regions that are unoxidized have in-plane (IP) magnetization. Akin to what happens inside a domain wall, the DMI produces a left-handed chiral alignment of magnetic moments in neighboring IP–OOP regions (figure 1a). If the DMI is strong enough, chiral ordering emerges spontaneously in racetracks composed of one or more sequences of IP–OOP elements. Moreover, switching the magnetization of an IP (OOP) element automatically causes the magnetization of the OOP (IP) element next to it to switch. That property allows for a key building block—a so-called domain-wall inverter—in Boolean logic circuits.

To be XOR not to be

A narrow IP region patterned into an OOP magnetized racetrack couples to its surroundings and forms one of the following left-handed configurations: ⊗→⊙ or ⊙←⊗. The DMI thus produces an antiparallel alignment of the OOP magnetization on the left and right of the IP region. When a domain wall in a racetrack is driven through such an IP region by a current-induced spin–orbit torque, the magnetization of the IP region flips. That, in turn, annihilates the incoming domain wall and nucleates a new domain wall of opposite polarity on the other side of the IP region. The new domain wall then continues to propagate along the current direction (figures 1a and 1b). The chirally coupled OOP-IP-OOP region therefore serves as an inverter capable of transforming an up–down domain wall into a down–up domain wall and vice versa. One can associate "1" and "0" with the down and up magnetization directions in the racetrack—a process equivalent to a NOT logical operation.

Building on the chiral coupling between OOP-IP-OOP regions, we designed majority gates where three OOP tracks (two inputs and one bias) meet at a common point (circled in red in figure 2a) delimited by an IP region, which connects them at the output track. The output is the opposite of the majority of the three converging tracks. The bias, specifically, dictates whether that corresponds to a NAND or a NOR function. A combination of the two gates completes our concept for current-driven domain-wall logic because any Boolean function can be implemented using them. Indeed, bifurcations in racetracks fan out, so that more gates can be cascaded on the same current line—no additional control circuitry required. As an example, we present a full adder circuit created by cascading 15 NAND gates in figure 2c.

In principle, the minimum size of a gate can be scaled down to dimensions approaching the width of a domain wall. That's about 10 nm in thin films. In combination with the current-dependent domain-wall velocity, that width constrains the speed of logic operations.

Additional resources

▶ D. A. Allwood et al., "Magnetic domain-wall logic," *Science* **309**, 1688 (2005).

▶ A. Manchon et al., "Current-induced spin–orbit torques in ferromagnetic and antiferromagnetic systems," *Rev. Mod. Phys.* **91**, 035004 (2019).

▶ S. S. P. Parkin, See-Hun Yang, "Memory on the racetrack," *Nat. Nanotech.* **10**, 195 (2015).

▶ Z. Luo et al., "Current-driven magnetic domain-wall logic," *Nature* **579**, 214 (2020); Z. Luo et al., "Chirally coupled nanomagnets," *Science* **363**, 1435 (2019).

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Iridium marks the spot

Between the reddish-brown, silty claystone and the gray limestone shown in this sediment core is a thin layer of clay, located at approximately the 34 cm mark in the image. Geologists identify that layer with the Cretaceous–Paleogene (K–Pg) boundary. At that geologic marker in time 66 million years ago, an estimated 75% of Earth's species became extinct, including the last dinosaurs. Two international collaborations in 2016 collected the sediment core from part of the Chicxulub crater buried underneath Mexico's Yucatán peninsula. Steven Goderis of Vrije Universiteit Brussel in Belgium and his colleagues recently analyzed the core's geochemistry. At the K–Pg boundary they found iridium in unearthly concentrations, which lends additional support to a long-held hypothesis: that an asteroid impact is responsible for the extinction event.

The researchers measured the concentrations of various elements in and around the K–Pg boundary layer of clay. They found the highest concentrations of iridium and other highly siderophile, or iron-loving, elements in the thin clay layer. Those elements aren't usually found at such high concentrations in Earth's crust and mantle, so their presence close to the surface indicates the deposition of meteorite material. Perhaps most telling, the high iridium concentrations match those of some 350 other places colocated in time, which suggests a meteorite impact with global environmental ramifications. (S. Goderis et al., *Sci. Adv.* 7, eabe3647, 2021; photo courtesy of J. Morgan et al., in *Proceedings of the International Ocean Discovery Program*, vol. 364, International Ocean Discovery Program, 2017.)

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