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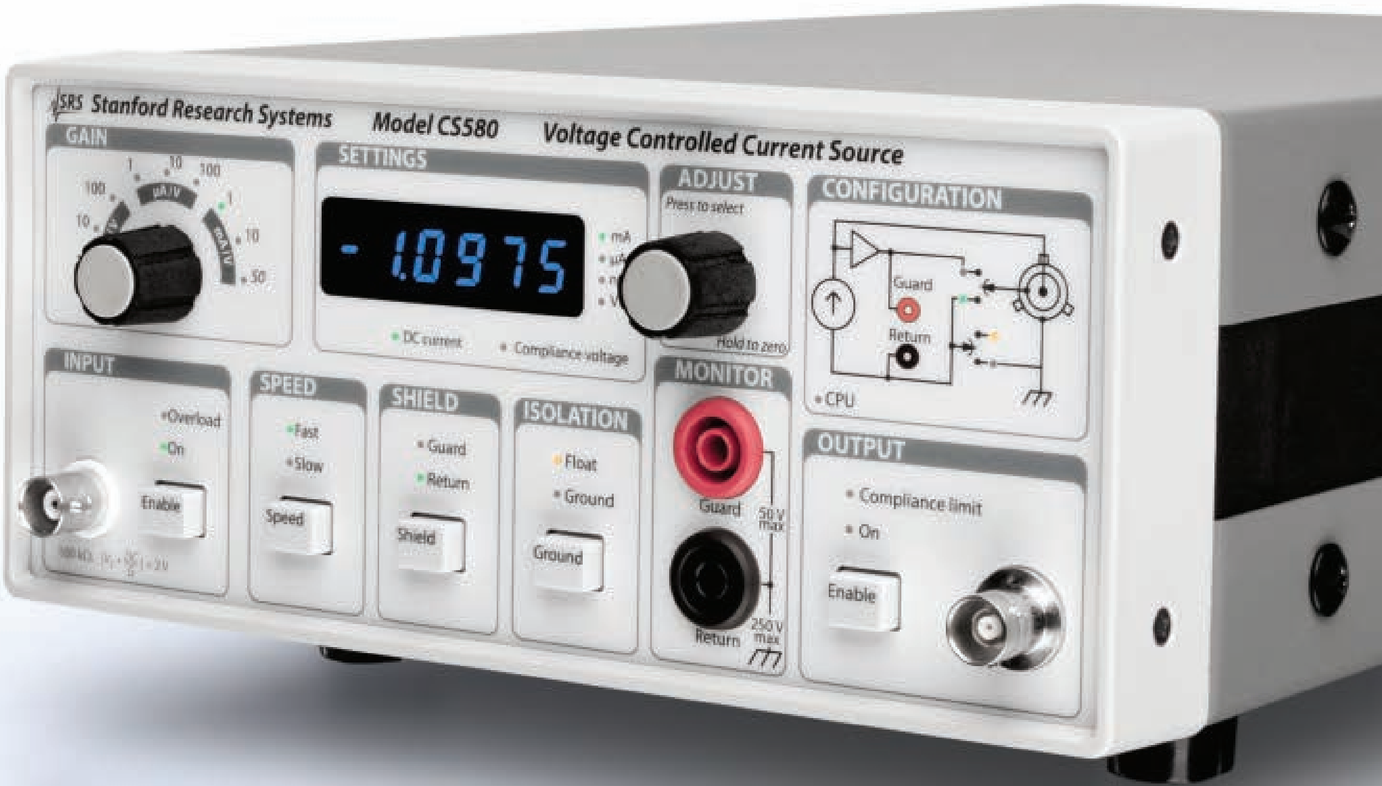

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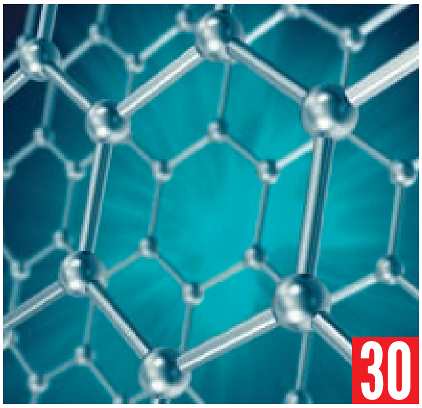

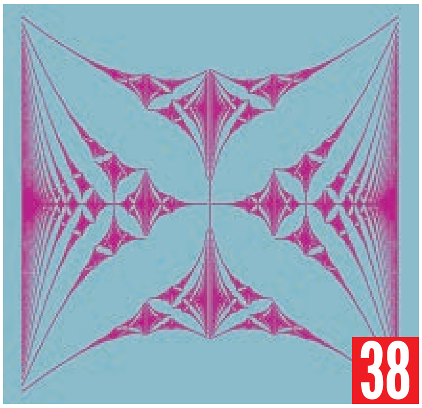

PHYSICS TODAY

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FEATURES

ON THE COVER: After dandelions flower, their heads close and reopen to reveal spherical white puffs of seeds. As illustrated here, each seed is topped by a bunch of filaments known as a plume or pappus. A new study shows that falling dandelion pappi produce a special type of vortex that retards their descent and extends the range of their wind-based travel. To learn more about how dandelion seeds fly, see the story on **page 17**. (Image by iStock.com/Godruma.)

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▶ Best of 2018

Take a look back at PHYSICS TODAY's most popular stories from last year, including several that can be found only online. Among the selections are a little-known anecdote about Albert Einstein and a story of a bitter feud between two top physical chemists that boiled down to a coding bug.

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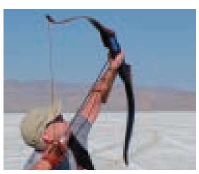

JAMES MARTIN

▶ On target

When James Martin isn't studying many-body interactions, he's shooting handcrafted arrows hundreds of meters. The physicist is a world-champion archer who has mastered flight shooting through skill, strength, and physics modeling. He describes his keys to success in a PHYSICS TODAY Q&A.

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▶ Relic references

Starting in May the SI kilogram will no longer be defined by a metal block. But some scientists continue to rely on artifacts as standards. PHYSICS TODAY's Alex Lopatka describes the water and old rocks, some of which are no longer available, that serve as reference materials for stable-isotope geochemists.

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Drafting physicists

Charles Day

George H. W. Bush enlisted in the US Navy in June 1942 as soon as he turned 18. Five months later all 18- and 19-year-old men in the US were made eligible for induction into the US military, whether they wanted to fight or not.

President Bush did not call on Congress to reinstate the draft to wage the Gulf War of 1990–91. He didn't have to. The military forces of the US-led coalition were sufficiently large and well equipped to secure victory in a swift, ferocious campaign. Crucially, the end of the Cold War had reduced the military threats facing the US.

That was not the case during the Vietnam War. To maintain its defensive commitments in Western Europe, South Korea, Japan, and elsewhere, the US reinstated the draft. And in the May 1967 issue of PHYSICS TODAY (page 136), the magazine's third editor-in-chief, R. Hobart Ellis Jr, devoted that month's editorial to the question of whether male physicists of military age should be drafted along with everyone else.

When Ellis began typing his editorial, Congress had yet to overrule President Lyndon Johnson's intended policy of ending deferments for all graduate students except for those pursuing degrees in medicine or dentistry. The struggle for Vietnam's independence and political system began in 1945, soon after British and French military forces displaced Japanese occupiers and restored French sovereignty. To Ellis, the prospect of a long war that diverted the country's young physicists from their education and careers likely seemed real and pressing.

Ellis's sympathies lay in drafting physicists along with everyone else. "Particularly in America," he wrote, "where sirs, vons and commissars have no special significance, tradition favors a democratic society in which all citizens share responsibilities equally." His own graduate education at Columbia University was interrupted by his service in World War II as a radar officer.

On the other hand, it was just as clear to the editorial's readers that Ellis was worried about the effect on US physics if the ranks of physics graduate students were significantly depleted for years.

By the time I reached the age of 18, compulsory military service in my native Britain had been abolished for two decades. It was only during graduate school, when I met young European astronomers, that I encountered contemporaries who had spent a year or so training to be airmen, sailors, or soldiers. A Norwegian uncomplainingly served for two years in the Norwegian military before starting on his BSc. Then, as now, Norway shares a land border with Russia. By contrast, an Italian resented spending eight months of his life in the army. He was proud, he told me, to have fired the minimum number of bullets—three, if I remember correctly—that his training required. A Dutch postdoc told me how he convinced the Netherlands draft board of his conscientious objection to war. Challenged by an examiner to say how he'd act if an enemy soldier was raping his sister in front of him, he replied that he and his sister would escape by climbing up a ladder: "If you can hypothesize an imaginary rapist, I can hypothesize an imaginary escape route."

By far the most thoughtful account by a physicist of being drafted appears in the captivating autobiography that Robert Laughlin wrote for the Nobel Foundation after being awarded the physics prize in 1998. The theoretical physicist had turned 19 when President Richard Nixon rescinded deferment for all students. Despite misgivings about the Vietnam War and despite recognizing that not being able to do physics for two years could harm his intended career, he did not evade the draft.

In his 1967 editorial, Ellis refrained from taking a position on drafting physicists. Instead, he closed it by encouraging readers to submit their thoughts on the question to the magazine. My position is conditional. If a country is a fully functional and representative democracy, then its citizens are obliged to follow its laws, including ones that mandate military service. To quote Laughlin about reaching his fateful decision,

> After stewing over this a long time I decided that I did not think defending one's country was wrong—although the Vietnam war had very little to do with defending one's country—that I could not lie about so important a matter [as my health], that I did not want to flee the country, and that I should obey its laws if I stayed. So that was that.

The question of whom to draft and when—to use the title of Ellis's editorial—remains relevant. Three years ago Representative Charles Rangel (D-NY) introduced a bill in the House to amend the Military Selective Service Act to reinstate the draft whenever the US is at war and to require women to register for selective service. Two years ago Senator John McCain (R-AZ) and others backed a provision of a defense bill that would have required women to register. The provision passed in the Senate, but it was later dropped. PT

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Reading through others' work can inspire new directions in my own work, even if it is relatively unrelated to my research.

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PHYSICS TODAY

Figures and quotes obtained from a *Physics Today* reader survey.

Commentary

Thinking about becoming a VPR?

If you are in a university that has a research portfolio of any size, odds are your institution has a VPR or VCR: a vice president/provost/chancellor for research. Whatever the titles and reporting structure, that person has responsibility for overseeing the institution's research enterprise, its integrity, and its compliance with legal and regulatory requirements, especially at the federal level. Depending on the school, other responsibilities may include graduate studies, university-wide institutes, or intellectual property, commercialization, and economic development. The VPR job often isn't seen as a rung on the ladder to a university presidency; the dean → provost → president path is more frequently trodden than any passing through the VPR's office.

When heading off to graduate school or deciding on a career, few academics likely had a goal of becoming a VPR—including those of us who have served in that role. I'm certain that none of us in the role fully appreciated the breadth, complexity, and challenges of the portfolio before we accepted it. So how did each of us get here, why do we love (and occasionally hate) the job, and what does it take to be successful? There are probably as many answers to those questions as there are past and present VPRs. My perspective is undoubtedly shaped by my own experiences—serving twice as a VPR (nonconsecutively and in different institutions), three times as a director of a center or institute, and seven years as a department chairperson.

Most VPRs come from the sciences, engineering, or medicine; my own education and academic home are in chemical engineering, with courtesy appointments in chemistry. Let's face it, if you don't have an appreciation for the capital demands, costs, regulatory issues, facilities needs, and safety responsibilities of conducting research in scientific fields, you will probably be underequipped for the role. Yet if you cannot credibly articulate the importance of and vigorously

JIM LYLE, TEXAS A&M UNIVERSITY

Mark Barteau joined Texas A&M University in February 2018 as its vice president for research. Earlier he served as senior vice provost for research and strategic initiatives at the University of Delaware.

support creative scholarship in the arts, humanities, and social sciences, including law, public policy, and business, you may find it difficult to provide vision and leadership of multidisciplinary efforts that address the grand challenges of today and tomorrow. Those efforts are not all about science and technology, even if scorekeeping by counting research dollars often gives that appearance. The best academic leaders are those who can recognize opportunity, articulate a vision, and draw in the talents and interests of faculty members in order to define and shape actions from the bottom up.

Research chops are also critical. A VPR who gives the impression that those who can't compete in research become research administrators is likely to be viewed by faculty members as a bureaucrat rather than as a champion and a leader. Nothing could be more damaging for motivating both the faculty and the VPR. Somewhere along the way one must also have learned to take satisfaction from fostering the success of others. Such servant leadership is essential. So is a real commitment to the professional development of team members at all levels.

Over the past decade or more, several trends have contributed to the need for larger, more complex, but also more agile operations under the VPR. Although some people may see that growth as yet another example of "administrative bloat," our response to the trends is critical to keeping US research universities, both individually and collectively, the best in the world.

The first trend is the ever-increasing compliance burden. A new VPR is likely to be hit with an alphabet soup of committees (IACUC [institutional animal care and use committee], IRB [institutional review board], and more) and responsibilities (research integrity, export controls, and biosafety, to name a few) to which he or she may have had limited exposure as a researcher. Changes in funding-agency requirements—whether dealing with archiving and securing data or with the Common Rule, which governs research on human subjects—necessitate that the compliance team be engaged with faculty members and effectively communicate why "the way it was done last time" may no longer be satisfactory.

Compliance oversight is often a balancing act: helping faculty members carry out research in a demonstrably compliant way, with minimized burdens and hurdles, while also working cooperatively with the lawyers and auditors who often see their jobs as risk minimization rather than risk management. At major research universities, the compliance infrastructure is usually reasonably complete in extent if not always in depth. However, having mentored leaders from aspiring research institutions participating in NSF's Experimental Program to Stimulate Competitive Research and the National Institutes of Health's Institutional Development Award program, I think it is fair to say that aspiring research institutions often underestimate the extent of their compliance needs.

The second, and more rewarding trend, is the rise of coordinated research development activities under the VPR. When I first hired an individual for such a role a decade ago, my short version of the job description was "matchmaker-in-chief"—someone who could help bring together faculty members from different fields and connect them with each other and with outside collaborators and funders to increase research competitiveness and impact. Around the same time, the National Organization of Research Development Professionals was established, recognizing the growing need for leadership and support in research development.

The drivers for the two trends have come from several directions, including the shift in federal funding away from single-investigator, curiosity-driven research and the increasing role of research universities, both public and private, in economic development. That expanding role has led to a heightened emphasis on intellectual property, entrepreneurship education for students and faculty, and commercialization. Although some people may view those topics as outside the traditional core of universities' research portfolios, they have become integral to developing partnerships and funding opportunities that benefit students and faculty and boost institutional reputations.

For me, what's important is not the title or prestige of being the VPR, it's the programs, partnerships, and facilities that I can drive forward in that role. It's enabling faculty and students to unleash their creative talents. It's the satisfaction of building launching pads for future research successes, whether they come quickly or long after one's leadership has been forgotten. Finally, it's the call to be a champion, both within the university community and beyond—to alumni, community and business leaders, elected officials, media, thought leaders, and more—for the vitality of our research universities. How better to help meet the challenges of today and to ensure that we advance the human and scientific capabilities to meet those of tomorrow?

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LETTERS

Modern society depends on publicly supported science

As a researcher who depends on grants for all of my work, I am alert to new funding sources. Therefore, I read "Foundations play a supporting role in basic science" (PHYSICS TODAY, June 2018, page 26) with interest. I was disappointed to find only positive anecdotes without any discussion of the potential downsides of privately supported science. Those downsides should be part of any examination of the topic.

It will not serve us well to depend on the whims of those who, using talents largely unrelated to scientific challenges, have accumulated the billions of dollars that allow them to make large donations. Those whims often tend toward the photogenic, the engaging, and the easily explained. Philanthropic choices happen almost by chance, depending on whom a donor met at an event, which news story caught her eye, or what appealed to his personal interest. The scientific judgment of billionaires is unlikely to coincide with the real needs of research progress.

Publicly supported science, in contrast, is an admittedly imperfect system of rational decision making about research investments. It recognizes that much necessary science is unglamorous and even routine. That is certainly the case in my field of climate science. Much of the real work consists of ongoing monitoring of field conditions; those measurements are essential for discerning slow and complex variations in an environment filled with chaotic day-to-day events. By definition, if you are looking for a signal that manifests over decades, you must be prepared for many years of careful observation without near-term reward. A philanthropist is not likely to support that task, especially since any "discovery" will make sense only in the context of a much broader research enterprise. It requires long-term public investment that is now sadly shrinking.

Other fields of science have their own examples, but we are long past the day when individual donors can direct the research that modern society depends on. That responsibility is inherently a public one in a physically and economically interdependent world, and the work is fundamentally communal and long-term. Increased taxes on great wealth could strengthen public science and produce a better result.

Disclaimer: The views expressed here are mine alone, not those of my employer.

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Quantum corral herds surface electrons into a fractal lattice

The method, based on scanning tunneling microscopy, lets researchers explore quantum mechanics in geometries not found in nature.

String theory notwithstanding, we live in three-dimensional space. But physics in other numbers of dimensions need not be a purely theoretical exercise. Atomically thin materials such as graphene are well described as 2D systems (see PHYSICS TODAY, December 2010, page 14), and polymers and quantum wires have many 1D characteristics.

Sometimes changing the number of dimensions effects a qualitative change in a system's properties. For example, the Ising model of coupled spins undergoes a phase transition at nonzero temperature in two or more dimensions, but not in 1D.

What if the dimensionality could be tuned continuously between 1 and 2? That's not just a hypothetical question: Fractals, such as the Sierpinski triangle in figure 1, have fractional dimensionality. But although fractal-like shapes abound in the natural world—rugged coastlines and branched leaf veins, for example—few platforms exist for realizing microscopic physics in fractal geometry.

Now Ingmar Swart, Cristiane Morais Smith, and colleagues at Utrecht University in the Netherlands have taken a step toward probing quantum physics in a real fractional-dimensional system.[1] On a (111) surface of copper, they placed carbon monoxide molecules (shown as black indentations in the figure 1 inset) to corral the surface electrons into a simplified Sierpinski triangle. The electron density inside the triangle is an approximation of the fractal, just as a graphene sheet is an approximation of an infinitely thin plane. But like graphene, the surface-electron system inherits some of the dimensional properties of its mathematical idealization.

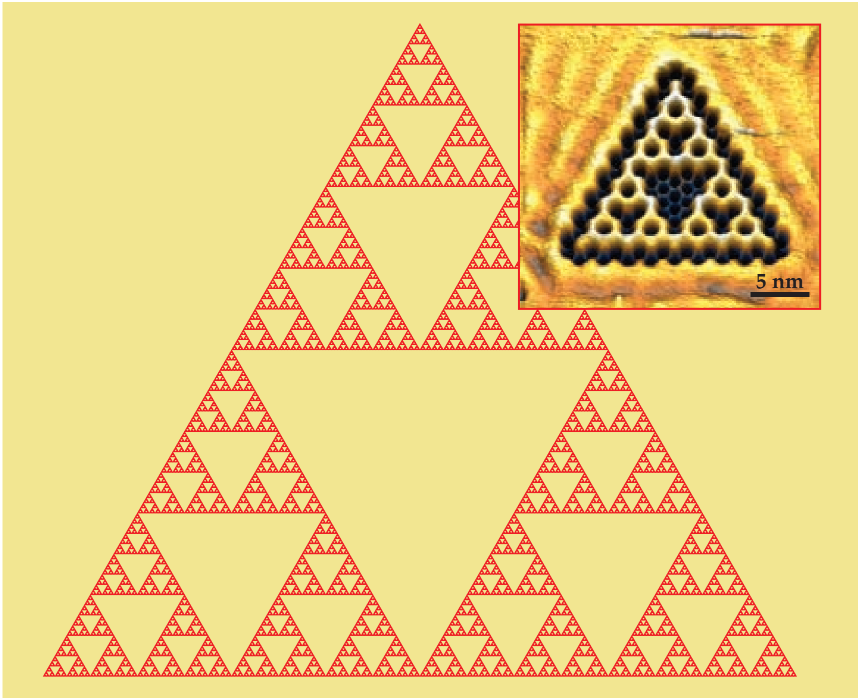

FIGURE 1. THE SIERPINSKI TRIANGLE is a self-similar fractal composed of three smaller copies of itself. The inset shows a scanning tunneling microscope image of a Sierpinski lattice created by the quantum corral method: Carbon monoxide molecules (black) on a copper surface confine the surface electrons to the fractal geometry. (Image by Beojan Stanislaus, CC BY-SA 3.0; inset courtesy of Cristiane Morais Smith.)

Physics in fractland

The basic definition of the dimension of a shape is the number of coordinates needed to specify a point within it. After allowing for topological transformations, whereby a donut is equivalent to a coffee cup, even a squiggly line has dimension 1, a crumpled plane has dimension 2, and so on. (Making that definition perfectly rigorous is surprisingly tricky, because it's possible to construct an infinitely long, infinitely squiggly line that visits every point in a higher-dimensional space. But mathematicians have figured it out.)

A century ago Felix Hausdorff came up with a new way of defining dimension that could take noninteger values. In effect, it's how the number of boxes needed to cover a shape scales with the size of the boxes. For most familiar shapes—points, lines, planes, and the like—the Hausdorff dimension is equal to the usual topological dimension. But certain infinitely intricate shapes, which wouldn't be called "fractals" until Benoit Mandelbrot coined the term in 1975, have fractional Hausdorff dimension.

Wacław Sierpiński, a contemporary of Hausdorff, first wrote about his triangle in 1915, although versions of it had been used decoratively for hundreds of years before that. The shape is defined by its exact self-similarity: The large triangle, 1 unit on a side, is made up of three copies of itself, each 0.5 unit on a side. Self-similarity does not by itself a fractal make, though. Nonfractal lines and planes are self-similar too: A 1-unit line segment is made up of two 0.5-unit copies of itself, and a 1-unit filled-in square is composed of four 0.5-unit squares. In each case, the Hausdorff dimension is equal to the base-2 logarithm of the number of copies, so the line has dimension 1, the square has dimension 2, and the Sierpinski triangle has dimension $\log_2 3 = 1.58$.

Since the early 1980s, theorists have

investigated the statistical and quantum physics of fractal lattices,[2] and one of the first problems they tackled was whether spin systems such as the Ising model undergo phase transitions at nonzero temperature in dimensions between 1 and 2. As it turned out, the answer depends not on the dimension but on the so-called order of ramification, a measure of how much cutting is required to break the system into disconnected pieces. The Sierpinski triangle has a low order of ramification—one can isolate any of the smaller triangles from the rest of the lattice simply by snipping its three corners—and the Ising model on a Sierpinski-triangle lattice exhibits no phase transition. But other, more robustly connected fractals do show phase transitions, even if their Hausdorff dimension is the same or lower than the Sierpinski triangle's.

Synthetic lattices

Limited only by their own imaginations, theorists can explore the physics of a system of any shape. But real atoms aren't known to naturally arrange themselves into Sierpinski triangles, so experimenters have an extra step. The technology for realizing artificial lattices on metal surfaces dates back a quarter century, but only recently have researchers begun to exploit it for that purpose.

In a defect-free bulk crystal, translational symmetry dictates that electron wavefunctions take the form of delocalized Bloch waves. At the crystal surface, however, that symmetry is broken, and the Schrödinger equation admits additional solutions localized at the surface. On Cu(111) and certain other metal surfaces, the surface-state energies coincide with a bulk bandgap, so the surface and bulk states cannot mix: Some electrons are physically confined to the surface, where they behave like an ideal 2D electron gas.

In 1993 Donald Eigler and colleagues at IBM's Almaden Research Center showed that they could corral those surface electrons with a ring of iron atoms placed on the surface with the tip of a scanning tunneling microscope (STM).[3] (See Physics Today, November 1993, page 17.) The adsorbed atoms have their own electrons bound to their nuclei, and repulsive interactions create an energy barrier—a fence—for the surface electrons, which are otherwise free to move around inside their corral. The STM serves a dual purpose: It not only moves the atoms into place but also maps the spatial density of the corralled electrons.

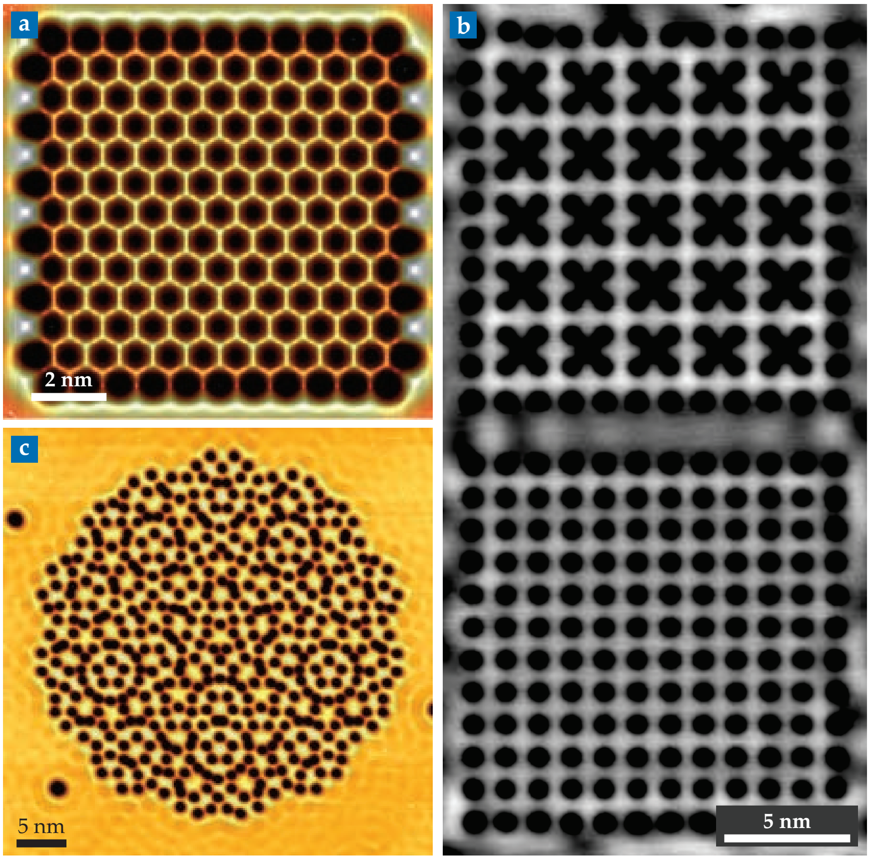

FIGURE 2. THE MANY SHAPES of quantum corral lattices. **(a)** Artificial graphene behaves much like real graphene, but its honeycomb structure is several times larger. (Adapted from ref. 4.) **(b)** The Lieb lattice (top) and square lattice (bottom) show that quantum corrals need not share the hexagonal symmetry of the underlying surface. (Adapted from ref. 5.) **(c)** With a quasicrystalline lattice, researchers have explored electronic states at the boundary between order and disorder. (Adapted from ref. 6.)

In 2012 Hari Manoharan and colleagues at Stanford University created the first quantum corral lattice, artificial graphene,[4] shown in figure 2a. The densely packed CO molecules leave the surface electrons confined to a honeycomb network of thin paths. The synthetic lattice has a couple of advantages over real graphene. It's several times larger, so the electron wavefunctions can be more readily mapped in real space. And it's tunable: Tweaking the lattice structure introduces effects analogous to charge-carrier doping and applied magnetic fields.

Figures 2b and 2c show some of the other lattices that have been created: The Lieb lattice and square lattice made by Swart, Morais Smith, and colleagues[5] and the quasicrystalline lattice assembled by Kenjiro Gomes and colleagues at the University of Notre Dame.[6] (For more on quasicrystals, see Physics Today, December 2011, page 17.) Importantly, the newer lattices break free of the underlying hexagonal symmetry of Cu(111). Together they show the potential of quantum corralling as a platform for simulating one quantum system—electrons in a solid, usually—with another. The current leading method for quantum simulation uses ultracold atoms in arrays of optical traps (see Physics Today, October 2010, page 18; August 2017, page 17; and the article by Victor Galitski, Gediminas Juzeliūnas, and Ian Spielman on page 38 of this issue). Corralled surface-electron systems can offer a complementary set of capabilities, such as having particles that are charged, not neutral.

Although the STM technology is mature, the experiments remain extremely difficult. To build and probe a lattice of dozens or hundreds of atoms takes about a week, during which time the STM tip must be held near the surface, with atomic precision, without ever touching it. (A single tip crash, a common user error even in well-automated experiments, will destroy an entire lattice.) Fortunately, Marlou Slot, Swart's PhD student at the fore of the experimental effort, was up to the task. "She is an outstanding STM professional," says Morais Smith, "and built our largest lattice in only one weekend."

Building the triangle

Inspiration for the Sierpinski lattice came from two directions. First was Morais Smith's past theoretical work on electrons in multilayer graphene, which behave in many ways that are intermediate between 2D and 3D. Second was her recent exploration of fractals to try to get her stepdaughter interested in math. A fractal quantum corral, she realized, could open up the largely uncharted experimental world of electrons between 1D and 2D.

It was a nontrivial task to find just the right arrangement of CO molecules to create the Sierpinski-like corral. Fortunately, the trial and error could be done computationally, saving the experimental team the effort of building too many lattices that wouldn't work. Calculations by Morais Smith's student Sander Kempkes settled on the arrangement shown in the inset in figure 1, and that's the one they realized experimentally.

The researchers used the box-counting method to calculate the Hausdorff dimension of the wavefunction inside the triangle: How many circles of radius r does it take to cover the wavefunction, and how does that number scale with $1/r$? With the true, infinitely detailed Sierpinski triangle, the power-law dependence with exponent 1.58 extends all the way to the limit of $r = 0$. For the quantum corral wavefunction, that's not the case, but the power-law relation still extends over more than an order of magnitude in r—similar to other fractal-like shapes in the physical world. Says Morais Smith, "We got shiny eyes when we realized the electrons were really living in 1.58 dimensions."

The proof-of-principle experiment is not yet at the point of revealing any new physics. One of the most intriguing open questions is how an ensemble of interacting electrons behaves in noninteger dimensions. Fermi liquid theory, which describes interacting electrons in two or more dimensions, breaks down in 1D. And Luttinger liquid theory, which replaces it, has some unusual features, such as the independent propagation of charge and spin waves (see PHYSICS TODAY, September 1996, page 19). What happens in 1.58 dimensions is not known. Unfortunately, the surface electrons of Cu(111) don't interact strongly enough to find out. Surfaces of other materials, however, might allow the researchers to study interactions in fractal geometry.

ON THE WEB
PHYSICS TODAY EDITOR JOHANNA MILLER shares her perspective on dimensional effects in physics and mathematics.
physicstoday.org/fractal

Johanna Miller

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Dandelion seeds are optimized for wind-based travel

A newly observed type of vortex stabilizes the flight of plumed seeds.

For a plant species to survive and proliferate, it must disperse its seeds. A seed is more likely to thrive away from its parent plant because there is less competition for resources. Spreading helps the population find new environments, be less vulnerable to predators and pathogens, and boost its genetic diversity.

Seeds, though, do not propel themselves; rather, they hitch rides on animals, flowing water, or gusting wind. For travel by wind, seeds use one of two mechanisms: wings or plumes. Winged seeds, like those from maple trees, generate lift by using a stable leading-edge vortex as they fall.[1] Plumed seeds, such as those of dandelions, amplify drag by using a bundle of filaments known as a plume or pappus. The additional drag prolongs the seed's descent and increases the chance that a breeze can arrive to carry it away.

Whereas some researchers assumed that pappus-mediated flight functioned in the same way as a parachute, Cathal Cummins, Ignazio Maria Viola, Naomi Nakayama, and their coworkers at the University of Edinburgh suspected that something else might be going on. They used a vertical wind tunnel to look at the flow around a falling dandelion seed and observed above the pappus a hovering ring of circulating air known as a separated vortex ring (SVR).[2] Such fluid flow had been considered theoretically, but until now was presumed too unstable to be physically realized.

During a seed's flight, the researchers found, aerodynamic interactions between filaments enhance the drag on the pappus so much that the pappus generates four times as much drag as a solid membrane of the same surface area. To investigate the source of the drag, they fabricated artificial dandelion seeds with different pappus geometries. Not every artificial pappus generated an SVR, but the researchers found that real dandelion seeds are optimized to do just that.

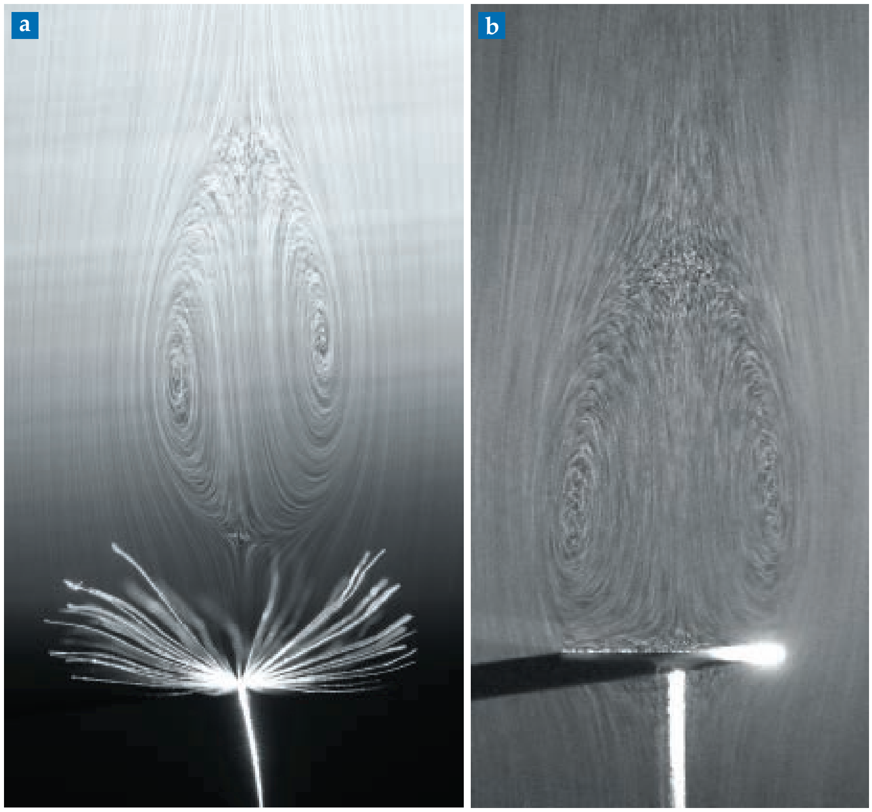

FIGURE 1. TWO TYPES OF VORTICES. **(a)** A dandelion seed in a vertical wind tunnel generates a separated vortex ring with the stagnation point sitting above the pappus. **(b)** By contrast, the vortex for a solid disk is attached and has a stagnation point on the disk's surface. (Images courtesy of Cathal Cummins, Madeleine Seale, Enrico Mastropaolo, Ignazio Maria Viola, and Naomi Nakayama.)

A new type of flow

A vortex that is generated in the wake of a falling object has two stagnation points at which the fluid velocity goes to zero. For a solid body, like a disk or a parachute, one of those points is attached to the surface of the object. A vortex creates a region of low pressure behind the object that retards its fall through the air. If the vortex becomes unstable, it separates from the surface and moves upward as another vortex forms in its place. That sequence of events creates an oscillating flow in the wake of the object and causes it to tumble chaotically like a falling coin instead of descending smoothly like a parachute.[3]

Unlike a solid body, a dandelion pappus is filamentous, so air can flow through it in addition to going around it. To investigate how that difference might affect the flow around the whole seed, Cummins built a vertical wind tunnel. He added smoke as a tracer and used laser light to image a two-dimensional vertical cross section of the three-dimensional flow. From the light scattered in the imaging plane, the paths of the smoke particles could be reconstructed and used as a proxy for the airflow.

When Cummins placed the dandelion seeds in the wind tunnel and tuned the flow such that the seeds hovered at a fixed height, he observed the formation of an SVR. In the images, it looked like a vortex bubble was hovering above the pappus, as shown in figure 1a. Unlike in the case of a solid disk, shown in figure 1b, the stagnation point sits above the pappus; it can't be attached because air is flowing through the filamentous structure. However, the separated vortex does not move away from the seed. Instead, it stays at a

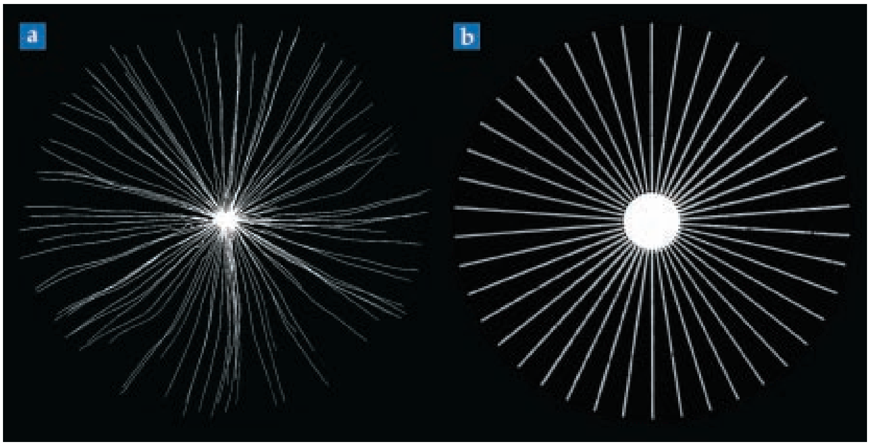

FIGURE 2. POROUS PAPPI. (a) Dandelion seed pappi have porosities close to 92%. **(b)** Replica structures made from silicon enabled the researchers to investigate the formation of a separated vortex ring. Pappus diameters are approximately 1 cm. (Images courtesy of Cathal Cummins, Madeleine Seale, Enrico Mastropaolo, Ignazio Maria Viola, and Naomi Nakayama.)

fixed height above the pappus and creates a low-pressure region that stabilizes the seed's flight.

When the researchers set out to study dandelion-seed flight, they didn't expect to find an SVR. "It was a surprise," says Nakayama. But they did have an inkling that they would see interesting flows. "We kind of knew that something cool was going on, so we were definitely keen to see the fluid behavior from the beginning." And their intuition proved right: The SVR, with its steady detached flow, had never been seen before. The mechanism they uncovered is "effectively a new way of flying," says Viola.

Artificial plumes

Nakayama, a biomechanics researcher, was always interested in studying plumed-seed flight for its implications in plant ecology and habitat establishment. However, it was not until she moved to the University of Edinburgh that she could tackle the problem. There, she teamed up with her "partner in crime" Viola, a fluid mechanist, and with Cummins, an applied mathematician studying biological flows.

After observing the SVR above the dandelion pappus, Nakayama, Viola, and Cummins wanted to further investigate seed flight and vortex formation. Natural dandelion seeds are remarkably uniform in their geometry. To explore a range of seed geometries, the researchers needed to replicate the delicate structures. Enrico Mastropaolo, a microfabrication expert at Edinburgh, became the fourth crucial collaborator on their team. He used photolithography and microfabrication techniques to make artificial silicon seeds with pappi ranging from solid to highly filamentous. One of his replica seeds is shown in figure 2.

The researchers found that a pappus's ability to form a stable SVR depended on two factors: its porosity, which is defined as the empty fraction of a circle enclosing the pappus, and the ambient Reynolds number, which describes the relative importance of inertial forces to viscous forces in the flow around the seed; for a seed fixed in the wind tunnel, the Reynolds number is directly proportional to the wind speed. Figure 3 shows the measured dependence of stable vortex formation on porosity and Reynolds number. At each porosity, the SVR became unstable above a critical Reynolds number, and that value increased with porosity.

All of the freely flying natural seeds that the researchers tested generated stable SVRs. Their measured Reynolds numbers were just below the critical value when they were falling at their terminal velocity (about 39 cm/s). At 92%, the porosity of a real pappus could hardly be higher, but if it were any lower, the resulting vortex would be unstable. Dandelion seeds have very similar porosities and weights wherever they come from, notes Nakayama. "A lot of things in biology tend to be so variable," she says, but for dandelions, "when you look at their design, their structure, the variations are quite tight. And that tightness is necessary to hit the sweet spot in how this flight mechanism works."

Generating drag

With such high porosity, it's not obvious that a dandelion pappus would be able to significantly slow a seed's descent. Traditional models of pappus drag assumed that each filament could be treated as a cylinder and that the total drag would be the sum of each filament's contribution. But the Edinburgh researchers found that the drag coefficient predicted by a noninteracting pappus model fell far short of the value they derived from their observations. The experiment was better described by a model for flow through comb-like structures. Such a

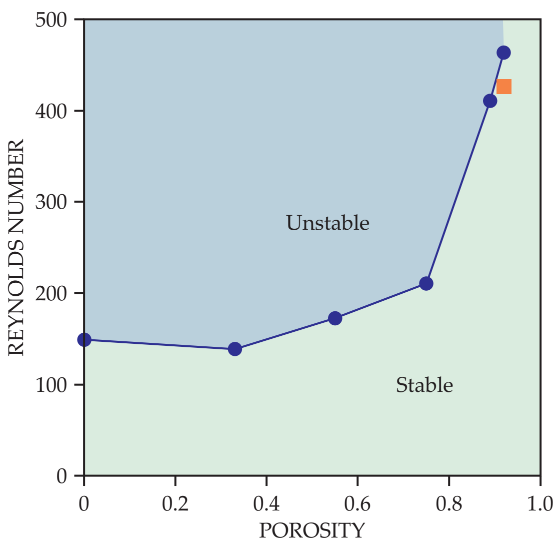

FIGURE 3. VORTEX STABILITY. The pappus porosity and Reynolds number, a dimensionless measure of a flow's turbulence, determine the vortex stability. For a given porosity, there is a critical Reynolds number below which a stable separated vortex ring (SVR) forms. Dandelion pappi, indicated by the orange square, have a porosity that is just high enough to ensure stability. That makes them optimized for generating drag with an SVR, which is how they fly. Above that value, the vortex ring is unstable and moves away from the pappus. (Adapted from ref. 2.)

model accounted for thick boundary layers around the filaments[4] and explained the increased drag that keeps a seed aloft.

To investigate how efficiently a real pappus generates drag, the researchers compared it with a solid disk that generates the same amount of drag. Because the dandelion seeds are naturally so uniform in weight and geometry, they had to be weighted and trimmed to vary their drag force. The researchers then determined the drag coefficients of the seeds by measuring their terminal velocities.

In each case, the solid disk that generated the same drag as a dandelion pappus had a smaller diameter but took up four times as much area. In terms of material used, that makes the pappus more efficient than a solid membrane. If an equivalent disk used as little material as a pappus, it would be about 1 μm thick, which is about the size of a small bacterium. The membranes of real seeds are typically hundreds of microns thick.[5]

Plants aren't the only ones using bristly structures to generate drag. Some small insects, such as *Thrips physapus*, have wings that resemble dandelion filaments. "They're just a bunch of hairs. And then they fly with it," says Nakayama. The wings of such insects have a similar size and porosity to dandelion pappi, which suggests that they may also generate SVRs when the insects fly. She also notes that underwater organisms use tentacled feeding structures to sift food out of water. "They're just around the right size for this kind of vortex to occur," says Nakayama, "so marine scientists wonder if they might navigate particles in water with this kind of interesting flow behavior."

Now that they know what to look for, scientists may find that SVRs underlie functions in a wide range of biological systems.

Christine Middleton

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An ancient merger helped form our galaxy

Measurements from the *Gaia* spacecraft suggest a large star system merged with the Milky Way 10 billion years ago.

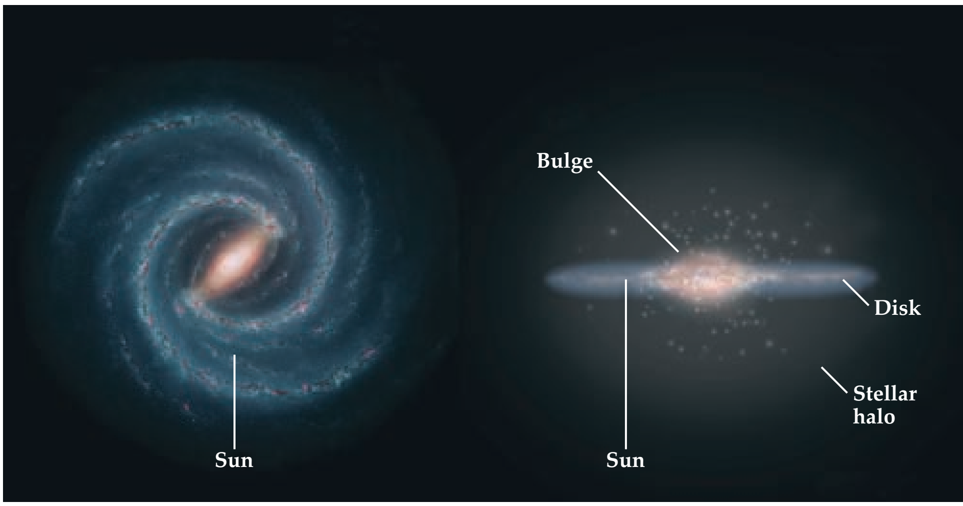

FIGURE 1. THE STRUCTURE OF THE MILKY WAY GALAXY. The Sun is about 8 kiloparsecs (about 26 000 light-years) from the galactic center. The disk is composed of a thin component surrounded by a thick component. The halo, a diffuse sphere of stars, envelops the galactic disk. (Left image by NASA/JPL-Caltech; right, ESA; layout, ESA/ATG medialab.)

The *Gaia* space observatory, built, launched, and managed by the European Space Agency, aims to create the most ambitious star catalog to date: a map of about 1% of the estimated 100 billion–400 billion stars in the Milky Way. The first data release in September 2016, DR1, provided astrometric information for about 1.1 billion stars. The second data set, DR2, released in April 2018, includes celestial positions for almost 1.7 billion additional stars.[1]

When a star is formed, it usually keeps the orbital energy and angular momentum from its parent galaxy (see the article by Joseph Silk, Physics Today, April 1987, page 28). By tracking the position and velocity of many stars, astronomers can learn whether any of them were part of a galaxy when it formed or whether a star group was accreted later in a merger. Today, it's relatively uncommon for two big galaxies to merge. But 12 billion to 13 billion years ago, when the Milky Way first formed, the probability of an event was likely higher because the universe was smaller and galaxies would have interacted more easily. Efforts to uncover that galactic history were limited before *Gaia*'s most recent star catalog release.

From the new data, astronomers Giuliano Iorio and Vasily Belokurov from the University of Cambridge have found new evidence that the Milky Way merged with a smaller galaxy long before the birth of our solar system.[2] A second, independent team, led by the University of Groningen's Amina Helmi, came to the same conclusion and determined that the merging galaxy collided with ours about 10 billion years ago.[3] The work from both teams suggests that most of the galaxy's halo, a diffuse sphere of stars that envelops the galactic disk, was formed from that singular event.

Stars, stars everywhere

Our location deep inside the Milky Way, 8 kiloparsecs (about 26 000 light-years) from the center, makes it impossible to see the galaxy from a bird's-eye view, but we can infer its structure. The barred spiral galaxy, as shown in figure 1, comprises a dense, central bulge; a disk with

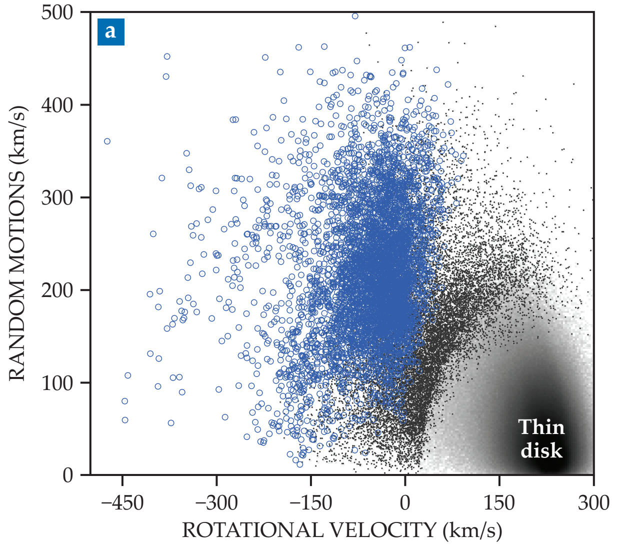

FIGURE 2. VELOCITY DISTRIBUTION of stars in the Sun's vicinity reveals two populations of different origin. **(a)** Velocity components of stars that are within 2.5 kiloparsecs (about 8200 light-years) of the Sun. Blue dots represent halo stars with predominantly retrograde orbits; black dots, halo stars without retrograde orbits and stars in the galactic disk. **(b)** Velocity components inferred from a simulation of a merger that formed the galactic disk. (Adapted from ref. 3.)

a diameter of 30 kpc; and a halo. The inner, thin disk is about 0.3 kpc high and is surrounded by a thicker disk 1.0 kpc high. In earlier efforts to study the Milky Way's halo, astronomers had only a small number of stars available, which covered a limited part of the sky. But the *Gaia* mission provides an all-sky view of the halo. The new astronomy data include proper motion—a star's movement across the sky—and parallax, a measure of the apparent change in a star's position, which can be exploited to determine its distance.

From the *Gaia* DR2 catalog, Iorio and Belokurov selected about 93 000 stars after removing those associated with globular clusters, satellite galaxies, and binary stars whose spectra cannot be resolved from one another. The stars are all of a type known as RR Lyrae stars and are located within 30 kpc of the galaxy's center. Belokurov says they "are a perfect tracer of the accreted stellar populations. They don't have contamination from the disk and can be found at many different distances from the center."

To analyze how the star density changes as a function of position in the galaxy, Iorio and Belokurov subdivided the sample into groups based on the stars' displacement from the galactic disk. They found that the stars' orbits in the inner halo, which is 5–10 kpc from the disk, were stretched and elongated. The shape indicated that in its past the Milky Way may have experienced a merger near the disk. When a galaxy merges with another, "the stars themselves are collisionless," says Belokurov. In a simplified, one-dimensional picture, when two galaxies smash together, he says, "the final configuration will be stretched along the line connecting them."

Whereas Iorio and Belokurov focused on stars far from the Sun, Helmi and her team selected stars within 2.5 kpc of it. "What our team discovered," she says, "is that there are a large number of stars moving in elongated and retrograde orbits." Figure 2a shows the measured velocity distribution of stars in the solar vicinity. Stars with the elongated, retrograde orbits occupy a region of velocity space that differs from the one occupied by stars in the galactic disk. That distinction provided Helmi and her team with their first clue that those stars traveling in the opposite direction may not have always been a part of our galaxy.

Evidence from chemical abundances

The idea that a large satellite galaxy merged with the Milky Way is not new. In a 2018 study,[4] Belokurov and colleagues analyzed stars located about 10 kpc from the Sun. They looked at velocity information from *Gaia* DR1 and chemical abundance data from the Sloan Digital Sky

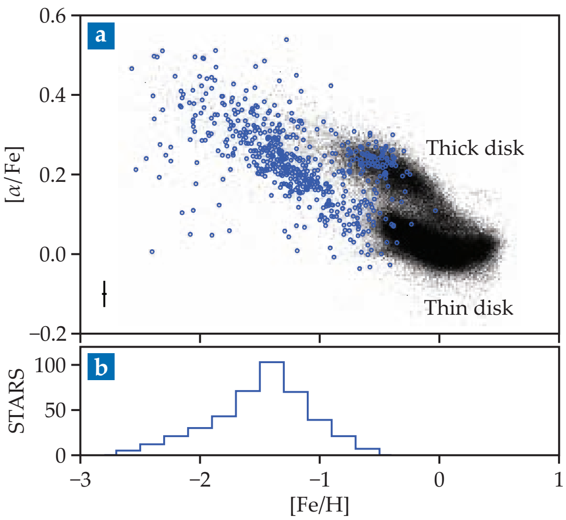

FIGURE 3. CHEMICAL ABUNDANCES of stars in the Sun's vicinity reflect their origin. In **(a)**, the same sample of stars from figure 2 were cross referenced with chemical abundance data from the Apache Point Observatory Galactic Evolution Experiment. The galaxy's thick disk surrounds its thin disk. α represents the collective abundance of oxygen, magnesium, silicon, sulfur, calcium, and titanium. Blue dots represent halo stars with predominantly retrograde orbits; black dots, halo stars without retrograde orbits and stars in the galactic disk. **(b)** A histogram of the iron-to-hydrogen abundance ratio of the stars with retrograde orbits. (Adapted from ref. 3.)

Survey. As a proxy for the rate of star formation, they used the abundance of iron relative to hydrogen.

When stars in a galaxy explode in supernovae, they enrich the gas around them with elements heavier than helium (see the article by Anna Frebel and Timothy C. Beers, PHYSICS TODAY, January 2018, page 30). In a small galaxy that lacks sufficient gravitational forces, those elements are expelled. But a massive galaxy like the Milky Way tends to accumulate those elements, and so more stars are formed in subsequent cycles. Two populations of stars emerged when Belokurov and company looked at their star samples from the halo. One population, with a large abundance of iron relative to hydrogen, was stretched in the radial direction. The population lower in iron was not. The abundance of metal was evidence that the merging galaxy was massive.

Although Helmi and her group had previously studied mergers, the release of *Gaia* DR2 allowed them to compare a larger sample of star velocities with their chemical abundances and test the merger hypothesis more rigorously. The chemical abundance information came from cross-referencing their *Gaia* data with that from the Apache Point Observatory Galactic Evolution Experiment. "The chemistry really pinned it down," says Helmi. In a plot of chemical abundance shown in figure 3, the stars with retrograde orbits occupy a different region than the stars in the disk. "This only can happen if the stars were born elsewhere," says Helmi.

The chemical abundance analysis also allowed Helmi and her team to estimate the merger's timing. The researchers plotted the stars on a Hertzsprung–Russell diagram, which at its simplest shows a star's brightness as a function of its temperature, or color. A model developed in 2014 determines a star's age based on its metallicity and location in the Hertzsprung–Russell diagram.[5] By matching age-modeling data with their sample of stars near the Sun, Helmi and her colleagues estimate that a merger happened roughly 10 billion years ago.

Simulating collision

To increase confidence in their observational results, Iorio and Belokurov compared the proper motions of their *Gaia* DR2 star selection with three kinematic models of star velocity. In the isotropic model, the radial- and tangential-velocity components are equal. In the radially anisotropic model, radial components are higher than tangential components. Those components are reversed in the tangentially anisotropic model.

The proper motions of most stars between 4 kpc and 30 kpc from the galactic center agreed best with the radially anisotropic model, which is expected after a major merger. What's more, the researchers inferred that most other halo-star kinematics indicate a merger, providing further support that the satellite galaxy was massive.

Helmi and her colleagues reached a similar conclusion. When they first plotted the retrograde stars, as seen in figure 2a, she had a moment of déjà vu. "I recognized the plot from that of a former PhD student who did an *N*-body simulation," she says. Sure enough, when they compared the measured velocities with the merger simulation completed 10 years ago,[6] reproduced in figure 2b, they found agreement. Whereas the simulation used a mass ratio of 1:5 for the satellite galaxy to the Milky Way, the observations showed a mass ratio of 1:4. The analysis suggests that the merging galaxy was relatively large. "I find it rather surprising," says Helmi, "that what we call the halo may actually be fully made from this one single object."

Now that the merger hypothesis has stronger support, one of the next research topics is learning how the event unfolded. "I think you need to go one step further and describe what happened to the gas," says Helmi. "In the past, galaxies were richer in gas, so that must have had a huge impact on star formation." The *Gaia* DR2 is an intermediate collection of data; an even larger and more complete star catalog should be completed in 2021.

Alex Lopatka

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PT

Iranian scientists persevere under renewed sanctions

The greatest impact on science and society comes from the devaluation of currency.

UNIVERSITY OF TEHRAN

ROBOTS that aid the sick and elderly are being designed at the University of Tehran; the next version is scheduled to come out in February. Such work proceeds despite the difficulties, under sanctions, of obtaining parts and exchanging know-how.

If you ask scientists in Iran, they are likely to say that not much changed for them professionally when the US pulled out of the Joint Comprehensive Plan of Action (JCPOA) last May and then renewed sanctions this past fall. Many will also tell you that the nuclear deal itself—signed in 2015, with sanctions lifted beginning in January 2016—did not lead to significant improvements. "We have learned to live and work in difficult conditions," says Ali Akbar Saboury of the Institute of Biochemistry and Biophysics at the University of Tehran. Saboury recalls the eight-year Iran–Iraq War, which ended in a stalemate in 1988 after hundreds of thousands of Iranians and Iraqis had lost their lives. As for the current sanctions, he says, "we continue our research."

Still, the anticipation of reduced restrictions did spark hope among scientists that they could participate more easily and fully in the international scientific community. And steps were taken in that direction. The effects of the renewed sanctions are tangled up with visa restrictions, with ongoing political uncertainties in the country, and with the free fall of Iran's currency, the rial, which last year alone plunged by more than two-thirds. "The bitter fact is that our policymakers on both sides have chosen to confront each other rather than move toward a sober and friendly cooperation," says astrophysicist Yousef Sobouti, founder of the Institute for Advanced Studies in Basic Sciences in Zanjan.

In pulling out of the JCPOA, President Trump called it a "horrible one-sided deal that should have never, ever been made." He said that the nuclear deal's restrictions should be permanent to prevent Iran from eventually obtaining nuclear weapons. Iran and the other signatories—China, France, Germany, Russia, and the UK—remain in the deal.

Sweet and sour hopes

Less than three years elapsed between the adoption of the nuclear accord and the US pullout. "It was not enough time to bear fruit," says Nasser Kalantar, a Dutch physicist originally from Iran. "And in that short period, not all restrictions were lifted." Moreover, he notes, subconscious bias against Iranians is widespread. "And the sanctions affect daily life of scientists in Iran on all fronts."

Nonetheless, during the brief thaw, suppliers of laboratory equipment and consumable materials reopened offices in Iran, and new suppliers began entering the market, says Mohammad Reza Ejtehadi of Sharif University of Technology and president of the Physics Society of Iran. Although international financial transactions were not always straightforward, for a time it was easier to buy equipment, subscribe to journals, contribute to joint international endeavors, and the like.

Abdol-Khalegh Bordbar is a biophysical chemist at the University of Isfahan. His university purchased instruments for nanoscience and other experiments, including for NMR, fluorescence, electron microscopy, dynamic light scattering, and x-ray diffraction. The timing was fortunate, he says, because with the renewal of US sanctions, such things can no longer be easily bought or repaired. The sanctions also make it difficult for other countries to sell to Iran. "You have to buy chemicals on the black market for a high price," Bordbar says.

Brain drain from Iran has been increasing for more than a decade, says Reza Mansouri, a physicist at Sharif University of Technology and a former deputy minister for research. He estimates that 80% of bachelor's students from Sharif leave the country, and he puts that percentage at 90% for physics students. "Fewer than 10% come back after a decade," he says. But after the signing of the JCPOA, notes Ejtehadi, there was an uptick in scientists returning to work in Iran.

The nuclear deal led to an increase in the flow of visiting scientists to and from Iran and to new informal and official collaborations. For example, negotiations began for Iran to join the international Facility for Antiproton and Ion Research (FAIR) under construction in Darmstadt, Germany. "They would have to build parts in Iran and ship them to Germany. There is nothing nuclear about it—it would be shielding material," says Kalantar, who works on the project. The German government hasn't officially stopped the collaboration, but it's on hold, he says.

After the nuclear accord, as many as 200 delegations came to Iran, mostly from Europe but also from Asia and the US, to pursue collaborations in such areas as agriculture, medical science, physics, and engineering, says Mansouri. But only a few new collaborations have shaped up. He estimates that out of some 100 000 researchers in Iran, about 10% seek international research partners. Despite decades of tense political relations,

ABDOL-KHALEGH BORDBAR

ABDOL-KHALEGH BORDBAR in his office at the University of Isfahan. The biophysical chemist notes that sanctions and associated difficulties force scientists to become creative.

Iranian scientists have many joint publications with scientists around the world, with the US topping the list (see the figure on page 24). The number of successful international collaborations will decrease due to the new sanctions, he says. "Collaborations need money, and it's impossible to transfer." Even when money isn't a problem, he adds, "[international] colleagues fear they may be pressured by the US in the future."

As an example of US pressure, Iranian and European scientists point to rules first implemented in 2015, whereby people who have visited Iran in the past five years must apply for a visa to enter the US even if they are citizens of countries that do not usually need a visa. That law, says Ejtehadi, limits scientific collaboration between Europe and Iran. "Some scientists who had planned to come to Iran for international conferences or to visit their colleagues canceled their trip because of this restriction."

"Some European colleagues are against the sanctions and the American policies, and they make the extra effort," says Kalantar. "But a lot of people, even if they want to help, don't want to go through the hassles" of applying for visas and risking future entry to the US. And even though the European Union is encouraging companies to continue activities in Iran, they pull out so as not to risk their typically much more profitable interactions with the US.

"We have had very rewarding collaborations with Iran," says the head of one of Europe's synchrotron light sources who requested anonymity. "We are open to everybody. And at this moment, such openness can cause problems for future collaborations with US companies and research institutions. It is really worrisome."

Javad Rahighi, who heads the Iranian Light Source Facility, which is in the early R&D stage, says that he and his colleagues "feel that most laboratories in Europe are less willing to work with us" since the US renewed sanctions. In a mistake apparently related to the sanctions, in early November he was stopped in Copenhagen and held for two days. (See "Iranian physicist erroneously detained in Denmark," 26 December 2018, PHYSICS TODAY online.)

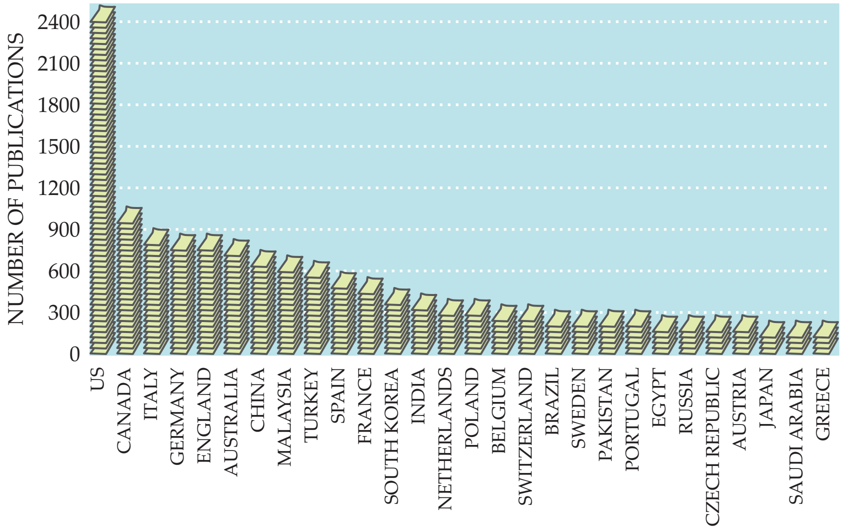
"Sanctions create paranoia"

Iran is the 12th leading country of origin for international postsecondary students in the US, according to the Institute of International Education. For the 2017–18 academic year, there were 12 783. That was a 1.1% increase over the previous year in the US but a reduction in the overall fraction of Iranian students who went abroad. Returning home during studies can be difficult because of the trouble and expense of reentering the US; many students have single-entry visas, and with no US embassy in Iran, they have to visit a third country to apply for a new visa. Occasionally students and other academics have been detained or jailed in Iran (see "Iran releases physicist after five-year imprisonment," 30 August 2016, PHYSICS TODAY online).

The travel ban implemented by the US in early 2017 exempts students but not faculty. For Iranians at the faculty level, getting into the US has been difficult for decades, says Ejtehadi. "It's always been expensive and time consuming. The possibility of rejection reduces the desire to visit the US."

Travel from the US to Iran can also be tricky. The US Department of the Treasury's Office of Foreign Assets Control has in some cases advised against visiting Iran. And US universities may discourage faculty members from traveling there. Statistics are not available, but Mansouri and others say that the number of visiting scientists to Iran has dropped since last spring.

The renewed US sanctions explicitly allow Chinese and Russian entities to continue working with the Iranians on the Arak heavy-water reactor facility and Fordow Fuel Enrichment Plant, as required under the JCPOA. The Arak reactor core is being converted to produce less weapons-usable plutonium, and the Fordow centrifuge is being modified to use for medical isotope production and research. But it is unclear whether a nuclear safety center that Europeans were working on in Iran can go forward, says Kelsey Davenport, director for nonproliferation policy at the Arms Control Association, a think tank in Washington, DC. Discontinuing the center would reduce opportunities for scientific cooperation, she says. "Cutting off scientific cooperation, particularly in the nuclear space, decreases transparency into Iran's nuclear program and its future trajectory."



JOINT PUBLICATIONS IN INTERNATIONAL SCIENTIFIC JOURNALS in 2017 by authors in Iran with scientists in other countries. (Based on data from the Web of Science.)

Overly vigorous interpretation of the sanctions exacerbates their negative impact on Iranian society and science. Some scientists, for example, report that their manuscripts are rejected by international journals because they come from Iran. Similarly, some companies stopped offering online courses in Iran and others cut off access to free scientific software.

"Sanctions create paranoia," says Kaveh Madani, an environmental management expert at Yale University. "Some academic people and institutions want to follow the rules and they become more Catholic than the pope, hurting scientific exchanges and progress."

Sanctions also facilitate corruption, Madani says. "They create opportunities for people close to power to make money." He has experienced firsthand the political dangers in his native Iran. In 2017 he left his faculty position at Imperial College London to serve as Iran's deputy minister for the environment. A few months into the job, the Iranian Revolutionary Guards accused him of spying. After being repeatedly arrested and interrogated, he fled the country.

Madani says that sanctions harm natural resources and human health. In the economic recession resulting from sanctions, he says, decision makers focus on crisis management "with no attention to the impacts on the environment." During a gas shortage, for example, the government made low-quality refineries to produce gas. People could drive, but air pollution increased, he says. "The effects can be irreversible and long term. You can't put water back into aquifers. You can't undo cancers."

Financial crisis

Even more than the sanctions themselves, Iranian scientists point to the devaluation of their currency as hampering their research and integration in the international science community. After getting her undergraduate degree in Iran, Rezvan Shahoei applied to more than a dozen US graduate programs before going to the University of Illinois at Urbana-Champaign in 2010 to pursue a

JOSEPH NIEMELA

SCIENTIFIC EXCHANGES and the building of an Iranian beamline at the Elettra synchrotron were discussed at a November 2016 meeting in Trieste, Italy. Plans for the beamline are now on hold because of the reduced value of Iranian currency. From left: Iranian physicist Reza Mansouri; Vahid Ahmadi, Iran's deputy minister for research and technology; Italian politician Debora Serracchiani; Alfonso Franciosi, head of the Elettra synchrotron; and Javad Rahighi, director of the Iranian Light Source Facility.

doctorate in physics. Today students can't afford to apply to so many programs, she says. Paying for the GRE and TOEFL exams has become hard. Combined with the travel impediments, Iranian students are turning increasingly to other countries or staying home.

Shahoei tells of a physicist in Iran whose relatively good salary is now equivalent to roughly $400 a month. The devaluation of the currency means that scientists can no longer afford to attend international conferences. And the weakened rial makes buying lab equipment, already tough due to the renewed sanctions, even more out of reach.

Some 14 Iranian scientists attended a school on plasma physics this past October in Trieste, Italy, held jointly by the Abdus Salam International Centre for Theoretical Physics and the International Atomic Energy Agency. "Only a few canceled. But we saw a lot of desperate people who were out of money," says Joseph Niemela, who coordinated the school. "We won't expect Iranian scientists to chip into the cost of participating in future events," he adds.

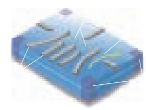
The devaluation of currency is also delaying completion of large projects such as the Iranian Light Source Facility and a beamline that Iranian scientists hope to build at the Elettra synchrotron facility near Trieste. But a 3.4-meter telescope is going ahead, says Mansouri. "The government has decided to support the Iranian National Observatory." It's about half paid for and is on track to be completed in a few years. The roughly $10 million to finish the observatory "is peanuts compared to government spending in universities, so it's not much influenced by the sanctions or our economic situation," he says.

If there is a bright side to the difficult conditions for science in Iran, it's that people are putting their ingenuity to work. In some ways research may benefit, says Bordbar. "We find solutions inside the country. People produce startup companies. We change the way we do research to fill gaps. The difficulties encourage creativity and independence." Says Mansouri, "I expect that the new sanctions will help us rethink what we as a nation want."

Inside and outside of Iran there is wide recognition that the benefits of international collaborations extend well beyond science. Engaging with scientists all over the world and contributing to scientific progress "can help to achieve more political stability in this region," says Rahighi.

"Science suffers in isolation," says Niemela. "It becomes a closed pool, and crazy ideas can grow in such a medium. I don't think that is ultimately in anybody's interest." Astrophysicist Sobouti agrees, but says for the situation to improve, "we have to sit and wait."

Toni Feder



National labs push to get technologies out the door

The Department of Energy is cutting red tape on cooperative R&D agreements and is organizing technology showcases.

When Vig Sherrill, an electrical engineer and serial entrepreneur in eastern Tennessee, went looking for a technology for his sixth startup company, he found one at Oak Ridge National Laboratory's annual technology innovation showcase: a process that had the potential to slash the cost of manufacturing graphene by orders of magnitude. He hired the inventor of the process, Ivan Vlassiouk, from the lab and formed a company, General Graphene, which is now producing graphene sheets at "well below" $100/m^2$—compared with $10 000/m^2$ using other, more established manufacturing processes. General Graphene just completed a major round of fundraising and is working toward commercial-scale production in 2022.

Chicago-based LanzaTech, which produces ethanol through fermentation of industrial gases and other carbon-rich wastes and residues, turned to chemists at Pacific Northwest National Laboratory. Together they developed a catalytic process to upgrade the ethanol to a jet biofuel, a 50-50 mix with conventional jet fuel. The company licensed the technology, and in April the Federal Aviation Administration approved the fuel for commercial flight. In October a Virgin Atlantic 747 made the first transatlantic flight using the synthetic fuel mix.

In 1992 Goodyear Tire and Rubber Company signed a cooperative R&D agreement (CRADA) with Sandia National Laboratories after the Department of Energy encouraged its labs to partner with industry. One result was the development of an award-winning all-weather tire made with innovative polymers, a success the company has said couldn't have happened without Sandia's help in developing modeling and predictive testing tools. Renewed multiple times since, that CRADA is now in its 27th year.

Licensing, spin-offs, and CRADAs from the DOE labs are hardly new, but they are receiving new attention and emphasis from an administration that hasn't always been known for its friendliness to science and research.

ANDREA STARR, PACIFIC NORTHWEST NATIONAL LABORATORY

USING CATALYTIC TECHNOLOGY developed at Pacific Northwest National Laboratory, a researcher at Chicago-based LanzaTech transforms ethanol derived from industrial waste gases into jet fuel.

"Making sure we get technology out to the marketplace, that it has an avenue with which to be commercialized, is very important to everybody," says Conner Prochaska, DOE's chief commercialization officer, a new title conferred in November by Secretary Rick Perry. Prochaska says the emphasis on technology transfer has come "straight out of the White House," in the form of a 2018 memorandum issued by the Office of Management and Budget and the Office of Science and Technology Policy to the federal agencies that support R&D.

Paul Dabbar, DOE undersecretary for science, has taken a particular interest in commercialization activities at the department's 17 labs. He initiated a series of workshops to bring together invited members of academia, manufacturers, potential investors, potential customers, and the laboratories' leaders in focused technology areas. "What I wanted to do was have venues in which we had a broader group of participants to facilitate conversations," he says. "Not just lab people talking to other lab people."

The first such InnovationXLab Initiative gathering, focused on batteries and energy storage, was hosted by SLAC in September. As of early December, 150 individuals, roughly half of the 300 attendees, have followed up with the labs, says Dabbar. A second InnovationXLab, focused on grid modernization and security, is slated for 23–24 January in Seattle. Two others, one on advanced and additive manufacturing and the other on biotechnology and drug development, are in the planning stages, he says.

But the show-and-tell process can also work at the individual lab level. Mike Paulus, director of technology transfer at Oak Ridge, says roughly half the technologies presented at the lab's annual showcase in recent years have been licensed. Several licenses have been accompanied by CRADAs or other collaborations to mature the technologies. "We try to be flexible and responsive to our licensees, recognizing that small businesses often operate on much shorter time frames than federal laboratories," he says.

More nimble and flexible

In November Dabbar unveiled two DOE measures aimed at easing the administrative burden of collaborating with the labs. One change allows lab directors to approve CRADAs that fall within a defined scope of work. Previously, the agency had to sign off on all CRADAs, no matter how small or related. Taking the department out of the loop will shave weeks off the approval process, say lab officials.

The second change will provide greater flexibility to the labs to negotiate R&D contract provisions related to indemnification. Potential commercial partners often balk at the standard provisions that require them to indemnify the labs and the federal government.

A year ago Perry extended to all the labs the authority to use a new mechanism, the Agreement for Commercializing Technology (ACT), in performing R&D for industry and other outside entities. The ACT framework allows the contractors that operate the labs for DOE to negotiate commercial terms with partners and take on some business risks that the agency won't. For example, in exchange for a negotiated fee, contractors can waive DOE's up-front R&D payment requirements or perform R&D for a fixed cost.

Lawrence Livermore National Laboratory used an ACT for a $50 million pact with the Czech Republic's Extreme Light Infrastructure facility to build a high-average-power petawatt laser beamline (see Physics Today, December 2018, page 18). Rich Rankin of Livermore's innovation and partnerships office says the European Union, which funded the Czech user facility, couldn't abide by standard US legal provisions. Because of the ACT, it no longer needed to.

Pacific Northwest, one of the labs that helped pilot the ACT initiative, is by far the largest user, with 130 of them under its belt. Lee Cheatham, the lab's director of technology commercialization and deployment, says DOE is currently piloting an extension of the ACT framework that will for the first time allow defense and other federal contractors to use pass-through government funds to pay for cooperative research at national labs.

OAK RIDGE NATIONAL LABORATORY

A 3D-PRINTED, LIFE-SIZE REPLICA of the classic 1963 Shelby Cobra sportscar was made at Oak Ridge National Laboratory's Manufacturing Demonstration Facility. The majority of the lab's 70 cooperative R&D agreements in 2017 involve that center.

DOE's applied energy programs are required by statute to devote 0.9% of their budgets to supporting collaborations with industry. The largest fraction of those dollars originates from the Office of Energy Efficiency and Renewable Energy, whose fiscal year 2019 budget is $2.4 billion. Funds allocated to a project must be matched by the industrial partner. Additional money for commercialization can be authorized by DOE program offices, and the labs each have funding that can be used at the discretion of the directors. But Jason Martinez, a CRADA specialist at Sandia, says most CRADAs at the lab are "funds-in," in which the private-sector party puts up the costs and the lab provides the principal investigator.

All about impact

The labs have clearly gotten the technology-transfer message from DOE. Argonne National Laboratory recently elevated its commercialization program to become a directorate, the lab's fourth. Paul Kearns, Argonne's director, says DOE also has upgraded the weight it gives to technology commercialization in its annual assessments of the labs' performance.

"We're all about impact," Kearns says when asked which commercialization mechanism the lab favors. "One of my better days as the lab director was when I was able to deliver not one but three seven-figure royalty checks to employees at the lab." The involved technology, a nickel-manganese-cobalt cathode that greatly improved the energy density, safety, and time between charges of lithium-ion batteries, has been licensed to General Motors, BASF, LG Chem, and others.

Argonne's Chain Reaction Innovations, a technology entrepreneurship mentoring program for inventors from across the nation, has attracted applications from between 80 and 100 startup hopefuls for only 6 available spots during its first two years. A third selection process is under way. Similar technology incubators, each funded in part by DOE, are in place at other national labs, including Lawrence Berkeley and Oak Ridge.

Sixty of the 70 CRADAs signed at Oak Ridge in 2017 involve the lab's Manufacturing Demonstration Facility, which focuses on the materials, processes, and equipment for additive manufacturing. The center produced a 3D-printed, full-scale replica of the original Shelby Cobra, the Anglo-American roadster of 1962–63. Other items fashioned include a house, excavator, jeep, and submarine. Paulus says the facility staff "as part of their day jobs are expected to work with industry to demo how to use equipment and how to optimize processes."

Oak Ridge's high-performance supercomputers—including Summit, now rated as the world's fastest—enable the computational design of new materials. Once synthesized, the new materials' performance is tested at the lab's Spallation Neutron Source. Through a CRADA with Oak Ridge, Fiat Chrysler Automobiles developed a high-temperature aluminum alloy for auto engines. The work took two years, much less than the typical time required to go from design to manufacture, Paulus says. The lab is seeking additional licensees for the technology.

A CRADA signed in July by Sandia and Canada's Emera Technologies covers R&D on community-scale direct-current microgrids. Emera Technologies CEO Rob Bennett said in a statement that a large and growing portion of electricity generation, storage, and home use requires conversion of alternating current to DC. He expects DC power systems and microgrids to form a large part of US energy infrastructure.

The CRADA may also advance Sandia's research on the control and stability of DC microgrids for military applications. The lab offers a facility housing three interconnected DC microgrids and another where research on energy systems integration takes place. Sandia's virtual power plant software anticipates the performance of energy storage and intermittent renewable sources to determine how to optimize operations and power balance.

Through CRADAs with Livermore, the Metal Improvement Company, now known as Curtiss-Wright Surface Technologies, developed a laser-peening process that can be used to prevent metal fatigue and extend the lives of jet fan blades. Some 100 000 blades have been processed and have saved the aviation industry billions of dollars, according to a Livermore spokesperson. The two lab researchers who developed the technology left to become employees of the company.

"It would be great if the American people had a concept for the number of things that have come out of the national labs," says Livermore's Rankin. Many of the improvements to auto fuel efficiency, medical instrumentation, the internet, and cybersecurity are by-products of work performed for the government, he notes.

In another form of collaboration, known as the Strategic Partnership Projects (SPP) program, the partner pays the full cost of having work performed at the lab and retains all intellectual property that results. Similar to an ACT, an SPP offers less flexible terms and must be approved by DOE. Sandia's Martinez says the SPP is "very transactional, 'Here's a battery, test it and send the data back to us.' A CRADA will be 'Here's this battery technology, let's augment it in some way.'" The labs are prohibited from competing with industry while performing SPP work.

Yet another type of technology commercialization occurs at DOE user facilities, such as the light sources, neutron sources, and nanotechnology centers, where industrial and academic users have developed new materials and pharmaceuticals with help from lab scientists. The researchers are allowed to use the facilities for free, provided they seek to publish their results. To perform proprietary work, they must pay a fee.

A more indirect sort of technology transfer occurs when lab researchers take ideas with them, rather than technologies or intellectual property per se, when they leave. Martín Casado is a notable example. Now a partner in the venture capital giant Andreessen Horowitz, Casado started two businesses in software-defined-network technology that were later acquired by larger companies. He credits his days working in network security and intelligence at Livermore as the source for many of the ideas he later commercialized while pursuing a PhD at Stanford University. He now returns to the lab periodically to help teach researchers about entrepreneurship.

"The labs are great at tackling real-world problems that other people don't have the luxury or are unlucky not to have to deal with," Casado says. "They are a massive untapped potential as a talent pool and knowledge that you just don't get elsewhere."

David Kramer PT

Joseph D. Martin teaches the history and philosophy of science at the University of Cambridge in the UK.

When CONDENSED-MATTER PHYSICS became king

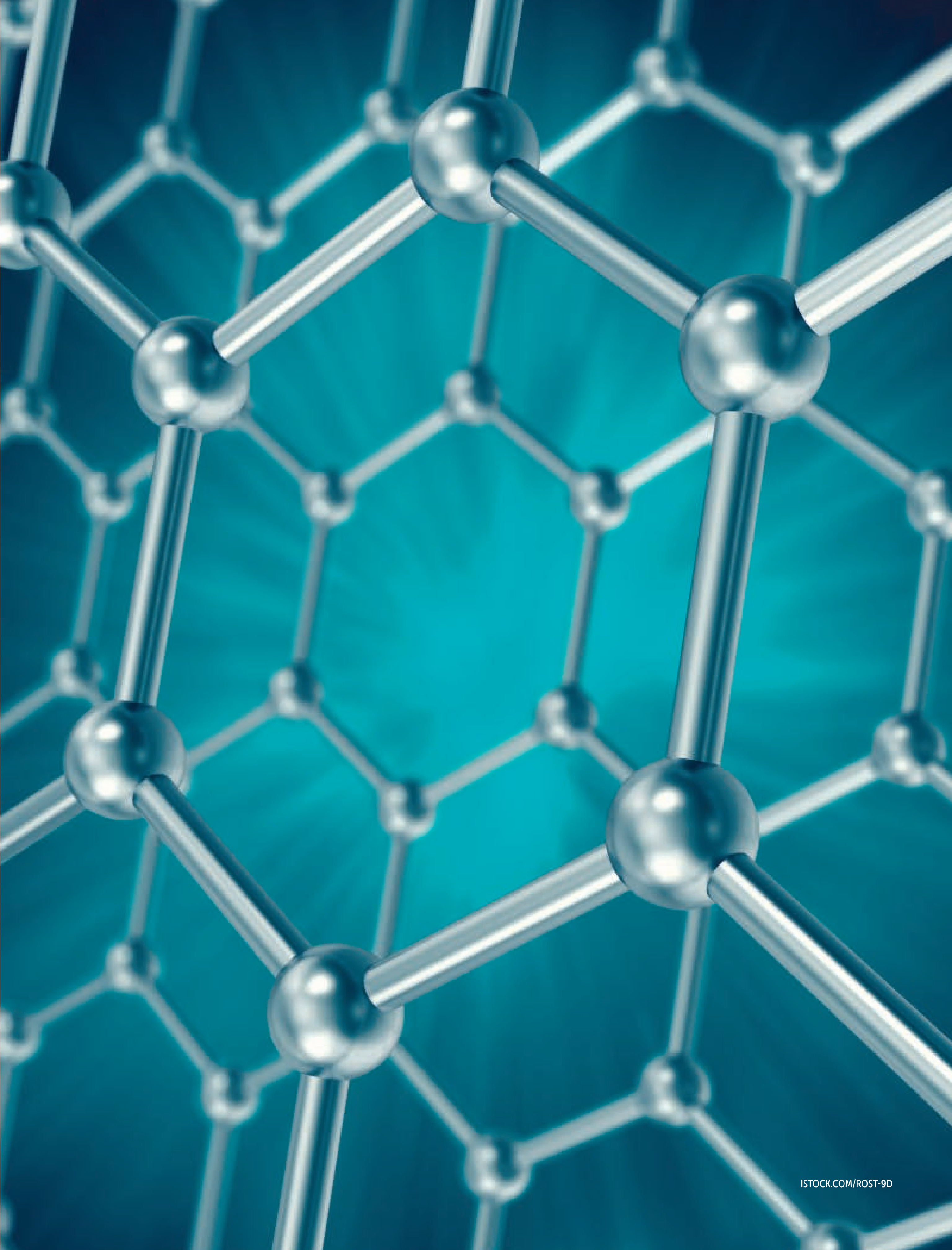
Joseph D. Martin

The story of how solid-state physics emerged in the postwar period and was eventually rebranded as condensed-matter physics illuminates some major shifts in the late-20th-century physics community.

Condensed-matter physics is huge. That statement will surprise no one who has attended a March meeting or perused the member rolls of the American Physical Society (APS). The division of condensed matter physics has been the society's largest for decades. But the prominence of condensed-matter physics is recent. Before World War II, no such field existed. It was not until the late 1940s that solid-state physics, its precursor, emerged as a physical subdiscipline.

In his superb book *When Physics Became King*,[1] Iwan Rhys Morus describes how physics itself grew into the preeminent science by 1900. No one in 1800 could have foreseen the vast changes in the status and fortunes of physics that the 19th century would witness. Morus describes physics as becoming "king" in the sense that it came to occupy a central role in Western culture. Physicists marshaled cultural resources—institutional spaces, audiences, patrons, and trust—to create an environment in which their science would become the one most trusted both to probe nature's secrets and to spawn new technologies.

Similarly, in 1900, when physicists were just beginning to probe the secrets of the atom, the prominence that the physics of complex matter would hold by the turn of the 21st century was scarcely conceivable. Condensed-matter physics inherited many of the cultural resources 19th-century physics had secured, so the manner of its coronation and the nature of its sovereignty differed. High-energy physics and cosmology continued to be known for uncovering nature's deepest secrets. But the rise of condensed-matter physics reconfigured how the field of physics was defined and subcategorized. It reflected new ideas about who should be considered a physicist. And it



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challenged the cherished ideals on which the US physics community—especially APS—had been founded.

Should physics be pure?

Henry Rowland, the first president of APS, was the foremost promoter of the ideals that defined turn-of-the-century US physics. Above all, he advocated the pure-science ideal, which held physics separate from applied or "practical" science. Rowland could count himself among the few Americans commanding the international physics community's attention. European physicists infatuated with stellar spectra eagerly snapped up Rowland's precision diffraction gratings (see figure 1). But the practically minded inventor Thomas Edison remained the public face of US science, and Rowland lamented that "much of the intellect of the country is still wasted in the pursuit of so-called practical science which ministers to our physical needs and but little thought and money is given to the grander portion of the subject which appeals to our intellect alone."[2] Rowland and 35 others founded APS in 1899 to minister to the intellect.

APS's advocacy of a pure-science ideal, however, scarcely slowed enthusiasm for science in technical quarters. In 1916, in the middle of World War I, John Carty, president of the American Institute of Electrical Engineers, considered it "the high duty of our institute … to impress upon the manufacturers of the United States the wonderful possibilities of economies in their processes and improvements in their products which are opened up by the discoveries in science."[3] Nor were physicists unreceptive to overtures from industry. Through the interwar period, industrial laboratories employed an appreciable proportion of US physicists and generated an appreciable proportion of the papers published in US physics journals.[4]

At that time, US industry was much enamored of physicists. Many reciprocated its affections, but other physicists stigmatized practical work. A song by physicist Arthur Roberts that made the rounds at MIT's Radiation Laboratory in 1944 manifests the attitude that prevailed in midcentury academic physics. The final verse disdained the comparative riches awaiting physicists who went corporate:

> Now all you bright young fellows with your eyes upon the stars,
> You graduate assistants who subsist on peanut bars
> If industry should woo you with two hundred bucks a week
> Refuse the job and say, without your tongue in your cheek,
>
> It ain't the money
> It's the principle of the thing
> It ain't the money
> There's things that money can't buy
> It ain't the money
> That makes the nucleus go round
> It's the philosophical ethical principle, we keep telling ourselves, of the thing.[5]

The idea that academic and industrial cultures were incompatible reflected a broader transition: Science, previously a calling for few, had become a vocation for many, not all of whom sought traditional academic employment. Sociologists of science like Robert Merton, seeking to understand the norms governing scientific practice, also observed the cultural incompatibilities that resulted from science's expansion.[6] After World War II, the prevalence of the attitude that industrial work compromised dearly held ideals, combined with rapid growth in the number of physicists employed in industry, created a rift within physics that many physicists hoped could be bridged.

Redrawing the map of physics

The field of solid-state physics emerged from efforts to ease tensions between industrial and academic research. But before describing those efforts, it will be useful to discuss the assumptions about the nature of physics that stood in their way. For a field like solid state to make sense, physicists had to begin thinking about physics differently.

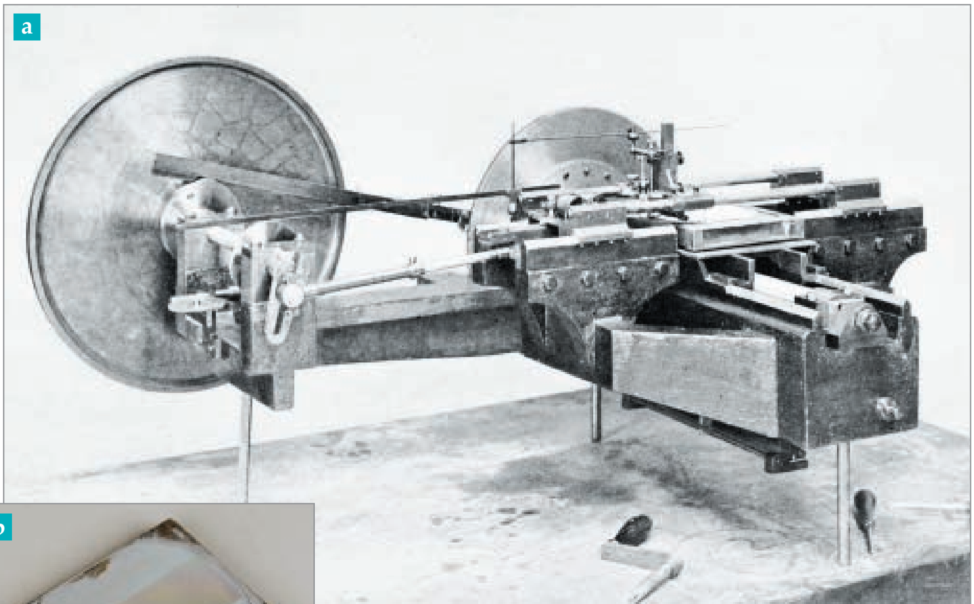
In 1940 physicist Bernard "Bern" Porter joined the Manhattan Project, which he would quit, traumatized and disillusioned, following the bombing of Hiroshima. He ultimately pursued his passion for art, through which he expressed his struggle with feelings of complicity in the use of nuclear weapons. But in 1939, when Porter was still enamored of physics, he drew a map of it (see figure 2). The map aptly reflects prewar attitudes about how physics was organized—attitudes that solid-state physics flouted.

Porter's map illustrates the view of physics that relegated applied and industrial research to its fringes. Porter represented provinces of physics as geographical regions linked by a river of energy. Joined by a reservoir of radioactivity at its delta, the river flows into an ocean labeled "Research: The Future of Physics." Thus represented, physics is conceptually unified. Defined by phenomena that exist in the world, "physics" means the same thing at one point in history as it does at any other. Physics is out there. Physicists are those called to discover it. Technology, at best, is a distant outpost, unworthy of depiction in a map of the metropole.

A decade later solid-state physics had emerged as a new province—but it is difficult to see how or where Porter might have included it on his map. Solid-state physics was not a self-contained assembly of topics and methods that could appear as an island, continent, or other natural feature of the disciplinary landscape. It drew from almost all of the regions of Porter's map. It was, in that sense, a strange category.

That strangeness is not a retrospective assessment. In the mid 1940s, the proposal that resulted in the APS division of solid state physics (DSSP) prompted University of Iowa theorist Gregory Wannier to declare, "Solid state physics sounds kind of funny." Two decades later, when the second edition of the American Institute of Physics handbook added a new chapter on solid-state physics, its editor griped that "adding a chapter so named to the conventionally labeled group of mechanics, heat, acoustics, and so forth is . . . like trying to divide people into women, men, girls, boys, and zither players" (see the article by Dwight Gray, PHYSICS TODAY, July 1963, page 41).

Those assessments seized on the oddness of an unusually broad field. The boundaries of solid-state physics were unconventional. They cut across the physical phenomena that defined more familiar categories like acoustics and optics. Furthermore, physicists did not tend to think in terms of subdisciplinary allegiance. Nuclear and high-energy physicists, for instance, continued to think of their work as simply *physics*. Until the late 1960s they shunned APS divisions for their activ-



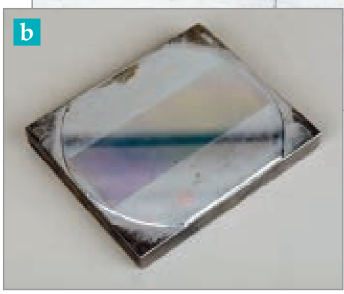


FIGURE 1. HENRY ROWLAND designed this ruling engine **(a)** to make precision diffraction gratings that were in high demand worldwide. (Image from *Popular Science Monthly*, May 1896, PD-US.) **(b)** This grating was ruled with one of Rowland's engines. (Image © the Whipple Museum, Cambridge, Wh.6610.)

ities, judging such institutional apparatus necessary only for peripheral fields. But solid state would be the first of many ostensibly peripheral, artificial categories that would become central to postwar physics.

A new division, a new discipline

Solid-state physics was strange by design. Industrial and applied physicists, feeling marginalized, had clamored persistently for greater representation in the institutions of US physics. When a 1931 amendment to the APS constitution permitted subject-based divisions, suggestions for a division of industrial physics began to roll in. The APS council balked. Industry, in the eyes of APS leadership, was not a subject; a division devoted to it would only deepen the academia–industry rift.

The needs of industrial physicists were nevertheless on the mind of Polish émigré and General Electric (GE) physicist Roman Smoluchowski (see figure 3) when he spearheaded a different proposal for a division of metals physics. Most industrial research, he reasoned, concerned metals—they suffused his day-to-day responsibilities at GE, where he often collaborated with metallurgists. A division of metals physics would offer a home to industrial researchers and also represent academic physicists interested in topics such as magnetism, electricity, and thermal conductivity.

But the APS council demurred when presented with Smoluchowski's proposal, which it judged as too transparently industrial. APS secretary Karl Darrow suggested that the solid state of matter—encompassing metals, other regular solids, and amorphous solids—might offer a better basis for a successful division. Smoluchowski, although initially concerned that a division of solid-state physics would have a more difficult time attracting interest from metallurgists, proved willing to compromise. Through that delicate sequence of contingencies, solid-state physics became a recognized subdiscipline of physics when the DSSP was approved in 1947.

As it is taught today, solid-state physics centers on quantum approaches to regular crystalline solids. Smoluchowski and his collaborators envisioned a significantly broader field, and they convened a January 1945 APS symposium to discuss the proposal for a new division and showcase both its experimental and theoretical scopes. The theorists on the program emphasized the links between the solid state and the latest developments in statistical and quantum physics. Wannier outlined new applications of statistical methods to cooperative phenomena, in which component parts can't be considered as acting independently. John Van Vleck surveyed ferromagnetism, beginning in the early 20th century with phenomenological treatments and later describing competing quantum mechanical approaches.

The symposium also demonstrated a commitment to applied research. Among the speakers were Richard Bozorth and Howell Williams of Bell Labs, who described their efforts to understand "the behavior of magnetic materials in apparatus developed as a part of the war effort."[7] Watertown Arsenal's Clarence Zener, presenting on the fracture stress of steel, noted that "the sinews of warfare, namely guns, projectiles, and armor, are made of steel."[8]

Van Vleck's interest in a robust, quantum-mechanical description of ferromagnetism had little to do conceptually with Zener's work on the phenomenology of steel. The link between those topics was much weaker than, say, the link between ferromagnetism and the magnetic susceptibility of gases, another Van Vleck specialty. The new DSSP aimed to unite a menagerie of approaches and questions, at least professionally.

Solid state's odd constitution reflected changing attitudes about physics, especially with respect to applied and industrial research. A widespread notion in the physics community held that "physics" referred to natural phenomena and "physicist" to someone who deduced the rules governing them—making applied or industrial researchers nonphysicists almost by definition. But suspicion of that view grew around midcentury. Stanford University's William Hansen, whose own

ON THE WEB

PHYSICIST AND BLOGGER DOUGLAS NATELSON WEIGHS IN ON THE MODERN IMAGE OF CONDENSED-MATTER RESEARCH.

physicstoday.org/Natelson

applied work led to the development of the klystron (a microwave-amplifying vacuum tube), reacted to his colleague David Webster's suggestion in 1943 that physics was defined by the pursuit of natural physical laws: "It would seem that your criterion sets the sights terribly high. How many physicists do you know who have discovered a law of nature? . . . It seems to me, this privilege is given only to a very few of us. Nevertheless the work of the rest is of value."[9]

The rest tended to agree. The unwieldy breadth of solid-state physics illustrates how they responded. The solid state of matter was an expedient category because it was broad enough to encompass such a diversity of topics. Its scope ensured that it would not discriminate against industrial or applied physicists, who often described their focus broadly. The new DSSP could span academic and industrial territories and topical categories that were otherwise dissociated.

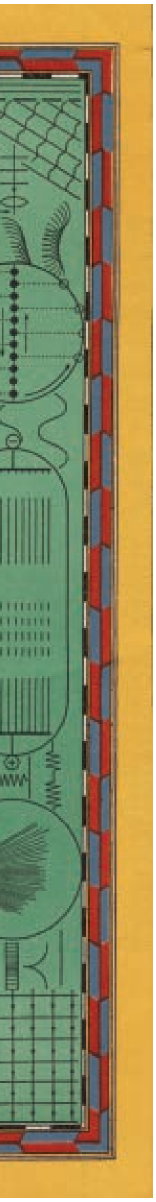
The solid-state boom

The new field flourished. In the early Cold War, government and industry were willing to spend liberally—indeed, almost haphazardly—on both abstract and technical research, and solid-state physics reaped the rewards of that largesse. It attracted a significant proportion of PhD students, generated ample new positions in universities and industrial laboratories, spawned copious conferences and workshops, and subsumed vast swaths of conceptual terrain. The transistor, invented in 1947 by Bell Labs physicists working with semiconductors, illustrates how the flexibility of the term "solids" (as opposed to

FIGURE 2. BERNARD PORTER'S MAP OF PHYSICS, 1939, illustrates a perspective in which physics is categorized in terms of natural phenomena. (Reproduced with permission of Mark Melnicove, literary executor for Bern Porter, mmelnicove@gmail.com. From the Bern Porter Collection, Special Collections, Miller Library, Colby College, Waterville, Maine.)

"metals") permitted solid-state physics to lay claim to lively new research areas. The late 1940s also saw the birth of NMR spectroscopy, another technique that would become central to solid-state research.

Two factors account for the rapid expansion of solid-state physics in the early postwar era. One, it scratched a persistent itch. Applied physicists, long underserved by the flagship institutions of US physics, embraced new organizational efforts that advanced their interests. Two, because the field was organized to address professional problems of the postwar era rather than to unite a coherent set of concepts or practices, solid state could serve physicists from many different topical specialties and those with diverse interests.



But because few research programs explicitly focused on the solid state of matter, solid-state physics often included research that had little solid about it. Van Vleck's classic work on the magnetic susceptibility of gases became part of the solid-state canon. The first maser, assembled by Charles Townes and his research group, was based on ammonia gas. And the superfluidity of helium, discovered by Peter Kapitza in 1937, launched a fruitful research program that solid-state physicists also called their own.

Some of those areas, such as semiconductor physics, were integral to solid-state physics when it formed. Others, such as NMR and low-temperature physics, the field claimed in retrospect. Because solid-state physics was an artificial category, it was a flexible one, with latitude to encompass promising new research areas. So long as solid-state physics provided a space for physicists who were working on the properties of aggregate matter, its practitioners were willing to turn a blind eye to any categorical oddities.

By the early 1960s, the DSSP had become—and has remained since—the largest division of APS. By 1970, following a membership drive at APS meetings, the DSSP enrolled more than 10% of the society's members. It would reach a maximum of just shy of 25% in 1989. Membership in the DSSP has regularly outstripped the division of particles and fields, the next largest every year since 1974, by factors of between 1.5 and 2.

David Kaiser has described the boom-and-bust cycles that characterized the explosive growth of postwar American physics as a whole, emphasizing the changes that growth exerted on graduate education.[10] Physics students, instead of being closely supervised, began to be trained en masse. Close mentorship of graduate students gave way to large lecture courses designed to quickly confer the necessary facility with the mathematical formalism of quantum mechanics, with a focus on calculation over foundations. Rapid quantitative growth, that is, led to a qualitative change in how physics was taught and, therefore, practiced.

The way in which solid-state physics, scarcely a glimmer in the eye of a few industrial researchers in the mid 1940s, grew into the largest province of US physics also speaks to a substantive transformation in US postwar physics. The new field embraced links between the abstract and the technical and sanctioned industry as a viable and even desirable career path. Even as high-energy physicists kept the pure-science ideal alive by championing the role of fundamental knowledge in sustaining national prestige, the complexion of US physics was changing. It was beginning to resemble a loosely aligned patchwork of specialties with varying degrees of commitment to APS's founding ideals. Physics as a whole was starting to look much more like solid-state physics.

Solid state becomes condensed matter

Solid-state physics was engineered to address a set of distinctive midcentury professional challenges. It is hardly surprising, therefore, that as time wore on and circumstances changed, the name began to seem old hat. Beginning in the 1960s, a subset of solid-state physicists began to prefer calling their field "condensed-matter physics" because of practitioners' increasing interest in nonsolid states of matter and the quantum many-body problem.[11]

FIGURE 3. ROMAN SMOLUCHOWSKI, an advocate for a metals division of the American Physical Society, works with alloy samples at General Electric. (AIP Emilio Segrè Visual Archives, courtesy of Roman Smoluchowski.)

The new name took hold in Europe before spreading to the US. The journal *Physik der kondensierten Materie*, published simultaneously in French as *Physique de la matière condensée* and in English as *Physics of Condensed Matter*, was founded in West Germany in 1962. The journal's editors contrasted their new publication's subject explicitly with solid-state physics, explaining, "Inclusion of work in the physics of both solid and the liquid phase is intended to increase closer contact between both areas and especially to further research in the area of liquids."[12] The University of Cambridge made a similar leap in 1968, when its prominent solid-state theory group rebranded its interests as "theory of condensed matter." Philip Anderson, a Bell Labs theorist who held a seasonal professorship at Cambridge, championed that change, and his support helped popularize the term in the US. In 1978, APS's division of solid state physics became the division of condensed matter physics.

The new name offered self-identified condensed-matter physicists distinct advantages. Crucially, it projected greater conceptual consistency. Even in the early days of solid-state physics, the name was maligned because the field's topics and techniques were often equally relevant to liquids, molecules, plasmas, and other nonsolids. So long as areas like semiconductor physics remained at the forefront, those inconsistencies were forgivable, but in the 1970s the frontiers shifted. Critical phenomena such as phase transitions, nonlinear dynamics of fluid systems, and liquid-helium research that had little or nothing to do with solids took center stage. Solid-state physics became too blatant a misnomer to ignore.

FIGURE 4. JOHN TREVER'S CARTOON "THE SUPERCOMPLIANT SUPERPROVIDER" depicts the disconnect between high-energy physicists' expectations and federal priorities. (© 1993, John Trever, *Albuquerque Journal*. Reprinted by permission.)

The name also highlighted the field's intellectual rigor. "Condensed matter" called to mind the notoriously difficult quantum many-body calculations more than "solid state," and trends during the 1960s prompted solid-state physicists to emphasize their intellectual contributions. As federal enthusiasm for basic research waned in the Vietnam War era, funding for fundamental solid-state research shrank, even as high-energy physics consumed more federal dollars for larger particle accelerators. Government and industrial funders began demanding clearly articulated, short-term technical payoffs.

Some practitioners worried that the good research questions were drying up alongside the easy money. Cambridge solid-state physicist Brian Pippard groused that "the disappearance of liquid helium, superconductivity, and magnetoresistance from the list of major unsolved problems has left this branch of research looking pretty sick from the point of view of any young innocent who thinks he's going to break new ground" (see Pippard's article, PHYSICS TODAY, November 1961, page 39).

Breakthroughs in areas like critical phenomena offered a way for solid-state physicists to defy such despondency. They also helped the field stake a claim to some of the intellectual prestige that high-energy physics enjoyed. In 1972 Anderson published a landmark essay in *Science* entitled "More Is Different," in which he argued that each new scale of complexity that scientists engaged with promised a cornucopia of new fundamental and intellectually stimulating questions.[13] As condensed-matter physicists tackled more complex physical phenomena, they could therefore expect to open up new intellectual frontiers. Adopting the name condensed-matter physics was more than a simple rebranding. It represented a priority shift driven by changes in both the intellectual and professional circumstances of US physics.

Condensed-matter physicists would test those priorities during the debates that swirled around the Superconducting Super Collider (SSC) in the early 1990s (see figure 4). In what high-energy physicists perceived as an unprecedented act of betrayal, many prominent condensed-matter physicists, including Nobel laureates Anderson and Nicolaas Bloembergen, opposed the SSC—not only in private but also before the policymakers who controlled the project's fate.

It was a conflict of ideals. For high-energy physicists, the route to fundamental knowledge was a one-way road leading to smaller and smaller length scales. Condensed-matter physicists, who perceived fundamental knowledge at many scales, argued that the funding regime that supported projects like the SSC hamstrung other fields in physics, including and especially their own. As Anderson told Congress in 1989, condensed-matter physics was "caught between the Scylla of the glamorous big science projects . . . and the Charybdis of programmed research . . . where you are asked to do very specific pieces of research aimed at some very short-term goal."[14]

Gripes like Anderson's were timeworn. Solid-state and condensed-matter physicists had long defended their intellectual worth against charges that they were engaged in *Schmutzphysik*, or "squalid state physics." And the concern that big accelerator facilities were vacuuming up funds that might otherwise be dispersed more equitably had been voiced repeatedly since the mid 1960s. But the significant numerical superiority solid-state and condensed-matter physics had enjoyed for decades, combined with the resurgence of its intellectual program, emboldened the field's leaders. By the late 1980s, condensed-matter physicists were prepared to argue not only that they deserved a place at the core of the discipline but that their aims better represented the aims of physics as a whole than did the parochial interest of high-energy physicists.

The power of categories

The story of how condensed-matter physics became a central endeavor of US physics is a story of categories and why they matter. In the early 20th century, physicists might have mapped their discipline like Bern Porter did—by tracing the categories they perceived in the natural world. But that method was freighted with ideology. It made a statement about the type of activity physics was supposed to be. It drew a line between who was a physicist and who wasn't, who could claim to be leading the field from the metropole and who was toiling in its outposts. The way scientists draw borders around their work shapes how that work is conducted and how it is valued.

Applied physicists, whose work had been relegated to the periphery by early 20th-century notions of physics, had learned that lesson well by the end of World War II. Solid-state physics was a category crafted to help industrial physicists navigate gnarly midcentury professional politics. Condensed-matter physics similarly redirected the field at a time when many sensed that "solid state" had grown long in the tooth and was holding portions of the field back. Both were efforts to redraw the map of physics to bring the outposts—applied physics in the first case, many-body theory in the second—closer to the metropole. But the process was not so simple as drawing borders around a new territory, appending it to an existing map, and calling it solid-state physics or condensed-matter physics. Creating those fields required changing the way those borders were drawn in the first place.

A common sentiment, articulated most sharply by historian Daniel Kevles, is that "physics is what physicists do."[15] The rise of condensed-matter physics, however, suggests a modification to the Kevles dictum: physics is what physicists decide it is. Solid-state physics, and condensed-matter physics after it, won prominence in large part because physicists recognized the power of categories and embraced their agency to craft them according to their needs.

This article is adapted from my 2018 book Solid State Insurrection: How the Science of Substance Made American Physics Matter.

Melinda Baldwin, Agnes Bolinska, Paul Cadden-Zimansky, and an anonymous referee, whose perceptiveness much improved this paper, have my gratitude.

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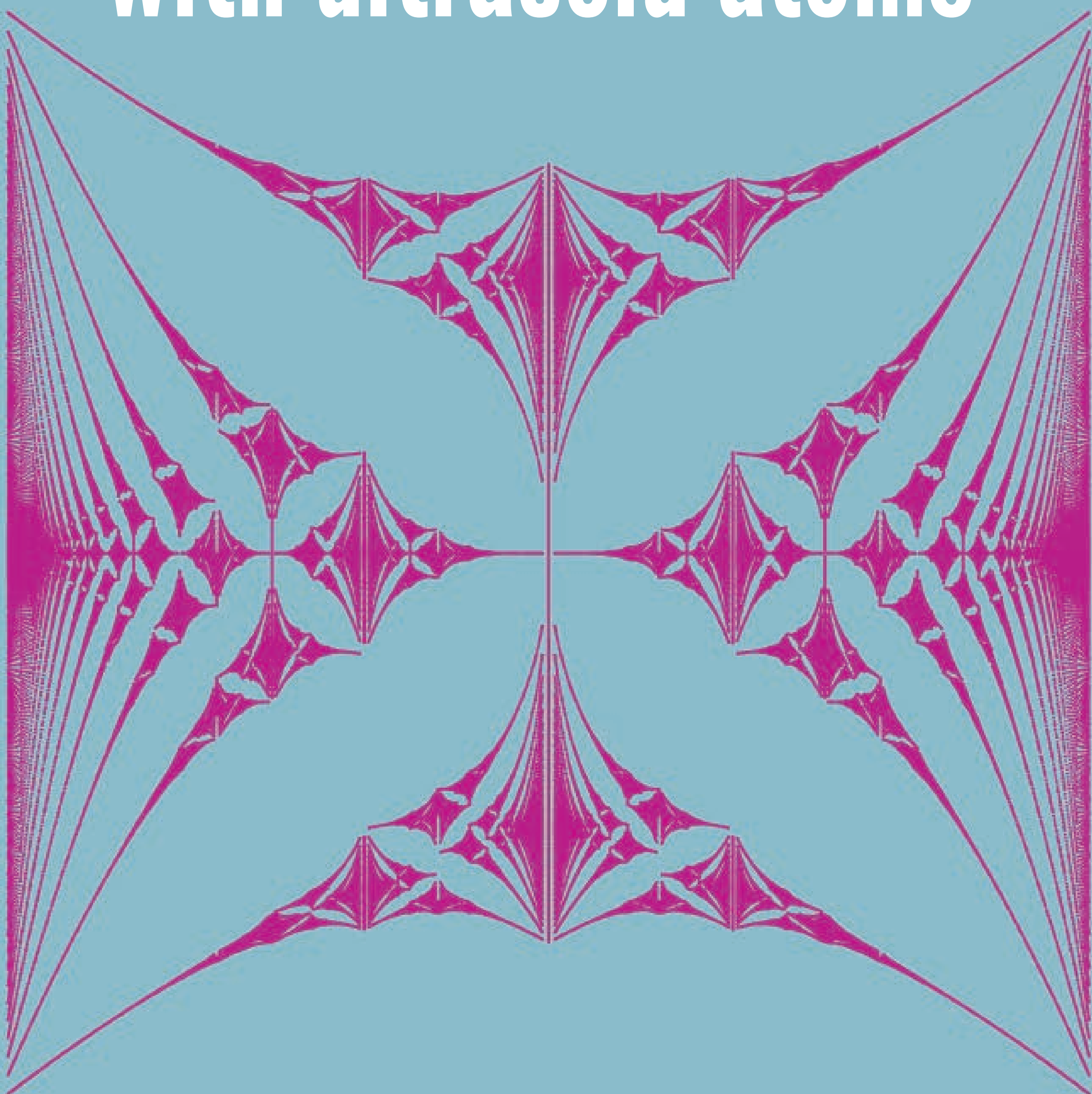
ARTIFICIAL GAUGE FIELDS with ultracold atoms



COURTESY OF INDU SATIJA

Victor Galitski and **Ian Spielman** are both fellows at the Joint Quantum Institute, in College Park, Maryland; the research partnership is between NIST, where Spielman is a NIST fellow, and the University of Maryland, where he and Galitski are professors. **Gediminas Juzeliūnas** is a research professor at the Institute of Theoretical Physics and Astronomy at Vilnius University in Lithuania.

Victor Galitski, Gediminas Juzeliūnas, and Ian B. Spielman

Suitable combinations of laser beams can make neutral atoms behave like electrons in a magnetic field.

Gauge fields are ubiquitous in nature. In the context of quantum electrodynamics, you may be most familiar with the photon, which represents the gauge field mediating electromagnetic forces. But there are also gluons, which mediate strong forces, and the W and Z particles, which mediate the weak forces. According to the standard model, those few gauge bosons, in fact, mediate all elementary interactions.

In materials physics, applied gauge fields in the form of laboratory magnetic fields are essential for realizing exotic quantum phenomena, such as the quantum Hall effect (see the article by Joseph Avron, Daniel Osadchy, and Ruedi Seiler, PHYSICS TODAY, August 2003, page 38). In a two-dimensional lattice, for instance, electrons that move through a periodic potential and a strong magnetic field are expected to exhibit a recursive, fractal energy spectrum known as Hofstadter's butterfly, pictured here.

Furthermore, strongly correlated systems can host new gauge fields or particles known as anyons, which obey unusual quantum statistics—not those of everyday fermions or bosons. This article explains how to create artificial gauge fields—made on demand in a controlled laboratory setting—by using ultracold atomic gases. The engineered gauge fields can lead to phenomena that naturally occur in other systems and to new phenomena that occur nowhere else in nature.

To understand the concept of a gauge field, one must confront a difficult and perplexing aspect of physics, in which the equations describing physical reality involve variables that are not measurable. Such equations occur even in elementary classical electrodynamics, where the magnetic vector potential **A**, satisfying **B** = ∇×**A**, is used in place of the magnetic field **B** to describe the familiar Lorentz force that curves charged particles around magnetic field lines. A static vector potential is not measurable by itself—only its curl, the actual magnetic field, is. Hence **A** is defined only up to an arbitrary curl-free function—allowing the so-called gauge choice—that keeps the observable electromagnetic forces intact. That reality cannot depend on an arbitrary function is an example of gauge invariance, a fundamental physical principle that requires all physical observables to be independent of the choice of a gauge.

The concept of gauge field is merely auxiliary in classical physics. Maxwell's equations and Newton's force law can optionally be reframed in the Hamiltonian or Lagrangian formalisms that replace physical fields with gauge potentials. Although the gauge potentials provide a convenient mathematical framework for solving some problems, a complete understanding of classical physics does not require the reframing.

In contrast, the gauge-field formulation is the only consistent mathematical description of quantum particles interacting with electromagnetic fields. Indeed, the central object in quantum mechanics, the wavefunction $\psi(\mathbf{r})$—often represented as a position-dependent complex function having both real and imaginary components—is not directly observable. The wavefunction's overall complex phase factor $e^{i\phi}$ can be changed with no physical consequence. For charged particles, that ambiguity in the definition of a wavefunction is tied one-to-one to the ambiguity in the choice of a gauge for the electromagnetic field.

Gauge ambiguity is not a mathematical curiosity. It's an intrinsic property of quantum mechanics and a source of many important and peculiar quantum effects, such as the Aharonov–Bohm effect (see the article by Herman Batelaan and Akira Tonomura, PHYSICS TODAY, September 2009, page 38) and topological phases of matter, the focus of the 2016 Nobel Prize in Physics (see PHYSICS TODAY, December 2016, page 14).

Ultracold atoms

Although gauge fields and their associated forces abound in physics, their properties cannot be fully controlled. For example, the charge of an electron is a fundamental constant, and the Lorentz force is a law of nature; both are nonnegotiable. And yet gauge-field physics can be simulated in tabletop experiments by using ultracold atoms.

A cloud of ultracold atoms, held at temperatures typically between hundreds of picokelvins to tens of microkelvins, is up to a million times thinner than air. The atoms live in ultrahigh vacuum, isolated from their environment and trapped by optical or magnetic forces. Each aspect of their physical description must be assembled from quantum mechanical building blocks.

The energy of the atoms' interactions with each other is feeble, typically on the order of 10^{-31} joules. Yet the gases can still form strongly interacting quantum systems. For example, neutral atoms trapped in an optical lattice—the standing waves formed by mutually interfering laser beams—tunnel from one site to another, just as electrons do in a crystalline solid, and repel each other whenever they share the same lattice site.

The energy balance between the atoms' tunneling and their interactions can be adjusted by changing the intensity of the interfering lasers. The change can drive the transition between an itinerant phase, in which atoms hop freely between lattice sites, and a crystalline phase, in which they are immobile, pinned to their sites. The change in intensity also provides a way to realize the Hubbard model in strongly correlated electronic materials (see the article by Gabriel Kotliar and Dieter Vollhardt, PHYSICS TODAY, March 2004, page 53). The Hubbard model and other standard theoretical models rarely occur in their pristine form in materials. To give such iconic and idealized models life in the laboratory, one can use cold atoms to forge a link between quantitative, precise atomic-physics experiments and many-body theory.

The response of a material to electromagnetic fields is perhaps the most versatile and informative way to probe its electronic phases. As simulators, though, cold atoms lack a crucial ingredient that makes such probing possible: electric charge. Because of their charge neutrality, individual atoms do not experience Lorentz forces in a magnetic field. It would therefore seem that a wide range of phenomena would be forever out of reach of cold-atom experiments. Fortunately, that's not so.

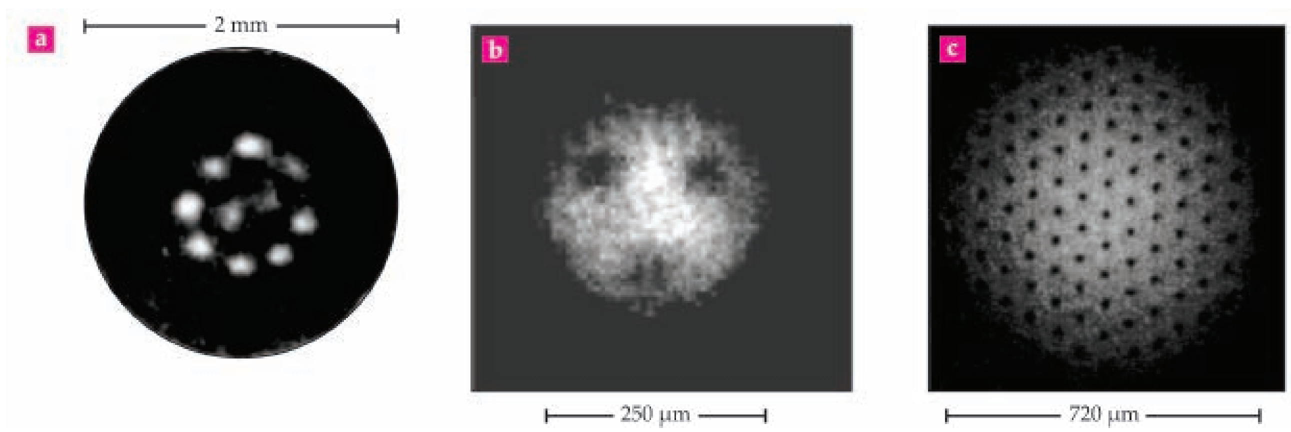


FIGURE 1. THE APPEARANCE OF QUANTIZED VORTICES in a rotating superfluid is a smoking gun for the presence of an artificial magnetic field. The density of vortices is in direct proportion to the artificial field's magnitude. **(a)** Quantized vortex arrays in superfluids were first imaged in liquid helium in 1979 at the University of California, Berkeley.[1] **(b)**They were later seen, in 2000, in a slowly rotating Bose–Einstein condensate (BEC) of rubidium.[2] **(c)** This 2003 image of a quickly rotating BEC of Rb captures a large array of vortices created at JILA.[4]

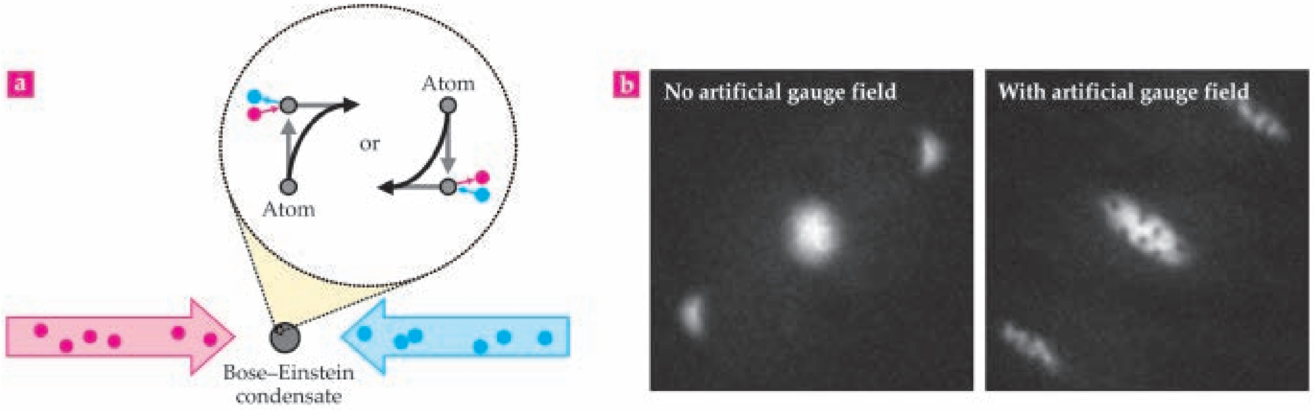


FIGURE 2. STIMULATED RAMAN TRANSITIONS. Two counterpropagating laser beams (pink and blue) incident on a Bose–Einstein condensate (BEC) can create artificial magnetic fields. **(a)** The beams drive stimulated Raman transitions in the atoms; each transition absorbs a photon from one beam and emits one into the other beam while imparting a momentum kick to the atom. As an atom is moving upward, say, it also moves right from the recoil. The reverse happens for atoms moving downward. The kicks simulate a transverse, velocity-dependent Lorentz force. **(b)** An atomic BEC with an artificial gauge field turned off (left) and turned on (right). The appearance of quantized vortices mark the presence of the artificial gauge field. (Adapted from ref. 5.)

Rotation as simulation

The first artificial magnetic field experiments using cold atoms exploited the equivalence between the Lorentz force in a uniform magnetic field and the Coriolis force in a spatially rotating frame. The equivalence may be most familiar in the context of the Foucault pendulum, whose axis of oscillation slowly rotates at an angular velocity ω. The reason for the rotation is simple: A particle traveling linearly with velocity v in a stationary frame undergoes curved motion in a rotating frame from the Coriolis force $\mathbf{F}_C \propto \mathbf{v} \times \boldsymbol{\omega}$, just as a charged particle follows a circular cyclotron orbit in a uniform magnetic field from the Lorentz force $\mathbf{F}_L \propto \mathbf{v} \times \mathbf{B}$.

One of the most beautiful and direct manifestations of superconductivity is the formation of vortices—sharply localized quanta of circulation of magnetic flux or angular momentum. Quantized vortices were predicted for superfluid helium by Lars Onsager in 1947 and by Richard Feynman in 1955. Russian theorist Alexei Abrikosov extended the prediction to superconductors in 1957 and showed that interactions between the vortices ordered them into a regular array, the so-called Abrikosov lattice. The achievement earned him a Nobel Prize in Physics almost 50 years later (see PHYSICS TODAY, December 2003, page 21).

Vortices can be induced in a superfluid by the effective magnetic field present in rotating systems. In 1979 Richard Packard and colleagues first imaged a vortex array, as shown in figure 1, in helium by using a rotating cryostat.[1] Two decades later, Jean Dalibard and colleagues found much the same thing—a small cluster of three uniformly spaced vortices—in atomic Bose–Einstein condensates (BECs) of rubidium-87 stirred by a focused laser beam.[2] The observation provided strong evidence for superfluidity in BECs.

The groups of Wolfgang Ketterle at MIT and Eric Cornell at JILA made technical improvements that led to observations of large vortex arrays—a qualitative leap beyond the earlier results found in liquid He and the atomic BECs.[3,4] Those large Abrikosov lattices set the stage for studying the dynamics of vortex crystals during melting and in other nonequilibrium settings.

As exciting as the experiments on rotating superfluids have been, though, they only probed phenomena observable in weak gauge fields. An important figure of merit in many-body

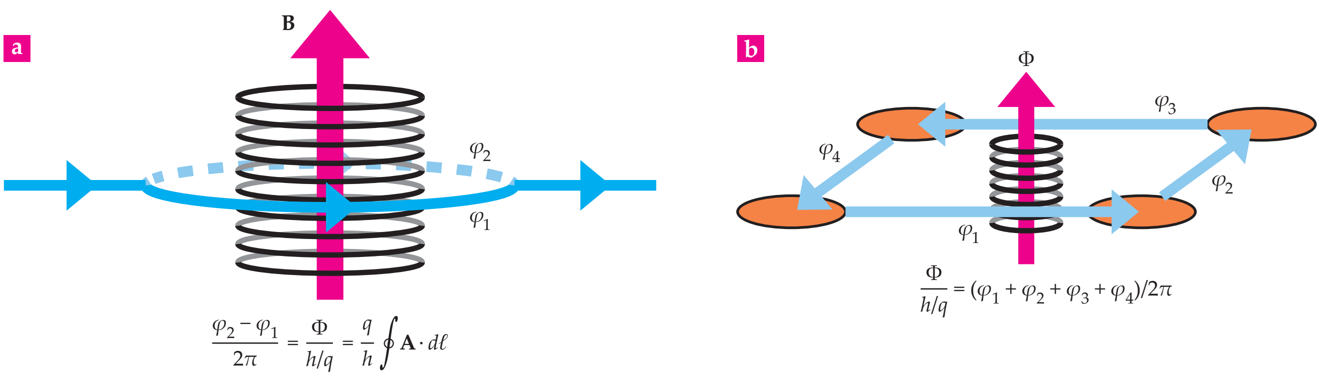


FIGURE 3. PHASE ENGINEERING. Quantum mechanical particles experience magnetic fields by acquiring Aharonov–Bohm (AB) phases. **(a)** In an AB interferometer, a magnetic field **B** is confined to the interior of a solenoid and is zero outside it. Nevertheless, a particle that travels on opposite sides of the solenoid will acquire a phase difference proportional to the enclosed magnetic flux Φ. That flux equals the line integral of the vector potential **A** around the solenoid. The charge is specified by q. **(b)** Particles that tunnel in a lattice experience an applied magnetic field in much the same way as in the AB effect. Their tunneling motion from one site to another acquires a so-called Peierls phase, such that the sum of the phases around a closed loop equals the enclosed flux.

systems is the ratio of the radius of the minimum cyclotron orbit to the average interparticle separation. The smaller the ratio, the stronger the magnetic field effects and the closer one gets to probing the difficult and exciting physics of strongly correlated topological phases of matter. Those phases include the fractional quantum Hall states, collective states of matter that occur in ultrastrong fields and in which electrons behave as if their elementary charge is a fraction of their actual charge. (See the article by Jainendra Jain, PHYSICS TODAY, April 2000, page 39.) Unfortunately, the range of rotation-induced artificial magnetic fields are far from that interesting territory. New approaches were required to reach larger artificial fields.

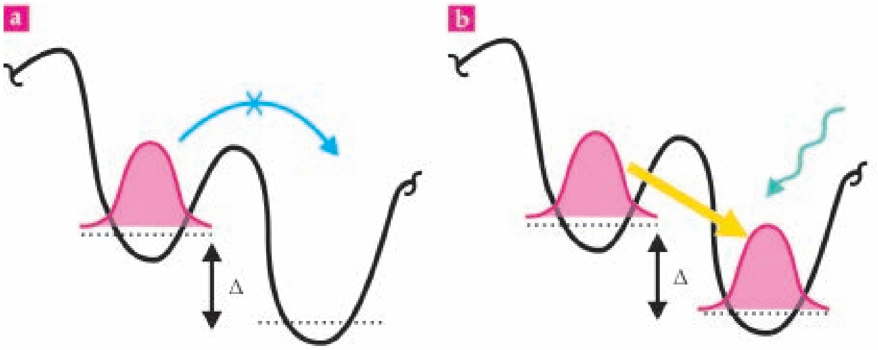


FIGURE 4. LASER-ASSISTED TUNNELING. The native tunneling in an optical lattice does not produce the phase differences required to emulate a gauge field. But the phases can be created in a two-step process. **(a)** When a potential gradient of energy Δ is applied to a lattice, the energy states in adjacent sites go out of resonance with each other, which blocks a localized atomic wavepacket (pink) from tunneling. **(b)** Additional laser fields illuminating the lattice can provide the required energy to reestablish tunneling (yellow arrow). The applied fields also imprint a local optical phase on the atom's wavefunction as it moves between lattice sites.

Laser-induced gauge fields

The first new approach in the laboratory used an atomic BEC illuminated by a pair of counterpropagating laser beams, each having a distinct wavelength λ (figure 2a). Most atoms, including those in a BEC, have several spin states that are distinguished by a combination of orbital, electron, and nuclear spin degrees of freedom. When the laser beams strike the BEC, they become quantum mechanically coupled to the spin states of individual atoms. During each interaction, an atom's spin flips, a process accompanied by the exchange of a photon from one beam to the other. The exchange imparts to the atom a momentum kick of $2h/\lambda$, which changes the atomic velocity by about 1 cm/s. The BEC atoms are so cold that even that tiny change exceeds the thermal velocity of the system.

The recoil of the atoms depends on their vertical motion and slight differences in the beam wavelengths. As an atom moves upward, for instance, it is stimulated to emit a photon into the leftward-moving beam (blue) in figure 2 and, as a result, acquires a kick to the right. The change in momentum emulates the transverse response of a Lorentz force, which moves the atom in circles, to use the classical analogy. An artificial magnetic field is created.

Although that intuitive picture alludes to forces, the quantum system is mathematically better described by the appearance of an electromagnetic vector potential—a gauge field.[5–7] In 2009, a team including one of us (Spielman) demonstrated the technique at NIST.[5] The artificial magnetic field was marked by the presence of vortices, as shown in figure 2b, but in the laboratory frame rather than in a rotating frame.

In the final analysis, the experimental scheme in figure 2 turned out to be well suited for creating elongated trapped-atom geometries but not for creating extended systems with large fields. Even so, the pioneering work opened the door for experiments that now do operate at large fields.

The Aharonov–Bohm effect

In quantum mechanical systems, gauge fields are inseparably intertwined with the wavefunction's phase. The connection is dramatically evident in the Aharonov–Bohm (AB) effect, shown in figure 3a, for charged quantum particles moving about an infinite solenoid. The magnetic field is zero outside the rings of the solenoid, where the particles actually move. But even though they never experience a magnetic field, the particles still respond to the electromagnetic vector potential, which, unlike the magnetic field, necessarily extends outside the solenoid.

Upon completing a closed loop, each particle's wavefunction acquires an additional phase—the AB phase—which is proportional to the magnetic flux enclosed by the solenoid. By Stokes's theorem, that flux is equal to the line integral of the vector potential around the loop traversed by the particle. Hence the acquired phase is a direct consequence of the vector potential, not the magnetic field itself.

One can see that connection in a lattice in which atoms tunnel between adjacent sites. The AB phase acquired by an atom as it encircles a square plaquette in the lattice, as shown in figure 3b, is just the sum of the four phases gained on the associated links.

Gauge fields in optical lattices

Extending that one plaquette to a larger array would produce a 2D square lattice with a constant magnetic flux in each unit cell. But how can the tunneling phases be created in the laboratory without the real magnetic field of a solenoid? The first theoretical proposal was to make an artificial gauge field that uses "laser-induced tunneling" of atoms between sites in an optical lattice.[8] In the proposal, the atoms don't tunnel through the barrier on their own volition; rather, they are pushed through it with additional laser fields.

The concept is illustrated in figure 4, using just two lattice sites: Imagine a conventional optical lattice that is tilted—with one site higher in energy than the other. The tilting takes the atoms in the two sites out of resonance with each other and prevents tunneling. Two light fields whose photon energies differ by the tilt energy then provide just the right amount of energy to link the states together.

In addition to reestablishing tunneling between sites, the laser-induced tunneling also imprints a position-dependent optical phase onto the wavefunction of the atoms. The phases emulate the quantum mechanical phases picked up by electrons tunneling between the lattice sites of a crystal in a real magnetic field.[7] The optical phases that accumulate around each square plaquette in the lattice are equal and emerge from a uniform artificial magnetic field.

Unlike in naturally occurring solids, where the magnetic flux through a plaquette is much smaller than the flux quantum h/q, where q is the magnitude of the relevant charge, very large laser-induced fluxes can be produced in an optical lattice. Figure 5a shows one experimental demonstration,[9] in which an atomic wavepacket prepared in a single site of an optical lattice undergoes cyclotron-like motion around a square plaquette; its center-of-mass motion, from dark green to light green, is plotted over 2 ms. A similar scheme was experimentally implemented by Ketterle's group around the same time.[10] Nontrivial phases have also been imprinted by literally shaking the optical lattices,[11] but in a way that does not correspond to a uniform magnetic field.

Synthetic dimensions

An essential step in creating gauge fields with laser-assisted tunneling is to suppress the native tunneling of atoms between lattice sites. In the preceding section, we took the natural approach of using a tilted lattice to do the job. But that's not the only solution. Five years ago, a group of researchers, including two of us (Spielman and Juzeliūnas), proposed a scheme using transitions between different spin states of the BEC atomic ground state to create "synthetic dimensions."[12]

Lattice sites, according to that approach, need not be in different places in space. Dimension can also refer to the connectivity, or number of independent states, into which the atoms can tunnel. In addition to a real dimension, along which motion corresponds to a displacement in space, there's a synthetic dimension that corresponds to the internal spin states of ultracold atoms. When lasers couple the spin states together, the resulting "motion" between the spin states is accompanied by an optical phase that gives rise to a uniform flux.

In addition to reestablishing tunneling between sites, the laser-induced tunneling also imprints a position-dependent optical phase onto the wavefunction of the atoms.

The concept, which Spielman and others subsequently implemented in 2015, offers new opportunities for control and measurement.[13] For one thing, it's easy to detect individual synthetic lattice sites using standard spin-selective detection techniques. Also in 2015 Leonardo Fallani's group concurrently demonstrated the utility of synthetic dimensions in a degenerate Fermi gas of ytterbium.[14]

Figure 5b presents the experimental trajectories followed by BEC atoms on a long, thin virtual strip, whose real dimension is space, plotted horizontally, and whose synthetic dimension is the atoms' magnetic quantum numbers $m = 1$, 0, and −1, plotted vertically.[13] By preparing the atoms on the strip's edges and then allowing them to move in the artificial magnetic field, the researchers observed them following "skipping orbits" along the top and bottom edges. Each time an atom struck the hard-wall potential along an edge, it reflected and began following yet another cyclotron orbit.

To be non-abelian

As we've seen, artificial gauge fields make charge-neutral particles curve as if they were under the influence of a Lorentz force. But in quantum systems, the rabbit hole is deeper: As we have noted, quantum particles have internal degrees of freedom, like the spin-up and spin-down of an electron.

That simple addition opens the door for new kinds of so-called non-abelian gauge fields, in which the effective Lorentz force can depend on the magnitude and sign of the spin or even drive changes to the spin state as the particle moves. (Such a non-abelian gauge field is distinct from the non-abelian

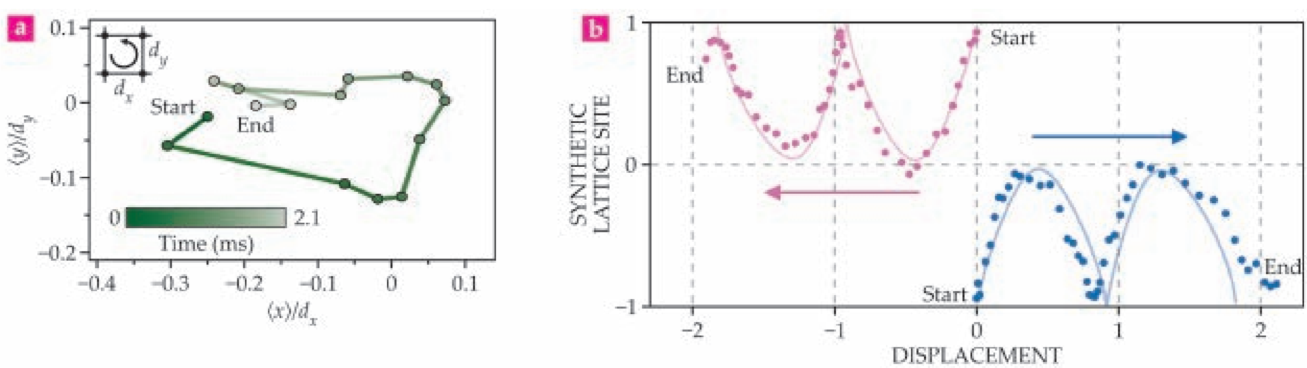


FIGURE 5. DYNAMICS IN AN ARTIFICIAL GAUGE FIELD. Atoms that move from one optical lattice site to another under laser-assisted tunneling circle through the sites, as in figure 3b. **(a)** One experiment measured the center-of-mass positions of atoms (dots) <x> and <y>, scaled to the lattice constants d_x and d_y, as the atoms move among the four sites (inset) over 2.1 ms. (Adapted from ref. 9.) **(b)** In another experiment, the positions (dots) of BEC atoms are mapped along the edges of a long, thin virtual strip. The horizontal dimension, scaled to the lattice constants, is real, and the narrow dimension is synthetic, formed by the atoms' spin states 1, 0, and −1. The edge currents to the left (pink) and right (blue) evolve in time with opposite velocities and are the result of the "skipping orbits," in which the atoms mimic cyclotron motion and periodically reflect from the strip's edges. (Adapted from ref. 13.)

quasiparticles that are potentially relevant for quantum computation. See the article by Nick Read, PHYSICS TODAY, July 2012, page 38.) In essence, the Aharonov–Bohm phases φ of figure 3a would each be replaced by a matrix that can give different phases for the different spin states or that can even change the spin state entirely.

Spin–orbit coupling in a material is an interaction between the electron's momentum and its spin. In many cases, the interaction is equivalent to a non-abelian gauge field. Spin–orbit coupling is responsible for various interesting physical phenomena—from the spin Hall effect to Majorana fermions and topological insulators (see the box on this page and PHYSICS TODAY, March 2011, page 20). By extending the ideas discussed above, certain types of non-abelian gauge fields have also seen the light of day in cold-atom experiments.[7]

Applications

The experiments described in this article serve as quantum simulations to better understand the toy models that approximately describe real materials. Vortex physics is an ideal target for quantum simulation. Because the motion of vortices is a leading source of dissipation in superconductors, understanding them has wide-ranging real-world impact, from high-field superconducting magnets used in medical magnetic resonance imaging to magnetic levitating trains.

Much is still unknown about quantum vortices: How do large collections of them interact and evolve? (See, for example, PHYSICS TODAY, January 2017, page 19.) When do their positions become pinned to the disorder potential? How do we understand the flow of angular momentum in a material with vortices, in analogy to the flow of electrons in a metal? Cold-atom superfluids in the presence of an artificial magnetic field serve as a medium for exploring those questions.

Artificial gauge fields provide new techniques for realizing topological states of matter (see the Quick Study by Mohammad Hafezi and Jake Taylor, PHYSICS TODAY, May 2014, page 68). Topological insulators and the integer and fractional quantum Hall effects were discovered and understood in conventional material systems, but the practical limitations of material systems hinder the ability to create new types of topological matter. For example, although many 2D models host anyon excitations, their only known physical manifestation is the fractional quantum Hall effect. Three-dimensional counterparts—interacting topological insulators—are beyond the reach of current experiment and theory. Cold atoms with artificial magnetic fields provide a realistic system experimentalists can use to engineer and observe their exotic states.

Artificial gauge fields can also host completely new physics that have no analogues elsewhere in nature. One example is spin-½ bosons made with spin–orbit coupling. Recall that bosons normally have integer spin and fermions have half-integer spin. As in quantum Hall systems, spin-½ bosons would boast a massively degenerate ground state and be ideally suited for creating strongly correlated topological matter.[16]

The gauge fields present in high-energy physics are, like the photon, dynamical gauge fields. Aspects of those dynamical gauge fields may be modeled with time-dependent artificial gauge fields. A dynamical gauge field samples all possible configurations of the associated classical field. In certain cases, quantum fluctuations in a dynamical gauge field have average properties similar to that of noise added to a classical gauge field. Sampling those fluctuations can be experimentally modeled using atoms in optical lattices coupled to a synthetic gauge field to which laboratory-controlled noise has been added. That would be a good first step to simulating lattice gauge theories in the low-temperature limit.

TOPOLOGICAL MATTER

Band insulators are crystalline materials with an energy gap between the materials' occupied valence bands and unoccupied conduction bands. A single excitation produces a mobile electron free to move in the crystal lattice. The charge and quantum statistics of that excitation are the same as those of the material's constituent electrons.

Topological insulators (TIs) are a broad class of band insulators, distinguished by different windings of the phase of the atom's eigenstates for different crystal momenta in the lattice. Although excitations deep inside TIs separate, much like conventional insulators, into valance and conduction bands, TIs form new conducting states at crystal boundaries. (See the article by Xiao-Liang Qi and Shou-Cheng Zhang, PHYSICS TODAY, January 2010, page 33.)

Strongly correlated materials give new excitations called anyons. As Frank Wilczek put it, "The statistics of these objects, like their spin, interpolates continuously between the usual boson and fermion cases."[15] Often referred to as fractionalized quasiparticles, anyons occur in strongly correlated topologically ordered states.

Such strongly correlated states are theoretically present in various quantum spin models. But laboratory realizations of TIs are few: They have been seen experimentally only in fractional quantum Hall systems, which require highly restrictive experimental conditions, such as ultralow temperatures, high magnetic fields, and ultraclean samples. Strongly interacting ultracold atoms subject to artificial gauge fields are one promising avenue for realizing those fractional states of matter.

For financial support, we thank NIST, the US Army Research Office, the US Air Force Office of Scientific Research, NSF through its Physics Frontier Center at the Joint Quantum Institute at the University of Maryland, and the Lithuanian Research Council. Victor Galitski and Ian Spielman also appreciate the support of Paul Baker and Peter Reynolds.

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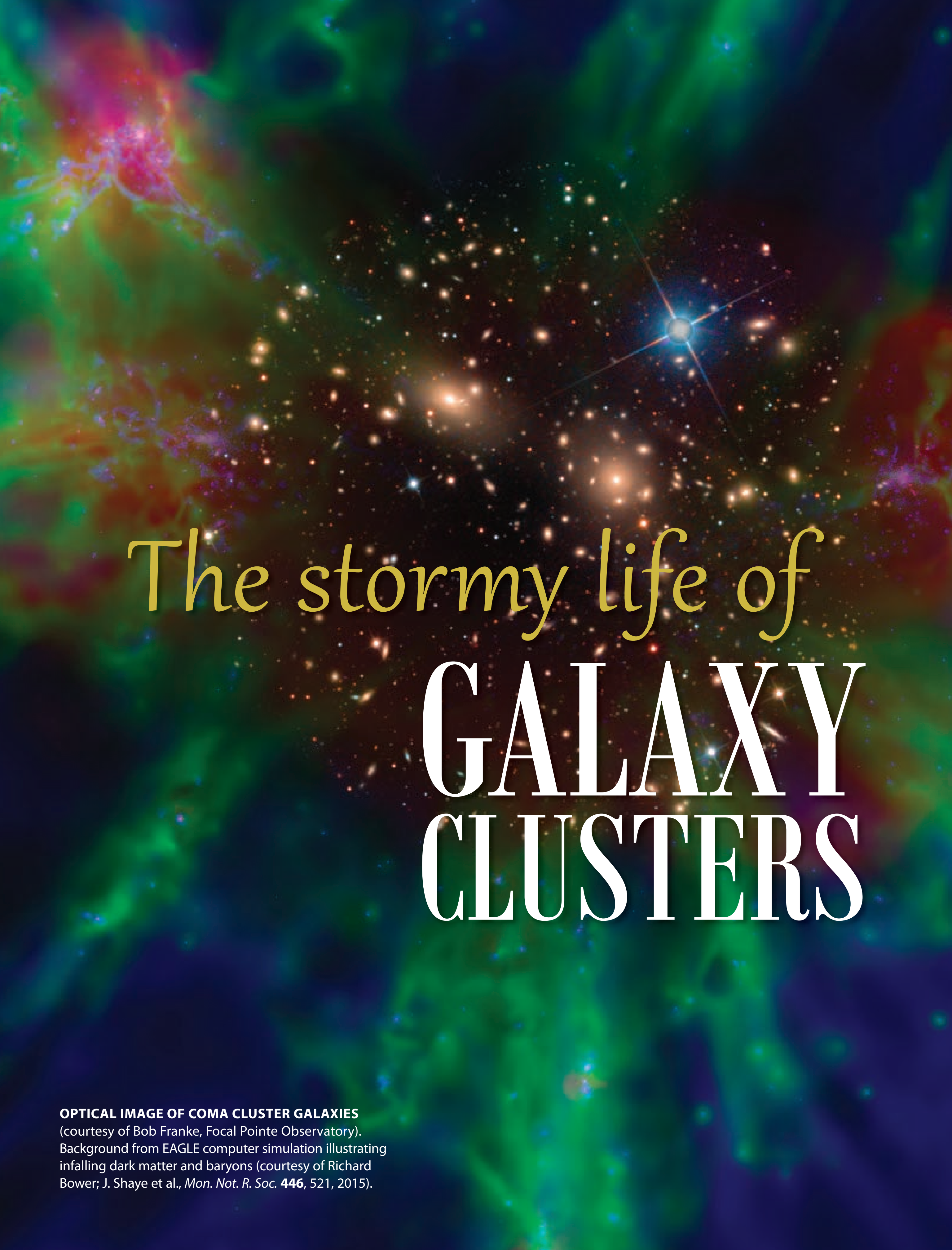
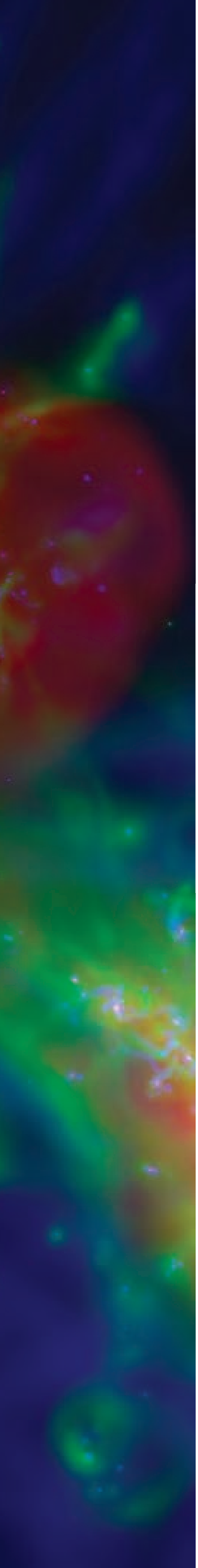


The stormy life of GALAXY CLUSTERS

OPTICAL IMAGE OF COMA CLUSTER GALAXIES (courtesy of Bob Franke, Focal Pointe Observatory). Background from EAGLE computer simulation illustrating infalling dark matter and baryons (courtesy of Richard Bower; J. Shaye et al., *Mon. Not. R. Soc.* **446**, 521, 2015).



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Lawrence Rudnick

Tempestuous interactions between plasmas, galaxies, and dark matter have shaped the history and current structure of the universe.

It's 1902 and astronomer Max Wolf is confused. Scrutinizing photographic plates of the star-poor region near the north pole of the Milky Way, in the constellation Coma Berenices, he spots an unusual concentration of fuzzy patches. In his article, "Die Nebelflecken am Pol der Milchstrasse" ("The fuzzy objects at the pole of the Milky Way"), Wolf provides meticulous descriptions of those objects, their sizes, and their morphologies—elliptical, spiral, and core brightened. He concludes with the understatement, "It would be premature to speculate on this strange result. Nonetheless, I must not miss pointing it out for general attention."[1]

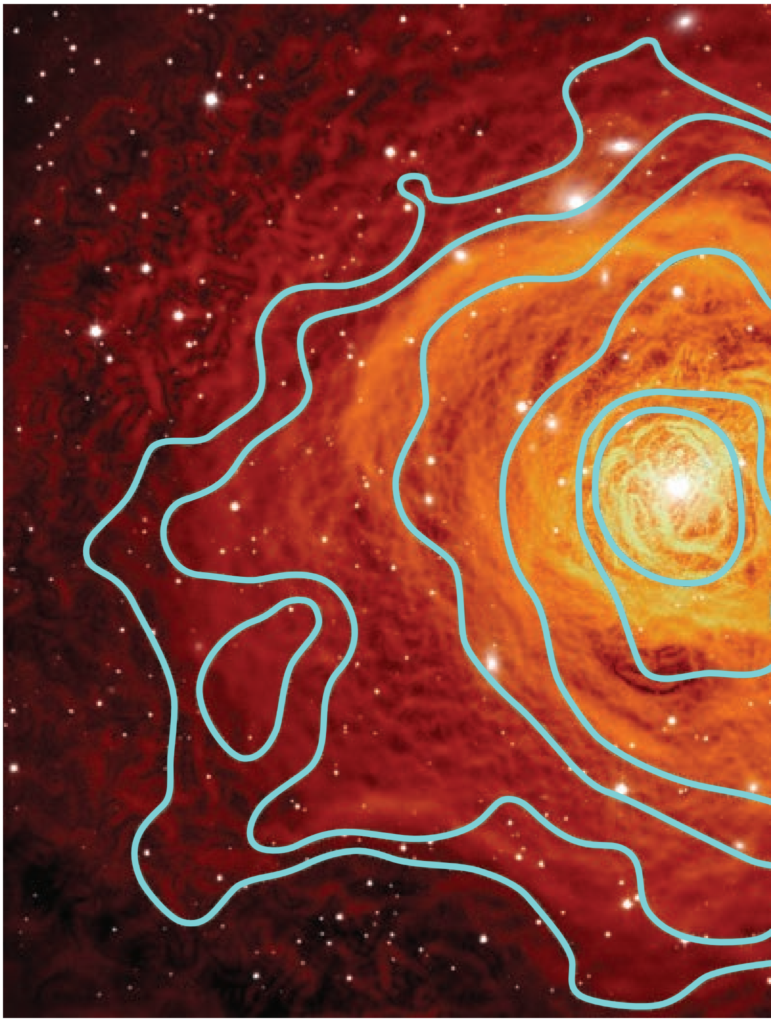
Thirty years later Wolf's fuzzy nebulae were shown to be island universes, what we now call galaxies, and first hypothesized by German philosopher Immanuel Kant. Today, Wolf's collection of galaxies is known as the Coma cluster—its central region of massive galaxies is shown in the opening image. They are each comparable in size to our own Milky Way, with hundreds of billions of stars.

But another mystery emerged in the early 20th century. Using the Doppler shifts of galaxies in the clusters, astronomers calculated that about 400 times the mass of the stars themselves would be required to keep clusters like Coma gravitationally bound. In 1933 the brilliant and eccentric Swiss astronomer Fritz Zwicky attributed that extra gravitational force to some unknown "dunkle Materie,"[2] or dark matter, whose nature remains a mystery to this day.

A brief glimmer of hope that dark matter might have been found appeared in the 1970s when astronomers discovered that clusters of galaxies were filled with an x-ray-emitting plasma—the intracluster medium (ICM)—at a temperature of 10^{7-8} K degrees. But estimates of its mass quickly established that it too fell far short of being able to bind the cluster. The ICM contributes only about 13% of the 10^{45} kg that make up the most massive clusters. Dark matter, whatever its nature, continues to dominate the overall cluster collapse and subsequent dynamical evolution.

Both computer simulations and observational studies of the three-dimensional distribution of mostly dark matter show that it is concentrated into filamentary structures that become evident approximately a billion years after the Big Bang (see Physics Today, March 2007, page 20). The opening image illustrates how clusters of galaxies are found at the intersections of those filaments, which have a continuing infall of both dark and baryonic matter that fuels the clusters' growth. In fact, those clusters are the largest gravitationally bound systems in the universe today, with characteristic sizes of a few megaparsecs (Mpc) or about 10^{20} km.

The opening image belies the sometimes violent and very long time-scale motions present as a cluster evolves over billions of years. A sped-up view would reveal a stormy mélange of interactions between the cluster's diffuse plasmas, galaxies, and dark matter.



The challenge is to re-create that evolution from sparse snapshots at different wavelengths.

Storm chasing

Clusters evolve relatively simply at first as material begins to fall into them, but shocks and other features soon develop in the diffuse plasma of the ICM. With densities of only $10^{2-4}/m^3$, the ICM has an enormous particle mean free path of about 10^{17} km. In that extreme "collisionless" plasma, which is not seen anywhere on or near Earth, interactions are driven by plasma wave scattering. With its high ratio of plasma to magnetic field pressures, the ICM plasma provides bountiful opportunities to investigate interesting questions far beyond the reach of a terrestrial lab: Which types of plasma waves dominate? How do plasma structures transfer energy to different spatial scales? How can ions and electrons reach equilibrium with each other? How do magnetic fields and cosmic rays co-evolve?[3]

The radiative processes of two cluster-wide plasmas help astronomers reconstruct the history of the cluster. The x-ray-emitting ICM plasma reveals itself through free-electron collisions with ions (thermal bremsstrahlung); the radio-emitting cosmic-ray plasma shows itself through synchrotron radiation generated when relativistic electrons spiral around a magnetic field. The ICM also creates distortions in the cosmic microwave background spectrum that can help in diagnosing ICM properties. The cosmic microwave background photons first pass through the cluster. On their way to Earth, they experience inverse Compton scattering off hot electrons in the thermal plasma. The mechanism, known as the thermal SZ effect, was named for Rashid Sunyaev and Yakov Zel'dovich, who first described it[4] in 1972. Magnetic fields provide yet another diagnostic tool, since they regulate the brightness and polarization properties of the synchrotron radiation. With typical strengths of 0.1–1 nT, the magnetic fields physically couple the thermal and relativistic plasmas and influence both the transport of heat in the ICM and the energization of the cosmic rays.

All those processes reveal different aspects of the plasmas, which astronomers use to determine densities, temperatures, the presence of shock waves, and other transient features in the ICM. They would love to watch the time-lapse maps of the radio and x-ray emissions to chart the passage of shocks and the generation and dissipation of turbulence. Unfortunately, the crossing time for clusters can approach a billion years, a bit beyond the typical astronomical career. But fortunately, weather vanes in clusters form when low-density and usually bipolar jets of plasma are ejected from supermassive black holes at the centers of some galaxies, the so-called active galactic nuclei. Those jets are deflected and distorted in their relative motion through the ICM and provide important insights into the dynamics of the thermal ICM plasma.

Gentle storms

Clusters have been growing over the past 10 billion years through the continuing infall of material, mostly clumps of dark matter, primarily along the filamentary structures. In some clumps, the accompanying baryonic matter has cooled sufficiently for stars and galaxies to form. Once those relatively compact galaxies reach the denser environment of the cluster cores, they are scattered by local irregularities in the gravitational potential. That process will eventually lead to an isotropic distribution of orbits and a situation known as "virial equilibrium," where the galaxies' average kinetic energy equals one-half the magnitude of their average gravitational potential.

But for the infalling baryons still in a diffuse state, a quite different fate is in store. The high kinetic energy from their gravitational infall is converted into thermal energy in the outskirts of the cluster, which slows the infalling material's velocity. That conversion happens at the so-called accretion shock, which causes a jump in density and temperature. Those shocks have been seen in computer simulations but not yet in observations. After conversion of its kinetic energy, the plasma—part of the ICM now—reaches a temperature of about 10^8 K, hot enough for astronomers to detect its radiation in x rays. As the stars in the cluster galaxies continue to age, winds and shocks transport stellar-processed material into the ICM, enriching it with elements, from carbon to iron, produced inside stars.

If that infall continues at a slow pace and without colliding with another massive system, the cluster can reach a relaxed state. While the higher-density galaxies approach virial equilibrium, the diffuse ICM reaches hydrostatic equilibrium, where gravity balances the gas pressure. Under those gentle conditions, a massive central galaxy 10^{13} times the mass of the Sun ($M_\odot$) can form with a supermassive black hole at its core. In the cluster's inner regions, the radiative cooling time for the ICM is shorter than the age of the cluster, so central regions actually become colder than the diffuse medium farther out. Such relaxed clusters have high x-ray luminosities due to their high

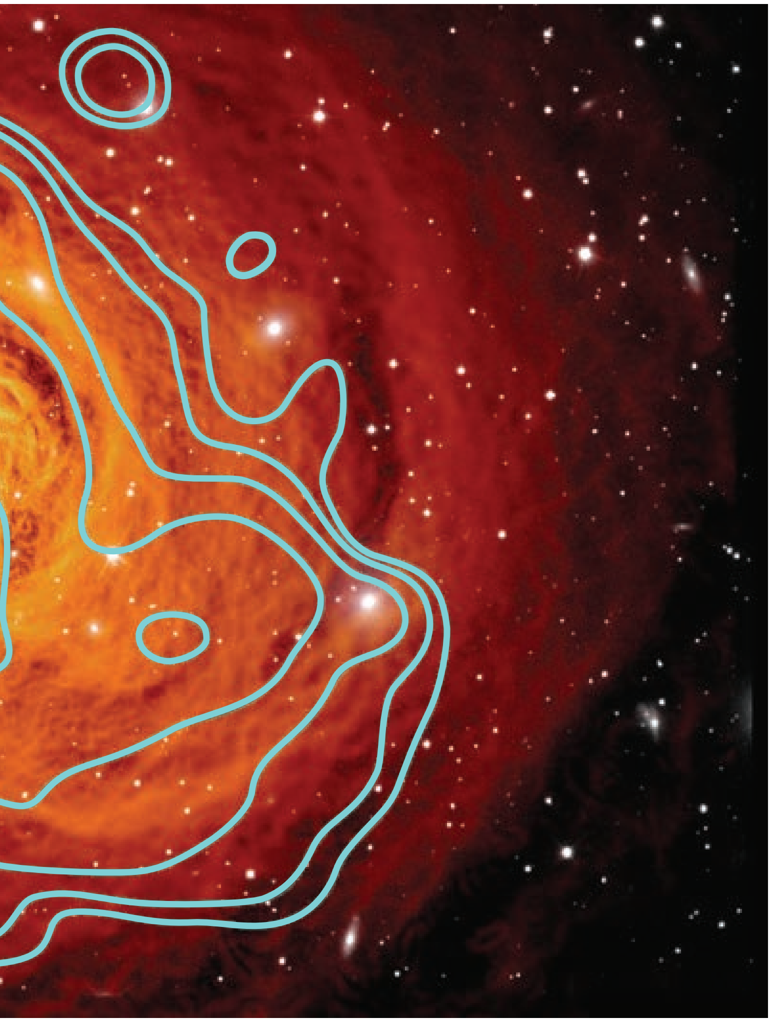


FIGURE 1. WHEN A MASSIVE COLD CLUMP of baryons and dark matter grazed the central region of the Perseus cluster, spiral-shaped ripples formed in the intracluster medium (ICM; orange, filtered from x rays). The image covers 400 000 parsecs; courtesy of Stephen Walker, NASA's Goddard Space Flight Center. The bright white patches show starlight from the cluster galaxies; they were observed with a 660 nm wavelength image from the Sloan Digital Sky Survey. Contours outline the corresponding synchrotron radiation from the relativistic plasma; courtesy of Marie-Lou Gendron-Marsolais, University of Montreal.

central densities. They are prominent in cluster surveys, where they are recognized by their bright, central x-ray cores, their Gaussian distributions of galaxy velocities, and their generally symmetric appearance.

That apparent cluster relaxation can be deceiving. If the smooth component of the cluster x-ray emission is filtered out, a new level of complexity reveals itself (see figure 1). The ripple structures arise when the infalling clumps of gas contain a substantial fraction of the cluster mass. Infalling material cannot be heated quickly enough, and a relatively cold (about 10^7 K) clump can penetrate deep into the cluster. The cold clump may also generate a bow shock that heats the surrounding medium. If the intruder is massive enough, it can even set off sloshing motions in the ICM baryons and produce spiral waves. Those sloshing motions can help mix the cooler and hotter gases, redistribute elements throughout the cluster, and induce turbulence that eventually dissipates the energy into heat.

The Perseus cluster, seen in figure 1, provides a dramatic example of sloshing motions in the ICM. And the likely culprit is an off-center encounter with a $10^{14}\ M_{\odot}$ clump approximately 2.5 billion years ago. Some of the energy also transferred into the cosmic rays, and the resulting synchrotron mini-halo is shown in the figure as cyan contours. Buried deep in the central galaxy NGC 1275, but not visible here, is also an active galactic nucleus, an accreting supermassive black hole. Its ejections evacuate bubbles in the x-ray emitting gas that may be seen as dark patches in the rich ICM structure.

Violent storms

When astronomers are lucky, they can catch one of the rarer major collisions between clusters of comparable mass. The Bullet cluster, seen in figure 2, shows the dramatic results of an encounter of greater than 10^{57} joules. The brightest, pink regions illuminate cooler ICM material from the original cluster cores. As the clump on the right passed through the preexisting ICM, it generated a pressure-matched, bow-shaped structure and beyond that, fainter, shock-heated regions. The diffuse plasma bore the brunt of the energy dissipation, while the cluster galaxies and dark matter had small enough cross sections that they passed through each other.

Looking at the synchrotron emission from cosmic-ray electrons and magnetic fields reveals additional information about stormy, multicluster mergers. Figure 3 shows the x-ray and radio synchrotron emission from the cluster Abell 2256, which likely formed—and is still forming—from the collision of two or three clusters. A few sharp edges in the x-ray emission reveal where cooler and warmer ICMs meet and create pressure-matched jumps in density and temperature; the x-ray emission otherwise appears mostly smooth. Likewise, the contours enclose an apparently smooth and faint region of radio synchrotron emission, called a radio "halo," coincident with the x rays. The smoothness, however, is an illusion, limited by imaging capabilities and the unavoidable averaging of the emission along each line of sight through the cluster. Cosmic-ray electrons will radiate away their energy in only about 10^8 years, which is far shorter than the time they need to diffuse across the cluster. Therefore, their energy must constantly be replenished throughout the cluster volume by some underlying flow structures in the ICM.

That energy is thought to be supplied by a great deal of turbulence throughout the ICM that not only accelerates the cosmic-ray electrons but also amplifies the ICM magnetic field. Looking beyond the central regions, the source of energy powering the dramatic filamentary synchrotron feature, shown in green in the upper right of figure 3, remains unclear. Although the energy source may be associated with shocks generated in the cluster-forming collisions, the corresponding x-ray features have not yet been seen.

When shock structures can be simultaneously detected in the two plasmas—radio and x-ray emitting—then astronomers can use that information to reveal the energetics and dynamics of the cluster merger. A textbook example of such x-ray and radio shocks is seen in figure 4, from the so-called Toothbrush cluster. Such shocks are often found on the periphery of cluster x-ray emission and are termed "radio relics" for historical reasons. Shocks can be described most simply by their Mach number, the ratio of their advance speed to the local sound speed.

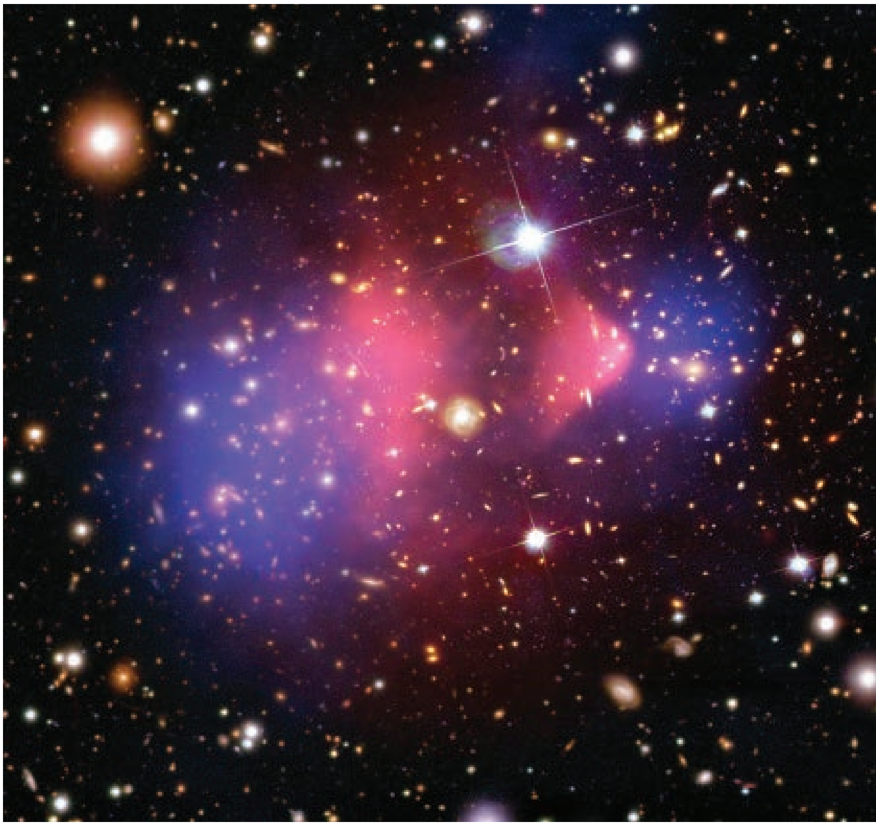


FIGURE 2. THE BULLET CLUSTER. X rays (pink) illuminate what remains of the intracluster mediums (ICMs) after a two-cluster collision. The clump on the right—one of the cluster's original, dense ICM cores—now generates a pressure-matched, bow-shaped feature in the surrounding ICM. The small cross sections of the galaxies (white) and dark matter (blue) allowed them to pass through each other with no interaction. (X ray: NASA/CXC/M. Markevitch et al. Optical: NASA/STScI; Magellan/U. Arizona/D. Clowe et al. Lensing map: NASA/STScI; ESO WFI; Magellan/U. Arizona/D. Clowe et al.)

Both the x-ray and radio shock features provide a way to estimate the Mach number, and their comparison helps astronomers determine whether they got the physics right. In the x rays, the jumps in density, temperature, or both are measured between the preshock and postshock material to calculate the Mach number. Astronomers must be mindful of uncertainties from limited spatial resolution and from averaging of emission along the line of sight. With these caveats, the discontinuity in the x-ray intensity profile shown on the right in figure 4 suggests the shock is quite modest, with a Mach number of about 1.3.

Because astronomers do not observe the radio preshock emission, they can't use the same kind of diagnostics to estimate the shock Mach number as they do for the x rays. However, astronomers know that cosmic rays can be energized at shocks, as is seen in solar flares. In a simple, idealized model of shock acceleration, often called diffusive shock acceleration, the cosmic-ray population follows a power law in energy, $N(E)\,dE \sim E^{-s}\,dE$. The synchrotron spectrum can be used to infer the power-law exponent, s, which is physically related to the Mach number. Observations of the Toothbrush relic reveal that instead of the very low x-ray-derived Mach number, the synchrotron-derived value is about 3.5. To first order, it's reassuring that those simple theories with very different underlying physics for interpreting the radio and x-ray observations both lead to low Mach numbers. But at second order, the discrepancies have led astronomers to look deeper at the uncertainties in both our observations and models.

Looking back at figure 3, another indicator of the hidden, large-scale flows in the ICM comes from the appearance of individual radio galaxies, shown in yellow with green tails. In those systems, oppositely directed jets of relativistic and thermal plasmas are ejected from supermassive black holes at the galaxy centers. As the jets encounter the ICM, they can be swept back by relative motion between the galaxy and the ICM. That relative motion gives the radio galaxy a tadpole-like appearance. And other bends and distortions to those radio tails provide a direct indication of otherwise invisible bulk motions in the ICM. Such distortions are sometimes spotted by astronomers in detailed studies of individual clusters. Sharp-eyed citizen scientists also help find those plasma-motion indicators by visually inspecting hundreds of thousands of images in projects such as Radio Galaxy Zoo.

The physics beneath the weather

One especially interesting and unanswered question arises from the radio synchrotron emission: What are the mechanisms by which the shocks and turbulence in the thermal plasma transfer energy to a small but highly energetic population of cosmic rays? The answer appears to lie in the smallest scales of the turbulence, where repeated scattering of electrons by self-excited and other magnetohydrodynamic waves slowly restores the energy that radiated away. Simultaneously, the magnetic fields required for synchrotron radiation start at very weak strengths as the cluster starts to form by processes that are currently unknown. Then shear motions in the turbulent ICM stretch the embedded fields and strengthen them by large factors. A better understanding of such a complex set of interconnected processes requires numerical simulations.

But numerical simulations of cluster plasmas face huge challenges. They need to start with two large-scale phenomena: the inflows of magnetized thermal plasma that originate during cluster formation and the more dramatic merging of clusters. At the same time, simulations must incorporate how turbulent energy dissipates on the smallest scales, far below the resolution of cluster-wide numerical simulations. Processes such as Alfvénic, compressive, solenoidal turbulence, and cosmic-ray self-excited modes are under intense study.[5]

Another important question that the simulations try to answer concerns the origin of the radio synchrotron emission: Where may a seed population of lower-energy electrons be obtained so that shocks can further accelerate them, as required by existing observations? One possibility is that the seed electrons belong to the 10^{7-8} K ICM. However, the low Mach number shocks found in theoretical work and inferred from some x-ray observations appear insufficient to provide the necessary acceleration. Another possibility is that the shock is fed by a preexisting population of relativistic electrons left behind by old radio galaxies. That approach looks promising, although the devil is in the details. Other mechanisms, such as shock drift acceleration need to be explored, and more

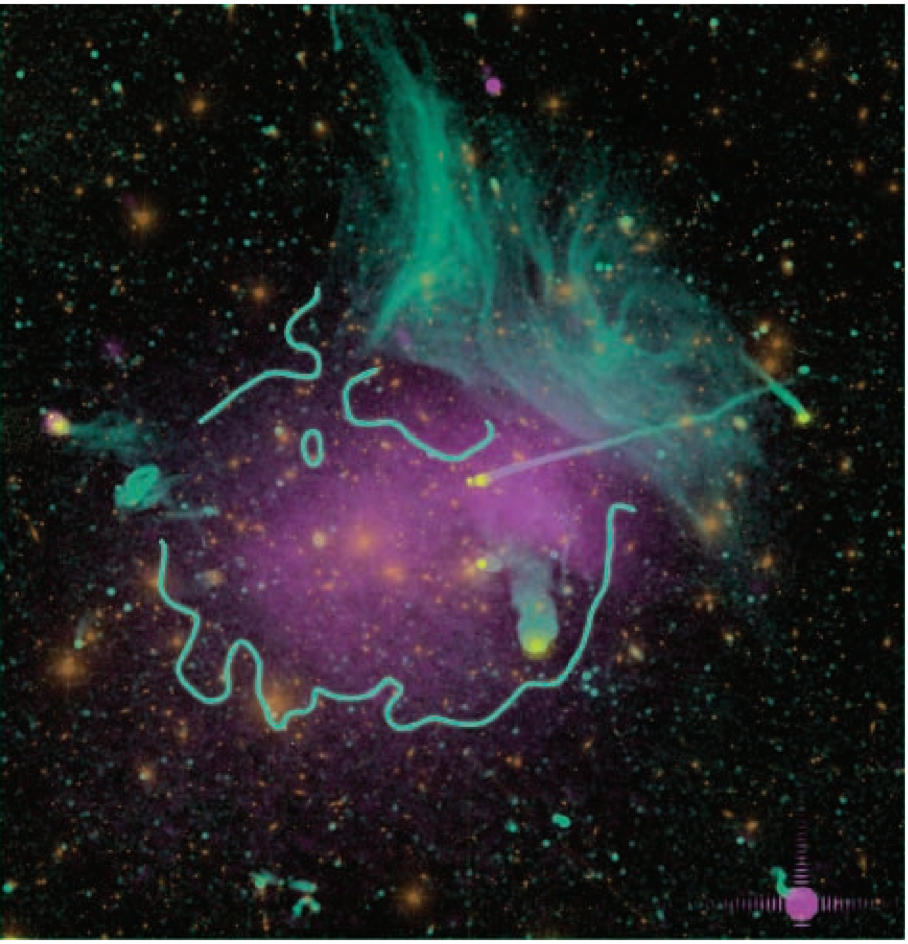


FIGURE 3. THE ABELL 2256 CLUSTER, generated from a multiple cluster merger, shows a rich variety of structures. Purple indicates the 2–10 keV x-ray emission from the intracluster medium (ICM). Orange shows the starlight from cluster galaxies in the near-IR band. Radio synchrotron emission from cosmic-ray electrons is displayed in green, and the contour indicates the extent of the diffuse synchrotron "halo." Yellow indicates a few of the cluster galaxies with supermassive black holes, whose radio jets have been distorted by relative motion through the ICM. (Adapted from ref. 6.)

combined x-ray and radio spectral diagnostic cases, along with advanced numerical simulations, will be required to sort out those issues.

The eye of the storm

Deep in the cores of relaxed clusters, ones that haven't been perturbed by a major merger in billions of years, another problem is brewing. In such a high-density region, the x-ray radiative cooling times of the hot ICM are short enough that hundreds to thousands of solar masses of material should be forming new stars each year (see the article by Christoph Federrath PHYSICS TODAY, June 2018, page 38). Instead, observations indicate that only tens of solar masses' worth of stars are turning on each year. Some other cooled material, independently found at millimeter wavelengths, also falls far short of the expected amount of cooled mass.

The gain or loss of heat from the ICM cannot be measured using only the temperature, T, since both T and the local density, n, can be changed by adiabatic processes. Instead, cluster astronomers define the entropy-like quantity $K = T/n^{2/3}$, which will change only when the ICM gains or loses energy. For simple but plausible scenarios of cluster formation, the expected variation of $K(r)$ can be calculated, where r is the distance from the cluster center. In the case of successive accretion onto a cluster whose mass is steadily increasing, the expected profile is $K(r) = K_0 r^{1.1}$, close to what is observed beyond the cluster cores. In the cores, however, the entropy drops more slowly

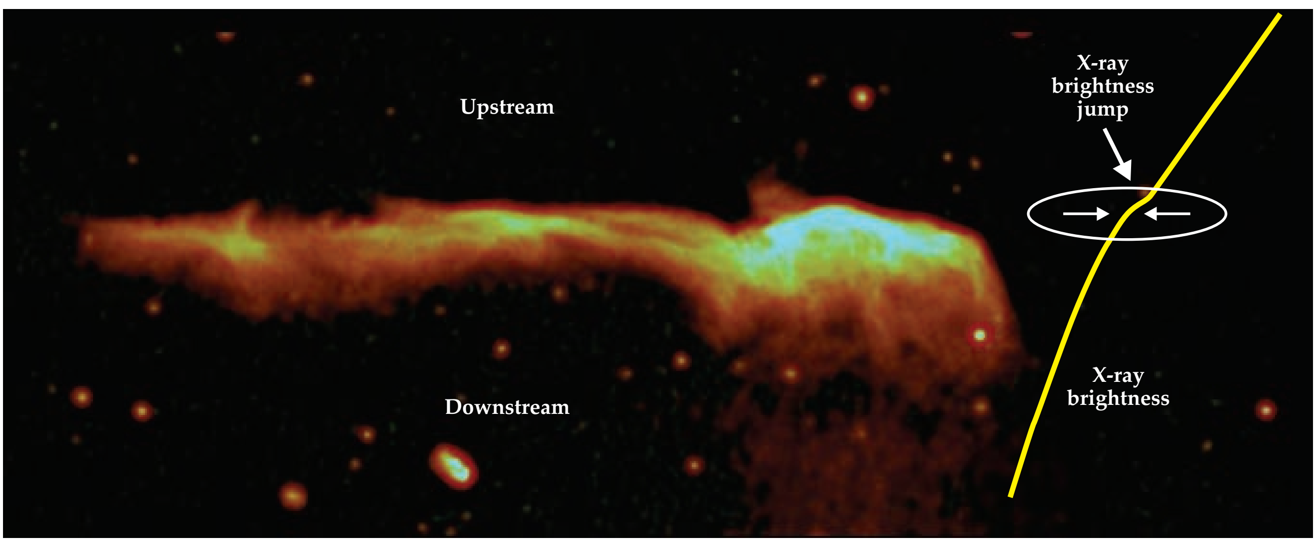


FIGURE 4. RADIO EMISSION FROM THE TOOTHBRUSH CLUSTER illuminates an upward-moving shock at the northern edge of its parent cluster. A profile of the x-ray emission along a vertical line through the brightest radio region from the downstream (postshock) to upstream (preshock) material is shown sideways on the right. A brightness discontinuity, the x-ray signature of a shock, can be seen at the same location as the radio emission feature. (Adapted from ref. 7.)

closer to the center, a trend that requires some additional input of heat to the ICM.

One likely source could be episodic ejections of relativistic plasma jets from the supermassive black hole in the bright central galaxy. Figure 5 shows the red synchrotron lobes from a radio galaxy that injected approximately 10^{55} J and excavated enormous cavities in its surrounding ICM. The work done by such outbursts and by cosmic-ray heating and sloshing motions in the ICM appears sufficient to balance the cooling. Clusters may therefore self-regulate over billions of years, and the infall of material onto the central supermassive black hole may be controlled by the cooling and instabilities near the cluster core, which are themselves controlled by the energy released from the emerging jets.

Naively, astronomers might have expected that those dense cluster cores had reached a quiet equilibrium state, even while the cluster outskirts continue to be perturbed by infalling material. But observations suggest the multiphase plasmas in cluster cores have their own complex dynamics full of interesting astrophysics and new challenges.

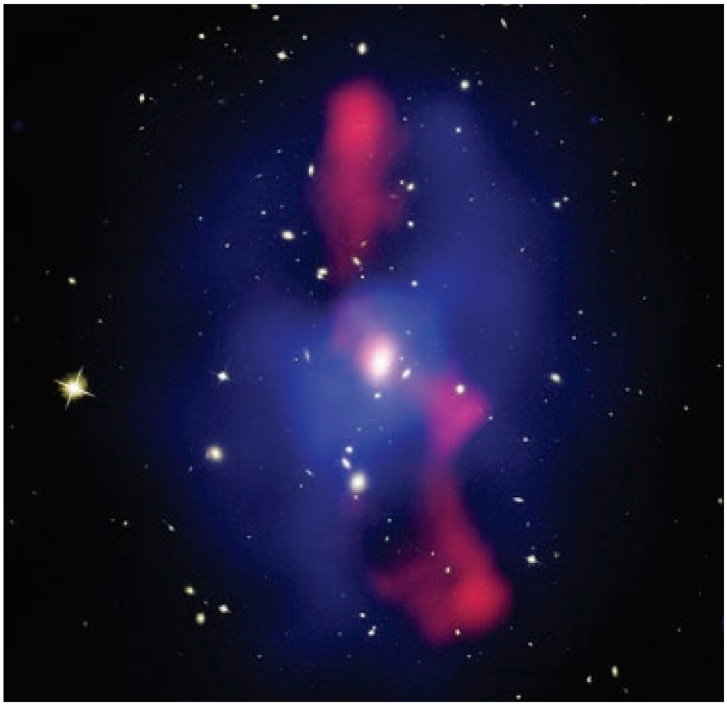


FIGURE 5. THE MS 0735.6+7421 CLUSTER. The cluster's inner 700 000 parsecs contain stars and galaxies observed at near-IR wavelengths around 800 nm (white) surrounded by the intracluster medium (ICM; blue), a thermal plasma seen in x-ray emission. The synchrotron emission (red) highlights the radio plasma that excavated cavities in the thermal ICM. (Adapted from ref. 8.)

The weather forecast

Astronomers very much want to discern the bulk motions in the ICM. In its far too brief 38 days in space, the Japanese x-ray satellite *Hitomi* gave a taste of things to come. With its exquisite spectral resolution, *Hitomi* directly measured the Doppler line broadening and centroid shifts of the lines from highly ionized iron in the core of the Perseus cluster. At 100–200 km/s, the observed velocities provided the first direct measurements of the streaming and random gas motions in the central regions of a cluster ICM. They also reflected energy inputs from both gravity and the jets from the supermassive black hole. While discovering those exciting signposts of ICM activity, *Hitomi* also confirmed that the ICM is still quite close to hydrostatic equilibrium.

Astronomers are eager for new instrumentation. On the x-ray side, eROSITA, a joint German–Russian venture, is projected to characterize the ICM in 50 000 to 100 000 clusters up from the current tally of approximately 2000. The haul will dramatically expand the capacity for statistical and cosmological studies. The exquisite spectral resolution and sensitivity of *XRISM*, a joint Japanese–US mission, will map out the details of velocity structures in the ICM. Further down the road, the European satellite *ATHENA* will allow us to study the history of how the ICM is heated and chemically evolves over cosmic times. Likewise, NASA is considering the *Lynx* mission, which could probe the diffuse medium in cluster-feeding filaments down to the astonishing low value of about 7 atoms/m^3.

Complementing those studies are a new generation of radio telescopes and surveys. At low frequencies, the LOFAR Two-Metre Sky Survey and the Murchison Widefield Array have begun to reveal the extensive cluster synchrotron structures that are no longer visible at high frequencies because of radiative energy losses. Polarization at low frequencies and the new very wide bandwidth capabilities at the Very Large Array will provide detailed probes of magnetic field irregularities in the ICM. And large area surveys using polarization, such as the Very Large Array Sky Survey and the Polarisation Sky Survey of the Universe's Magnetism on the Australian Square Kilometre Array Pathfinder telescope, will allow statistical studies to connect the magnetic structures in the ICM with other physical properties of clusters far beyond current capabilities. Yet another major leap will occur with the Square Kilometre Array itself.

Even more lies on the horizon. Detector technology has yet to reach the sensitivity needed to realize two other potentially powerful diagnostics: the x-ray inverse Compton radiation from the upscattering of cosmic microwave background photons by the cosmic-ray electrons, and the gamma rays expected from pion decay after they are produced by cosmic-ray and thermal proton collisions. But instrumentation is becoming ever more powerful and computer simulations increasingly sophisticated. The weather outlook for the ICM is both stormy and exciting!

Thanks to many colleagues across the spectrum for their most wise counsel and for support from NSF through grant AST 1714205 to the University of Minnesota.

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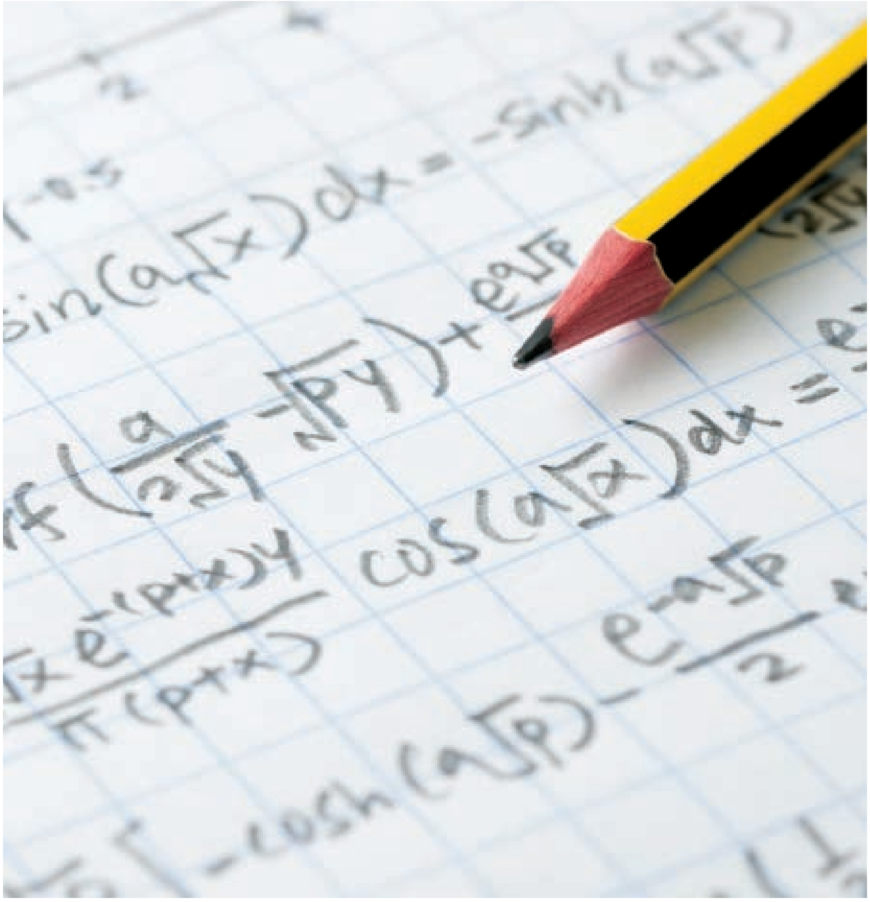


Can the scientist play a role in the laws of physics?

In chapter 10 of *Third Thoughts*, a delightful collection of essays for the general reader, Steven Weinberg remarks, "I generally review a book only if I think it will give me a chance to sound off on some issue that interests me." I couldn't agree more.

Many of the book's essays originally appeared in the *New York Review of Books*, but others are from more obscure venues or are previously unpublished. Weinberg often hits the nail right on the head. In chapter 14 he writes, "It is a bad sign that those physicists today who are most comfortable with quantum mechanics do not agree with one another about what it all means." In chapter 15, "The manned space flight program masquerades as science, but it actually crowds out real science at NASA, which is all done on unmanned missions. . . . The only technology for which the manned space flight program is well suited is the technology of keeping people alive in space." And in chapter 20, "It is generally foolish to bet against the judgments of science, and . . . when the planet is at stake, it is insane."

Third Thoughts
Steven Weinberg
Harvard U. Press, 2018. $25.95

That we are kindred spirits is vividly confirmed in chapter 23, where Weinberg says scientists "often have an experience that is deeply enlightening, and is not granted to everyone. It is the experience of finding that you have been wrong about something. . . . The world has been greatly damaged by political and religious leaders who were sure they knew the truth." I expressed a similar sentiment in my 2005 book *It's About Time*: "This process of discovering that one's former beliefs are wrong . . . is what makes the pursuit of science so engrossing. The world would be a far better place for all of us if this joy in exposing one's own misconceptions were more common in other areas of human endeavor."

Although I often agree wholeheartedly with Weinberg, I do want to sound off on one issue that greatly interests me. It is indeed bad that physicists comfortable with quantum mechanics disagree on what it all means, but I reject Weinberg's conclusion that the disagreement "may be warning us that the theory needs modification." He hopes for a theory in which a wavefunction collapses after measurement because "superpositions of states of large things . . . suffer an actual rapid spontaneous collapse."

In the dozen pages leading to that conclusion, Weinberg repeatedly uses the word "measurement" colloquially and uncritically; he does not elaborate on its meaning, even though he explains most technical concepts. Yet measurement is one of the most problematic terms in quantum mechanics. John Bell famously said that the word "has had such a damaging effect on the discussion, that I think it should now be banned altogether in quantum mechanics." In 1981 Bell wrote to Rudolf Peierls that "the ideal instantaneous measurements of the textbooks are not precisely realized anywhere anytime, and more or less realized, more or less all the time, more or less everywhere." Yes indeed!

By my definition, a measurement is any action anybody takes on the world, and the outcome of the measurement is the experience the world induces back on the person who took it. This view of measurement, called QBism by its proponents, is unacceptable to Weinberg because it incorporates "the relation of humans to nature" into "what we suppose are nature's fundamental laws." He hopes for a physical theory that would explain "what happens when people make measurements from impersonal laws that apply to everything, without giving any special status to people in these laws."

Here he unwittingly puts his finger on what I believe is the actual source of the near-century of discomfort and disagreement. There is an implicit assumption, shared by almost all physicists, that the scientist must be separated from the science. The usual appeals to measurement with classical outcomes, it seems to me, are unsuccessful attempts to objectify and impersonalize processes in which an individual scientist acts on and is reacted upon by the world. The collapse of the wavefunction after measurement represents nothing more than the updating of that scientist's expectations, based on his or her experience of the world's response to the measurement. Weinberg hopes to keep the scientist out of the laws of nature, but our chronic failure to agree on the meaning of quantum mechanics demonstrates the futility of his hope.

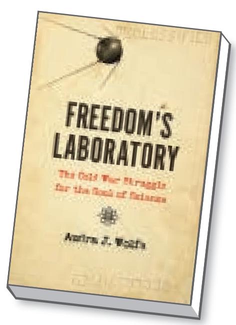
Nor does Weinberg's hope make sense to me. Science is a highly developed form of human language. Embedded in books and papers, it is a distillation of the communicated individual experiences of all scientists. Why insist that science should make no reference to the process that has established it? The laws of quantum mechanics are exactly the same for everyone who uses them. In that important sense they are entirely objective. If a scientific law involves both the scientist and the world, it does not mean that science can tell us nothing about people, as Weinberg mysteriously worries, any more than it means that science can tell us nothing about the world.

Usually I agree with Weinberg. When I disagree, the challenge of articulating my dissent gives me fresh insights into my own understanding. In both cases I find this a stimulating and admirable book.

N. David Mermin
Cornell University
Ithaca, New York

A sign at the 2017 March for Science in San Francisco, CA.

The legacy of Cold War science propaganda



Freedom's Laboratory
The Cold War Struggle for the Soul of Science
Audra J. Wolfe
Johns Hopkins U. Press, 2018. $29.95

Audra Wolfe makes clear that the meticulously researched *Freedom's Laboratory: The Cold War Struggle for the Soul of Science* was in preparation long before Donald Trump entered the presidential race. In 2019, however, it is hard to imagine a history of science that is more timely than one that situates our current political environment in the context of the Cold War.

As Wolfe notes in the epilog, the post-2016 sociopolitical moment gave rise to the March for Science movement, which sought to "apolitically" defend science's role as "a pillar of human freedom and prosperity." But, as Wolfe explains in the text that precedes that observation, the notion that science is free from politics has the most political of origin stories. US intelligence organizations crafted that message as part of anti-Communist propaganda campaigns both at home and abroad. In other words, March for Science organizers who insisted that it was possible for science to be apolitical were in fact making themselves spokespeople for old propaganda.

Is the propaganda wrong? Given the dearth of history of science in science curricula, it's hard to imagine that scientists are on the whole equipped to make an informed assessment. To come up with an answer, scientists will have to consult their consciences and study difficult and potentially embarrassing history. In that sense, Wolfe's text is essential reading for both students and scientists who have been immersed in the idea of science as an apolitical pursuit.

Freedom's Laboratory is at turns unsurprising and terribly shocking. While it is hardly news that the Central Intelligence Agency and other US government entities believed in the importance of cultural propaganda during the Cold War, what caught me off guard was the sheer number of scientists whom I recognized and what they were up to. For example, I knew that James Webb—for whom the oft-delayed but promising NASA *James Webb Space Telescope* is named—was a homophobe who went to great lengths to ensure that lesbian, gay, and bisexual people were excluded from NASA employment. But I was unaware of his significant, and in my view questionable, role in Cold War politicking as a leading advocate for the development and use of psychological warfare. I found myself surprised that those activities never came up in all the recent discussions about Webb's failed politics.

Wolfe highlights an interesting contrast between Soviet scientists, who were disproportionately active in human rights organizing relative to their countrymen, and US scientists, who arrived at human rights work relatively late in the game. In both cases, most scientists went along with their governments, but it was Soviet scientists and not Americans who were more likely to use their scientific training to question what their government was feeding them and demanding of them. I wish the book had spent more time on those Soviet–US contrasts because of their relevance to current conversations about how a sense of political urgency arises—or doesn't—in scientists.

The chapter on the CIA-backed Asia Foundation's efforts to use translations of biology textbooks as propaganda in Taiwan caught me off guard. I had some quibbles with Wolfe's presentation, which could have done more both to acknowledge that Taiwan is a nation distinct from China and to question language that suggests Taiwan is historically unscientific and undeveloped.

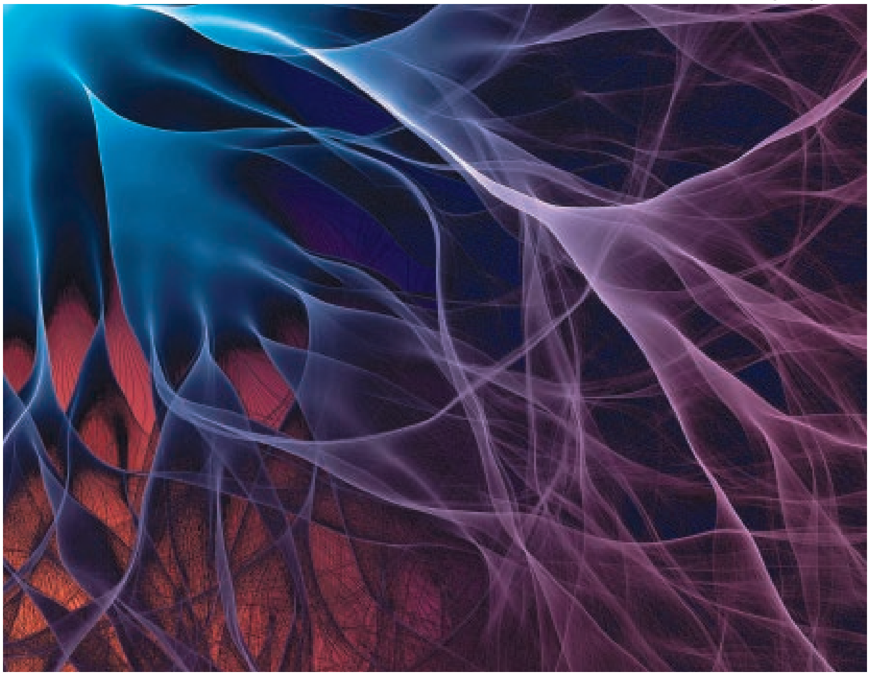
But ultimately what I found most striking about the chapter was the heavy dose of politics in the biological knowledge tests Wolfe analyzes. Here is one sample multiple-choice question, first offered to US schools and then translated for Taiwanese classrooms: "In discussing our country's disarmament policy, a famous scientist declared that we must continue our experimenting with nuclear bombs. What is the best evaluation we can give to this scientist's statement?" The question is obviously not about biological knowledge. Rather, the bizarre list of possible answers—for example, "His conclusion is probably right, since he approaches the problem with a scientific attitude"—is designed to undercut students' confidence in their right to disagree with the scientific establishment.

I have difficulty imagining how students can grow into open-minded scientists if that is how they are socialized into scientific thought, yet that messaging is the intellectual food my academic grandparents were fed. It is messaging that their advisers and heroes, including J. Robert Oppenheimer, helped craft. Given that history, it's hardly surprising that many scientists still struggle to support students and colleagues who deviate from established norms.

Furthermore, as Wolfe notes, "the particular version of 'scientific freedom' promoted by postwar scientific administrators and US propaganda was a racist, sexist, and antidemocratic vision of science." Wolfe writes that "Vannevar Bush's generation assumed that scientists operated in a meritocracy" while ignoring the "routine discrimination and structural barriers that severely limited . . . minorities' access to scientific careers." Years later March for Science organizers once again echoed old propaganda when they cited their desire to be "apolitical" to justify ignoring the fundamental political needs of minoritized scientists. The march paid lip service to diversity only after significant pressure from those scientists.

As a Martin Luther King Postdoctoral Fellow at MIT for nearly five years, I spent a decent amount of time in the Vannevar Bush Room. I will never look at its name the same way again, now that I've read about Bush's efforts to protect US scientists from having to be accountable to anyone but themselves. Rather than seeing him as a scientific hero, I now see him as a leader who successfully took science's relationship with society in a questionable direction. Readers of *Freedom's Laboratory* may find that they too will see familiar names in a different light.

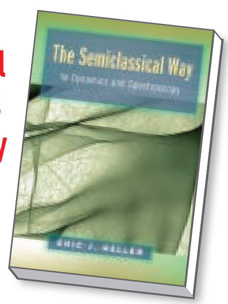
Chanda Prescod-Weinstein
University of New Hampshire
Durham



The forking paths of semiclassical physics

Which is more fundamental, classical mechanics or quantum mechanics? Admittedly, it is illogical to claim that an approximate description that is only valid in certain limits is more fundamental than the complete theory it sometimes resembles. Nonetheless, Eric Heller's new book *The Semiclassical Way to Dynamics and Spectroscopy* can be read as an argument that classical mechanics underpins quantum mechanics. The path integral, which is expressed in terms of familiar quantities from classical mechanics, is the tool that allows physicists to entertain that point of view.

The Semiclassical Way to Dynamics and Spectroscopy
Eric J. Heller
Princeton U. Press, 2018. $99.50



Heller centers his book on the semiclassical physics of a few continuous degrees of freedom. He is an acknowledged grand master in that area and is known for discovering the mysterious and deep phenomenon called scarring—the existence of energy eigenstates whose wavefunctions are enhanced on certain classical periodic orbits. In *The Semiclassical Way to Dynamics and Spectroscopy*, Heller intentionally emphasizes physics in the time domain. Less explicitly intentional is his emphasis on continuous few-body systems, as opposed to spins or many-body systems. By narrowing the focus to situations in which semiclassical methods can be applied, he is able to provide a relatively uniform treatment of various rich phenomena.

Heller begins with a review of phase-space dynamics of few-variable systems, and proceeds to examine the path-integral formulation of quantum mechanics and its approximation by stationary phase, culminating in the Gutzwiller trace formula and its time-domain counterpart. Even the elementary part of the discussion is punctuated by partisan interjections, such as Heller's claim that the equation for the short-time limit of the free-particle Green function "can (and should!) be taken as the founding postulate of quantum mechanics." The shortcomings of that starting point, however, would become glaring when one tried to study systems with finite dimensional Hilbert spaces.

The book really gets started with a collection of methods to approximate dynamics of few-body systems, based on the idea of treating the wavefunction as a wavepacket and the instantaneous potential around the center of the wavepacket as quadratic. I was not previously aware of that line of work, which the author pioneered.

Much of chapter 19 illustrates those methods' successes by giving an extremely detailed semiclassical account of the spectrum of a particular organic molecule. The description of the molecule's wiggling is startling in its precision. Indeed, I would have liked to see some explanation of the success beyond "serendipity," such as an analysis of the regime of validity or, better still, of systematic corrections. I was unable to find such a discussion in the text. In its place I found many instances of baffling phrases like "as $\hbar$ goes to zero" and "when $\hbar$ is small." Heller's intended meaning is that the constant $\hbar$ is small compared with some scales in the problem. Such colloquialisms are useful only when everyone knows what those scales are.

The book's final part, on chaos and quantum mechanics, includes a discussion of wavefunction nodes and Berry's conjecture that chaotic energy eigenstates can semiclassically be approximated as random superpositions of suitable classical states. Heller's presentation is rich and thought-provoking. But I must quibble with the assertion that "nodal surfaces in wavefunctions are by definition . . . co-dimension 1." In the absence of time-reversal symmetry, they occur at codimension two.

Furthermore, the discussion of Berry's conjecture concludes with what I found to be a misplaced analysis of the short-time behavior of Green functions in noninteracting particle systems. Any smooth potential is a relevant perturbation of the free-particle Hamiltonian $p^2/(2m)$, hence its effects disappear at short times and high energies. I believe that, rather than any manifestation of chaos, is what is illustrated by the noninteracting calculation Heller discusses.

Stylistically, the book has many idiosyncrasies: sentences that are extremely long, colloquialisms that some readers may find off-putting, captions that are too short for figures on which the narrative relies. The book oscillates between huge chunks of equations and huge chunks of words. Most difficult for the uninitiated reader is that many concepts are mentioned in crucial sentences long before they are explained. In many places the discussion could be streamlined. For example, in section 25.3, the book sets up an artificial two-dimensional system interacting with a bath; several pages later the essential physics is declared to be visible in one dimension, and the second dimension is discarded.

The book's discussion of many-body physics is often problematic. For example, in a subsection devoted to celebrating the Laughlin wavefunction, the author complains that it is not "the exact ground state." That dismissal fails to acknowledge the Laughlin wavefunction's key victory—namely, that it represents the same phase of matter as is realized in quantum Hall experiments.

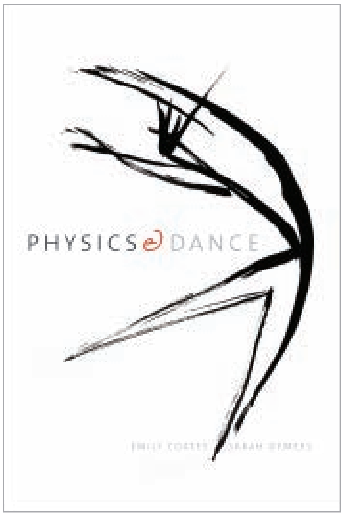
The most prominent feature of the book is its unusual point of view. The preface led me to expect that the book would explain why the world often seems classical even though it is fundamentally quantum mechanical. But the only route to be found to classical mechanics is through large quantum numbers. Chapter 25, on decoherence, is, alas, somewhat incoherent itself; for example, a complete summary of the arduous section 25.3 is "interactions create entanglement." Problematic, too, are the scare quotes surrounding "entanglement" in a quantum mechanics textbook published in 2018. That Heller feels the need to protect himself in that way is an indictment of the popular writing on the most essential feature of quantum mechanics.

The target audience for the book is not obvious. Its narrow focus makes it inappropriate as a principal text for an introductory course on quantum mechanics, but it can be a good source of supporting material. Chemists working on the quantum dynamics of few-body systems should find the book useful, as many of the examples are drawn from molecular chemistry and spectroscopy.

The Semiclassical Way to Dynamics and Spectroscopy is full of provocative ideas and insightful material that won't be found elsewhere. A second edition to fix the shortcomings described above would be welcome.

John McGreevy
University of California, San Diego

NEW BOOKS & MEDIA



Physics and Dance

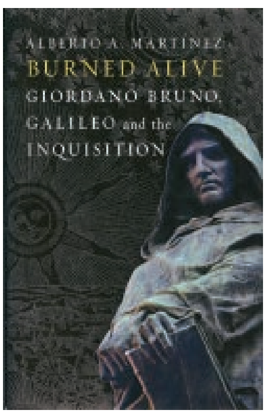
Emily Coates and Sarah Demers
Yale U. Press, 2019. $30.00

Dance studies professor and dancer Emily Coates and particle physicist Sarah Demers, both at Yale University, team up to explore the connections between dance and physics. In their intriguing book *Physics and Dance*, they look at how both disciplines approach phenomena like friction, momentum, space, time, and gravity. Many passages are devoted to modeling dancers' movements mathematically; equations, graphs, and elegant sketches accompany those models. Mathematically inclined dance lovers will welcome a chance to see the plié and tour jeté through new eyes. A chapter of physics problems could provide inspiration to professors looking for new homework challenges. —MB

Almanac 2019

National Geographic, 2018. $19.99 (paper)

Following up on its popular *Kids Almanac* launched almost a decade ago, National Geographic has published *Almanac 2019*, its first-ever annual for adults. The 400-page paperback is divided into sections such as "Exploration and Adventure," "This Planet and Beyond," and "The Science of Us." Stunning imagery is combined with timelines, maps, infographics, trivia quizzes, and a wealth of information about geography, history, nature, and science. Covering topics from gene editing to the pitfalls of plastic and the birth of the universe, *Almanac 2019* is billed as the ultimate guide to our planet. —CC



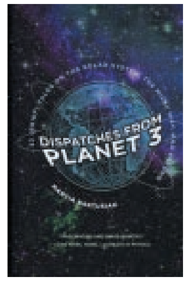
Burned Alive

Giordano Bruno, Galileo and the Inquisition

Alberto A. Martínez
Reaktion Books, 2018. $40.00

In his provocative new book, Alberto Martínez, a historian of science at the University of Texas at Austin, revisits the grim fate of Italian natural philosopher Giordano Bruno, who was burned at the stake in 1600. Bruno was an innovative thinker with unusual views on the nature of the universe; he believed that life on other worlds might exist, that the motion of planets was not perfectly circular, and that Earth itself had a soul. Many modern historians have argued that the Catholic Inquisition's decision to sentence Bruno to death was not primarily about his cosmological views but about other heresies against Catholic teachings, such as his denial of transubstantiation. Martínez, however, draws on the Inquisition's records to argue that Bruno's cosmology was in fact the major reason that Inquisitors singled him out as a dangerous and heretical thinker. *Burned Alive* also shows that some of those same Inquisition personnel were involved in Galileo's trial in 1633, which provides further evidence of the Inquisition's interest in stamping out heresies about the cosmos. —MB

Dispatches from Planet 3



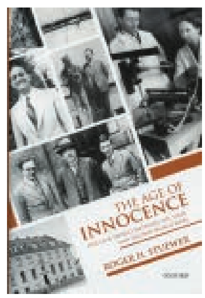
32 (Brief) Tales on the Solar System, the Milky Way, and Beyond

Marcia Bartusiak
Yale U. Press, 2018. $26.00

Science writer Marcia Bartusiak's latest book is a collection of stories about the history of astrophysics. Some of the figures she discusses, such as Albert Einstein and Jocelyn Bell Burnell, will be familiar to many readers. Others, like English geologist and astronomer John Michell, are less well-known. The book's 32 chapters are organized into three sections: astronomy within our solar system, galaxy-level observations, and cosmology. Bartusiak's lively voice and the diversity of the stories she tells make this a fast-paced, engaging read. —MB

The Age of Innocence

Nuclear Physics Between the First and Second World Wars



Roger H. Stuewer
Oxford U. Press, 2018. $55.00

University of Minnesota historian Roger Stuewer dives into the rich history of nuclear physics in his latest book, which focuses on developments in the 1920s and 1930s. Those were fertile decades for physics; they saw the discovery of the neutron, the detection of alpha decay, and the discovery of artificially induced radioactivity. Ernest Rutherford, Frédéric Joliot, Irène Joliot-Curie, Paul Dirac, Ernest Lawrence, and other famous figures make appearances. *The Age of Innocence* also keeps the political backdrop in mind and explores how the growth of fascism in Europe affected the careers of physicists such as Lise Meitner. Piled high with primary-source quotes, footnotes, and photographs, Stuewer's book is a valuable resource for anyone interested in the history of nuclear physics. —MB PT

NEW PRODUCTS

Focus on photonics, spectrometry, and spectroscopy

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 the product description. For all new products submissions, please send to ptpub@aip.org.

Andreas Mandelis

Plug-and-play time-resolved spectrometer

PicoQuant's latest luminescence spectrometer, the FluoTime 250, is a compact, robust system designed to make it easy for users to acquire time-resolved data. Because of the system's series of comprehensive software wizards, even novice users of the fully automated device can perform complex measurements, such as fluorescence decays and time-resolved anisotropy studies, in a short time. Advanced users have full access to all instrument capabilities through a point-and-click interface or integrated scripting language. The spectrometer supports both time-correlated single-photon counting and multichannel scaling data acquisition, and it covers lifetime ranges from picoseconds to milliseconds. With the addition of an optional monochromator, the FluoTime 250 can measure time-resolved emission spectra. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

Near- to mid-IR tunable light source

The Carmina tunable IR light source covers an IR and mid-IR wavelength range from 2.15 μm to 15 μm, which is the widest of any laser system on the market, according to the manufacturer APE Angewandte Physik & Elektronik. That wide tuning range and the source's high resolution and sensitivity are achieved with an optical parametric oscillator and difference-frequency generation architecture. The combination of 300 cm^{-1} broadband and 20 cm^{-1} narrowband emission makes the Carmina suitable for the two complementary nanoscale IR techniques: scattering near-field scanning optical microscopy and atomic force microscope IR spectroscopy. A pulsed mode consisting of a burst with a 50% duty cycle is included for AFM-IR applications. The light source is suitable for use in near-field imaging and spectroscopy of organic and inorganic samples. ***APE Angewandte Physik & Elektronik GmbH***, *Plauener Str 163–165, Haus N, 13053 Berlin, Germany, www.ape-berlin.de*

Chemical imaging and spectral analysis system

According to Agilent, its compact 8700 laser direct IR (LDIR) system represents a new approach to chemical imaging that will bring greater clarity and higher speed to pharmaceutical, biomedical, food, and materials science studies. With its quantum cascade laser technology, rapid scanning optics, and intuitive Agilent Clarity software, the system provides fast, high-definition (HD) chemical imaging and accurate analysis of the composition of tablets, laminates, tissues, polymers, and fibers. The 8700 LDIR produces images free from laser coherence artifacts and provides HD images of large areas. Its automated operation, with no need for liquid nitrogen, makes HD chemical imaging accessible to operators at all levels of expertise in academic and commercial facilities. ***Agilent Technologies Inc***, *5301 Stevens Creek Blvd, Santa Clara, CA 95051, www.agilent.com*

Soft x-ray to extreme-UV spectrometer

McPherson now offers its model 251MX high-energy flat-field spectrograph with three diffraction gratings that cover the spectrum from 8 eV to more than 2000 eV, or wavelengths of 150–0.5 nm. The laminar groove profile of the gratings helps keep a high-energy spectrum clean and more easily interpretable, especially at short wavelengths. The gratings are designed for grazing-incidence optical beams. A shallow 1.5-degree grazing-incidence angle improves efficiency for high-energy photons at wavelengths below 5 nm. The model 251MX is optimized for high-energy photons, including soft x ray and extreme UV (EUV). According to the company, it is easy to use and delivers reliable performance for water window imaging, high-harmonic-generation laser spectroscopy, x-ray plasma diagnostics, EUV lithography, optical characterization, metrology, and calibration. ***McPherson***, *7A Stuart Rd, Chelmsford, MA 01824, www.mcphersoninc.com*

Digital gamma spectrometers

The Ortec Products Group of Ametek's Materials Analysis Division has added two advanced digital spectrometers for high-resolution gamma spectroscopy applications to its line of DSPEC 50 and DSPEC 502 digital spectrometers. The new DSPEC 50A and DSPEC 502A models include high-precision coincidence timing to simplify Compton suppression and cosmic-veto system configurations. According to the company, the coincidence-timing functions are simple to operate and offer high performance. The spectrometers feature 64 K analog-to-digital conversion gain for superior low-energy peak shape in broad-energy-range applications. Web-based interfaces permit custom application development and allow use of the DSPEC 50A and DSPEC 502A on computers running any operating system. ***Ortec Products Group****, 801 S Illinois Ave, Oak Ridge, TN 37831-0895, www.ortec-online.com*

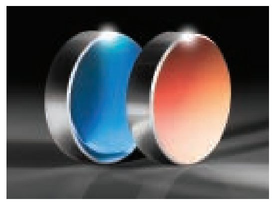
Fixed grating spectrograph

According to Horiba Scientific, its Lumetta F/2 fixed grating spectrograph features the highest optical throughput in the compact spectrograph class. Lumetta is designed to optimally gather light from most fibers and high-angle scattering phenomena. The imaging spectrograph can perform such advanced techniques as multitrack spectroscopy and fast hyperspectral imaging. With multitrack spectroscopy, it can measure multiple independent spectral channels, which either improves throughput for similar measurements on different samples or allows simultaneous measurement of different but complementary spectra, such as photoluminescence and absorbance, from the same sample. Lumetta's CCD, which is deep-cooled to −50 °C, and its low-noise 16-bit electronics deliver high sensitivity for low-light applications. ***Horiba Scientific****, 20 Knightsbridge Rd, Piscataway, NJ 08854, www.horiba.com*

Camera for physics and astronomy

Andor, an Oxford Instruments company, has launched its Marana 4.2B-11 back-illuminated camera platform. Marana features 95% quantum efficiency, vacuum cooling down to −45 °C, and high sCMOS sensitivity. According to Andor, it is the largest field-of-view sCMOS commercially available. Marana combines a 4.2 MP array format with 11 μm pixels resulting in a large, 32 mm sensor diagonal. Its 48 fps rate makes the camera useful for high-time-resolution astrophysics—for example, in pulsar studies—and for dynamic quantum research experiments. Integrated with Andor's spectrograph range, Marana offers fast spectroscopy modes that can monitor rapid kinetic processes and reactions at thousands of spectra/s and allow for fast multifiber hyperspectral imaging applications. ***Andor Technology Ltd****, 7 Millennium Way, Springvale Business Park, Belfast BT12 7AL, UK, https://andor.oxinst.com*

Extreme-UV flat mirrors



Flat mirrors designed for extreme-UV (EUV) beam steering, coherent diffractive imaging, materials science research, and harmonic separation applications are now available from Edmund Optics. The precision EUV mirrors feature nearly ideal reflectivity at 13.5 nm. They are offered in two versions: 5° angle of incidence (AOI) mirrors suitable for use with unpolarized beams and 45° AOI for steering *s*-polarized beams. Their superior thermal stability results from a coating deposited on a super-polished single-crystal silicon substrate. The metal–semiconductor coating includes a molybdenum–silicon multilayer with a Si top layer. The mirrors have a surface flatness of $\lambda/10$ at 632.8 nm and 6.35 mm thickness. They exhibit a surface roughness less than 3 Å and greatly reduce incident light scatter. ***Edmund Optics Inc****, 101 E Gloucester Pike, Barrington, NJ 08007, www.edmundoptics.com*

Femtosecond oscillators

Laser Quantum has added the Gecco Power and the Venteon Boost to its Gecco and Venteon femtosecond oscillator ranges. They are designed to maximize output power and pulse energy and to surpass the values achieved by other Gecco or Venteon laser models. The Gecco Power is a fully equipped, compact femtosecond laser in a sealed enclosure. With an average power of greater than 1 W and a pulse duration of less than 20 fs, it is suitable for Raman spectroscopy and microscopy and amplifier seeding. The pulse energies for the Venteon Boost few-cycle pulse femtosecond laser are greater than 11 nJ, and the average output power is greater than 900 mW. The Fourier-transform-limited pulse has a duration of less than 10 fs. The Venteon Boost is suitable for applications such as two-photon microscopy, ultrafast time-domain spectroscopy, and asynchronous optical sampling. ***Laser Quantum USA****, 47673 Lakeview Blvd, Fremont, CA 94538, www.laserquantum.com* PT

PHYSICS TODAY PRODUCT PICKS

Leon Max Lederman

A giant among particle physicists, Leon Max Lederman died on 3 October 2018 at a nursing home in Rexburg, Idaho, having suffered from dementia for several years.

As an experimentalist, he was a trailblazer from early in his career. The experiments on which he worked were among the first to exploit advances in electronic counter methods. He was constantly on the cutting edge—he called it the "bleeding edge"—of discovery.

Lederman was instrumental in the invention and study of neutrino beams, which led to the 1962 discovery of the muon neutrino. His decade-long pursuit of lepton production in hadron collisions resulted in the 1977 discovery of the bottom quark. Other seminal breakthroughs in which he had a leading role include the observation of parity violation in the weak interactions and the discovery of the long-lived neutral kaon.

Born on 15 July 1922 in New York City, Lederman received his undergraduate degree in chemistry from the City College of New York in 1943. After spending three years in the Army Signal Corps, he began graduate studies at Columbia University, where the physics department was constructing a 380 MeV synchrocyclotron at its Nevis Laboratories. Lederman joined the project in 1948 and worked with Eugene Booth, the project's director. As part of his doctoral work, Lederman built a Wilson cloud chamber, receiving his PhD in 1951. He then taught physics at Columbia; he became a professor in 1958 and Eugene Higgins Professor in 1972.

While at Columbia, Lederman was influential in the 1967 founding of Fermilab in Batavia, Illinois, near Chicago. He pushed for the laboratory to be truly national in nature. After the resignation of its founding director, Robert Wilson, Lederman left his Columbia faculty position and Nevis directorship to become Fermilab's second director in 1979. During his tenure he transformed the lab from a "bare bones" operation to a facility that gave experimenters the tools and environment they needed to thrive. Those environmental changes included opening an after-hours restaurant at the Users Center and bringing the top chef from CERN to advise on improving the cafeteria.

Lederman was a founding member of the federal government's High Energy Physics Advisory Panel in 1967 and the International Committee on Future Accelerators in 1977. While Fermilab director, he oversaw the construction of the Tevatron, the first superconducting accelerator and the most powerful of its day, capable of producing proton beams of 1 trillion eV and of colliding protons and antiprotons at energies up to 2 trillion eV, which led to the discovery of the top quark. Probing deeper into the structure of matter would require even more firepower; accordingly, throughout the 1980s Lederman was an energetic advocate for government funding for the Superconducting Super Collider, which was approved to be built in Texas. That dream was dashed when Congress canceled the project in 1993.

Toward the end of his tenure as Fermilab director, Lederman shared the 1988 Nobel Prize in Physics with Melvin Schwartz and Jack Steinberger for the discovery of the muon neutrino. Among his other honors, Lederman received the National Medal of Science in 1965, the Wolf Prize in Physics in 1982, and the Vannevar Bush Award in 2012.

After 10 years at the helm, Lederman turned over the reins of Fermilab and took a faculty position at the University of Chicago. In 1992, having reached the mandatory retirement age there, he moved to the Illinois Institute of Technology (IIT), where he chose to teach freshman physics. He retired in 2011.

Among Lederman's most notable and successful outreach efforts were his initiatives for improving science education and popularizing science. He had a deep interest in teaching physics to nonexperts, from pre-med and humanities students at universities to the general public. At Fermilab, Lederman started the Saturday Morning Physics program, which attracts some 300 high school physics students each year for weekly lectures and tours. He also helped found the Illinois Mathematics and Science Academy for promising Illinois students and the Lederman Science Education Center, which brings thousands of grade school students to Fermilab each year for hands-on physics demonstrations and serves as a resource for area science teachers.

FERMILAB

Leon Max Lederman

Recognizing that he could reach more students by working through teachers, Lederman founded the Illinois Research Corridor science and math summer program. He also founded and chaired the Teachers Academy for Mathematics and Science, designed to retrain 20 000 teachers in the Chicago Public Schools in the art of teaching science and mathematics. Lederman pushed for Physics First, a reversal of the standard high school biology-chemistry-physics pedagogical sequence, which he viewed as outdated. He and Ray Burnstein at IIT collaborated on ways to make lectures more engaging, which led to an interactive, wireless, RF-keypad approach, now in widespread use.

Lederman was probably best known to the general public for coining the term "God particle" for the elusive Higgs boson. It became the title of his popular 1993 book (with coauthor Dick Teresi), *The God Particle: If the Universe Is the Answer, What Is the Question?*

Lederman had a wonderful leadership style. He encouraged and valued contributions from everyone, whether senior scientist or beginning student. He had a subtle way of steering people in productive directions without dictating what they should do, and he was a master at using humor to make his points.

Jeffrey A. Appel
West Chicago, Illinois
Daniel Kaplan
Illinois Institute of Technology
Chicago

David Pines

PIERS COLEMAN

David Pines

David Pines, a preeminent theoretical physicist and a convener of numerous academic efforts, died of pancreatic cancer at his home in Urbana, Illinois, on 3 May 2018. Over his long and illustrious career, David made major contributions to condensed-matter physics, nuclear physics, and astrophysics and created lasting national and international institutions.

Born in Kansas City, Missouri, on 8 June 1924, David received a bachelor's degree from the University of California, Berkeley (UCB), in 1944. After two years in the US Navy, David began graduate studies at UCB and continued them at Princeton University. He earned his doctoral degree from Princeton in 1951 under David Bohm; his thesis was titled "The role of plasma oscillations in electron interactions." During the next three years, David and Bohm published three seminal papers related to those collective oscillations and developed the random-phase approximation, which remains a key method of many-body theory. It also provided David's first glimpse into the emergence of collective behavior, which could not readily be deduced from the behavior of individual components. Emergence would remain a central concept in all of David's work.

From 1950 to 1952, David was an instructor at the University of Pennsylvania. He then joined John Bardeen at the University of Illinois at Urbana-Champaign (UIUC) as a research assistant professor. In 1955, together with Bardeen, David published a key article on the electron–phonon interaction in metals and showed that phonon-retardation effects could induce an attractive interaction between electrons. That crucial insight underlies the theory of superconductivity that Bardeen, Leon Cooper, and J. Robert Schrieffer proposed in 1957 and that earned them the Nobel Prize in Physics in 1972. David's 1958 paper with Aage Bohr and Ben Mottelson pointed out a possible analogy between the excitation spectra of nuclei and of superconductors; that paper played a similar foundational role in the work of Bohr, Mottelson, and James Rainwater on the connection between collective and particle motion in nuclei, for which they were awarded the 1975 Nobel Prize in Physics.

David was an assistant professor at Princeton from 1955 to 1958 and a member of the Institute for Advanced Study in Princeton from 1958 to 1959. David then returned to UIUC as a professor of physics and electrical engineering; he remained in that role until his retirement in 1995. During that 36-year span, David made important contributions to the theory of quantum fluids, including liquid helium-3 and helium-4 with Charles Aldrich III, and to the theory of rotons in ^{4}He with Alfred Zawadowski and one of us (Bedell). He also studied superfluidity in neutron stars; in a series of papers with several collaborators, he developed a model for the "glitches" observed in emissions from pulsars.

The discovery of high-temperature superconductivity in 1986 provided David with a new challenge ideally suited to his background. Inspired by his familiarity with paramagnons in ^{3}He, David advocated strongly for a mechanism based on spin fluctuations and was gratified when the expected *d*-wave pairing was observed in the mid 1990s. Despite his tireless advocacy, the full theory of high-T_c superconductors remains elusive.

In retirement, David remained vigorously involved in research and spent time at many institutions, including Los Alamos National Laboratory, UC Davis, the KTH Royal Institute of Technology in Stockholm, and Trinity College Cambridge. In addition to continuing his work on high-T_c superconductivity, he applied principles of emergence to complex adaptive systems, including biological systems and soft matter. In more recent years, David created several projects in science education, including the international Think Like a Scientist initiative, which aims to bring the approaches of science to students in middle schools.

David's enthusiasm for science was matched by his passion for creating and supporting institutions to facilitate collaboration. He led the Center for Advanced Study at UIUC from 1967 to 1970, served as vice president of the Aspen Center for Physics from 1968 to 1972, and cofounded the Santa Fe Institute in 1984 and the Institute for Complex Adaptive Matter in 1999. Internationally, David was a trailblazer in spanning the divide between the scientific communities of the US and the Soviet Union. Following the collapse of the Soviet Union in 1991, David was instrumental in helping several of its physicists find new careers in the US.

David's many honors include the 1985 Dirac Medal for the Advancement of Theoretical Physics from the University of New South Wales, the 1985 Eugene Feenberg Memorial Medal for many-body theory, the American Association of Physics Teachers' 2013 John David Jackson Award for Excellence in Graduate Physics Education, and the 2016 Julius Edgar Lilienfeld Prize of the American Physical Society.

David Pines was indefatigably enthusiastic and persistent in pursuing his own science and in creating institutions to foster the science of others. Like many of our colleagues, we share wonderful memories of scientific and personal interactions with him. His powerful and inspiring presence will be missed, but his legacy is vast and permanent.

Kevin Bedell
Boston College
Chestnut Hill, Massachusetts
David Campbell
Boston University
Boston, Massachusetts
Robert Laughlin
Stanford University
Stanford, California PT

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Rakesh Mogul is a professor of biological chemistry at the California State Polytechnic University, Pomona.

Protecting planets beyond Earth

Rakesh Mogul

Part of exploring other worlds is to prevent harmful organisms from hitching a ride from or to our planet.

Since the 1950s the international scientific community has debated the necessity of protecting the solar system, including Earth, from interplanetary biological and organic contamination. In fact, the notion of avoiding "harmful contamination" of celestial bodies was formally integrated into space policy in 1967, when the United Nations Outer Space Treaty came into force. For planetary bodies such as Mars, Europa, and Enceladus, the rationale for those efforts is primarily scientific, as contamination by Earth life could dramatically interfere with the search for extraterrestrial life. For Earth's biosphere, the reasons are more tangible: Biological or chemical agents returned from explored planetary bodies might deleteriously affect humans, animals, and plants.

Currently the term "planetary protection" is used to describe the practice of preventing, or at least minimizing, "forward" and "backward" contamination in the solar system. Forward contamination refers to the biological contamination of solar-system bodies by Earth life as a result of robotic or crewed exploration. Backward contamination is the contamination of Earth as a result of spacecraft and extraterrestrial samples that are returned to us. To date, exploratory missions have brought back samples only from the Moon, two asteroids, a comet, and the solar wind—environments that have little if any likelihood of harboring life. However, there is tremendous international interest in returning samples from Mars, Europa, and Enceladus and organizations such as NASA, the European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA) are devising safe protocols for the return of extraterrestrial samples.

Resilient life

Microorganisms such as bacteria, archaea, and fungi that have the ability to survive or perhaps even thrive in harsh environments can affect the search for life. On Earth, certain microorganisms tolerate extreme conditions such as high radiation, concentrated salts, hot or cold temperatures, high or low pressures, high acidity, low abundances of water, and the absence of light. Strikingly, those extreme settings mimic conditions in many of the environments found on planetary bodies in our solar system.

The Martian subsurface, for instance, includes abundant permafrost and ice. In comparison, Arctic permafrost and Antarctic ices on Earth contain trace veins and films of liquid water that harbor active microbial life. The icy moons Europa and Enceladus have interior oceans whose chemical and physical properties may be similar to those of Earth's oceans, where life is abundant. In the clouds of Venus, temperatures and pressures are similar to those found on Earth, and the acidic properties of the water droplets in the clouds are perhaps not so different from the acidic hot springs found in Yellowstone National Park, where microbial life abounds.

Biological contamination

On Earth, we've learned that mitigating the spread of invasive species is paramount to watershed, soil, and human health management. For instance, all across the US last summer, boats and water-related equipment got inspected for zebra mussels, faucet snails, and Eurasian watermilfoil, since those species, when left unchecked, harm swimmers, decimate local waterfowl populations, and outcompete native aquatic plants, respectively. Many countries and US states banned felt-soled waders because those "fisherman's boots" are linked to the spread of didymo, a diatom that harms aquatic populations. And we effectively keep many bacterial and viral infections at bay with proper hygiene and cleanliness.

Such practices serve as a proof of principle for planetary protection. When conducted over long periods, they also serve as conservation efforts, which ensure that generations of people will enjoy the recreational, economic, and scientific benefits of Earth's resources.

Planetary protection for Mars

According to NASA, a defining strategy of Mars exploration is to seek signs of life. So far, an international bevy of spacecraft has orbited around, landed on, and roved the planet as part of missions to systematically study the geology, atmosphere, habitability, and chemistry of Mars (see the article by Ashwin Vasavada, PHYSICS TODAY, March 2017, page 34). By necessity, those missions were spread out over decades because of the time and costs associated with interplanetary travel.

All those spacecraft were built on Earth, where microorganisms are abundant. Consequently, the multistep exploration strategy could inadvertently bring Earth microbial life to Mars. In turn, contamination of promising study sites could compromise current and future science efforts and, in particular, obscure any findings that support the presence of life.

To avoid those issues, well-developed planetary protection guidelines—exemplars for thoughtful policymaking—mandate that missions to Mars maintain high cleanliness standards during spacecraft assembly and storage. In support of that goal, spacecraft are assembled in clean rooms, such as the one shown in the figure, where strict controls are placed on the amounts

ONE OF THE LARGEST CLEAN ROOMS IN THE WORLD is at NASA's Jet Propulsion Laboratory in California. The specially clothed technicians here are working on the Mars *Curiosity* rover. (Photo courtesy of Yvette Cendes.)

of dust, aerosols, and other particulates in the air; humidity; atmospheric composition; and clothes people wear. Moreover, those facilities are routinely cleaned with chemical agents that remove biological and nonbiological particles from surfaces and floors.

That cleaning fluid was delicious!

Despite the robust cleaning procedures, microbes find a way to survive. Molecular genetics shows that the clean rooms harbor a small but diverse microbiome (a collection of microorganisms) and that the abundances and taxonomic profiles of the microbes change during the different phases of spacecraft assembly. To help explain that observation, my research team has shown that the cleaning agents used during assembly may be biodegraded into carbon or energy sources—food—or into noncleaner components by members of the spacecraft microbiome.

To deal with the persistent microbiome, technicians don't just clean spacecraft, they sterilize them. Treatments include exposures to dry heat, hydrogen peroxide vapor, gamma radiation, high-pressure steam, and low-temperature plasmas. Typically, sterilization (or bioburden reduction) is required for missions that are focused on life detection and habitability. For Mars missions, special care is given to components—wheels, drills, scoops, and other sampling-system elements—that may contact the planet.

Bioburden reduction has been implemented on several spacecraft, including the *Curiosity*, *Opportunity*, *Spirit*, and upcoming Mars 2020 rovers; the *InSight* and *Phoenix* landers; and, most extensively, the Viking landers. After sterilization to prevent recontamination from transport or any subsequent assembly, test, launch, or operational procedures, the spacecraft are wrapped and appropriately stored. During the entire assembly process, technicians sample, characterize, and store microorganisms from the clean rooms and spacecraft, so that the scientific community may know what was carried to Mars.

After launch, planetary scientists protect Mars through trajectory biasing. During the cruise phase between Earth and Mars, the spacecraft, with its unsterilized propellant tanks and aeroshell (the casing that protects the craft during reentry), is aimed away from Mars to prevent a crash landing. Once in firm control, the spacecraft is then steered back toward Mars.

Debating points

The selection of landing sites and areas of study on Mars are also key components of planetary protection. Among the topics of vigorous debate are the science payoff, contamination probabilities, and operational feasibility. Special Regions, areas of Mars where Earth life may replicate, are the subject of particularly lively discussions regarding whether the requirements for Mars exploration are too restrictive or not restrictive enough. Further, the prospect of crewed missions to Mars demands reassessment of bioburden restrictions, development of new sampling strategies, and careful consideration of human health needs.

Indeed, the questions regarding the purposes of planetary protection, degree of required protection, and length of conservation efforts—should they extend over years or decades?—continue to be relevant to the space-science community. Today that community includes not only Mars scientists from ever more nations but commercial space enterprises, such as private mining operations and space tourism. In the new chapter about to be written, should commercial claims be regarded as equal to the needs of science? Or should the questions of how life originated and whether we are alone remain as the driving forces behind space exploration?

In this exciting future, we will need a balanced approach of streamlined regulations that promote smart resource and recreational management. At the same time, we must empower scientific study, as finding life elsewhere will monumentally affect global society.

Additional resources

▶ R. Mogul et al., "Metabolism and biodegradation of spacecraft cleaning reagents by strains of spacecraft-associated *Acinetobacter*," *Astrobiology* (2018), doi:10.1089/ast.2017.1814.

▶ NASA Office of Planetary Protection, https://planetaryprotection.nasa.gov/documents.

▶ NASA, "Mars Exploration Program and Missions, Overview," https://mars.nasa.gov/programmissions/overview.

▶ NASA, "Solar System and Beyond Overview," www.nasa.gov/topics/solarsystem/overview/index.html. PT

Bipolar climate couplings

Ice cores extracted from the Greenland and Antarctic ice sheets have preserved climate records for the past 100 000 years or more. Deep Greenland ice cores in particular have yielded records with subannual time resolution. Seeking comparably detailed Antarctic chronologies, researchers drilled in 2013–16 in the West Antarctic Ice Sheet (WAIS) Divide, which separates regions of ice flowing in opposing directions. At 10 cm in diameter and 3405 m in total length, the core they extracted provided well-preserved environmental records for the past 62 000 years. This photo shows a freshly extracted section.

Synchronization between the WAIS Divide core and Greenland ice cores showed that abrupt climate changes, known as Dansgaard–Oeschger events (see the article by Edouard Bard, PHYSICS TODAY, December 2002, page 32), in the North Atlantic Ocean triggered countervailing temperature changes in the Antarctic, with a lag of about 200 years. Christo Buizert (Oregon State University) and his colleagues have now used volcanic markers trapped in the ice to synchronize the WAIS core with four additional ice cores from other Antarctic regions. That multiway synchronization revealed regional climate variations and a second coupling mode between the two polar regions. In addition to the "bipolar seesaw," which is mediated by deep ocean waters and is homogeneous across Antarctica, a synchronous, atmospheric mode shifts the Southern Hemisphere's westerlies and produces varying regional temperature changes. (C. Buizert et al., *Nature* **563**, 681, 2018; photo by Tommy Cox.) —RJF

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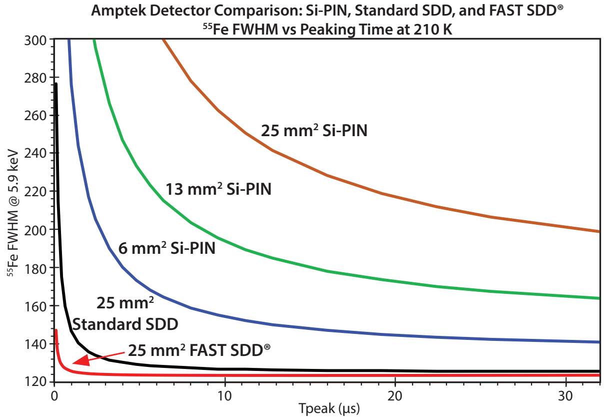

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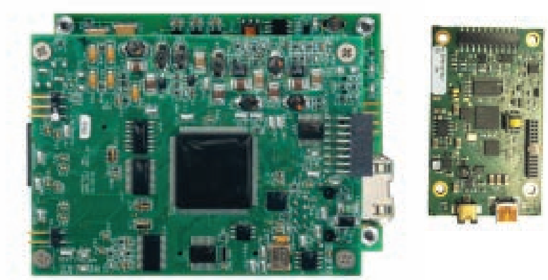

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