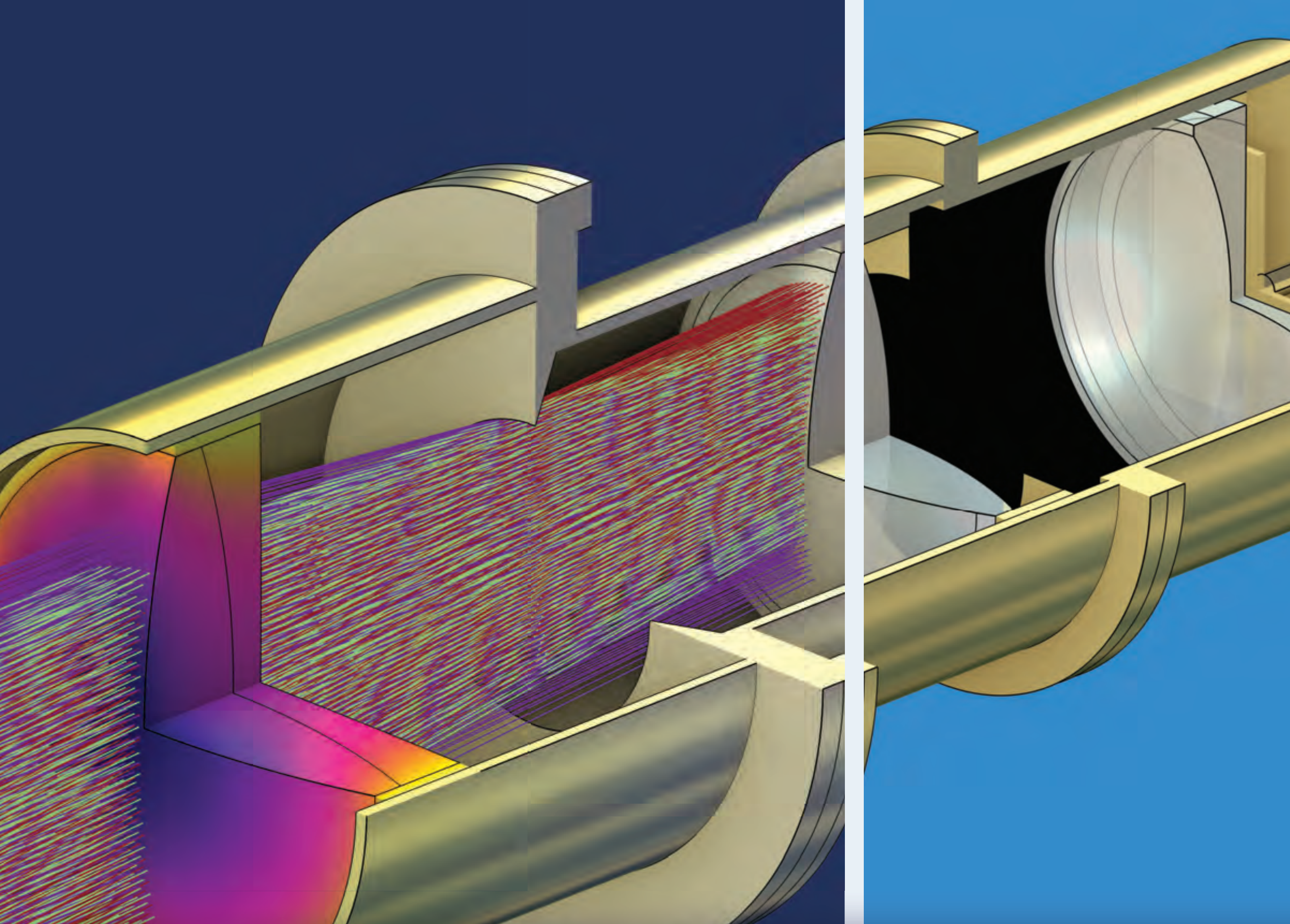

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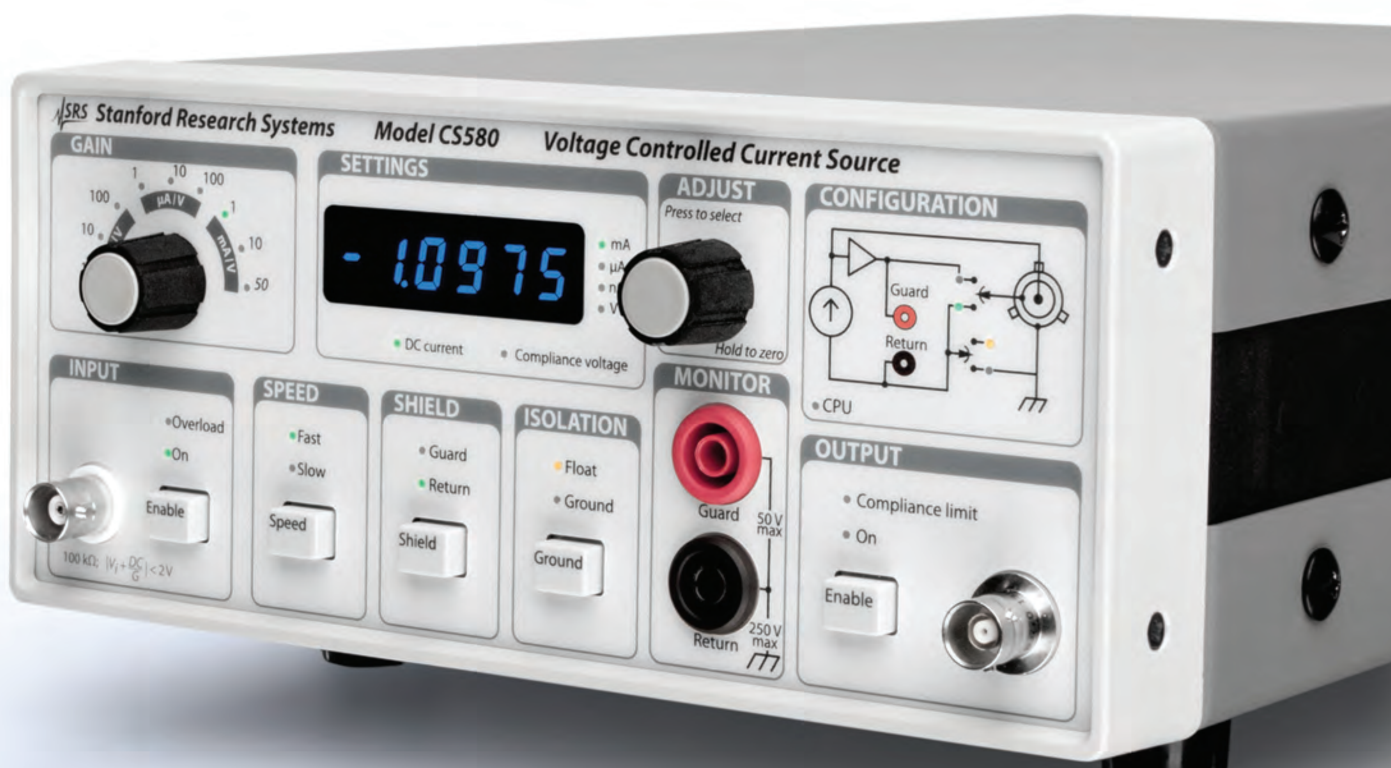

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PHYSICS TODAY

April 2023 | volume 76 number 4

FEATURES

ON THE COVER: Last austral summer, researchers stayed in this field camp near Allan Hills, Antarctica, where they had found bits of multimillion-year-old ice. International teams also aim to drill continuous cores that peer further back in time than ever before; air trapped in old ice provides a unique archive of the ancient atmosphere. In other Antarctic research, scientists are probing Thwaites Glacier with an instrument that swims below it. See **page 18** for more on the search for the oldest ice and **page 16** for surprises about glacial melting. (Courtesy of Julia Marks Peterson.)

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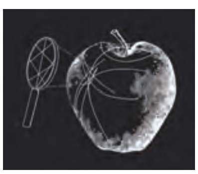

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Gravitation turns 50

In 1973 Charles Misner, Kip Thorne, and John Wheeler published their famed general-relativity textbook, *Gravitation*, which remains in print. Despite its subject's weightiness, the book "is tonally distinct, infused with a sense of whimsy that remains captivating," writes Physics Today's Ryan Dahn.
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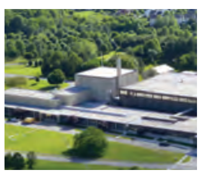

NIST

NIST reactor

Two years after an accident forced the closure of NIST's research reactor, the Nuclear Regulatory Commission has approved the restart of the facility. Physics Today's David Kramer reports on the improvements NIST implemented and on plans to accommodate the backlog of research proposals.
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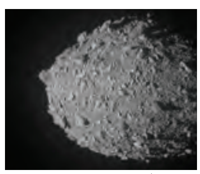

NASA/JHU APL

Rubble-pile asteroids

When NASA's *DART* deflected an asteroid last year, the spacecraft did not crash into a monolithic mountain of rock. Rather, it struck a conglomeration of boulders, stones, and sand that are loosely bound by gravity. Understanding the physics of such rubble-pile asteroids is crucial for safeguarding our planet.
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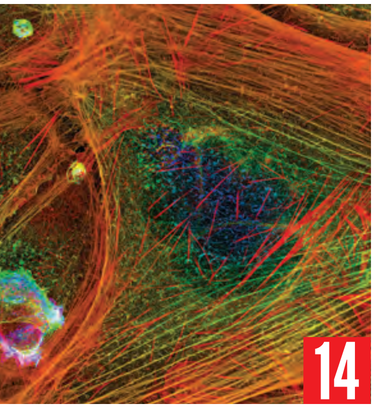

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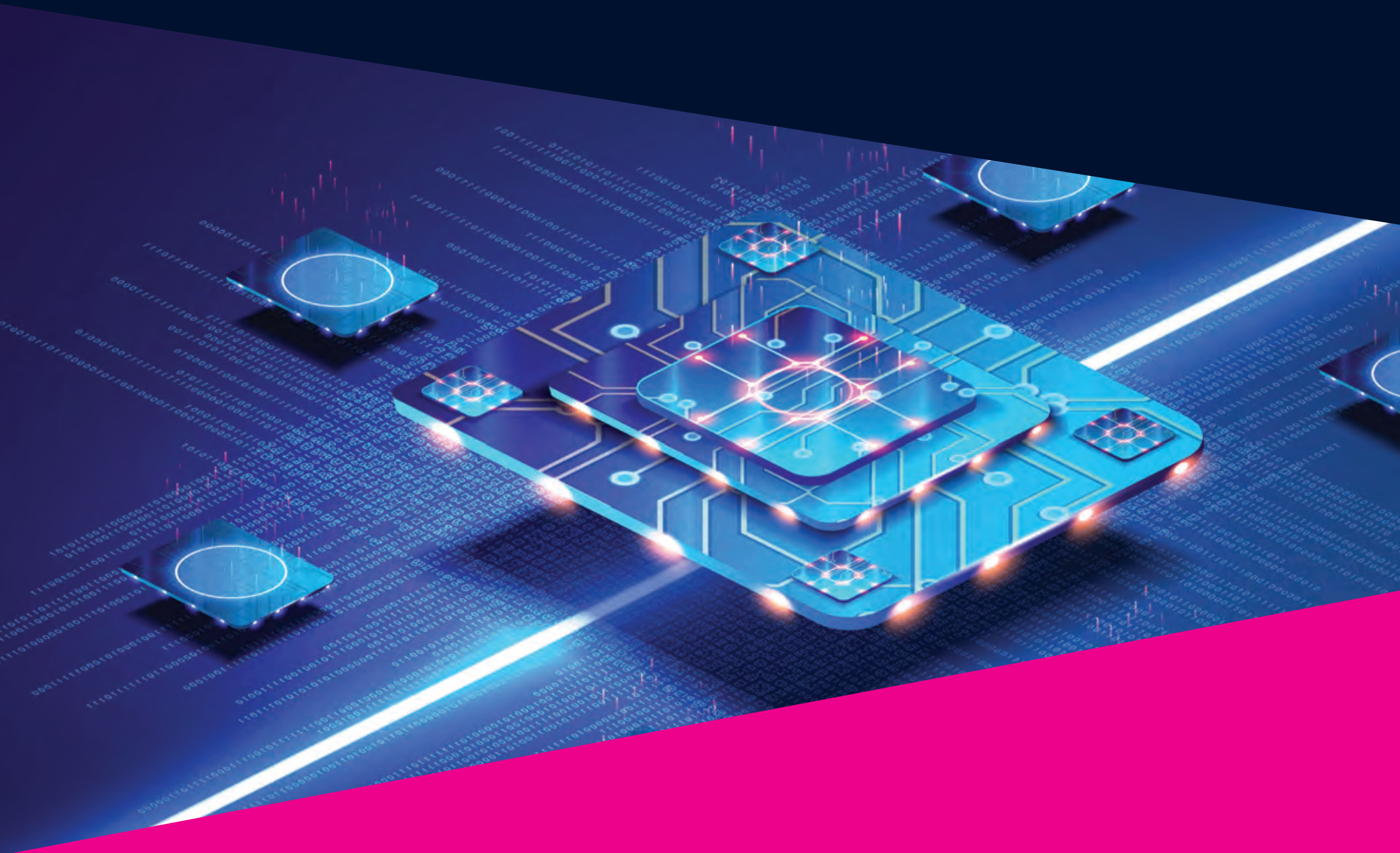

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READERS' FORUM

Physics and poetry revisited

In his editorial "Physics and poetry" (PHYSICS TODAY, April 2022, page 8), Charles Day states that he found "barely a handful" of poems related to physical phenomena in the online poem collection of the Poetry Foundation. He might have had better luck looking in 19th-century sources.

We are the editors of the MIT website the Net Advance of Physics, which includes a section called "Watchers of the Moon"[1] (an allusion to the famous paintings by Caspar David Friedrich). It is an anthology of science-themed poetry from the (very) long 19th century, which we define as 1750–1925. The lower limit is arbitrary; the upper limit has to do with copyright law. The section features poems by the usual suspects (William Wordsworth, Edgar Allan Poe, and so on), but also by obscure and forgotten writers. The quality, it need hardly be said, spans a similarly broad range.

We have also included the verse of James Clerk Maxwell and other literarily inclined scientists. We suspect our page "The One of Time, of Space the Three: The Collected Poems of Sir William Rowan Hamilton" might be of particular interest to physicists and mathematicians. Because of our linguistic limitations, "Watchers of the Moon" presently includes only poetry in English (with a few translations); we would welcome suggestions for 19th-century poems from other cultural and linguistic backgrounds.

Reference

1. The Net Advance of Physics Retro, "Watchers of the Moon: Poetry and Mathematical Physics in the Long Nineteenth Century," https://web.mit.edu/redingtn/www/netadv/SPpoetry.html.

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TWO MEN CONTEMPLATING THE MOON, by Caspar David Friedrich, oil on canvas (1819), Dresden State Art Collections/public domain.

In his April 2022 editorial (page 8), Charles Day opens with a quote from Paul Dirac: "The aim of science is to make difficult things understandable in a simpler way; the aim of poetry is to state simple things in an incomprehensible way. The two are incompatible." As a poet with a bachelor's in applied math, I find Dirac's comment to be clever but misguided.

Doubtless many poets would say that physics makes the simple incomprehensible. Comprehension is a function of training, and mathematical formulation remains baffling to many. Meanwhile, we should always be suspicious of the Dunning–Kruger effect when judging others' fields as dealing with especially simple matters, particularly when we can see that we do not understand the results.

Poets have diverse aims, not primarily obfuscatory. Some poets explore the limits of language, seeking to say that which is unsayable in everyday speech—a task tackled elegantly by quantum formalism in a domain for which our vernacular has not evolved. The very syntax of human language obscures fundamental understanding of the "really real world" beyond the prosaic and the mesoscale.

Dirac was 13 years old when the poet Hugo Ball presented his "Dada Manifesto" (1916) in pursuit of "poems that are meant to dispense with conventional language." Such "experimental poetry" may reveal aspects of how language functions or how the brain constructs meaning. Poetic diction may be deliberately dissociated from lyric expression to examine language distinct from confounding factors of sentiment (see, for example, the Language poets of the 1960s and

1970s, such as Ron Silliman, Lyn Hejinian, and Bernadette Mayer).

Incomprehensible? Yes, often. But it misses the mark to say that the simple has been made so. Poetry is a kind of laboratory environment where language can be brought to exhibit all sorts of odd behaviors that won't occur in plain prose. The process may appear bizarre, and the results ambiguous. Surely a physicist can relate.

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Charles Day's column, "Physics and poetry," in the April 2022 issue (page 8) is correct to push back on claims that the two are "incompatible" (attributed to Paul Dirac). But I disagree with one of his later statements, "Physics is abstraction. Its use for metaphor and simile is limited."

Physics is rich with metaphors, its very abstraction itself perhaps accounting for many of them. The pendulum as an oscillation about a mean between two limits on either side of an equilibrium is a hoary metaphor in ordinary language and the social sciences. It gets an even wider meaning in the hands of a physicist who sees the same mathematics and physics of harmonic oscillations in contexts far from material bobs on strings or swaying branches. Richard Feynman, a name that Day rightly invokes, rendered poetically many a physical theme and saw in the design of a Japanese gate a poetic "explanation" for broken symmetry in nature as seen in theoretical physics.[1] Some other examples of metaphors across physics are in my book, *The Beauty of Physics: Patterns, Principles, and Perspectives* (2014).

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Reference

1. R. P. Feynman, *Six Not-So-Easy Pieces: Einstein's Relativity, Symmetry, and Space-Time*, Basic Books (2011), p. 47.

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The clean-energy challenge

The Issues and Events item "Electrification of cars and trucks likely won't disrupt the grid" (Physics Today, April 2022, page 22) by David Kramer is timely and accurate as far as it goes. But by omitting mention of nonhighway transportation, and the rest of the economy for that matter, it unintentionally makes the growth in electricity usage on the path to decarbonization of our economy seem to be nearly business as usual. Several recent studies, however, show that a carbon-neutral US economy in 2050 will require around four times as much electricity as we use today.[1–3]

Synthesis of chemical fuel for aviation, military, and nonhighway vehicles will require more electricity than the electrification of highway vehicles discussed in Kramer's story. The electrification of homes, businesses, and industry—including synthesis of hydrocarbon feedstocks—will require twice as much again. That prodigious increase in generation, transmission, and, hopefully, storage is most certainly different from what was needed to support the introduction of air conditioning.

The new electric grid will be much larger and will operate very differently from the old one. Power will be transmitted longer distances from regions where sunlight and wind are abundant. Roughly half that power will be for battery charging and a massive new electrochemical industry, both amenable to load management to match the remaining intermittence of renewable power supply. The tendency to treat decarbonization of economic sectors in isolation and thereby miss the big picture is in part a reflection of the incremental approach in our policy. To plan and finance the greatest industrial build-out since the railroad boom of the late 19th century, we must have a comprehensive policy that sets clear goals and brings long-term investor confidence. And we need it soon. We only have 30 years to complete the project!

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2. M. Ram et al., *Global Energy System Based on 100% Renewable Energy: Power, Heat, Transport and Desalination Sectors*, Lappeenranta U. Technology and Energy Watch Group (March 2019).
3. J. H. Williams et al., *AGU Adv.* **2**, e2020AV000284 (2021).

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David Kramer has in the past two years written several items discussing components of the clean-energy challenge. One from the April 2022 issue is on charging electric vehicles, or EVs (page 22), and another from the September 2021 issue is on energy storage (page 20).

While the stories are informative, both are missing context. For example, the story on EVs doesn't discuss how they are only as clean and efficient as the process by which the required electricity is produced. The storage story fails to acknowledge that grid-scale storage capacity adequate to power cities or countries is not and will not be available in the foreseeable future. Even more importantly, dependence on storage is not acceptable, even if attainable, because no one knows the duration of future wind and solar droughts.

I urge Physics Today to do more to rationalize the discussion of renewable energy.

That renewable energy is intermittent is not contentious. That renewable energy sources must be complemented by storage or backup is not contentious. That grid-scale storage is unavailable at urban scale may be more contentious but is nonetheless true. Relying on backup implies that whenever renewables are producing power, their backup (which is paid for) sits idle. Thus, renewables don't increase capacity; they duplicate dispatchable (always available) sources. That duplication is responsible


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for California's "duck curve," discussed by Kramer.

As California and Germany have demonstrated, renewables can't replace grid-scale dispatchables, of which there are just two, hydrocarbons and nuclear. It appears that fusion will enter the market in the same time frame as molten-salt fission reactors, but it is unlikely to be cost competitive. Fission has an attractive safety record, and molten-salt reactors are both safer still and cheaper than existing reactors. A plausible future is fusion for the rich and fission for the rest. An especially good discussion of the inadequacy of both energy storage and renewables generally is available at https://jackdevanney.substack.com/p/nuclear-and-windsolar.

There are only four fundamental forces in nature, and their strengths differ dramatically. Those differences are manifest in the energy density and footprint of competing energy technologies. For example, the relative strength of nuclear forces allows hydrocarbon furnaces to be "surgically" replaced by nuclear reactors, leaving turbines and other infrastructure in place. Conversely, the extreme weakness of gravity makes storage based on raising and dropping weights unpromising.

Grid-scale renewable energy is a distraction, one that is delaying productive action on an important problem. Physics Today can play an important role here.

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Correction

April 2022, page 8—Cornell University is incorrectly described as Richard Feynman's alma mater. He was a professor, but never a student, at Cornell. PT

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Actin assembly is a physics problem

Simple mechanical forces may be key to understanding an essential biological process: the formation of cytoskeletal components that give structure to every cell in your body.

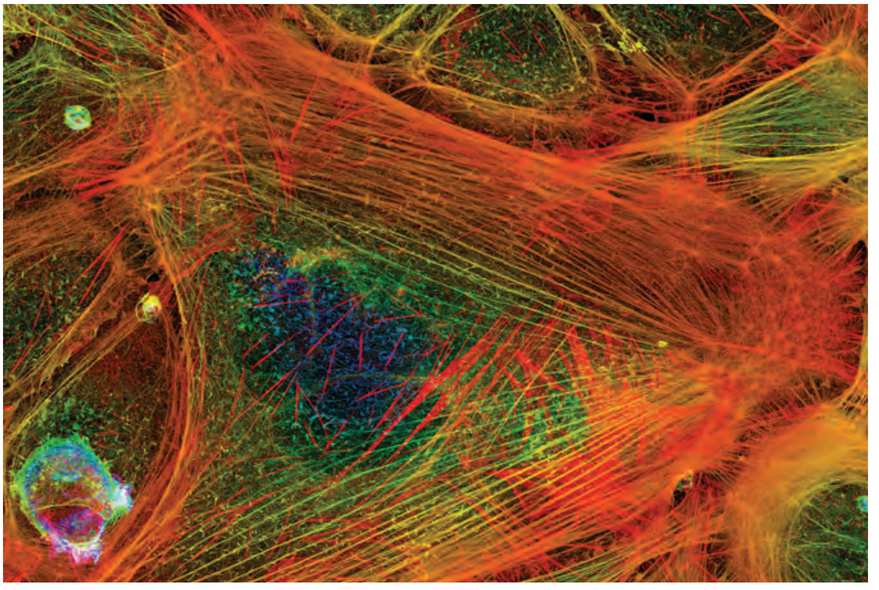


FIGURE 1. LIVING CELLS get their structure and organization from a dynamic network of actin filaments, highlighted in this fluorescence image. New research suggests that the gathering of actin filaments into bundles—essential for functions such as cell crawling and cell division—is regulated by the mechanical forces in phase-separated liquid droplets. (Courtesy of Howard Vindin, CC BY-SA 4.0.)

The adult human skeleton doesn't change much over time. Traumatic injury excepted, its 206 bones stay fairly constant in number, size, and shape. The cytoskeleton—despite the similarity of the name—is always in a state of flux. Its intricate network of protein tubules and filaments, as shown in figure 1, is constantly building up, breaking down, and reorganizing itself as cells move around, change shape, respond to stimuli, and divide.

Orchestrating that cytoskeletal reorganization is a dizzying ensemble of proteins and biochemical reactions. But new research led by Kristin Graham (University of Texas at Austin) and Aravind Chandrasekaran (University of California, San Diego), mentored by Jeanne Stachowiak and Padmini Rangamani, respectively, has uncovered a surprising additional influence: surface tension.[1]

Specifically, phase-separated liquid-like droplets serve as microreactors that forge a cytoskeleton protein called actin into filaments and then into bundles. The growing actin bundles stretch the drops that confine them, and the drops' surface tension pushes back. The competition between actin's stiffness and droplet surface tension dictates the evolving shape of the droplet, which in turn helps to shape the developing actin bundle.

In recent years, researchers have begun to appreciate the importance of liquid–liquid phase separation in cells. Phase-separated droplets—like bubbles of oil in a vinaigrette salad dressing—are known to influence a cell's chemistry: By concentrating certain molecules in one phase or the other, they influence the molecules' propensity to react. (See the article by Christoph Weber and Christoph Zechner, Physics Today, June 2021, page 38.) The new work shows how the drops can have a physical influence too, by mechanically shaping the structures that form inside them.

Rings and rods

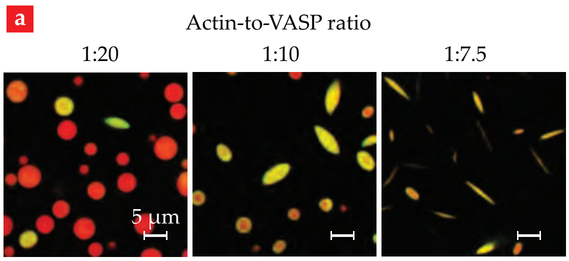
Actin isn't the only protein in the cytoskeleton, but it's a highly prevalent and versatile one. About 5% of all the protein in a typical animal cell is actin; at any given time, about half of it is floating around as free globular proteins and the other half is bound up in cytoskeletal structures.

Those structures take a variety of forms and perform many biological functions. The most basic actin structure is a thin, flexible polymer, also called a filament. Filaments can be cross-linked into two- and three-dimensional meshes, or they can be collected into strong, stiff bundles. Actin bundles—the focus of Graham and colleagues' new research—are the basis for, among other things, the fingerlike projections cells use to probe their surrounding environment and the contractile rings that pinch off pairs of dividing cells.

Many proteins and other biomolecules are involved in creating actin structures. Graham and colleagues focused on one called VASP (vasodilator-stimulated phosphoprotein), a multifunctional enzyme that forms actin monomers into filaments and filaments into bundles. In cells, VASP molecules tend to cluster together in liquid-like droplets. But it wasn't known what, if any, purpose the clustering might serve.

Graham didn't set out to answer that question. Instead, she wanted to build on related work by Feng Yuan, her colleague in Stachowiak's group, that explored how protein phase separation can influence the bending of biological membranes. Using a synthetic model membrane—chosen to eliminate the complexity of a living cell—Yuan and colleagues found that adding phase-separating proteins transformed the membrane from a perfect spherical bubble to one with deep ruts and pockets.[2]

Graham wanted to see how actin filaments would affect the rutting and pocketing. Actin structures are integral to the shape of a cell, she reasoned. "So I thought that maybe adding actin poly-



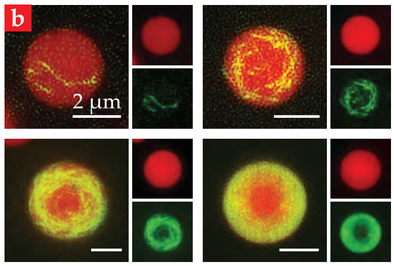


FIGURE 2. DROPLETS of a protein called VASP (vasodilator-stimulated phosphoprotein) forge actin monomers into filaments and then into bundles. **(a)** Fluorescence images at different actin concentrations show how the drops change shape during the bundling process. VASP is fluorescently labeled in red and actin in green, so both proteins together appear yellow. **(b)** Some representative droplets, with the VASP and actin images shown to their right, illustrate how actin filaments accumulate in a ring around the edge of the drop. (Adapted from ref. 1.)

merization would bend the membrane even more," she says.

But when she introduced actin and VASP to the model membrane system, the most striking effect wasn't on the membrane but on the VASP drops themselves. "They looked like Cheerios," says Graham, "but there were others that looked like rods. What was going on? What was driving this system?" She decided to investigate further.

Zooming in

It's often challenging, if not impossible, to discern the mechanism of a biochemical process by watching it in real time, because everything happens so fast: The system can be completely transformed in mere seconds, if not less. To slow the actin–VASP dynamics down, Graham reduced the amount of actin. A typical cell might have 10 or more times as much actin as VASP. Graham reversed those proportions and looked at actin-to-VASP ratios on the order of 1:10.

Some ensemble images at different actin concentrations are shown in figure 2a, and some illustrative single drops are shown in figure 2b. In all of the images, VASP is fluorescently labeled in red and actin in green—so when both molecules are present together, they appear yellow. The actin concentration serves as a rough proxy for time: Systems with less actin resemble earlier stages in the bundling process, and those with more resemble the later stages.

Together, the images start to tell the story. As actin accumulates inside the VASP drops, it's first polymerized into single, unbundled filaments. Sometimes the filaments are individually resolvable, as in figure 2b, and sometimes they appear as a diffuse haze. Eventually, the filaments coalesce into a ring around the droplet's edge. After that, the rings elongate into rods.

That sketch of the process still leaves gaps to be filled in: Why rings, and how do the rings turn into rods? To flesh out the details, Stachowiak reached out to her longtime collaborator Rangamani, whose group specializes in mathematical and mechanical models of biological systems, and through her put Graham in touch with Chandrasekaran.

Not spherical

"This was a good system to model," says Chandrasekaran, "because the experiments are not so far removed from the modeling. When we model living cells, we have to make a lot of assumptions, and we end up talking about spherical cows." But in Graham's experiments, she'd stripped away most of the complexity of the cell. So the actin–VASP droplets' energetics were defined by only a few variables: The bending energy of actin, the surface energy of the VASP drop, and the wetting interaction between them.

Wetting physics explains why the actin filaments remain confined to the VASP drops instead of poking out into the surrounding solution: Actin energetically prefers to be bathed in VASP rather than anything else. So when the filaments grow longer than the drop's diameter, they bend. They end up hunched up against the inner droplet surface, as shown in the leftmost panel of figure 3.

As more and more filaments form, they all accumulate at the droplet surface. So when VASP starts forging the filaments into bundles, the bundles also are curled around the inner droplet surface. But actin bundles aren't as flexible as single filaments are. As a bundle grows thicker, it becomes more resistant to bending. Eventually, as shown in the middle panel of figure 3, the bundle's rigidity stretches the VASP drop from a sphere into a flattened disk.

As the bundling continues, the ring-shaped bundle grows, and the disk-shaped drop becomes wider and flatter. But the growth cannot continue indefinitely. When the bundle bending energy and droplet surface tension reach their collective breaking point, the ring buckles, as shown in the rightmost panel of figure 3, and becomes a rod.

A key insight from the analysis is that the rings Graham saw in her images weren't all the same thing. Some were spherical VASP droplets uniformly lined with unbundled actin filaments—a 2D projection of a 3D spherical shell looks brighter at the edges. Others were spherical droplets containing ring-shaped actin bundles, and still others were droplets that were deformed into disks. Similarly, the rods and elongated rings that appear in figure 2a also represent a variety of morphologies. Some really are rods and elongated rings, while others are circular disks seen from the side.

Living rings?

It remains to be seen to what extent the droplet-driven processes play out in living cells. Observing actin bundling directly

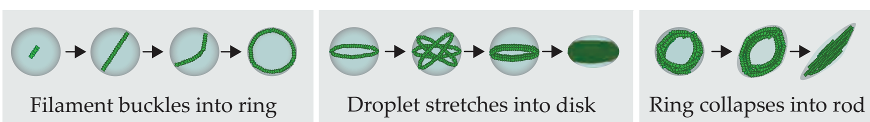


FIGURE 3. MODELING THE FORCES in the droplets uncovers the mechanism behind the structures shown in figure 2. First, actin filaments curl around the inside surface of the drop. Next, the filaments are bundled into a single ring, which pushes back against the drop and deforms it into a two-dimensional disk. Finally, the ring collapses into an elongated rod. (Adapted from ref. 1.)

in cells would be difficult for all the same reasons that researchers opt for simplified model systems in the first place: Cells' chemistry is orders of magnitude more complicated than simple actin–VASP drops, and their high actin concentrations drive the reactions quickly. Furthermore, VASP drops in cells are 1 μm or less in diameter, so they're harder to see than the ones in the experiments, which are several times as large.

When a system is too challenging to observe directly, one way to figure out how it works is to break part of it and see how the rest does or doesn't function. A version of that approach is on the researchers' to-do list. There's a mutated form of VASP that can still polymerize and bundle actin but can't form phase-separated droplets. If a cell were genetically engineered to produce the mutant VASP, would its actin-bundling ability be hindered? If so, that would be strong evidence that VASP droplets—and the forces inside them—are essential to actin bundling.

Johanna Miller

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Melting underneath Thwaites Glacier is more complicated than expected

A robot exploring beneath the vulnerable Antarctic glacier has found new features that affect its melt rate.

Thwaites Glacier, located in western Antarctica (see the figure 1 inset), is one of the fastest receding ice masses on the continent, retreating 1–2 km/yr over the past few decades.[1] The roughly 120-km-wide ice mass is at a high risk of total collapse as soon as the end of this century,[2] which would raise global sea levels by 0.5 m. If it triggers the collapse of the entire West Antarctic Ice Sheet, sea levels could rise by 3 m (see Physics Today, July 2014, page 10).

Given the continent's harsh conditions and remote location, most observations of Thwaites Glacier have come from satellites, radar systems, and autonomous instruments. Those data, however, offer only a limited view of what's underneath the ice and of how fast it's melting at the base. (For more on Antarctica's hydrology, see the article by Sammie Buzzard, Physics Today, January 2022, page 28.) To remedy that deficit, in 2018 NSF and the UK's Natural Environment Research Council launched the International Thwaites Glacier Collaboration.

As part of the collaboration's MELT project, researchers traveled to the glacier and measured the depth of the ice and the ocean's temperature and salinity through a newly drilled borehole and the remote-controlled underwater vehicle Icefin.

In two simultaneously published papers, the team shows that although above-freezing water at the base of Thwaites Glacier is melting it as expected, the ice topography varies unexpectedly over small scales and interacts with the ocean conditions to produce highly variable melt rates dependent on location.[3,4] The improved measurements underneath the ice should make projections of melting and sea-level rise in glacier models more accurate and precise.

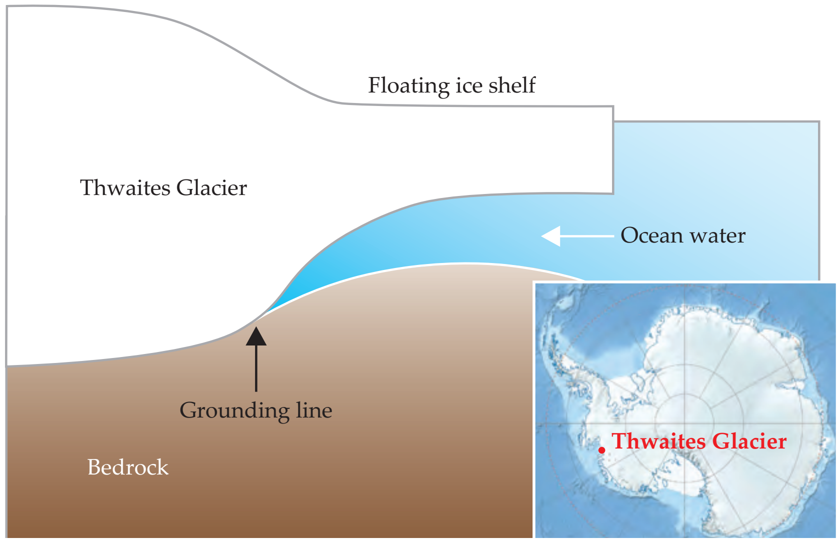

FIGURE 1. BELOW THWAITES GLACIER, in western Antarctica, the land slopes downward away from the ocean. When relatively warm water interacts with the cold ice, the grounding line beyond which the glacier is no longer supported by bedrock retreats landward, making the ice shelf extending over the ocean less stable and thus more prone to collapse. (Inset by Alexrk2, Wikimedia Commons, CC BY-SA 3.0; image by Freddie Pagani.)

Under the radar

Glaciers are always on the move. Changing temperatures, precipitation rates, and ocean–ice dynamics all influence whether the ice accumulates or diminishes. Even changes in the predominant atmospheric winds over a glacier can help melt ice. (See Physics Today, October 2019, page 14.)

Thwaites Glacier is especially prone to ocean-driven melting because the depth of its base increases farther inland, as shown in figure 1. That slope means that its grounding line—the boundary beyond which the glacier stops being supported by the land surface and becomes an ice shelf stretching over the ocean—is steadily nudged inland when the ocean warms.

Over time, more ice that was grounded consequently flows into the ocean, causing sea levels to rise. And eventually, the entire ice shelf may become destabilized and collapse into the ocean.

The goal of the MELT project has been to go beyond that simple explanation and study in more detail how warm waters at the grounding line are melting Thwaites

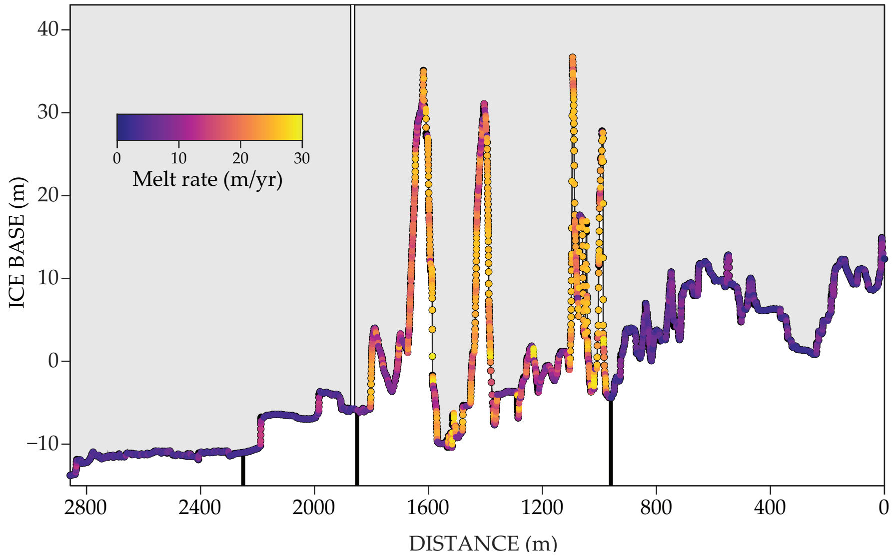

FIGURE 2. THWAITES GLACIER is melting at its base, but the rate varies substantially depending on the underside's topography. The steep, near-vertical faces of large crevasses are melting more quickly than steplike terraces and flat regions of the ice base because of more mixing of warm, salty ocean water with cold freshwater from the ice. (Adapted from ref. 3.)

Glacier and at what rate. A change in the melt rate of the base increases the glacier's speed and drives the retreat of its grounding line. With dedicated funding from the UK and US, the International Thwaites Glacier Collaboration deployed various instruments to monitor the ice column and the underlying water.

The borehole was drilled through about 0.5 km of ice and 2 km seaward of the grounding line. Through it, a sensor collected measurements over the entire 54 m water column beneath the ice. Researchers have drilled boreholes to investigate other glaciers before but not through Thwaites Glacier. Now it has three boreholes: one drilled for the MELT project and two others drilled simultaneously for another project of the collaboration.

Compared with previous efforts, the MELT project collected more data near and around Thwaites Glacier's grounding line. Icefin's five expeditions below the ice, one of which reached the grounding line, gave the collaboration the opportunity to observe how the melting of the underside varies by location. Icefin was equipped with various other sensors to monitor ocean conditions and measure the ice base. In addition to those data, a ground-based, phase-sensitive radar system measured the basal melt rate.

Rough topography

Data from the borehole profiler and the nearby measurements collected by Icefin show water temperatures around −0.8 °C at the glacier's base. The water temperature steadily increases with distance from the ice and reaches 0 °C at the ocean bottom farther from land. To help quantify melting, a useful metric is thermal driving—the difference between the ocean temperature and the *in situ* freezing point. (The *in situ* freezing point is affected by salinity and pressure.) As expected for Thwaites Glacier, the thermal driving of about +1.5 °C near the base is strong enough to trigger melting.

Although melting was expected, Britney Schmidt of Cornell University and colleagues report several surprising features that were discovered at a small region of the glacier that extends laterally for a few kilometers.[3] The bottom of the ice is characterized by a rough topography of ridges, crevasses, steplike terraces, and other structures. Coauthor Peter Davis, of the British Antarctic Survey, says, "We've seen in data before that these sorts of structures exist, but this is the very first time that we've been able to visually image them in such a critical region. They're just right there."

The highest melt rates were measured along some of the steep ice faces found in crevasses, as shown in figure 2. There the water's fast flow velocity encourages turbulent mixing and heat transfer. In contrast, the flat regions on the underside are isolated from the heat of the ocean below because of the poorly mixed freshwater layer and the low current velocities. Davis says, "The most surprising result to me is that the rate of melting that the warm water was driving was a lot lower than we were expecting on flat surfaces."

Models need improvement

Not only do the observations reveal heretofore unseen topography of Thwaites Glacier, but they also act as critical benchmarks for evaluating ice models. In the absence of concrete data on the glacier's basal conditions, modelers simulated melting ice by assuming the presence of turbulent, well-mixed water, which was found only in the areas with steep ice faces. In that turbulence regime, melting rates—and by extension, sea-level projections—depend on a combination of the water's flow velocity and its thermal forcing on the ice.

Under those assumptions, models predicted that Thwaites Glacier is melting at a rate of 14–32 m/yr, which is an order of magnitude higher than the 2–5 m/yr observed for the flat parts of the ice base by the new papers. Davis and colleagues argue that the discrepancy arises because the models didn't account for the observed density stratification in the ocean beneath the flat regions on the underside.[4]

"Unfortunately, we cannot consider our results to be 'good news' or optimistic," says Davis. "The grounding line is still retreating rapidly, and our results don't change that fact. Instead, they show that grounding-line retreat beneath Thwaites can be driven by weaker basal melting than previously expected."

Atmospheric convection, turbulence, ocean heat transport, and other complexities that affect glaciers and sea ice have made it difficult to model the climate of polar regions. (See the article by Tapio Schneider, Nadir Jeevanjee, and Robert Socolow, Physics Today, June 2021, page 44.) With observations from the new work and other studies, though, models should soon be more representative of real-world processes and capable of offering more precise estimates of future sea-level rise.

Alex Lopatka

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Scientists drill for oldest ice to reveal secrets about Earth's climate

Nations collaborate—and compete—to access million-plus-year-old ice in Antarctica.

Over about seven weeks in December and January during the most recent austral summer in Antarctica, a team of researchers from Europe drilled the first 808 meters of an intended 2700-meter ice core; 10 Australian scientists traversed 2300 kilometers round trip across the continent from a year-round research station to where they plan to start deep drilling next season; Japanese researchers selected a drilling site; a Russian team worked on an upgrade to its station; and US researchers drilled a couple hundred meters into the ice sheet of Allan Hills.

Those teams—and ones from South Korea and China—are all after the same thing: the oldest ice.

In the late 1990s, several teams drilled to around 3000 meters in the interior of Antarctica. The cores dated to varying ages, with the one obtained by the European Project for Ice Coring in Antarctica (EPICA) going back farthest, to 808 000 years.

Around 20 years ago, scientists from around the world together set the goal of retrieving two or more continuous ice cores that go back 1.5 million years. Marine sediments show that ice-age cycles subsequently stretched out from about 40 000 years to roughly 100 000 years and became more extreme, in what's known as the Mid-Pleistocene Transition. "We want to get ice cores that go back to the 40 000–year cycles," says Eric Wolff, a University of Cambridge professor of Earth sciences who coordinates international partnerships for drilling old ice. "The idea is to see what happened to carbon dioxide and to figure out why the cycles changed."

Air trapped in old ice contains a unique archive of the ancient atmosphere. Ice also preserves dust and the isotopic makeup of water. Ice cores can shed light on many aspects of Earth's climate, including greenhouse gas concentrations, ocean and surface temperatures, and sea level. They are the only way to directly measure ancient CO_2 levels, notes Edward Brook, a paleoclimatologist at Oregon State University and director of the NSF Center for Oldest Ice Exploration (COLDEX). The big question is, he says, "How sensitive is the Earth system to high levels of carbon dioxide?"

The teams from around the world are in a collaborative competition, says Wolff. "We actively help each other with ideas, how to date ice, and sometimes with flights and other logistics. But we'd all like to be the ones to get the first data."

Selecting drill sites

"It's not like you get a better drill and drill deeper," says Brook. "The challenge is to figure out where the oldest ice is preserved." Ice is always flowing, and in most places the oldest ice is gone, he says. "But the international ice community believes there should be places where you can get continuous records to 1.5-million-year-old ice."

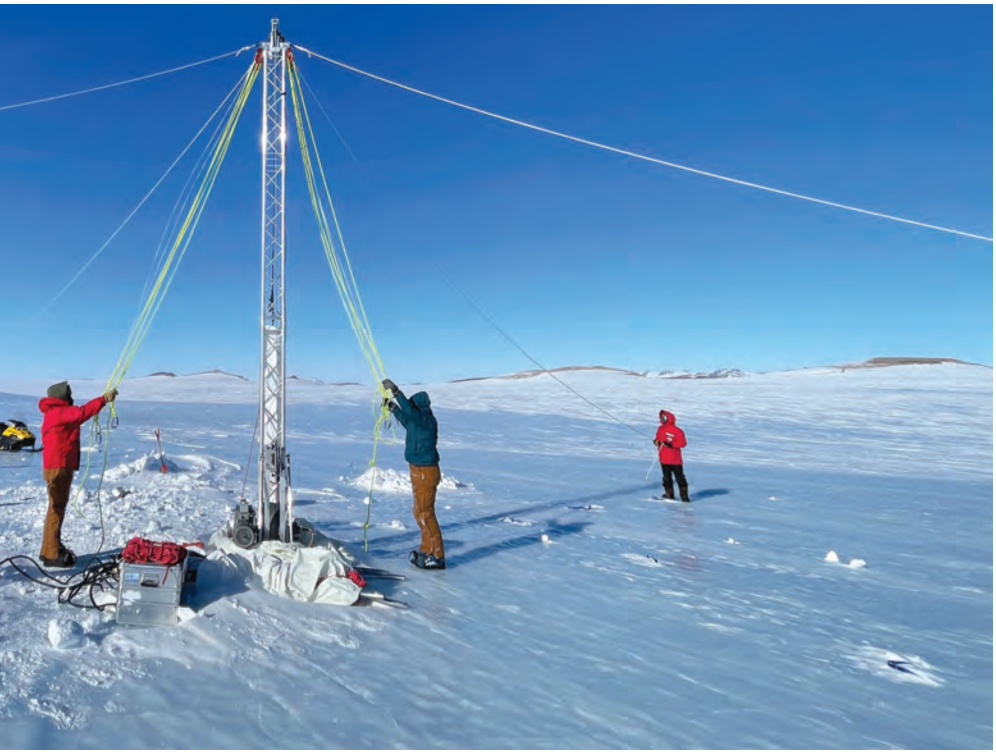
In searching for promising sites, the teams use ice-penetrating radar data and ice-sheet modeling. "You are looking for the right thickness and topography," says Robert Mulvaney, a glaciologist with the British Antarctic Survey. The ice needs to be deep to get the best time resolution. But if it's too deep, then geothermal heat can melt the ice, he explains. EPICA drilled to 3200 meters, he says, "and any ice older than 800 000 years had melted." Likewise, the Russian team's Vostok core, which was drilled over several decades, was folded and deformed at the bottom. In 1998 the core exceeded 3600 meters in depth and recorded 420 000-year-old ice.

Based on ice-flow data, the Russian team is targeting its search about 300 kilometers upstream of its original borehole. The team's plans are not yet funded, says Vladimir Lipenkov, head of the Climate and Environmental Research Laboratory at the Arctic and Antarctic Research Institute in Saint Petersburg, but "the chance of securing funding from the government will improve with completion of the new Vostok station." The Russian team hopes to begin drilling in the 2026–27 austral summer.


PETER NEFF

In 2015–16 Beyond EPICA—as the new phase of the European project is known—used airborne radar to narrow its search for a potential site. Mulvaney spent the next two austral summers towing a surface radar across the 16 km × 12 km area at 9 km/hr to get a better sense of the ice layering. "We were lucky to find a site only 40 kilometers from our existing Concordia Station," he says. Beyond EPICA has €11 million (about $11 million) for 2019–26 from the European Commission, plus money or in-kind contributions from each of the 10 participating nations.

The countries that have already selected drilling sites have each found them reasonably close to their respective Antarctic stations, which is useful from a logistical standpoint. Australia, which is joining the game this go-around, has a



A DRILLING TOWER at Allan Hills, Antarctica, in December 2022. Chunks of multimillion-year-old ice discovered there have made finding more a priority of the US team.

site a few kilometers from the Beyond EPICA drilling site.

Old—and older—ice

Last summer Sarah Shackleton, part of the COLDEX team, dated a section of discontinuous ice from Allan Hills to 4 million years. The Princeton University postdoc's finding built on the nearby discovery of 2.7-million-year-old ice, which shifted the COLDEX plans. A continuous core is still a goal, says Shackleton, but now the team is taking a multifaceted approach in its search for old ice.

COLDEX's first aim is to look for more multimillion-year-old ice in Allan Hills, which is about 110 kilometers northwest of McMurdo Station, the US logistics hub. The shallow area, on the edge of a mountainous subglacial ridge, traps ice that has been dragged up toward the surface by glacial flow.

The second step for COLDEX—to begin next year pending availability of logistics resources from NSF—is to drill a core around 1100 meters deep in Allan Hills. Jeffrey Severinghaus is a geosciences professor at the Scripps Institution of Oceanography at the University of California, San Diego. He hopes that the team finds old ice with better resolution: Instead of 4-million-year-old ice "being squished" into a 1-meter-thick layer of ice, "maybe it will be spread over 60 meters," he says. "That would let us learn more about changes in climate."

As its third component, the COLDEX team plans to drill a continuous 1.5-million-year-old core. That would need to be somewhere other than Allan Hills. COLDEX is funded at $25 million for five years through 2026. The site will be chosen by then, says Brook, and, if COLDEX is renewed for five years, drilling would begin later in the decade.

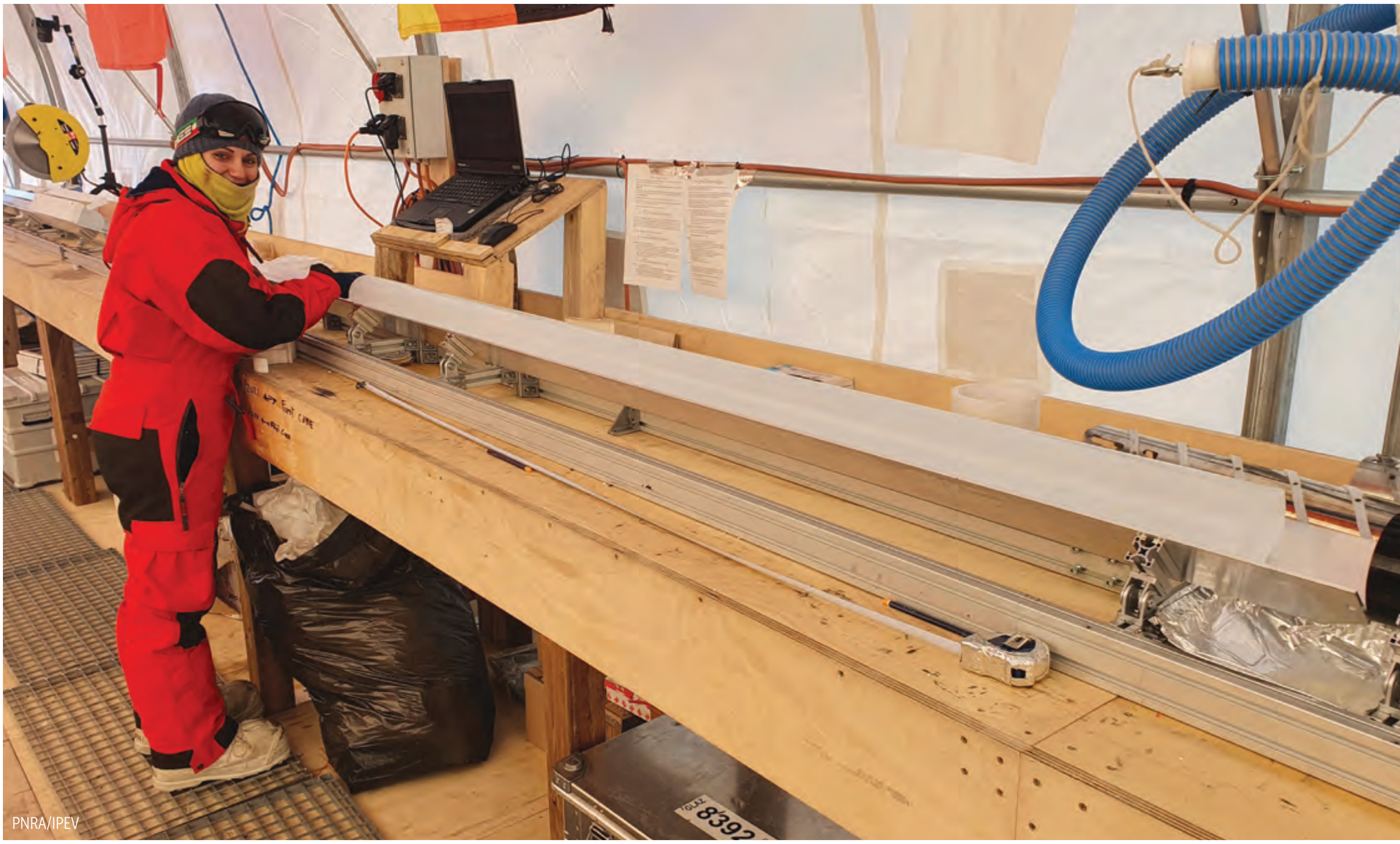
In seeking a site for drilling a continuous core, the US will deploy a new rapid-access tool, the ice diver, that can date the ice near bedrock. A flanged barrel with roughly the diameter of a soda can, the ice diver melts vertically downward, steered by a pendulum system and powered by a high-voltage, surface-based electrical generator. Control signals and data are transmitted via an attached cable that unspools from the device as it descends. For COLDEX, the ice diver will observe scattered blue laser light to profile dust concentration as a function of depth. "By comparing to other records we can translate dust cycles to ice ages," says Dale Winebrenner, a research professor in Earth and space sciences at the University of Washington and one of the developers of the ice diver.

"Even with high-quality, advanced radar," says Severinghaus, "it's still hard to say how old the ice is down near the bottom." And, he says, it takes five years and $50 million to drill a deep ice core. Determining the age of ice with the ice diver before drilling will increase the chances of obtaining old ice. Winebrenner and colleagues plan to conduct tests with the ice diver this summer in Greenland and to deploy it in Antarctica in the 2024–25 austral summer. For now, each handmade, single-use device costs around $20 000. The instruments and cables are left in the ice after use.

Drill, log, store, probe

Ice cores are extracted with cylindrical drills, typically about 3 meters in length and with core diameters of about 10 cm. The drill descends attached to a cable, which powers the drill rotation. When the drill barrel is full, the drillers break the core from the ice below. They raise it, remove the ice core, clean the drill, and then lower it back down the hole.

"Ideally, you deliver 3 meters of ice each time," says Mulvaney. "But it doesn't work that way. You run into problems." At depths of roughly 500–1000 meters, the pressure in the bubbles makes the ice brittle and easy to shatter; deeper, clathrates form and the brittleness dissipates. Each round of drilling takes more than an hour—longer as the hole deepens. The Beyond EPICA team introduced a 4.5-meter barrel this year, Mulvaney says. "We hope to reduce the number of trips down."



GIUDITTA CELLI, a PhD student at the Ca' Foscari University of Venice, logs a freshly drilled ice core for the Beyond EPICA project.

"It's always nerve-racking if you are the one operating the drill," Mulvaney says. "You have to get a decent core and bring it back up without losing the drill. And you worry about getting the drill stuck and breaking the cable." He recalls when a drill got stuck during EPICA. "We had to start over with a new borehole. We lost a couple of years."

Scientists label and log the ice core in segments. They note any damage, and they write the depth and orientation directly on the ice. The next core will be matched to it.

The Beyond EPICA team is testing transportation of ice cores at –50 °C. "Maintaining the low temperature poses problems when crossing the hot equator," says project spokesperson Carlo Barbante, director of the Institute of Polar Sciences and a professor of analytical chemistry at the Ca' Foscari University of Venice. Until now, ice cores have generally been transported and stored at standard freezer temperatures of –20 °C. But, explains Barbante, the lower temperature decreases diffusion of the trapped gases.

The COLDEX team, at least for now, will stick with –20 °C for transporting and storing ice. "It's a trade-off between the cost and how much the science is affected," says John Higgins, a Princeton geoscientist and lead for COLDEX's shallow coring. "We feel that –20 °C, –30 °C is okay."

In the past, some of the ice analysis was done near the site of extraction. Nowadays the instruments are more sophisticated and harder to transport and maintain in the cold. So researchers retrieve ice-core segments from their home storage sites—the main US one is in Denver, Colorado—and study them in their labs.

Fossil air

One of the main methods to date very old ice is to measure the ratio of argon-40 to argon-38 found in air bubbles. The lower the concentration of ^{40}Ar, a decay product of potassium-40 from the Earth's crust and mantle, the older the ice. Other dating methods include counting annual ice layers, matching them to known volcanic events or variations in Earth's orbit, modeling glacier flow, and using methods based on air–hydrate crystal growth or radiometric dating with krypton-81. Ice age can also be logged on coarser time scales by the amount of trapped dust and by Earth's magnetic reversals: When the field is weak, more cosmic rays enter the atmosphere and, through collisions of oxygen and nitrogen, introduce transient maxima in beryllium-10, which is archived in ice.

With confidence in the ice time line, scientists will probe ancient atmospheric temperature by various methods, including measuring the ratio of ^{18}O to ^{16}O in the ice. Because of how temperature affects the relative condensation and evaporation of the isotopes, that ratio during ice ages is lower than between ice ages.

Scientists expect to learn about greenhouse gas concentrations and other atmospheric chemistry from the trapped air. "The gas levels are small, and the amount of ice available, particularly for the very oldest ice, will be extremely limited," says Joel Pedro, a paleoclimatologist at the University of Tasmania and the lead scientist with Australia's Million Year Ice Core project. "A lot of work is underway to drive down the sample size needed while maintaining high precision."

"We extract the gases by melting or crushing the ice and use standard techniques" for analysis, including gas chromatography, mass spectrometry, and laser spectroscopy, says Christo Buizert, an Oregon State University assistant professor in Earth, ocean, and atmospheric sciences who coordinates COLDEX ice-core analysis efforts. Measurements of CO_2, methane, and noble gases anywhere are globally representative because those gases are relatively long-lived in the atmosphere. By contrast, trapped particulates, including salt, dust, and volcanic materials, tend to reflect more local processes.

Dust in Antarctica comes mainly from the Patagonia desert. Levels are higher when it's cold, dry, and windy and lower when the climate is wetter and stiller. "Dust is a proxy for humidity and windiness," says Olaf Eisen, a glaciologist at the Alfred Wegener Institute in Bremerhaven, Germany. "You can learn a lot. That's why it's exciting."

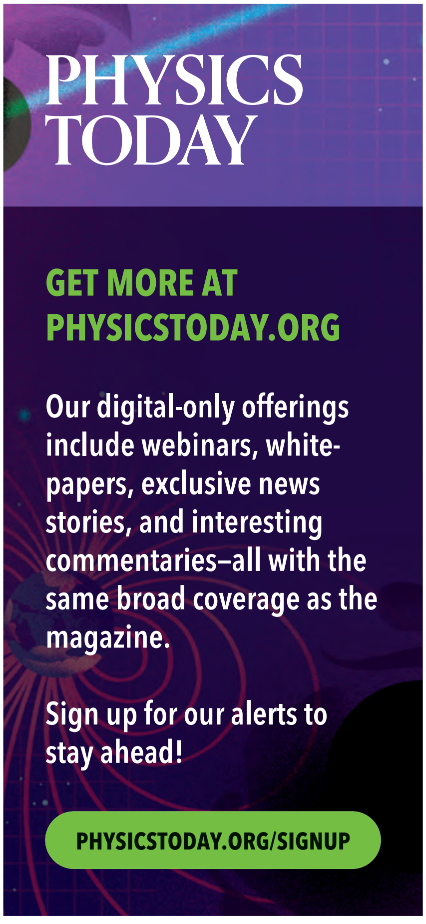

PETER NEFF

ICE CORES are transported back to researcher teams' home countries for study. The main US storage facility is in Denver, Colorado.

And more salt in the ice core may indicate more sea ice, Pedro says, because brine crystals, which form on the surface of sea ice, are lofted by winds and stored in the ice sheet. He notes that Australia is investing around Aus$45 million ($30 million) to revive skills for working in Antarctica. The country wants a seat at the table on the future of Antarctica, he says. "The politics is aligned with the big science objectives of recovering the oldest ice core. It has implications for Australia in terms of sea-level rise and climate."

Measurements that give snapshots in time are already coming in from Allan Hills ice. Continuous records going back to the Mid-Pleistocene Transition could be available as early as 2025 from the Beyond EPICA team and toward the end of the decade from the other research teams.

Toni Feder



Despite unknowns, NNSA plunges ahead on plutonium pits

The National Nuclear Security Administration has delayed by several years the date by which it will comply with a congressional mandate to build 80 pits per year.

TECHNICIANS PERFORM radiological control assessments after working with plutonium in a glove box at Los Alamos National Laboratory. The availability of new glove boxes is a key constraint on when the NNSA will be able to achieve its goal to produce 80 pits per year.

The US has spent billions of dollars over the past 20 years to reestablish pit manufacturing at scale. With prodding from Congress, the Department of Energy's National Nuclear Security Administration (NNSA) will spend billions more over the next decade to build two pit factories.

But the NNSA has scrapped four different plans to establish pit factories over the past two decades, notes a January report from the Government Accountability Office (GAO). And as the agency embarks on the latest one, questions linger: How long will a plutonium pit last? How many new pits are needed and when? How many retired pits could be recycled? How long will it take, and how much will it cost to reconstitute manufacturing capability?

Pits—hollow, grapefruit-sized spheres cast from about 3 kg of plutonium—are designed to implode when compressed by the high explosive surrounding them. The prompt critical mass that results fissions and creates a flood of x rays to trigger the warhead's secondary, fusion–fission stage.

NNSA and Defense Department officials have told lawmakers that they will not be able to meet a 2030 deadline that Congress had established for the NNSA to manufacture at least 80 pits per year. In an interview, Marvin Adams, the deputy administrator for defense programs at the NNSA, said he could not provide a new estimated time frame.

In the January report, the GAO said that the NNSA lacks a comprehensive schedule and an overall cost estimate for the 80-pit-per-year capability that meet GAO standards. On the basis of the NNSA's fiscal year 2023 budget documents, though, the GAO estimates the total price tag to reestablish pit production at the required rate will be at least $18 billion to $24 billion—which could be the NNSA's largest investment to date.

Aging concerns

Large-scale pit manufacturing ended in 1989, when the Rocky Flats Plant near Denver, Colorado, was permanently shut down after a Federal Bureau of Investigation raid revealed widespread violations of environmental regulations. The site has been remediated and is now a wildlife refuge. (See the article by David Clark, David Janecky, and Leonard Lane, Physics Today, September 2006, page 34.)

The US has thousands of surplus pits that have accumulated from past generations of weapons. Many could be reused. But some experts are concerned that aging plutonium might change the shape or strength of pits and thus alter their compressibility, causing warheads to not perform as designed.

Plutonium-239, the desired fissile isotope for weapons use, has a half-life of more than 24 000 years. Yet its decay by alpha particles leaves helium trapped within the metal's lattice. If those tiny bubbles were allowed to expand at room temperature and pressure, the volume of helium after 50 years will be equal to that of the plutonium, Adams says. Over the same period, every atom of plutonium will be knocked off its lattice site at least once.

"These radioactive decays are microscopically disruptive events," says Adams, who was a member of the JASON advisory group that in 2019 urged the NNSA in a brief report to establish pit manufacturing capabilities "as expeditiously as possible."

NNSA officials worry that the helium

bubbles might grow into larger voids in the metal, causing swelling. But Frank von Hippel, a retired Princeton University physicist, notes that research has indicated that even as the bubbles increase with age, they remain tiny and trapped within the lattice. (See the article by Victor Reis, Robert Hanrahan, and Kirk Levedahl, PHYSICS TODAY, August 2016, page 46.)

A more detailed JASON report from 2006 asserted that the pits in most types of stockpiled warheads would last at least 85 to 100 years and that the oldest pits in the stockpile should not require replacement before 2063 (see PHYSICS TODAY, July 2018, page 22). Several Los Alamos National Laboratory (LANL) directors, including current director Thomas Mason, have said that the classified version of that report was not as sanguine.

A 2012 study by Lawrence Livermore National Laboratory (LLNL) employed accelerated aging techniques in finding that plutonium—but not necessarily pits, which contain other materials—should "age gracefully" for 150 years. The study discounted worries about helium bubbles and phase changes. Plutonium metal has six phases, each with varying densities and crystal structures. Alloying small amounts of metals such as gallium or aluminum stabilizes plutonium in its desired delta phase.

Pits are hermetically clad, typically in stainless steel or beryllium shells. Plutonium will oxidize if the cladding is breached. Corrosion of the cladding can occur in the presence of moisture and chlorides, according to the Defense Nuclear Facilities Safety Board. Galvanic corrosion can occur at joints between dissimilar metals. And differing thermal expansion rates among pit materials can induce stresses that might cause cladding to fail.

Yet cladding can be replaced if corrosion is spotted during stockpile surveillance. Russian scientists told their US counterparts in the past that pits in Russia's stockpile were replaced about every decade because of corrosion at the welds. In some historical cases, a reaction with the high explosive material has caused cladding corrosion.

Varying margins

"You should be quite suspicious of a blanket statement that pits will last for 85 or 100 years," says Adams. "Not all pits are the same. And not all systems have the same amount of margin against degradation." In other words, some pit designs are more forgiving than others to aging.

The NNSA could extend pit lifetimes by increasing the amount of tritium that's injected into the pit during implosion, von Hippel says. Tritium has a half-life of about 12.5 years, and canisters that contain it in warheads are replenished about every 5 years. Loading more tritium into the canisters provides a bigger boost to a pit yield. "That's a great bullet, and we've used it," Adams replies. But it can only go so far. "You do it once and you're done."

The JASON reports from 2006 and 2019 both called for the NNSA to establish a focused research program to improve understanding and mitigate potential risks of pit aging. Steve Fetter, a University of Maryland physicist who studies national security issues, says that a more definitive pit lifetime estimate should be completed before the NNSA proceeds with mass production. Still, Fetter and von Hippel agree LANL should be able to demonstrate a capability to build a small number of pits. "There has been a loss of confidence due to the fact that LANL hasn't been able to produce reliably," notes von Hippel.

To help improve its understanding of aging effects, the NNSA carries out experiments using subcritical amounts of plutonium or surrogate materials at LANL's Dual-Axis Radiographic Hydrodynamic Test facility and the National Ignition Facility at LLNL. Underground subcritical tests are performed at the Nevada National Security Site, and a new subterranean subcritical test device known as Enhanced Capabilities for Subcritical Experiments is under construction there (see PHYSICS TODAY, February 2020, page 23). The new facility is designed to provide more detailed observations of the later stage of plutonium implosions.

Simple math

At a rate of 80 new pits per year, refurbishing the entire US stockpile of nearly 4000 warheads would take 50 years. Since casting 80 new pits each year likely will not be possible until the mid 2030s, the last of the legacy pits will be more than 90 years old when they are removed from

service. "No one has ever seen a 90-year-old pit," Adams says.

Some but not all pits are interchangeable, Adams notes. The NNSA wants to use the first of the newly made pits in two new warhead types being designed to use insensitive high explosives (IHEs). Compared with conventional high explosives (CHEs), IHEs are less likely to detonate in an accident that will spew plutonium and possibly injure or kill those in the vicinity. All warheads are engineered so that an accidental nuclear explosion won't occur in any case.

Because IHE has lower energetics and burns slower, pits that are paired with IHE require a different design from those coupled with CHE. Adams says there are no mothballed IHE pits that are suitable for the new warheads. Some of the new warheads will have to have recycled pits made for CHE, because not enough newly built pits will be ready when warhead assembly begins in the 2030s. "That puts constraints on you, and it's not optimal," he says.

The recycled pits, 40 or more years old when they are installed in the new weapons, must then endure for several more decades. "We've got more science work for the labs to do to be able to say that in 2035 or so that a pit of that age will last for another 30 years," Adams says.

A two-site solution

When the stockpile peaked at more than 30 000 warheads in the late 1960s, Rocky Flats cranked out between 1000 and 2000 pits each year. Since production was halted there in 1989, LANL has built 31 pits that were qualified for the stockpile, the last one in 2012. Qualification to enter the arsenal requires sign-off by the weapons design laboratory (LANL or LLNL) and certification of pit components that are made elsewhere and assembled at LANL. The lab has fabricated 35 noncertified demonstration pits in recent years.

To address the lack of physical space at LANL, the NNSA in 2018 devised a two-site strategy: The sprawling Savannah River Site (SRS) in South Carolina was designated to fabricate 50 pits out of the 80-pit requirement per year. That plan requires repurposing a partially completed 46 000 m^2 facility that was intended to turn surplus weapons plutonium into mixed oxide (MOX) fuel for commercial reactors. (See "Los Alamos to share plutonium pit production with Savannah River facility," Physics Today online, 18 May 2018.) Much of the MOX building's interior will be reconfigured and existing equipment torn out, a two-year process.

Congress appropriated $1.3 billion this year for the SRS project. The NNSA expects to achieve the 50-pit goal in the mid 2030s.

Assigning a pit-production role to the SRS placated South Carolina's congressional delegation, notably Senator Lindsey Graham (R), who fought vigorously against scrapping the MOX project. But Senators Martin Heinrich and Tom Udall (both D-NM) helped ensure that LANL wasn't left out, says Greg Mello, executive director of the Los Alamos Study Group, a watchdog organization.

Unlike LANL, the SRS has plenty of room to expand output beyond its initial annual target rate. Jill Hruby, NNSA administrator, told attendees of a Washington, DC, conference in February that the NNSA already foresees years in which it will need more than 80 pits.

Dual sites will provide resilience when one plant is shut down for maintenance or when breakdowns occur, says Adams. But the strategy requires duplicating the

LOS ALAMOS NATIONAL LABORATORY

A BLAST CONTAINMENT chamber is lowered into place at the Dual-Axis Radiographic Hydrodynamic Test facility at Los Alamos National Laboratory. Explosive tests on mock pits made from surrogate metals are used to help determine how plutonium will compress as the pit of a nuclear weapon implodes.

fabrication processes and equipment that are in development at LANL. It also necessitates hiring and training an SRS workforce from scratch. A 2019 study by the Institute for Defense Analyses warned that success for the two-site plan was "far from certain," pointing out that no successful major NNSA project costing more than $700 million had been completed in less than 16 years.

Environmental organizations opposing SRS pit production won a victory of sorts in February when a federal judge ruled that their lawsuit seeking to compel the NNSA to prepare a programmatic environmental impact statement of the pit plan could proceed. Such studies require extensive public input from impacted regions and often take years to complete.

Mello says his group didn't join the plaintiffs because their objective is limited to preventing pit operations at the SRS. "[The plaintiffs] have calculated that pit production solely at LANL is the lesser of two evils."

30 pits at Los Alamos

Over the past two decades, the NNSA spent more than $5 billion to modernize and sustain LANL plutonium operations, according to the GAO. The spending addressed widespread safety and operational deficiencies at its plutonium facility.

In February, the NNSA approved a $1.8 billion package of equipment needed to meet the 30-pit annual requirement at LANL in 2030. Three additional acquisitions are planned, for which the NNSA says it does not have firm cost estimates. Congress appropriated $1.5 billion for plutonium modernization activities at LANL this fiscal year, an increase of more than $500 million from last year.

The first stockpile-certified pit at LANL is scheduled to be built in 2024, a year later than planned because of a design change made late last year to simplify its manufacture. "What you need is mature enough production processes so that a large fraction of the pits you build will pass all their specifications," Adams says. "For that to happen, you have to have a design for the pit that is manufacturable enough."

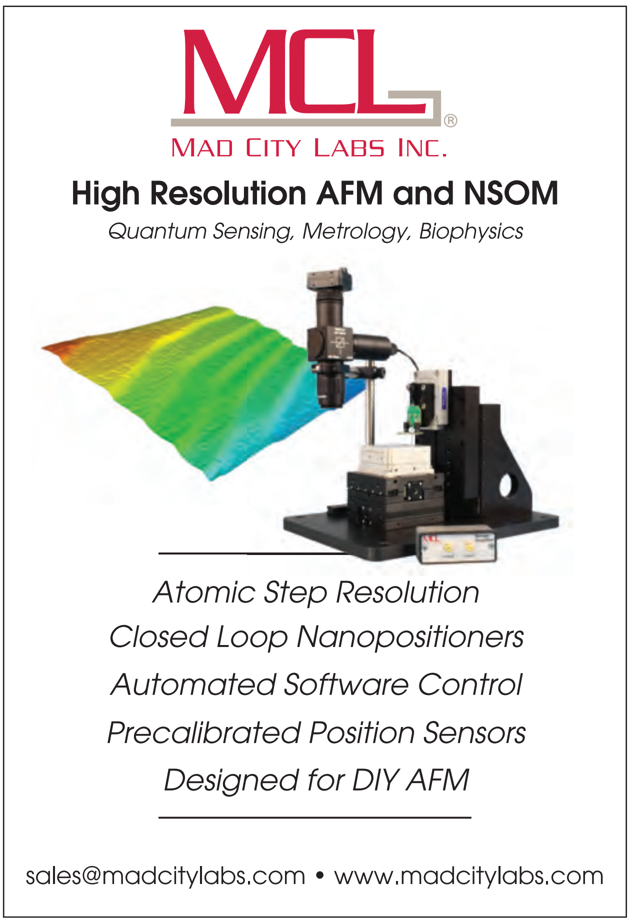
Mello says LANL's limited capacity makes its role over time of little value. "It's a lot of money to pour into Los Alamos for a very limited product even under optimistic conditions." The 2019 report by the Institute for Defense Analyses advised that two-shift operations at the plutonium facility—which will be required to make 30 pits per year—is high-risk.

Currently, work at LANL focuses on decontaminating and removing old glove boxes and equipment. The new components will be installed at night, in the same rooms where other mission work occurs in the daytime. "It's a complicated choreography," says Adams.

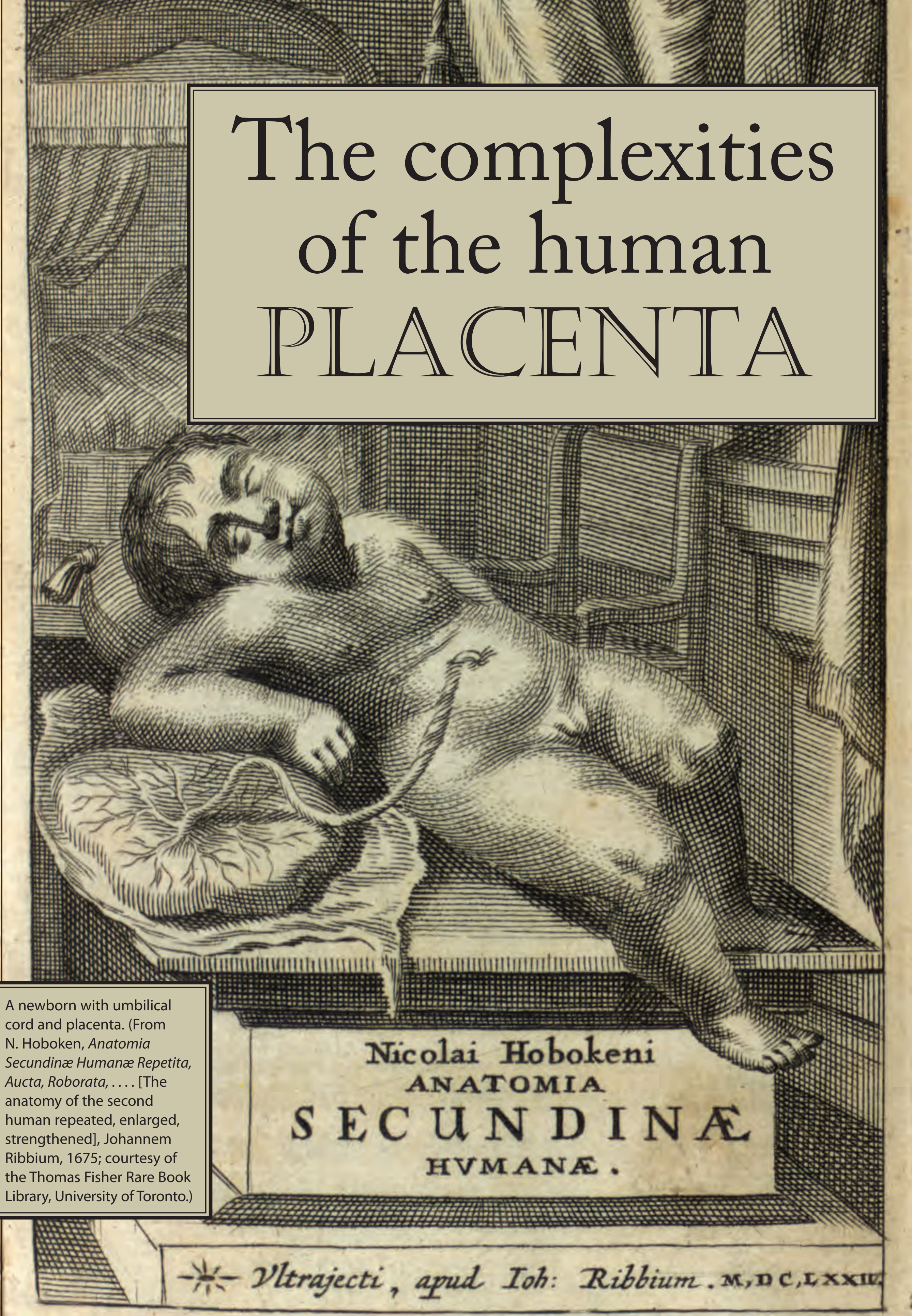
Procuring new glove boxes is a major bottleneck, Adams says. They are often custom-made, room sized, and designed to fit around production equipment and require attachment to gas supplies and conveyor belts.

There are only a small number of US glove-box manufacturers. The NNSA has invoked authorities that give priority to national security needs. Congress has appropriated funding in the current fiscal year to allow the agency to place advance orders, and Adams says he hopes that will encourage manufacturers to increase their capacity.

David Kramer PT



The complexities of the human PLACENTA



A newborn with umbilical cord and placenta. (From N. Hoboken, *Anatomia Secundinæ Humanæ Repetita, Aucta, Roborata, ...* [The anatomy of the second human repeated, enlarged, strengthened], Johannem Ribbium, 1675; courtesy of the Thomas Fisher Rare Book Library, University of Toronto.)



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Alys R. Clark, Igor L. Chernyavsky, and Oliver E. Jensen

The flow and transport of solute molecules in the intricate structure of the placenta make the organ a fetal life-support system.

Before birth, you were nourished by a unique and extraordinary organ: the placenta. That fetal organ formed an interface between the nutrient-rich blood in your mother's body and your own, without the two blood supplies ever mixing. The interface supported your growth in the womb, where it effectively served as your lungs, gut, kidney, and liver.

The placenta is unique in being a short-lived but versatile organ. Modern imaging techniques reveal its complex microstructure, which is intimately connected to its primary role in exchanging solutes between mother and fetus. Computational image-based modeling helps scientists understand how the intricate spatial organization of maternal and fetal blood vessels influences that exchange and how disease can disrupt it. This article provides a tour of the organ and of physics-based approaches to understanding its life-sustaining role.

Anatomy

Many anatomists throughout history, including Leonardo da Vinci, William Harvey, and Nicolaas Hoboken (discussed in box 1), have investigated pregnancy and the placenta. They and others believed that the blood circulations of mother and child were directly connected. Confirmation that the two circulations are actually separated is often credited to the Scottish anatomist and obstetrician William Hunter in the 1770s. Our understanding of the anatomy and physiology of the placenta has advanced significantly since then, aided by a recent explosion in imaging techniques that have revealed detailed insights into the organ's structure.

Fetal blood vessels in the placenta occupy complex structures, called villous trees, shown in figure 1. Despite being packed inside a disk the size of a frisbee, the placenta has a huge surface area—about 10 m^2, or roughly 10% of the surface area of an adult human's lungs—for the exchange of solutes.

A unique, multinucleated cell known as the syncytiotrophoblast covers the entire surface of the placenta, providing a barrier between maternal and fetal blood. The fetal blood vessels themselves branch out from the umbilical cord, over the fetal-facing surface of the placenta, and into the placental tissue in the villous trees. Millions of capillaries sit close to the surface of the placenta, where nutrients and waste are exchanged with maternal blood, as shown in figure 2.

To establish a successful pregnancy, not only must the villous trees develop effectively, but the placenta must also ensure a good blood supply to its surface from the uterus. That process is extraordinary: Placental cells invade the uterine wall and transform the smallest blood vessels into wide nonmuscular channels that allow a significantly increased supply of blood to flow in late pregnancy. (Physicians estimate that the flow increases 15-fold compared with the amount of blood supplied to the nonpregnant uterus.) Even blood vessels that are not invaded by placental cells increase in size—up to twofold—and their behavior is modulated by pregnancy hormones.

The success of a pregnancy therefore relies on the establishment of two blood-supply systems—one fetal (the placenta) and one maternal (the uterus)—in addition to the development of the fetus itself. The interface between the two circulations is of critical importance. They need to be in close contact for effective exchange of solute molecules, but it is dangerous if the blood supplies mix or potentially harmful compounds are transferred to the fetus. Disruptions to blood flow in either circulation can affect the structure of the placenta and the exchange barrier between maternal and fetal blood.

For scientists to understand pathologies of the placenta, they need to have a genuine comprehension of what is normal. That varies widely between human pregnancies and even more so between species. Some pathologies are unique to humans, in part because placentation has evolved to be remarkably different between placental mammals. Accessing the placenta *in vivo* is challenging because physicians cannot look inside a

FIGURE 1. THE PLACENTA, ILLUSTRATED. Fetal blood vessels radiate from the umbilical cord (A) over the upper surface of the placenta (the chorionic plate, B) and enter villous trees (C) beneath it. The fetal side of the placenta is protected by an amniotic membrane (D). (From N. Hoboken, *Anatomia Secundinæ Humanæ Repetita, Aucta, Roborata,* . . . . [The anatomy of the second human repeated, enlarged, strengthened], Johannem Ribbium, 1675; courtesy of the Thomas Fisher Rare Book Library, University of Toronto.)

pregnant mother daily, nor can they use techniques that expose the uterus to ionizing radiation. The placenta is delivered at the end of pregnancy, however, which allows for studies of its structure and function outside the body.

Because the placenta is inaccessible during an ongoing pregnancy, it's important for scientists to determine what keeps it healthy. We can readily observe snapshots of anatomical structure in delivered placentas, but we need tools to link those snapshots to the drivers of function and dysfunction in the nine months before delivery. Physics-based models help link structure to function and therefore help physicians understand what to look out for in clinical practice, where routine ultrasound scans provide low-resolution insight into placental function during pregnancy.

Pathologies

Several pathologies that relate to the placenta significantly affect the success of a pregnancy and have potentially lifelong effects on the baby.[1] The biggest risk for a pregnancy is stillbirth, which has devastating consequences for the families involved. And the greatest contributor to that risk is a condition known as fetal growth restriction (FGR), whereby a fetus does not grow as well as it should. The pregnancy complication known as preeclampsia is often associated with elevated maternal blood pressure and a poorly adapted circulation in the uterus, and it often accompanies FGR. If untreated, preeclampsia can lead to other complications, including premature delivery and eclampsia—the development of seizures during pregnancy—which is dangerous to both mother and fetus.

Both FGR and preeclampsia are associated with a reduced density of villous structures in the placenta, as compared with the density of those in a normal placenta (see figures 3a and 3b). Diabetes in pregnancy often leads to the opposite effect—an overproliferation of blood vessels in the placenta (see figure 3c). All those complications emerge from a compromised structure, which produces dysfunction in the placenta or the uterine circulation. It is the uteroplacental dysfunction that often leads to premature delivery or stillbirth or puts the child at risk of cardiovascular and other health conditions later in life.

Pregnancy complications are notoriously difficult to predict. Problems in low-risk pregnancies need to be picked up early to ensure that any concerns are monitored effectively. Such monitoring reduces the risk of stillbirth in many cases because it allows decisions, such as when to deliver, to be made at the appropriate time. To detect problems early, physicians need a solid understanding of what processes can produce a pathological pregnancy and a way to spot them with the clinical tools available. Despite significant progress, replicating the many roles of the placenta remains a significant technological challenge (see box 2).

Imaging

Examining an evolving human placenta requires various complementary imaging techniques.[2,3] Traditional light and electron microscopy and ultrasound imaging have recently been supplemented by magnetic resonance imaging and microcomputed tomography.[4–6] Synchrotron x-ray tomography of soft biological tissues resolves structures across four orders of magnitude—from microns to centimeters. Applying synchrotron x-ray tomography to the intricate multiscale architecture of the human placenta is opening new windows into placental pathology and providing new opportunities for image-based modeling. Recent advances in x-ray tomography have been enabled not only by robust sample preparation and improved scanning techniques but also by efficient semiautomated segmentation based on machine-learning algorithms.

Even with access to detailed placental microstructure, however, a gap remains in our understanding of how the physics of flow and transport at the organ scale emerges from the dominant processes at the finest anatomical scales. Furthermore, clinical diagnostic tools, such as MRI and Doppler ultrasound, bring an additional layer of complexity because the interpretation of images relies on the physics of imaging technologies and multiple assumptions about the geometry and physical

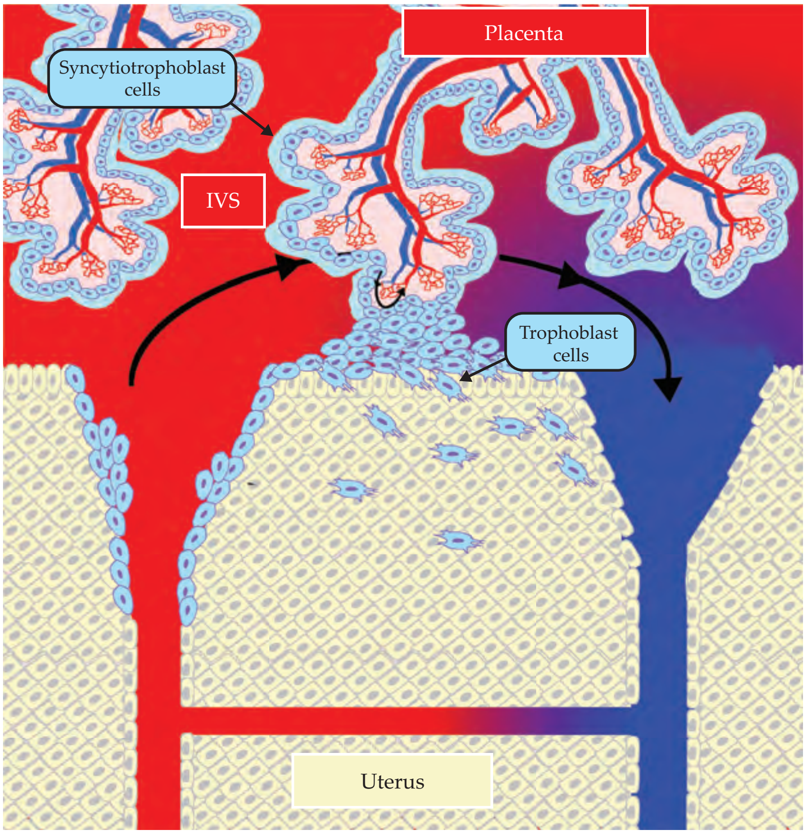


FIGURE 2. OXYGENATED, MATERNAL BLOOD (red) flows from a spiral artery (left) in the wall of the uterus into the intervillous space (IVS). There, it flows past villous trees in the placenta before being collected in a nearby decidual vein (blue), having lost its oxygen to fetal blood flowing in capillary networks in the villous trees. The maternal and fetal circulations are separated by the syncytiotrophoblast (light blue) and other placental tissues, including trophoblast cells (blue ovals) that invade and remodel the wall of the uterus. Arrows show the flow directions of maternal and fetal blood. A shunt vessel, illustrated in the lower part of the image, connects the uterine artery and vein.

properties of the probed tissue. Future advances in clinical imaging depend on a new generation of physics-based models that can assimilate data from diverse sources across multiple length scales.

Probing the heterogenous multiscale structure of the human placenta also poses significant challenges for quantifying the uncertainties. Many statistical estimates of geometric and material properties of complex soft tissues are intrinsically scale dependent.[6] Care is needed to identify a representative region of interest and to characterize associated fluctuations in key quantities—for example, specific volumetric and surface-area densities or structural-correlation length scales.

Exchange physics

Small molecules, such as oxygen and carbon dioxide, readily diffuse across the syncytiotrophoblast (see figure 2). Larger molecules, if they can cross at all, diffuse more slowly. Some, such as amino acids and glucose, require the active involvement of specific membrane-bound proteins or intracellular vesicles to cross cell membranes and reach the fetus.[7]

Suppose that it takes a typical time T_S for a particular solute to cross the syncytiotrophoblast, either by diffusion or active transport. Fetal blood delivered to a terminal villus will spend a typical time T_V, say, passing through its capillary network before being returned to the larger conducting vessels of the fetoplacental circulation.

If T_V is sufficiently small compared with T_S, then diffusive or active transport across the syncytiotrophoblast regulates exchange; in that case, exchange is often called "diffusion limited." If T_S is much smaller than T_V, then the rate at which solute is delivered to the fetus is regulated by how fast the blood flowing in the capillaries can carry it through the villus. In that case, exchange is called "flow limited."[8]

One can characterize the way in which a given solute moves across the walls of a terminal villus by using a dimensionless number, the fetal Damköhler number Da_f, defined as the ratio of advective to diffusive fluxes in a typical villus (see figure 4). The Da_f is proportional to the ratio T_V/T_S: Very small Da_f values correspond to diffusion-limited transport, and very large Da_f values to flow-limited transport. Overall, for fixed maternal conditions, the rate at which solute passes between the intervillous space (IVS) and the fetal circulation rises from low values—in the flow-limited state, regulated by the weak fetal flow—to a maximum value in the diffusion-limited state.

The maximum solute flux that a villus can absorb in the diffusion-limited state can be expressed as $L_v D_t \Delta C$, where L_v is a length scale that captures the complex geometric structure of the villus, D_t is a diffusion coefficient in fetal tissue, and ΔC is the difference between fetal and maternal concentrations. The length scale L_v can be interpreted, crudely, as the typical surface area for exchange divided by the typical distance over which solutes must diffuse through villous tissue. It is defined by the shape of the villus and the arrangement of capillaries in it.[9]

Suppose that it takes a typical time T_m for a packet of maternal blood to pass through the IVS—from spiral artery to decidual vein. If each villus exchanges solutes with a volume V_m of the IVS, then a characteristic rate at which solute can be exchanged is $L_v D_t/V_m$, which assumes diffusion-limited transport in the villi.

Comparing that exchange rate with the transit rate $1/T_m$ defines a dimensionless maternal Damköhler number Da_m, which is proportional to $T_m L_v D_t/V_m$. Once again, diffusion-limited and flow-limited states are defined by the size of Da_m: Very small Da_m corresponds to fast flow and relatively slow solute exchange, regulated by the exchange capacity of the villi, with maternal blood leaving the IVS before villi have had time to exchange all the solute. Large Da_m, by contrast, describes the case when maternal blood flows slowly relative to the exchange rate. That means that solute can be extracted from maternal blood long before it has left the IVS, but with the net flux passing between mother and fetus falling short of the full exchange capacity of the villi.

Solute exchange is therefore regulated by the strength of both maternal and fetal circulations, as mapped in figure 4. It is weakest when the transport is flow limited for both maternal and fetal circulations (large Da_f and large Da_m), and it rises to

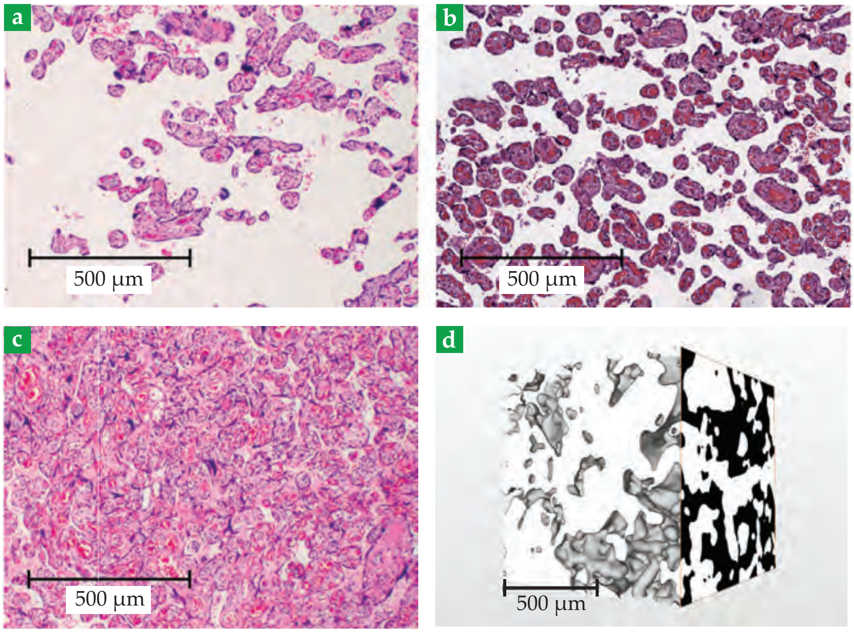


FIGURE 3. PLACENTAL TISSUE. Three cross-sectional images show the intervillous space (IVS; beige) and villous trees (dark spots). Those structures illustrate the typical features of **(a)** normal, **(b)** preeclamptic, and **(c)** diabetic placentas. (Adapted from ref. 13.) **(d)** This three-dimensional image of placental tissue (white) and the IVS region (dark) was obtained by synchrotron x-ray tomography. (Unpublished, based on ref. 14.)

a plateau when both become diffusion limited (small Da_f and small Da_m).

One might imagine the existence of a sweet spot, with both Da_f and Da_m of order unity, that allows effective transport without excessively rapid flows. A striking feature of placental transport, however, is the variability in Damköhler numbers for different solutes. Smaller molecules, such as CO_2, are more likely to be flow limited, whereas larger molecules, such as glucose, are likely to be diffusion limited, with both being transported simultaneously.[9] (That simple picture becomes richer when one accounts for additional biochemical processes,[8,10] such as the binding of oxygen to hemoglobin, and when one accounts for the metabolism of solutes by placental tissue itself.)

The complex architecture of the placenta must accommodate the transport of a broad range of solutes rather than be optimized for a single purpose. An important question to ask then is how the transport of all those solutes may be compromised during disease, when both flow and solute exchange are directly influenced by structural factors that affect both the diffusive exchange capacity and the resistance to flow. If villi are packed too densely, as they are in diabetes patients, they present a high resistance to flow. If villi are packed too sparsely, as in preeclampsia patients, the resistance to flow is low, but the diffusive exchange capacity of the placenta is significantly reduced.

A multiscale complex system

The placenta's function is regulated by its morphology across multiple spatial scales. At the cellular scale, the particulate nature of blood influences its flow properties in fetal capillaries and the smallest pores of the IVS,[6] whereas the thickness of the syncytiotrophoblast, shown in figure 5a, regulates the local solute exchange.

The larger-scale vasculature shown in figure 5b forms an intricate network of bewildering complexity. The number of individual villi in the placenta is estimated[1] to be more than 10 million. With at least one artery and one vein (and many capillaries) in each villus, it is infeasible to represent every blood vessel in assessing the physics of blood flow in the whole placenta. Two tools that simplify the job are homogenization—a smooth-

Box 1. The anatomists' perspective

Leonardo da Vinci is renowned for his detailed anatomical drawings. In his depictions of the placenta, he described the interface between maternal and fetal blood as interwoven hands, and correctly suggested that the two circulations were separate. The prevailing view of early philosophers and many anatomists—from ancient Greek texts through 18th-century scientific literature—was, however, that the maternal arteries of the uterus and fetus enjoyed a direct connection at the placenta.

Seventeenth-century anatomists, such as William Harvey and Nicolaas Hoboken, questioned that view, just as da Vinci had, but they did not have the tools to confirm the functional separation of the two circulations. William Hunter is credited with that achievement. He described how wax injected into the uterine circulation did not appear in the fetal circulation; likewise, wax that he injected into the umbilical vessels did not enter the uterus. He presented his findings in his detailed anatomical atlas *Anatomia Uteri Humani Gravidi Tabulis Illustrata; The Anatomy of the Human Gravid Uterus Exhibited in Figures*, published in 1774. For a comprehensive history of scientists' understanding of the placenta, see ref. 16. (Drawing by Leonardo da Vinci of a fetus in the womb, ca 1510–13, Royal Library, Windsor Castle/public domain.)

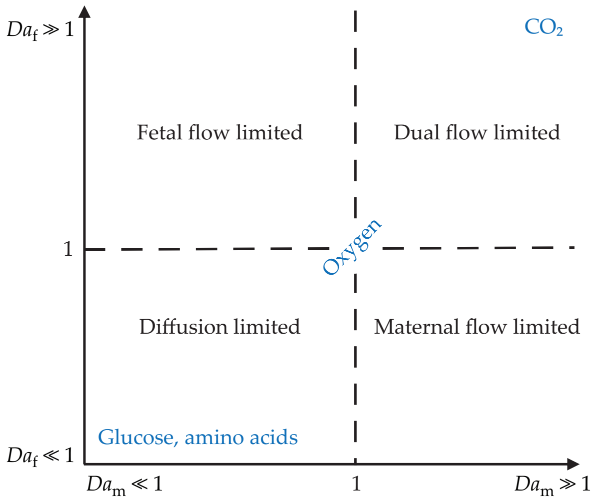


FIGURE 4. THE PLACENTA TRANSPORTS multiple solutes simultaneously, with different physical processes regulating the rate at which they pass between mother and fetus. Small molecules, such as carbon dioxide, diffuse quickly across the syncytiotrophoblast, so that exchange rates are regulated by flow conditions in both the maternal and fetal placental circulations—so-called dual flow-limited transport. The transport of large molecules, such as amino acids, is regulated by the speed at which they cross the syncytiotrophoblast—so-called diffusion-limited transport. The regimes are mapped out here using two dimensionless numbers: the maternal and fetal Damköhler numbers Da_m and Da_f, respectively. The strength of transport by maternal and fetal blood flow is proportional to $1/Da_m$ and $1/Da_f$, respectively. Typically, oxygen exchange is regulated by both flow and diffusion. (Adapted from ref. 9).

ing approach used in porous-medium models—and image-based simulations of transport in vascular networks that are representative of a particular scale of interest.

Homogenization, to date, has mostly been used to simulate blood flow in the IVS, which can be thought of as a disorganized network of pores, through which maternal blood percolates around obstacles—the villous trees. Researchers have widely studied flow through such porous media, particularly in geophysical applications, and have adapted modeling techniques to the placenta.[10]

Early studies used two-dimensional cross-sectional images of placental tissue, such as seen in figure 3a, to quantify spatially averaged pore spaces and to predict maternal blood flow through functional regions of the placenta, fed by a single maternal artery. More recently, a trend toward investigating mesoscale pore structures in three dimensions, such as in figure 3d, has allowed researchers to incorporate spatially varying tissue properties in those simulations. Those models have brought insights into how the observed structure of the placenta at delivery relates to both maternal blood flow and oxygenation.

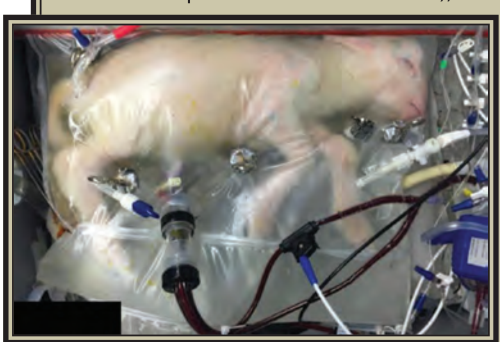
In fetal and uterine circulations, branching blood vessels can be considered mathematically as graphical networks at multiple scales—from disordered capillary networks to large-scale vascular ones. In those models, the flow of blood can be captured using simplified governing equations. The equations do not necessarily incorporate flow disturbances at branching points of the vessels, nor do they explicitly track the movement of oxygen-carrying red blood cells in the vessels. They have, however, provided significant insights into the distribution of blood in the uterus and placenta, and they have been used to identify such features as uterine "shunt pathways," which are blood vessels that bypass the placenta and directly connect arteries and veins. Network models have highlighted the roles of those pathways in interpreting clinical ultrasound[11] and have paved the way for more in-depth assessment of the uterus to guide future clinical tools.

Because the placenta is structurally so complex, current physics-based assessments make simplifying assumptions to capture its function at different scales of interest. As imaging techniques advance and computational power increases, however, researchers are exploring more complex phenomena in structures representative of the placenta. For example, red blood cells affect both the nature of blood flow in small vessels and the transport biochemistry.

Box 2. A premature lamb grown in a bag

The mystery of childbirth has always fascinated humans. Still, from the time of Leonardo da Vinci to the present, our management of pregnancy and its complications has not changed dramatically. The exceptions involve assisted reproductive technologies, such as *in vitro* fertilization.

Recently, however, reproductive bioengineering has moved even further afield and begun supporting pregnancies with premature delivery. In 2017, for example, Emily Partridge, Marcus Davey (both at the Children's Hospital of Philadelphia Research Institute), and their colleagues developed an artificial, fluid-filled womb, or incubator, from which they delivered a healthy lamb. Starting as an extremely premature fetus, the lamb was successfully grown outside the maternal body for nearly a month in the incubator, shown here.[17]



Although those nascent reproductive technologies do not resemble their depiction in Aldous Huxley's *Brave New World* (1932), proof-of-concept artificial wombs suggest that the poor outcomes of premature birth could be mitigated. Many practical challenges remain, however, including the design of efficient and robust solute-exchange systems that do not overburden the delicate fetal or neonatal heart.[6] With a deeper understanding of the unique aspects of the human placenta, researchers may be able to develop artificial-womb and placenta technologies to help rescue premature babies and ensure healthy outcomes.

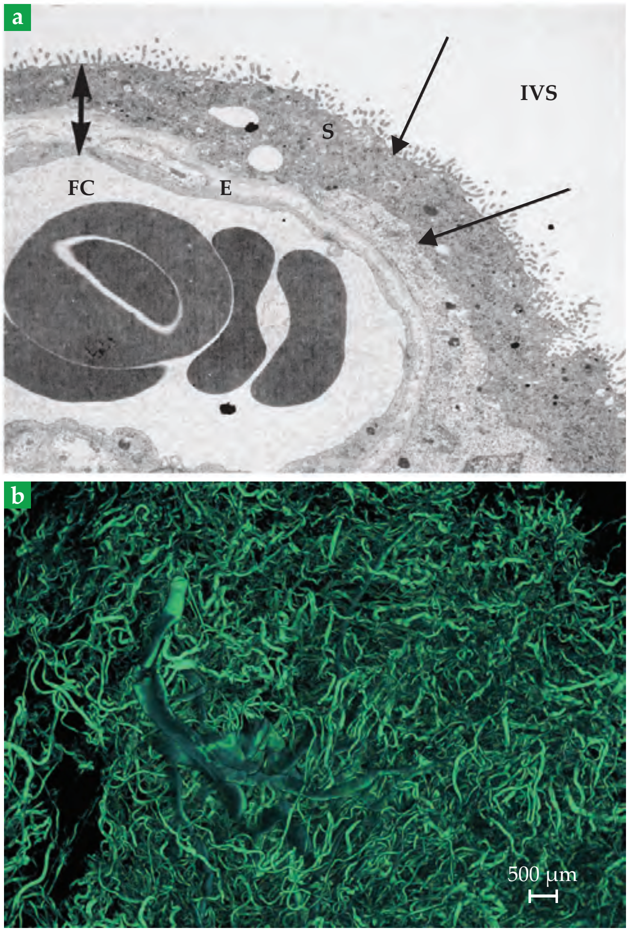


FIGURE 5. THE PLACENTAL EXCHANGE BARRIER (a) separates maternal blood in the intervillous space (IVS) and fetal blood in a fetal capillary (FC). The barrier tissue consists of the syncytiotrophoblast (S) that faces the IVS and endothelial cells (E) that line the FCs. Fetal red blood cells (central blobs) have a maximum diameter of about 8 µm. The double-headed arrow illustrates the distance that solutes must travel between maternal and fetal blood. Single-headed arrows identify the maternal- and fetal-facing sides of the syncytiotrophoblast. (Adapted from ref. 15.) **(b)** A micro-computed-tomography image of the fetoplacental vascular network highlights its complexity and the transition between large and small placental blood vessels. The largest visible blood vessel has a diameter of 450 µm. (Image courtesy of Vijayalakshmi Srinivasan, Mary Spring, Dane Gerneke, and Joanna James, University of Auckland, based on ref. 5.)

(As oxygen carriers, red blood cells must be considered in simulations of exchange capacity.)

In addition, the deformability of the placenta is altered in pathology, but that complexity is rarely considered in simulations of placental function. The compressibility of blood vessels in elastic tissue may have important functional implications when the uterus contracts over the surface of the placenta.[12]

The placenta is not the only system determining the health of a pregnancy. Maternal adaptations to pregnancy are important, including the capacity to carry 1 liter per minute of extra blood. The fetus also grows in response to nutrients delivered from the placenta and adapts when it does not get enough.

Scientists are beginning to assess maternal and fetal circulatory health via mathematical models and are developing new tools to noninvasively assess physiology.[12] Maternal and fetal heart rates can be measured at the body surface—with ultrasound or electrodes placed on the stomach—and wearable devices are increasingly being developed that can measure the hearts' health. The variability in fetal heart rate (and thus cardiac output) can be significant, a factor that affects the amount of blood delivered to the placenta. Understanding the link between the placenta and the fetal circulation that supplies it with nutrients is an ongoing challenge.

What's ahead?

The mystery of what makes a healthy pregnancy and childbirth is continually being teased out by new technologies. They include well-established medical diagnostic tools, such as ultrasound and MRI, but also machine-learning analyses of images of the placenta and physics-based simulations of how it works. Simulations enable testing of hypotheses and inspire new avenues to investigate.

One of the major challenges in simulating placental function is harnessing the organ's complex geometry on multiple spatial scales. Researchers need to develop meaningful ways to reduce that complexity and find new strategies for extracting the greatest amount of information from different imaging methods.

Alongside simulation, physics and engineering are providing new tools, such as surface measurements of uterine and fetal electrophysiology, for assessing placental performance and for improving the health of a developing fetus or a newborn via artificial life-support systems. It is likely that the design of those devices and systems could benefit from the results of simulations as well. As scientists from different fields work together, we should see the evolution of new ways to monitor and improve the health of pregnant women and their babies.

Work on "Multi-modal studies to understand pregnancy and prevent stillbirth" is supported by Wellcome Leap as part of the In Utero Program.

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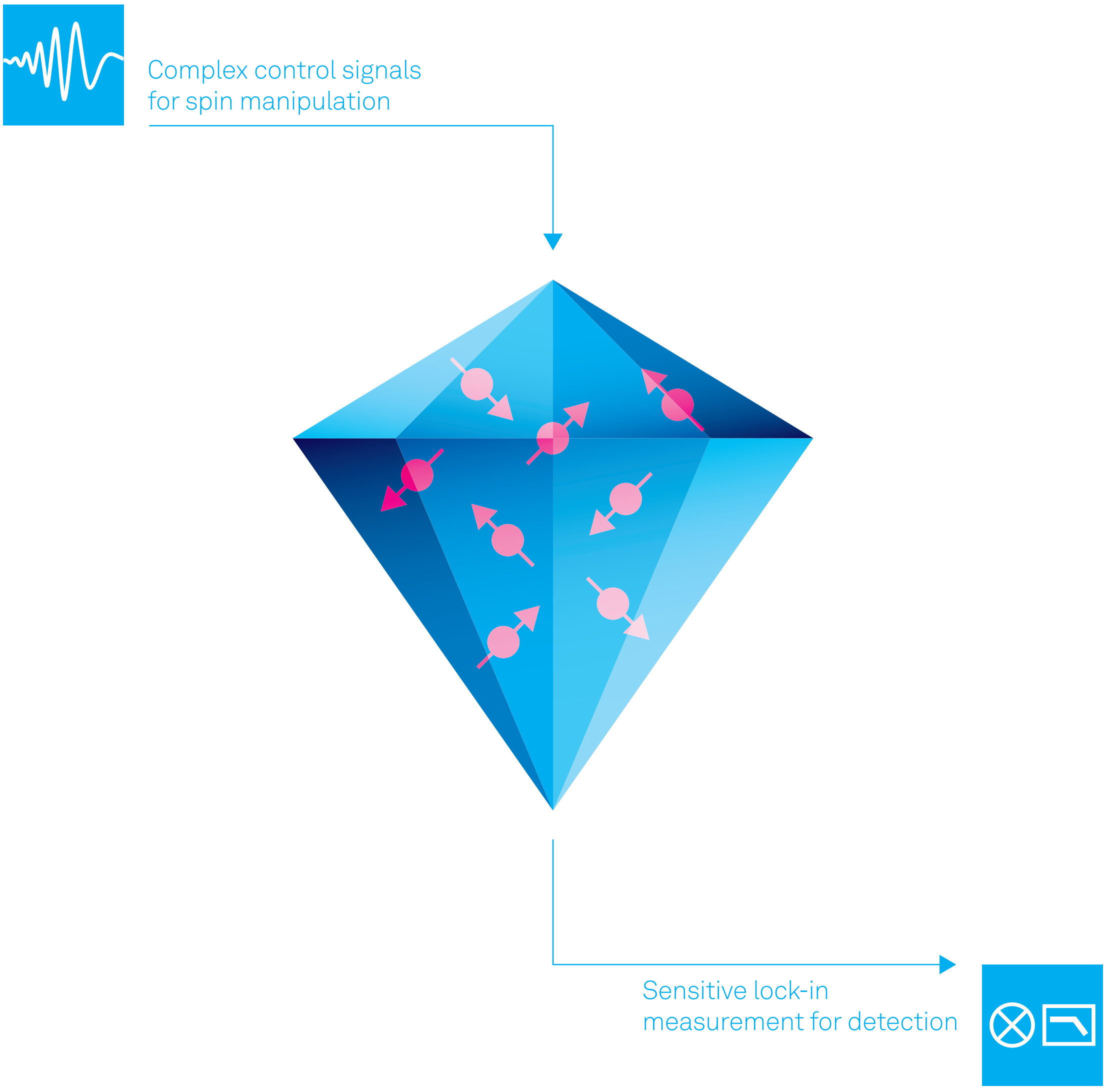

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Unveiling the mystery of solar-coronal heating

Leonardo Di G. Sigalotti is a professor and **Fidel Cruz** is an associate professor in the department of basic sciences at the Azcapotzalco campus of the Metropolitan Autonomous University in Mexico City. Their research focuses on astrophysics and computational fluid dynamics.

Leonardo Di G. Sigalotti and Fidel Cruz

Miniature flares recently discovered by probes that have approached the Sun's surface are helping physicists understand how the Sun's corona reaches temperatures of millions of kelvin.

One of the most vexing questions in modern solar physics is the coronal-heating problem. We all know from our own experience that when we move away from a hot body, the surrounding temperature decreases. So why is the Sun's corona—the atmosphere of hazy plasma that extends millions of kilometers into space and is visible as a pearly white crown during total solar eclipses—so much hotter than the visible surface of the Sun? The temperature difference is tremendous: The average effective temperature of the photosphere—the surface layer of the Sun, where its light originates—is 5800 K. In comparison, the corona's average temperature[1] is a staggering 1–3 × 10^6 K, and parts of it can reach temperatures as high as 10^7 K during highly energetic solar flares.

Since the early 1990s, when a wave of solar space missions returned a previously unparalleled amount of observational information, most solar physicists have believed that wave heating and magnetic reconnection are the most likely mechanisms to explain solar-coronal heating. Although there is not yet a definite solution to the problem, new clues to unveiling the mystery of coronal heating have begun emerging recently, as the European Space Agency's *Solar Orbiter* (*SolO*) and NASA's *Parker Solar Probe* (*PSP*) are venturing closer to the Sun than any spacecraft has ever been before.

An artist's rendering of *Solar Orbiter*. (Courtesy of ESA/ATG medialab.)

The coronal-heating problem

The solar corona and its tremendous temperatures have baffled astronomers for more than a century. Over the last four decades, solar physicists have proposed several theories to explain it, two of which have survived to date as promising candidates. The first is wave heating, which posits that mechanical energy is transported by magnetic waves into the corona and deposited there as heat by wave damping at sufficiently low heights.[2] The second is magnetic reconnection, the tumultuous process in which oppositely directed magnetic field lines break and reconnect in a plasma and convert magnetic energy into thermal energy.[1] Scientists have long believed that some combination of the two processes will explain coronal heating, although the details of that combination are not yet understood.

Magnetic reconnection relies on electric currents that are induced by the solar magnetic field in the electrically conductive plasma. It is the mechanism that causes solar flares, the largest explosions in our solar system. Satellite missions launched in the 1990s, such as the *Solar and Heliospheric Observatory* (*SOHO*) and the *Transition Region and Coronal Explorer* (*TRACE*), demonstrated that significant oscillatory activity occurred in the solar corona, part of which came in the form of magnetoacoustic and Alfvén waves. The former are linear magnetohydrodynamic waves that are driven by thermal pressure, magnetic pressure, and tension effects; the latter are low-frequency, transverse magnetohydrodynamic waves that are produced by the oscillatory motion of ions anchored to the magnetic field lines that emerges from the interaction between the magnetic fields and the electric currents in the plasma. Both magnetoacoustic and Alfvén waves can carry energy through the chromosphere and corona for a considerable distance before dissipating into heat. That forms the basis of the wave-heating theory, which was first proposed by Evry Schatzman[3] in 1949.

Missions launched in the 21st century have added to the picture. The solar spacecraft *Hinode*, put into orbit in 2006, revealed that the heating of the solar chromosphere and corona may be related to small-scale magnetic reconnections.[4] The space-based observatory *Interface Region Imaging Spectrograph* (*IRIS*), launched in 2013, provided evidence that discrete, small explosive events such as smaller nanoflares may contribute to the coronal heating budget.[5] And *SolO*'s recent discovery of numerous miniature picoflares—even smaller bursts of energy or explosions on the solar surface—that occur randomly and dissipate rapidly has brought solar physicists one step closer to solving the enigma of coronal heating.[6,7]

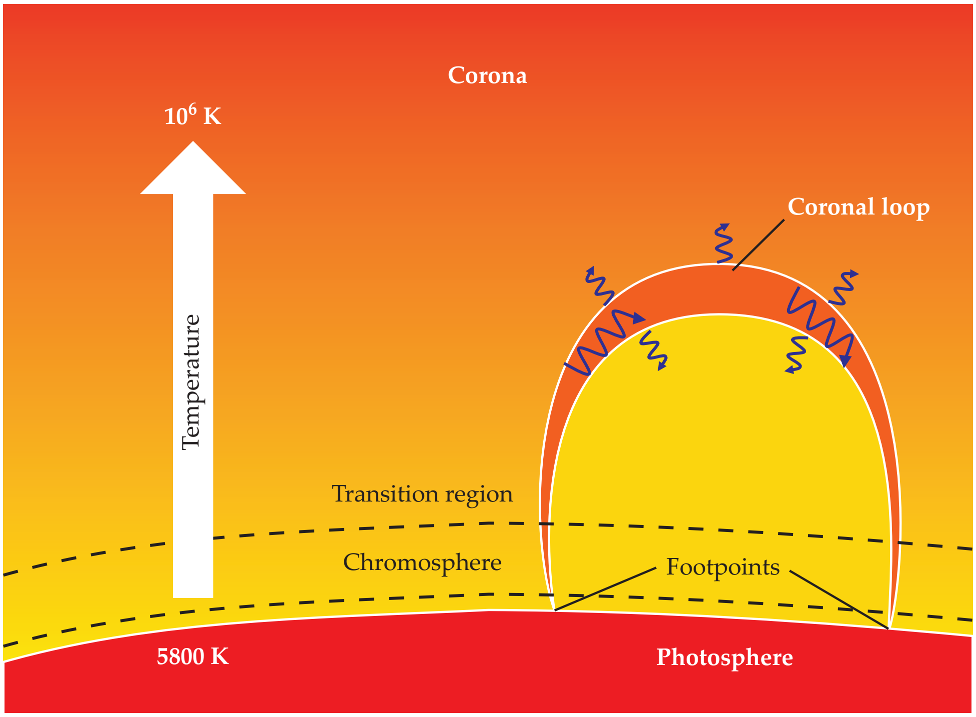

FIGURE 1. THE SOLAR ATMOSPHERE'S LAYERS. The lowest is the photosphere, which comprises the visible portion of the Sun. Next is the chromosphere, which is about 2000 km thick and is visible as a reddish flash during a total solar eclipse. Above that is the narrow transition region, only about 200 km thick, where solar temperatures rise dramatically to 10^6 K. The largest is the corona, which extends millions of kilometers into space and consists of extremely hot plasma. Like the chromosphere, the corona is observable during a solar eclipse. Coronal loops are anchored on both ends at footpoints in the photosphere; they project into the chromosphere and transition region and extend high into the corona. The wavy lines indicate how magnetohydrodynamic waves and heat propagate through one such loop.

Wave heating

It was not until 1997, with the aid of *SOHO*'s Ultraviolet Coronagraph Spectrometer, that astronomers detected the first direct evidence of waves propagating into and through the solar corona in holes (regions of cooler, less dense plasma) high above the Sun's surface.[8] But those undulations—compressible, slow magnetoacoustic waves—are capable of carrying only 10% of the energy required to heat the corona. On the other hand, incompressible Alfvén waves, which are launched by solar flares, can carry enough energy but do not damp out rapidly once they enter the corona. In addition, solar flares are transient, sporadic events that cover relatively small regions of the Sun's surface. Slow magnetoacoustic waves are longitudinal waves that are similar to ordinary sound waves in air. They can exist either as standing waves, which do not have an average net propagation of energy, or traveling waves, which do have an average net propagation of energy.

Coronal loops—arch-shaped magnetic flux tubes filled with chromospheric plasma—are one basic structure along which longitudinal waves stand and propagate in the lower corona (see figure 1). They extend tens or hundreds of thousands of kilometers above the solar surface, and their extremes, known as footpoints, are anchored in the photosphere. The loops are visible in x-ray, UV, and visible wavelengths and can have a variety of temperatures. Cool loops have temperatures below 10^6 K, warm loops hover around that temperature, and hot loops exceed it. Bright coronal loops, which take the form of coronal condensations (regions of warmer, denser plasma) and bright spots, are common around the time of solar maxima. Larger faint loops that last days or weeks are more typical of the quiet corona, when solar activity is low.

In the recent past, solar researchers believed that coronal loops were static, plasma-filled structures. But movies made from observations with *TRACE* showed bright blobs of plasma racing up and down the coronal loops. That feature was confirmed by observations by *SOHO*, which also revealed that those blobs move at thousands of kilometers per second. That evidence led researchers to the view that coronal loops are jets of hot plasma that are propelled in opposition to gravity—like an arch of water from a fountain—and flow along the alleys between the strong coronal magnetic fields. Observations also indicated an apparent temperature increase in coronal loops because of a height-dependent weighting function, which implies that they are indeed nonstatic, nonequilibrium states.[9] Figure 2 shows an image of an active region with many warm coronal loops.

Standing slow waves were seen in hot coronal loops with temperatures beyond 6×10^6 K in the form of strongly damped, large Doppler-shift oscillations, with periods in the range of 9–32 minutes and decay times between 3 and 42 minutes.[10] Observations of propagating slow waves are by far more abundant. Such oscillations have been detected by *SOHO* in hot loops and polar plumes with periods of 10–15 minutes[8] and by *TRACE* in cooler loops near their footpoints with periods between 2 and 9 minutes.[11] But periods as long as 20–35 minutes have also been reported in coronal-hole regions. Those waves were detected as intensity oscillations that propagate in the plasma with approximately the local speed of sound. In addition to compressible and Alfvén waves, solar physicists have also pointed to propagating transverse kink waves in loops and sausage oscillations of flaring loops as further possible explanations for coronal heating.

Although significant progress has been made in understanding the phenomenon, open theoretical and observational questions still remain. For example, there is no definite answer on how propagating and standing slow waves are triggered and excited. Researchers have variously proposed that kink-mode, Kelvin–Helmholtz, Rayleigh–Taylor, thermal, or resistive instabilities could explain coronal heating. The quasiperiodic nature of the outwardly propagating waves observed by *TRACE* suggests that they may well be driven by oscillations in the lower solar atmosphere, which stem from either chromospheric motions or the turbulence of granulation on the photosphere induced by currents of plasma within the Sun's convective zone, the outermost layer of the solar interior. In addition, multiwavelength observations point to small-scale transient brightenings as a mechanism for exciting propagating slow waves. A further possibility was put forward by Bernard Roberts,[12] who theorized that those waves could be generated impulsively when an energetic event such as a flare arises near the magnetic footpoints of a coronal loop.

Modeling coronal loops

Because slow magnetoacoustic waves are guided along the magnetic field and behave essentially like ordinary sound waves, most studies of coronal-loop oscillations have relied on numerical solutions of the one-dimensional equations for a compressible fluid, which are extended to include the effects of solar gravity and energy dissipation by viscosity and thermal conduction. Researchers have also examined other effects, including field-line divergence, heating, and radiative losses.

One interesting model calculation is to consider the evolution of a narrow, localized Gaussian pulse in velocity that starts near a coronal-loop footpoint and mimics an impulsive, reconnection-like event. In a homogeneous, isothermal medium where energy dissipation isn't considered in the calculation, the spikelike pulse will immediately split up into two independent and oppositely moving pulse waves that each travel at the adiabatic sound speed. In response to the velocity pulse, disturbances in the density and temperature arise in the form of Gaussian monocycle waves. As the velocity spike splits up, the monocycle waves detach and produce two pulses of inverted polarity that propagate in opposite directions. Under solar gravity, when one of those pulses propagates up toward the top of the loop, it experiences decreasing densities and therefore decreasing pressures, which increase its amplitude. But the picture changes when the effects of energy dissipation are introduced because the original pulse's higher-order Fourier modes will decay faster than the fundamental one.

The prediction that a highly localized pulse arising near one footpoint of a coronal loop can effectively excite longitudinal oscillations that propagate along the loop with a velocity close to the local sound speed introduces an alternative mechanism for wave triggering. But we won't know if the model is valid until we have more detailed observations of coronal-loop oscillations.

Nanoflare and picoflare heating

IRIS was designed to track temperature and hot-gas motions in the lower levels of the solar atmosphere at improved spatial,

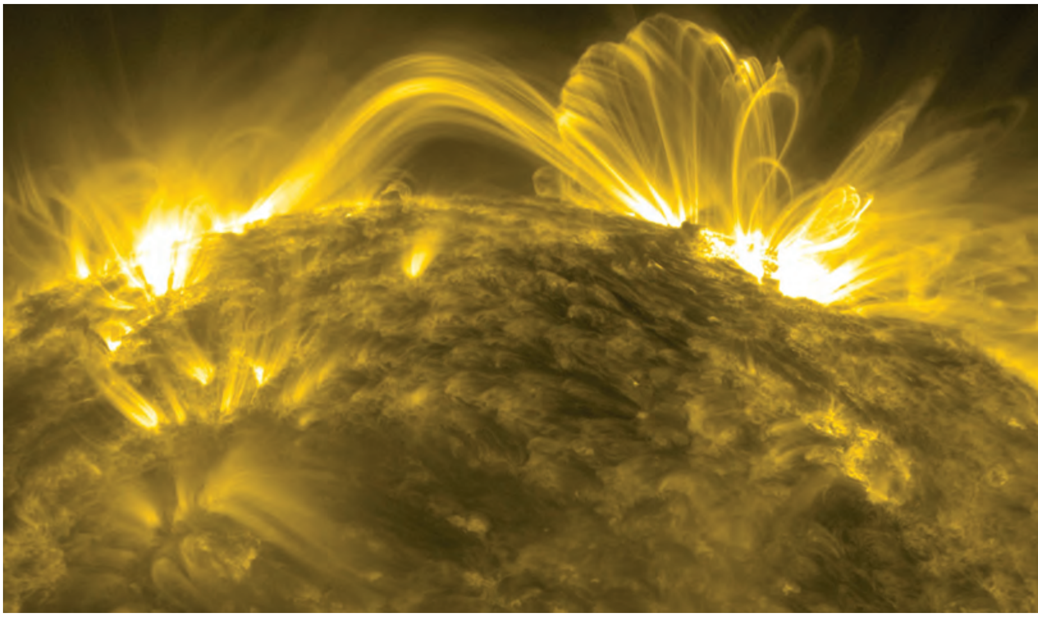

FIGURE 2. AN ACTIVE REGION of the Sun with many warm (approximately 10^6 K) coronal loops, as imaged at 171 Å by NASA's *Solar Dynamics Observatory*. (Courtesy of NASA/*Solar Dynamics Observatory*.)

temporal, and spectral resolutions. Recent spectrographic observations by *IRIS* demonstrate that heat is delivered in discrete, explosive events—called nanoflares because they are analogous to tiny solar flares—that occur when magnetic fields in the corona crisscross and realign.[5] The resulting energy is deposited in the corona. Although the explosions are probably only one of a variety of complex processes that cause coronal heating, they may cause the heat to spread out over large regions because the corona behaves as a large thermal conductor.

In comparison with the spectacular high-energy solar flares that occur in active regions of the Sun, nanoflares are low-energy events. Although their frequency has not yet been well established, they are certainly more prevalent than large flares. Those larger events are notorious for producing a wide range of high-energy electromagnetic radiation, including x rays; microflares and nanoflares are considerably more difficult to observe because their x-ray energy content is lower. Figure 3 shows a microflare observed on 4 September 2016 by the Swedish 1-m Solar Telescope on La Palma in Spain's Canary Islands.

The solar-physics community now generally agrees that convective motion below the photosphere is responsible for the random movement of magnetic-loop footpoints, which build up magnetic stresses that are ultimately converted to heat. The invisibility of sunspot-to-sunspot loops, which are rooted in the strongest observed magnetic fluxes, provides fresh evidence that photospheric convective motions are likely drivers of coronal heating. Many solar physicists say that picture, known as the impulsive-heating scenario, is the likely mechanism for heat conversion. Indeed, new evidence for episodic impulsive heating in weak flaring sites associated with coronal loops is emerging in active regions.[13] But it is unclear if that type of heating can also operate when the Sun goes quiet. Highly sensitive Japanese observations have recently confirmed that nanoflares occurred frequently in a region of the corona where no solar flare activity was taking place (see figure 4).

Because the Sun's UV radiation is mostly blocked by Earth's atmosphere, observing the solar corona typically requires the use of a space-based telescope. But significant data have also been obtained at much lower cost through the launch of UV telescopes on suborbital sounding rockets. NASA's High Resolution Coronal Imager (Hi-C), for example, returned detailed UV images of the solar corona taken during brief suborbital flights in 2012 and 2018. During the latter flight, Hi-C was equipped with a 24 cm mirror, which allowed it to capture an image of the corona every five seconds. Even though the Hi-C flights only lasted a little over 10 minutes, they revealed that sustained magnetic activity is present in the solar atmosphere, which might be responsible for the high temperatures of the coronal plasma.

The Focusing Optics X-ray Solar Imager (FOXSI), which was launched into space for about 6 minutes on three brief flights in 2012, 2014, and 2018, is another example of a solar telescope carried on a suborbital sounding rocket. X-ray data obtained by FOXSI revealed that a region of the Sun free of large-size solar flares nevertheless emitted high-energy light. Researchers have ascribed that light to intense nanoflares that crop up and dissipate quickly but produce small regions of extremely hot plasma that can reach temperatures above 10^7 K.[14] At that time the detection of those tiny flares was still beyond the technological capabilities available to solar physicists. But the situation has changed over the last few years: Radio instrumentation has improved to the point that, during the Sun's quiet period, it can now produce high-fidelity images of weak impulsive emissions from the corona with a duration of about one second.

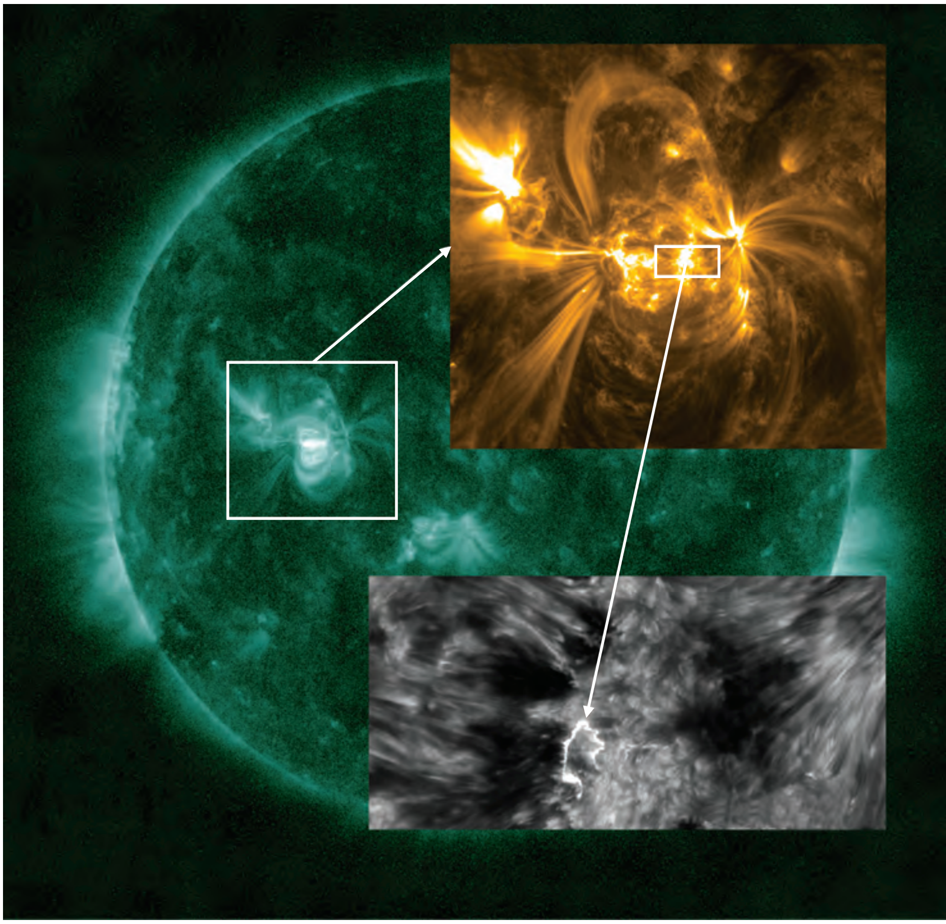

FIGURE 3. A MICROFLARE that occurred on 4 September 2016. In the green image, recorded at 94 Å, a hot coronal loop of more than 7×10^6 K is produced by magnetic reconnection. The upper inset, recorded at 171 Å, shows the active region with bright magnetic loops in high detail, and the lower inset, recorded at 3934 Å, depicts the region where electrons from the reconnection event impact the Sun's lower atmosphere. (Adapted from a composite image by Helle Bakke/Rosseland Centre for Solar Physics/University of Oslo, courtesy of the European Solar Telescope; background and upper inset courtesy of NASA/*Solar Dynamics Observatory*/Atmospheric Imaging Assembly; lower inset courtesy of the Swedish 1-m Solar Telescope/CHROMospheric Imaging Spectrometer.)

Solar probes

The last five years have also seen the start of two solar missions. The first is the *PSP*,[15] which was launched in 2018. A robotic spacecraft that will fly as close as 8.85 solar radii from the Sun,

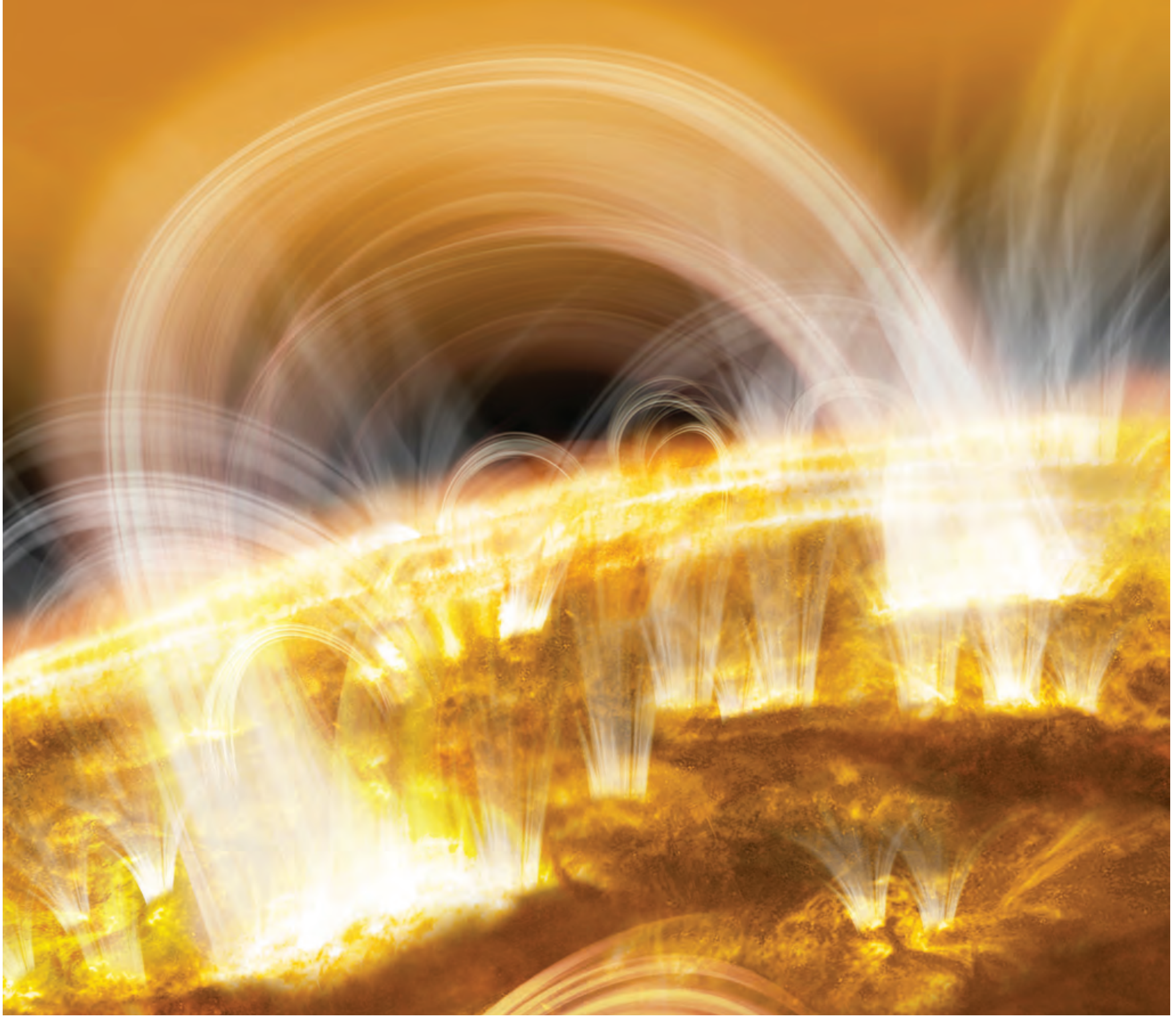

FIGURE 4. A SWARM OF NANOFLARES populating the Sun's surface in a region with no discernible solar flare activity. (Courtesy of the Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency.)

the *PSP* aims to investigate coronal heating and the origin of the solar wind. It has been called humanity's first visit to a star (see the article by Nour E. Raouafi, Physics Today, November 2022, page 28). During its eighth flyby of the Sun, on 28 April 2021, the *PSP* flew within 18.8 solar radii of the solar surface, crossed the Alfvén critical surface—the location where the Alfvén-wave speed and the solar-wind speed are equal—and entered the corona. Data from the flyby showed that the Alfvén critical surface is not a smooth sphere but instead has highly irregular peaks and valleys.

On 11 December 2022, the probe made its 14th flyby of the Sun and got within about 12.2 solar radii of the Sun's surface. Data from that approach are currently being analyzed and will be published this month. The *PSP* will continue to spiral closer to the Sun, and the diminishing distance will give the *PSP*'s telescopes progressively higher spatial resolution so that they can capture solar features in more detail.

The second recent solar mission is *SolO*, a satellite developed by the European Space Agency in collaboration with NASA. Launched in 2020, *SolO* aims to address fundamental open questions in solar physics and heliophysics.[16] Unlike the *PSP*, which focuses on the corona, *SolO* is designed to observe the solar surface. It will eventually come approximately as close as 60 solar radii from the Sun and will provide the closest images ever taken of the Sun's surface. Figure 5 shows an image taken by *SolO* on 7 March 2022. It depicts the full Sun in extreme-UV light at about 108 solar radii from the Sun's surface—halfway between Earth and the Sun.

Images taken by *SolO* that were released on 16 July 2020 depict miniature flares all over the solar surface, a stunning new phenomenon that can be called picoflares to emphasize that they are smaller than microflares and nanoflares. Those miniature solar flares are short-lived brightenings that last for 10–200 seconds and are 400–4000 km long. Flickering like candles, they reach temperatures over 10^6 K. They are the smallest and weakest solar events ever observed, and their abundance suggests that they may be the missing piece of the coronal-heating puzzle.[7] Appearing as loop-like, dot-like, or even more complex structures, picoflares have unclear formation mechanisms and connections to the photospheric magnetic field. One possible explanation is that the formation and triggering of picoflares may be related to the magnetic-flux cancellation between weak flux patches.

SolO's first observations, which occurred during the minimum of solar cycle 24, revealed that large-amplitude, nonlinear Alfvén waves that propagate away from the solar surface may also be ubiquitous in slow solar-wind streams, particularly in

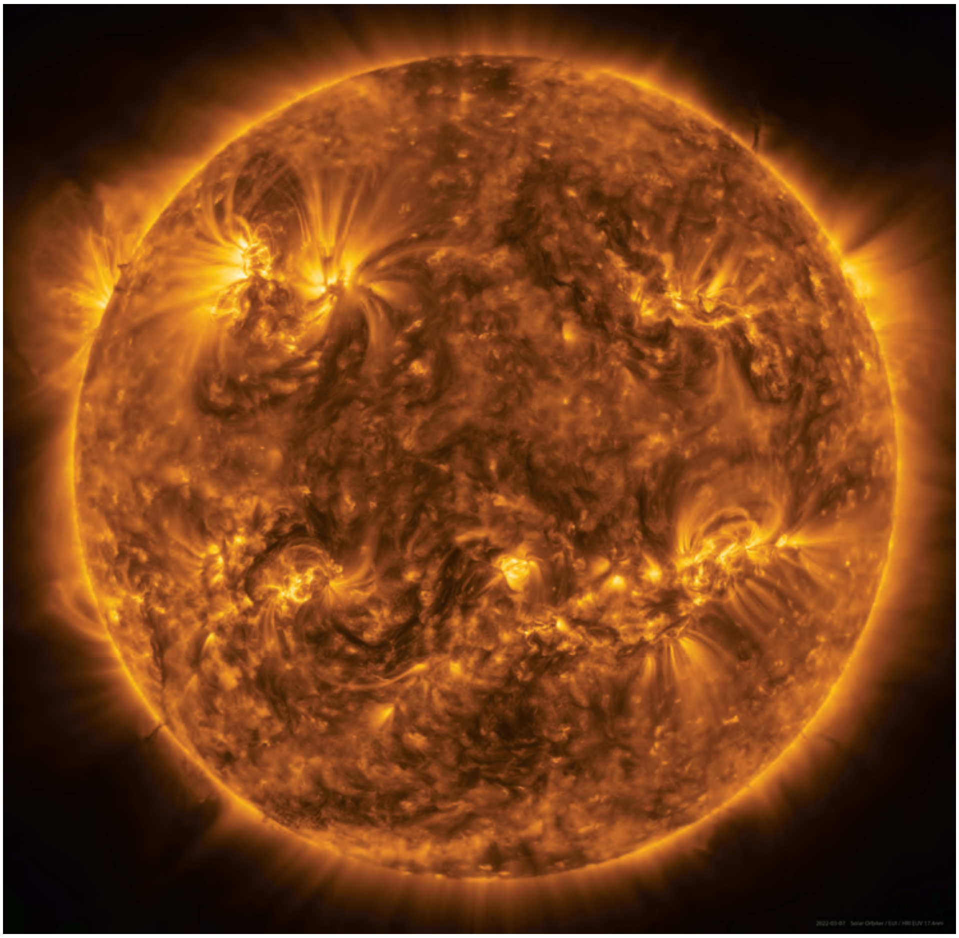

FIGURE 5. A HIGH-RESOLUTION PHOTO of the Sun taken by *Solar Orbiter* on 7 March 2022 when it was at a distance of about 108 solar radii from the Sun's surface. (Courtesy of ESA and NASA/*Solar Orbiter*/Extreme Ultraviolet Imager team; data processing by E. Kraaikamp/Royal Observatory of Belgium.)

the inner heliosphere.[17] The *PSP* also made similar observations. But Alfvénic slow wind is more frequently observed during the maximum of solar activity. Over the coming years, *SolO* will fly closer to the Sun and increase its orbital inclination so that it can explore the Sun's polar regions. *SolO* and the *PSP* will both make unprecedented measurements of the inner heliosphere inside Mercury's orbit in 2023–26, the cycle 25 maximum. Those measurements are expected to shed light on the origin and evolution of the Alfvénic solar wind.

Is the mystery ending?

Data from new computer models suggest that there may be additional factors that will help account for coronal heating. Coronal loops, for example, have long been accepted as a part of the Sun's atmosphere. But the groundbreaking Max Planck Institute for Solar System Research/University of Chicago Radiative Magnetohydrodynamics (MURaM) solar model, one of the most realistic and powerful solar simulations ever created, suggests that the situation may be more complicated. The MURaM model extends from about 10 000 km below the Sun's surface to 40 000 km into the corona, which allows scientists to simulate the complete life cycle of a solar flare.[18]

The MURaM model indicates that coronal loops can overlap one another when we observe the Sun, which makes it difficult to discern which loops are in the foreground and which are in the background and how thick they are. Researchers who have worked with the model suggest that some of the observed loops might actually be optical illusions that are caused by a fold in a sheet of plasma. Other scientists unaffiliated with MURaM have pointed out that the corona could be home to even smaller flares that cannot be resolved by presently available technology but might contribute to the overall energy balance in the solar corona.

So are we close to solving the coronal-heating problem? *SolO* will continue to provide higher-resolution images of the Sun's surface as it tightens its orbit around the star. And as it dives deeper into the solar corona, the *PSP* will measure the flow of energy that heats the corona and accelerates the solar wind and determine both the structure and dynamics of the solar magnetic field. Data from both probes will help the community better understand coronal heating. But, as Jack Zirker and Oddbjørn Engvold wrote in their solar-corona article a few years ago, "Answers to existing questions will inevitably raise new questions" (see PHYSICS TODAY, August 2017, page 36). In any case, the answers to some existing questions will need to wait for the next flybys by *SolO* and the *PSP*.

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European scientists swear allegiance to the US in 1952 at the US Army Signal Corps Engineering Laboratories in Fort Monmouth, New Jersey. Harold Zahl, the US-born director of research, is third from left. Hans Ziegler, a German researcher, is third from right in the front row. The image is from Amy Gerber-Stroh's 2012 documentary *My Grandfather Was a Nazi Scientist: Opa, Von Braun and Operation Paperclip*.

Johannes-Geert Hagmann is the head of the curatorial department for technology at the Deutsches Museum in Munich. This article is expanded from Hagmann's essay "Push & Pull: Über die Abwanderung von Wissenschaftlerinnen und Wissenschaftlern in die USA nach Ende des Zweiten Weltkriegs," *Physik Journal,* volume 21, issue 6, page 24, 2022.

PHYSICISTS AS REPARATIONS?

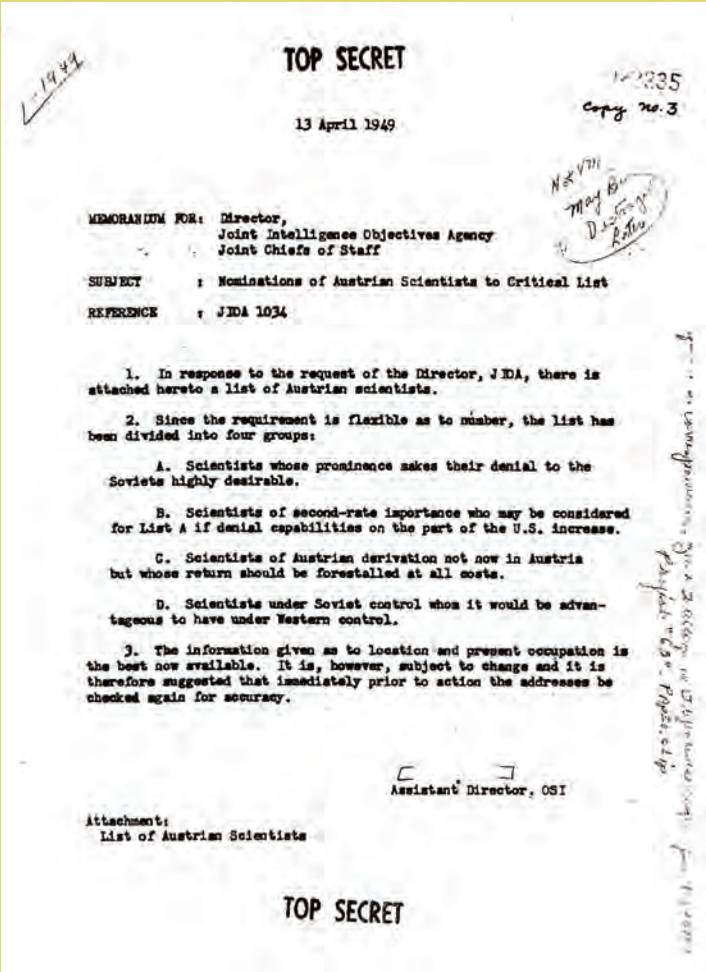
Johannes-Geert Hagmann

In addition to recruiting more well-known rocket scientists, the US government brought from Europe thousands of other scientists who helped to advance numerous research fields during the Cold War.

Before the end of World War II, the US and other powers, including the UK and France, became preoccupied with securing technical and scientific knowledge from Germany and its allies. In addition to large-scale field missions that aimed to secure technology and its documentation, the US initiated programs for the evacuation and relocation of specialist scientists, engineers, and technicians from Germany, Austria, and other countries. Despite the secrecy of those operations, the programs were public knowledge: As early as November 1945, the *New York Times* reported on the arrival of groups of specialists, many of whom would go on to support government research in ballistic missile development and the US space program.

Representations in popular media—for example, those of the aerospace engineer Wernher von Braun and the physicist Heinz Haber in Walt Disney's 1955 documentary *Man in Space*—contributed to foreign-born researchers' public profile as experts in rocket science and space research. Later caricatures of scientists and engineers, such as the fictional Dr Strangelove in Stanley Kubrick's satirical 1964 film of the same name, were reminiscent of the sudden career transitions of real-life figures from working for Nazi Germany to helping fight communism in the US.

Those popular depictions, however, obscured in the public eye the larger scope of the immigration programs and their impact on US research beyond the ballistic


TOP SECRET

13 April 1949

Copy no. 3

MEMORANDUM FOR: Director,
Joint Intelligence Objectives Agency
Joint Chiefs of Staff

SUBJECT : Nominations of Austrian Scientists to Critical List

REFERENCE : JIOA 1034

1. In response to the request of the Director, JIOA, there is attached hereto a list of Austrian scientists.

2. Since the requirement is flexible as to number, the list has been divided into four groups:

A. Scientists whose prominence makes their denial to the Soviets highly desirable.

B. Scientists of second-rate importance who may be considered for List A if denial capabilities on the part of the U.S. increase.

C. Scientists of Austrian derivation not now in Austria but whose return should be forestalled at all costs.

D. Scientists under Soviet control whom it would be advantageous to have under Western control.

3. The information given as to location and present occupation is the best now available. It is, however, subject to change and it is therefore suggested that immediately prior to action the addressees be checked again for accuracy.

Assistant Director, OSI

Attachment:
List of Austrian Scientists

TOP SECRET

FIGURE 1. A TOP-SECRET MEMORANDUM from 1949 lists four categories of Austrian scientists whom the US government hoped to prevent the Soviet Union from employing. (From "Nominations of Austrian Scientists to Critical List," memorandum, 13 April 1949, box 54, folder 2, Second Release of Subject Files Under the Nazi War Crimes and Japanese Imperial Government Disclosure Acts, record group 263, US National Archives and Records Administration.)

rocket and space programs, despite extensive historical research and books on the subject.[1] Although the transplanted specialists included a sizable cohort of physicists, their stories are mostly unknown to the physics community. Looking in the archives of Physics Today, for example, yields few articles related to the post–World War II immigration programs and their history.

Why is there an apparent gap in the collective scientific memory? One hypothesis is ignorance: Physicists mistakenly associate the historical episode with "rocket scientists," many of whom were engineers, rather than with the history of their own discipline. A second possibility, admittedly more difficult to prove, is avoidance: Dealing with the events requires acknowledging the subordination of research to political aims and opportunism in the management of the scientific workforce.

This article moves the focus from rockets to other areas of physics and engineering. Physics-oriented research done by recruited scientists fits into a broader spectrum of military and industrial research in the US during the Cold War. Recruitment programs serving the aims of exploitation and denial of scientific talent for national interest lasted at least through the early 1960s. Beyond the space program, the recruited specialists made vital contributions to semiconductors, atomic and molecular physics, metrology, and many other research areas. Historians have discussed the impact on post–World War II reconstruction in Germany from the brain drain created by the US's and other countries' recruitment programs. I argue that an evaluation of those researchers' contribution to a kind of intellectual war reparations should, in future research, be balanced by an account of the careers of researchers who participated in those programs but later returned to Germany.

The origins of Project Paperclip

The 20th century was shaped by World Wars I and II. Tens of millions of people became victims of murder and war, and many others had to emigrate from their home countries to escape persecution. But that phase of motion and migration did not stop at the end of World War II.

In a variation of a famous quote by the military theorist Carl von Clausewitz, the historian Roy MacLeod commented not only that war is a continuation of policy by other means, but that "warfare has become the continuation of science by other means."[2] Before and during World War II, many countries, including the US, prioritized scientific and technological research for military applications. To that end, the US Office of Scientific Research and Development (OSRD) was founded in 1941 to coordinate research relevant to the war.

In addition to guiding research on microwaves, radar, advanced medical therapy, and the first atomic bomb, the OSRD advised the US government on key policy questions. OSRD director Vannevar Bush laid out his vision for postwar research policy in a July 1945 report titled *Science: The Endless Frontier* that eventually led to the creation of NSF. Concerned with the support and formation of scientific talent, Bush not only described various measures to foster domestic education but also foresaw "the official reception of foreign scientists of standing in this country."[3]

Even before the end of the war, Allied military intelligence units started to assess and document the scientific and technological state of the art of research in enemy territories. Between 1944 and 1947, they created more than 3000 reports describing research in academic institutions and companies and identifying key personnel. Advancing onto German soil in the spring of 1945, the US Army interviewed an increasing number of specialists in captivity about their work during the war.

Later in July 1945, the US started an initially secret recruitment program for selected German scientists, engineers, and technicians with the asserted aim of curtailing the war in the Pacific. After the war, the program received the name "Paperclip," a reference to the clips holding the personnel dossiers of candidates. The program and its successors were organized by the Joint Intelligence Objectives Agency (JIOA) of the Joint Chiefs of Staff.[4]

"Exploitation" and "denial"

Among the first cohort brought to the US were scientists and engineers who had been working in aeronautical and rocket research. The US government had two main motivations for rapidly relocating specialists who had contributed to wartime research in Nazi Germany. First, it aimed to catch up in certain areas of scientific and technological research considered to be less developed in the US at the time—a motivation often referred to by the shorthand "exploitation."

But a second goal became dominant as tensions increased with the Soviet Union. Similar to the US, France, and the UK, the Soviet Union had started its own recruitment efforts, called Operation Osoaviakhim, to exploit German research by deporting specialists to work in its defense programs. By evacuating personnel to the regions of Germany and Austria under US control—the American occupation zones—or by offering employment in the US, the US government aimed to foil access to key researchers by the Soviet Union and other countries, a strategy referred to by the shorthand "denial."

The US compiled target lists of individuals under consideration for employment. Figure 1 shows an example from 1949 of such a list for a subcategorization of Austrian specialists. List C comprises Austrian citizens whose return to Austria "should be forestalled at all costs," given that Vienna lay in the center of the Soviet zone. It named, among others, Lise Meitner, Erwin Schrödinger, and Wolfgang Pauli. The JIOA was not alone in compiling those types of lists: Other countries' intelligence services likewise systematically assessed the status and the scientific capacity of researchers in the occupied zones.

Officials in Germany, including physicists, watched the departures of colleagues with concern. In 1947 a German physics conference took place in Heidenheim, where the US Army had relocated 400 scientists and their families from Jena, which was in the Soviet zone. In an opinion article entitled "Physiker als Reparationen" ("Physicists as reparations"), Werner Kliefoth, a nuclear physicist and then mayor of Heidenheim, noted that dismantled factories could be rebuilt, but lost scientific talent could not be replaced.[5]

FIGURE 2. HANS ZIEGLER (left), Harold Zahl (right), and their colleagues pose with a weather satellite in 1959. (Image by Andreas Feininger/The LIFE Picture Collection/Shutterstock.com.)

Alien specialists for national defense

Between May 1945 and December 1952, 642 so-called alien specialists entered the US as part of Paperclip and related programs.[4] Not all were German or Austrian; the lists included smaller numbers of other nationals as well. Many of the selected scientists, engineers, and technicians were directly approached and invited to the US. But not all the courted individuals wanted or intended to emigrate. Some declined invitations, referencing the need to reconstruct research in Germany.

The small selection of experts from Jena who were offered employment and eventually migrated to the US included several former employees of Carl Zeiss, the German optics company. Among them were Georg Joos, the former head of research and a physicist; Gerhard Schwesinger, an expert on airplane cameras; Werner Weihe, an electronics researcher; Karl Leistner, a photography and photochemistry specialist; Oleksandr "Alexander" Smakula, inventor of antireflective coatings; and Eduard Gerber, an expert on piezoelectric crystals.

Joos and Schwesinger returned to Germany after a few years, while Smakula, Gerber, Leistner, and Weihe stayed in the US. The Ukraine-born Smakula, who initially appeared on a UK list and whom the US traded with British intelligence for another crystal specialist, became a professor at MIT[6] in 1951. Weihe worked for the military at the Night Vision Laboratory in Fort Belvoir, Virginia. Gerber and Leistner worked for several years at the US Army Signal Corps Engineering Laboratories in Fort Monmouth, New Jersey. Beyond the aviation and rocket specialists, the group of specialists at Fort Monmouth was among the largest fraction of Paperclip participants in a single location. Between 1947 and 1962, when the JIOA was disbanded, historians estimate the number at at least 50 specialists.

The article's opening photograph shows the first cohort with the Signal Corps during the ceremony that conferred permanent residence status on Paperclip personnel. The event took place under a picture gallery of atomic bomb tests as if to symbolically underline the sincerity of the commitment. Harold Zahl, the director of research at the Engineering Laboratories, later wrote,

> I have in my office a photo of the first 16 which came over, hands up, swearing allegiance to the United States, as they moved into Schedule-A. Of these 16, now twenty years later, 11 still remain at the Monmouth laboratory, all in very high positions, and one in the very highest. It was a wonderful experience to see the old "Melting Pot" in action.[7]

The recruitment of European scientists came at just the right time for military research institutions. Many US physicists

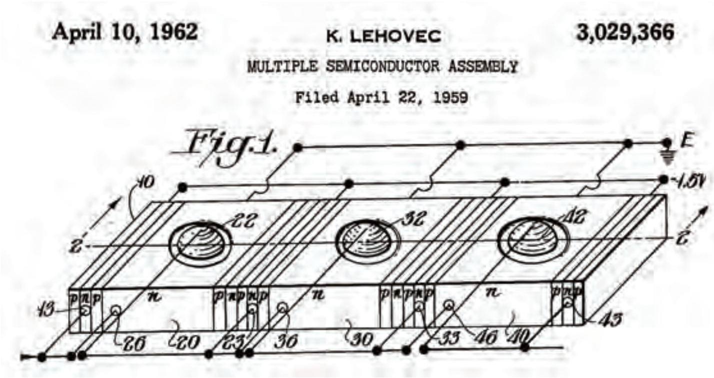


FIGURE 3. THE P–N JUNCTION ISOLATION, whose original patent design is shown here, was invented by Kurt Lehovec, a Czech physicist recruited to work after World War II at the US Army Signal Corps in Fort Monmouth, New Jersey. (K. Lehovec, "Multiple semiconductor assembly," US Patent 3,029,366, 10 April 1962.)

employed by government laboratories during the war had quit national service to start careers in academia or industry. At the same time, the number of graduates from US universities and colleges was insufficient to fill the demands of research facilities. Project Paperclip helped partially alleviate that deficit. The many specialists recruited for Fort Monmouth thus shaped and expanded research operations for the Signal Corps.

Solar cells and satellite electronics

The individual highlighted by Zahl in the "very highest" position was not recruited out of the blue, as were most Paperclip recruits. Konrad Johann "Hans" Ziegler started his career developing proximity fuses for the German army and eventually moved to applying solar cells to US satellites. His path took him from immigrant to US citizen and chief scientist and from volunteer recruit to active recruiter for the Paperclip program.

Ziegler studied electrical engineering at the Technical University of Munich. After earning his degree, he briefly worked for the company Siemens & Halske before eventually joining Rosenthal Isolatoren in Selb, the porcelain capital of the Upper Franconia region in Bavaria. He initially worked in the field of high-power isolators, but during World War II, his department supplied the German army and air force with fuse systems for bombs, shells, and mines.

Most specialists moved to the US because of relocation re-

Immigrant specialists in private research institutions

The US government was not alone in the search for scientific talent from Europe. Industrial research institutes similarly recruited from Germany. One notable example is Herbert Kroemer, a physicist whose talent was recognized by Edward Herold from Radio Corporation of America (RCA)[17] in 1953. Although the Joint Intelligence Objectives Agency (JIOA) had no direct involvement in the recruitment, the agency helped expedite Kroemer's visa. The scientist had an exceptional career in the US, and in 2000 he was awarded the Nobel Prize in Physics, alongside Zhores Alferov, for the development of semiconductor heterostructures; they shared the prize with Jack Kilby for his contribution to the development of integrated circuits.

The JIOA sought placements in industry for those researchers who were considered for government work but failed to receive a contract. Editha Karl-Kroupa, a part of the small group of women in the Project Paperclip cohort, exemplified some of the difficulties faced by numerous immigrant scientists. Seen in the photo, Karl-Kroupa was an inorganic microchemist who specialized in radioactive elements. Her research on radium, in particular, gained international recognition before the outbreak of World War II. She and her husband arrived in the US in June 1953, and they initially resided in the Hotel Alamac at 71st Street and Broadway in New York City, seen in the postcard. Because of the hotel's location in the German-speaking area of Yorkville, the JIOA chose it as a transition center for scientists, engineers, and technicians who had yet to obtain a government contract and visa and thus remained under military custody.

Most government research institutes expressed a lack of interest in Karl-Kroupa's profile or expected delays in obtaining necessary security clearance for her work, so the JIOA agents searched for an industry placement. They wrote to more than 20 large corporations, including Shell, Standard Oil, General Motors, and Ford Motor Company.[18] After more than six months of waiting and interviewing, Karl-Kroupa started to work for Monsanto Chemical Company as an analytical chemist in January 1954.

Women specialists like Karl-Kroupa were a minority in the recruitment program: Among the 1704 names in the Foreign Scientist Case Files kept at the US National Archives and Records Administration (see the discussion on page 48), only 24 (1.4%) are women. The group also included Gisela Elsholtz (Eckhardt), a physicist and coinventor of the Raman laser. (Photo of Editha Karl-Kroupa courtesy of the Smithsonian Institution Archives, accession 90-105, Science Service Records, image no. SIA2008-4975; postcard courtesy of Seymour B. Durst Old York Library Collection, Avery Architectural & Fine Arts Library, Columbia University.)

FIGURE 4. POLYGRAPHS, such as this one from the 1960s, became part of the vetting process for potential recruits during the Cold War. (Image by dpa picture alliance/Alamy Stock Photo.)

quests from the Office of Military Government for Germany (US), which was a military-established temporary government in the American zone of Germany after World War II. Ziegler, on the other hand, actively pursued opportunities to immigrate from Germany to the US. In March 1947 he received his first contract with the Signal Corps and entered the US before a so-called denazification court (*Spruchkammer*) reached a verdict in his trial, which was eventually terminated because of Ziegler's absence.[8] In order for applicants to obtain employment in military research facilities, US authorities investigated their criminal records and political biographies, including possible membership in Nazi organizations—although membership in the Nazi Party and other groups did not render candidates ineligible. Applicants had to name contacts for interviews about their past and present political views and professional and personal conduct.

Similar to many other Paperclip researchers, Ziegler came to the US without a valid visa and remained under military custody. While he was under custody, a Signal Corps officer submitted regular reports tracking his performance and behavior in and outside of work, and investigators checked his private correspondence. In May 1949, after his successful probation, the Signal Corps sent Ziegler and an escorting officer on a business trip to Niagara Falls, where they crossed over to Canada to regularize his residence permit on reentry into the US.[9] He obtained permanent residency in 1952, alongside other members of the Paperclip group, as a step toward naturalization as a US citizen, which came in 1954.

After initial research on power generators and transformers, Ziegler focused on electronics for the space program (see figure 2) starting in mid 1950s. At the Engineering Laboratories, scientists, engineers, and technicians worked in more than 75 technical fields, including microwave and radar systems, battery technology, satellite electronics, photography, and time standards. Research on satellite components intensified after the 1957 launch of *Sputnik 1*, which led the comedian Bob Hope to joke about the success of the Soviet Union: "It just proves one thing, . . . their German rocket scientists were better than our German rocket scientists."[10]

Despite the growth of the laboratory, scientific personnel were in short supply, which led the Signal Corps to recruit in Europe. In November 1952, as part of that recruitment, Ziegler joined an army delegation traveling to Vienna and to Heidelberg, Salzburg, and Berlin with the objective of hiring 60 young experts. More trips followed in later years, and Ziegler advised the project on its strategy for recruiting. For example, a major attraction for candidates was a salary considerably higher than the available income in West Germany at the time. (The US, UK, and France merged their occupation zones in 1947–48 and granted them limited independence as West Germany in May 1949. In October of that same year, the Soviet Union established a client state, East Germany, in its occupation zone.)

Ziegler's scientific and administrative success earned him successive promotions at the Signal Corps. By the end of his career in the early 1970s, he was director of a research laboratory with oversight of 400 staff members and an annual budget of $30 million.[11]

Semiconductors and integrated circuits

Although Ziegler's and the Czech physicist Kurt Lehovec's work in the US started in a similar way at the Signal Corps, Lehovec's career took a path into industry and academia, which other Paperclip personnel would follow. Lehovec attended school in Troppau, Czechoslovakia, before entering the German University in Prague in 1936, where he later became a scientific collaborator of the semiconductor physicist Bernhard Gudden. From 1942 to 1945, Lehovec's research on selenium rectifiers was associated with the Süddeutsche Apparate Fabrik in Nuremberg and Nazi Germany's Ministry of Aviation. He joined the Signal Corps as an expert on semiconductor physics in June 1947, shortly before transistors were invented.[12]

Although highly successful in his work and prolific in his publishing while at the Signal Corps, Lehovec asked for a release from government work to join industry, where salaries were significantly higher. In summer 1952, he was hired by the Sprague Electric Company, and he continued to work in the private sector for 20 years before eventually taking a professorship at the University of Southern California in 1972. Although some Paperclip recruits would likewise first work for the government before joining industry, others started directly in the private sector (see the box on page 46).

Lehovec's broad areas of scientific activity included battery technology, solar cells, and LEDs. Most notable, however, was his 1959 patent of the p–n junction isolation, shown in figure 3, which is considered one of the key papers in the development of integrated circuits.

Time standards and metrology

Project Paperclip, later known as Project 63, in 1956 received another new title directly communicating its ambition: the Defense Scientist Immigration Program (DEFSIP). In the 1940s the political screening focused on researchers' ties to Nazi

Germany, but by the 1950s, authorities instead began investigating communist beliefs or connections. In 1954 Senator Joseph McCarthy (R-WI), whose name became synonymous with the Cold War and a climate of denunciation, took aim at the Signal Corps in Fort Monmouth. The electrical engineer Julius Rosenberg—who was convicted of spying on behalf of the Soviet Union and was executed alongside his wife, Ethel—had worked for the Signal Corps during World War II. McCarthy used his case as a pretense to claim the existence of a larger spy ring at Fort Monmouth.[13]

As a consequence, recruitment efforts from 1955 on included additional screening with polygraphs, such as the one shown in figure 4. The devices recorded body activities, including respiration, pulse, and skin conductance, in theory to establish whether interviewees were telling the truth. The US applied the debatable procedure in Germany at several US stations, but it is unknown how many researchers were identified as a risk because of polygraph tests. In 1965 a Department of Defense official testified before a subcommittee of the US House of Representatives' Committee on Government Operations that DEFSIP was not a recruitment program, and that the program's security experience had "proved favorable,"[14] an intentionally vague claim. In a different case of espionage, in 1967 the US sentenced former JIOA director William Henry Whalen to prison for handing over military secrets to the Soviet Union.

Gernot Winkler, an Austrian astrophysicist, was one specialist in the first wave of DEFSIP recruits who underwent the new procedures. In March 1956 Winkler—who had a cousin behind the Iron Curtain and had been investigated while he was a US prisoner of war—passed the two-hour examination in Munich without any incident. At the time of his recruitment, Winkler was working at a distillery, but he had a background in the theory of microwave propagation, particularly in the ionosphere.[15]

Although how they first connected is unclear, the Signal Corps developed an interest in Winkler for its Camp Evans Signal Laboratory, where he could help calculate wave propagation in different meteorological conditions and atmospheric effects. With the Signal Corps, Winkler became involved in frequency control and research on atomic clocks—in particular, the commercially produced Atomichron. During the first year at Fort Monmouth, he consulted for the US Naval Observatory, where in 1966 he would become director of time services, a leadership position in metrology that he would hold for 30 years.

Uncertain numbers

Although these research biographies highlight contributions from recruited scientists, what is known about the immigration programs more broadly is limited. Historians and researchers still lack access to basic information, such as exactly when the DEFSIP program was discontinued and how many scientists were recruited. The historian Michael Neufeld estimated that the US brought over about 900 specialists from Germany and Austria and about 6000–7000 total from around the world.[16] The Foreign Scientist Case Files at the US National Archives and Records Administration contain approximately 1700 records in 186 archival boxes. Those records, however, include files for people who did not enter the US through Project Paperclip and subsequent programs or, in fact, never left Europe.

Although the evacuation and recruitment of specialists from postwar Germany and Austria contributed to immigration, when considering the concept of "intellectual plunder," historians often do not recognize the factors contributing to voluntary migration. Those include the scientific, economic, and social opportunities that the US offered to their prospective employees. Previous studies on war reparations have included intellectual reparations in the form of technology transfer and the migration of personnel.

But the damage done to research in Europe after World War II because of the relocation of personnel must be considered alongside the subsequent return of physicists from the US to West Germany. That nuanced understanding requires the systematic evaluation of archival holdings, which is an extensive project given the large number of case files. Further research on the topic will improve our understanding of the transnational development of science and engineering, and of physics more specifically, after World War II.

I would like to thank Rachael Kirschenmann (now at the Smithsonian Institution's National Air and Space Museum), Dirk Burgdorf (Advanced Archival Associates Research LLC), and Floyd R. Hertweck (US Army Communications-Electronics Command History Office) for their kind support with research in the US National Archives and Records Administration.

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PT

PAUL EHRENFEST JR/AIP ESVA/WEISSKOPF COLLECTION

The theorists Markus Fierz, Wolfgang Pauli, and Hans Jensen (from left to right) engaging in discussion over beers during a conference at Niels Bohr's Institute for Theoretical Physics at the University of Copenhagen, sometime in the 1930s.

Something rotten in the state of Denmark

Few periods in the history of physics have received as much attention from scholars as the birth of quantum mechanics in the 1920s. That focus is well deserved: Between 1925 and 1927, a new theory was forged, one that laid the foundation for later advances and had tremendous philosophical consequences. Unfortunately, despite the vast scholarly literature on the quantum revolution—which easily comprises hundreds of books and articles—a mythologized version of the story remains prevalent in textbooks and popular literature.

Although every iteration of the mythologized quantum tale is slightly different, certain canonical elements are almost always present. One example is Werner Heisenberg's summer 1925 trip to the island of Helgoland in the North Sea. Heisenberg made a crucial breakthrough in the development of matrix mechanics during that trip—at least according to his version of the story!—and quantum hagiographers typically mention it with a kind of mystical reverence. Another example is the portrayal of Niels Bohr, who hosted many of the quantum revolutionaries at his institute in Copenhagen. The Danish physicist is ordinarily depicted as a sage, who encouraged his young protégés to push the bounds of physics with the right word at the right time.

All the major players in the quantum revolution, including Erwin Schrödinger, Wolfgang Pauli, and Paul Dirac, usually are presented as larger-than-life demigods. But as the well-known historian of physics Alexei Kojevnikov demonstrates in his recent book, *The Copenhagen Network: The Birth of Quantum Mechanics from a Postdoctoral Perspective*, Heisenberg, Bohr, Schrödinger, Pauli, Dirac, and the rest of the quantum gang were undeniably human like you and me—complete with egos, feelings, and insecurities. Contrary to what many of them proclaimed later in their lives, the genesis of quantum mechanics was quite rocky.

Those looking for quantum gossip will find plenty of juicy nuggets here. Among other things, Kojevnikov reveals that in 1923 Bohr had a falling-out with the doyen of experimental physics, Arnold Sommerfeld, who felt that he deserved a share of Bohr's Nobel Prize; that Heisenberg vehemently disagreed with Bohr's early theories, contrary to what both claimed after World War II; and that Bohr possessed tremendous diplomatic skills but was a bad public speaker.

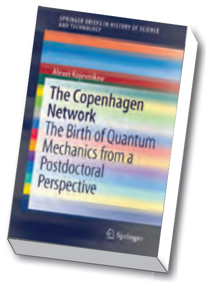
If Kojevnikov's sole achievement in *The Copenhagen Network* was to dethrone the quantum demigods, his book would already be a valuable contribution to the ever-growing literature on the quantum revolution. But it's much more than that. The book poses a question few have thought to ask: How was it that the Danish capital of Copenhagen, which at that time had essentially no history as a center of physics, became the global nexus for theoretical physics in the 1920s and 1930s?

The Copenhagen Network

The Birth of Quantum Mechanics from a Postdoctoral Perspective

Alexei Kojevnikov

Springer, 2020. $69.99 (paper)



In the traditional hagiographic story, the answer to that question is obvious: Bohr's magnetic personality, brilliant ideas, and wise words attracted young luminaries to the new institute. But Kojevnikov rightfully notes that no matter how brilliant Bohr was, it was "a rather improbable task to make a country as small as Denmark the world leader in any major field of science."

The main reason for Copenhagen's emergence as a physics metropole, he writes, was not Bohr's genius but the interwar political situation. Germany, the traditional powerhouse of the natural sciences, had been weakened by defeat in World War I and was subject to an international scientific boycott by the former Allies (see the article by Dirk van Delft, PHYSICS TODAY, April 2022, page 30). Denmark had been neutral during the war and retained ties with Germany, which lent an air of impartiality to Copenhagen. It became a site where scientists from both sides could meet and exchange ideas.

The unstable economic situation in Germany and the Austro-Hungarian successor states also aided Bohr's institute. Not only did Bohr attract postdoctoral scholars from the newly independent countries of Austria, Hungary, and Poland who might previously have studied in Germany, but economically stable Copenhagen began to look more appealing to young German scholars, including Heisenberg, Friedrich Hund, and Pascual Jordan, who would never have left home before the war. All three worked under Bohr via fellowships provided by the US Rockefeller Foundation.

As the subtitle suggests, *The Copenhagen Network* approaches the early years of quantum mechanics from the perspective of postdoctoral scholars like Heisenberg, Hund, Jordan, and Pauli. I do have to quibble with Kojevnikov's ahistorical use of the word "postdoctoral," which was employed only seldomly in the 1920s or 1930s. But his decision to center the book on the early-career experience is innovative. Kojevnikov rightly points out that senior scholars with permanent positions, like Bohr and Max Born, held incredible power over the quantum postdocs, who made crucial breakthroughs while holding temporary positions with minimal job security. (Sound familiar?)

I suspect the main reason the mythologized version of quantum history remains persistent is because many of the major players in the revolution—including Bohr, Heisenberg, Born, Dirac, and Jordan—remained active into the 1960s and 1970s. As elder statesmen of physics, they propagated a burnished version of the quantum origin story that became part of the discipline's collective memory. But hagiography isn't history. *The Copenhagen Network* admirably depicts the quantum revolution as the messy, uncertain reality it was.

Ryan Dahn
PHYSICS TODAY
College Park, Maryland

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The launch of the *James Webb Space Telescope* on 25 December 2021.

More machine than human?

The End of Astronauts
Why Robots Are the Future of Exploration

Donald Goldsmith and Martin Rees
Harvard U. Press, 2022. $25.95

The past two years have seen the start of a new era in spaceflight: On 25 December 2021, the *James Webb Space Telescope* (*JWST*) was launched, and on 11 December 2022, the *Orion* spacecraft splashed down in the Pacific Ocean after its voyage to the Moon. The two missions highlight the tension between science and exploration that forms the subject of *The End of Astronauts: Why Robots Are the Future of Exploration*. The purely robotic *JWST* was launched without any assistance from the astronauts who were so critical to the success of its predecessor, the *Hubble Space Telescope*. The *Orion* spacecraft, on the other hand, marks NASA's renewed commitment to human exploration beyond low Earth orbit.

Authored by Donald Goldsmith, an astronomer and science writer (and, in the interest of full disclosure, a longtime friend of mine), and Martin Rees, the former UK astronomer royal, *The End of Astronauts* argues that almost all space science—including the exploration of the Moon, Mars, and beyond—should be carried out only by robotic explorers. While acknowledging the deep, vicarious exhilaration of watching flesh-and-blood ambassadors explore other worlds, Goldsmith and Rees argue that robotic probes, orbiters, landers, and even helicopters have brought us startling images and detailed knowledge of Mars, Jupiter, Saturn, Pluto, and other objects in our solar system at modest cost when compared with crewed spaceflight and at no risk to human life. More powerful artificial intelligence, improved mechanical dexterity, and expanded remote sensing, they assert, will inexorably tilt the cost–benefit ratio even further in favor of robotic exploration.

In nine chapters, the authors address the human imperative to explore regions ever farther from our home planet: low Earth orbit, where crewed space stations and *Hubble* repair missions occur; the Moon, which is a site of past glories but also ambitious future plans that include Antarctic-style habitats and harvesting helium-3 for unlimited fusion energy; Mars, which holds an inevitable attraction because of its size, its subsurface ice, its potential fossil traces of former life, and the dream to colonize or even terraform it for human habitation; metal-rich asteroids, which could be mined for a trillionaire's ransom of rare elements; and interstellar space, where science-fiction dreams of space colonies and multigenerational spaceships remain captivating.

Those aspirations are brought back to Earth with sobering discussions of radiation dosages in deep space and the relative costs of human versus robotic exploration. (The former bests the latter by a whopping 50 to 1.) Finally, a chapter on space law points out the importance of carrying out those endeavors in accordance with norms for environmental stewardship and international treaties on extraterrestrial governance, none of which, the authors point out, have spacefaring nations yet agreed on.

A number of themes underlie the author's arguments: that the rapid evolution of robotic and artificial-intelligence technology will supplant the need for human senses, strength, mobility, and judgment; that putting humans into space for long trips to Mars greatly increases costs while creating unnecessary risk; and that humans might pollute the very Martian environments where we wish to search for evidence of life.

As a child of the 1960s, I sat in darkened school gymnasiums watching Mercury and Gemini liftoffs and splashdowns in black and white. Later, I was awed by *Apollo 8*'s Christmas lunar flyby and proud of humankind's achievement in landing on and returning safely from the Moon. But, despite a nearly successful bid to enter the astronaut program myself in the early 1980s, I became bored with the slow pace of human expeditions as compared with the dramatic progress in robotic space exploration. The space shuttle operated in the cosmic equivalent of Earth's littoral waters, where it built the International Space Station, an artificial island just 250 miles offshore. In the meantime, the dark black of space and the distant shores of the Moon and Mars beckoned, unvisited.

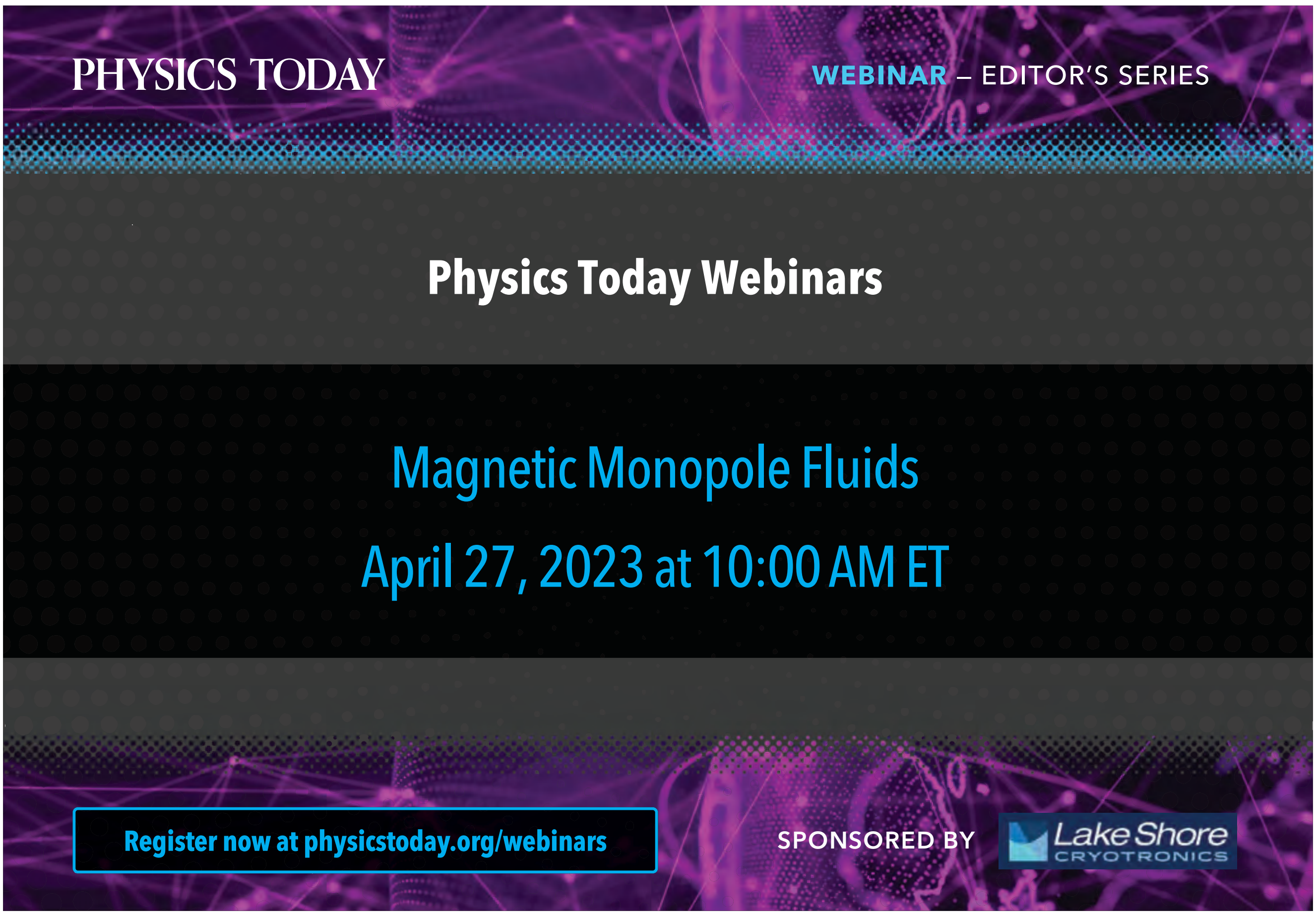
In my 40-year career as an astronomer, I've worked on a succession of space telescopes of ever-greater power, culminating in the successful commissioning of the *JWST*. During that time, other colleagues studied Earth, Mars, and the outer planets with ever-more powerful capabilities and achieved astounding results. Children today are more likely to be awed by pictures from Mars rovers, the *New Horizons* spacecraft, and the *JWST* than by images from the International Space Station. In recognition of space science's growing importance, NASA increased its funding from about 15% of the agency's budget in the mid 1990s to over 30% today.

Will those trends change as the Artemis program proceeds and humans once again explore the Moon and begin training to go to Mars? Will the vision and drive of private space ventures—with their cheaper launch vehicles, commercial motivations, and acceptance of higher levels of risk than national agencies—change the dynamics and economics of human exploration? Will geopolitical competition with China extend to human spaceflight?

Goldsmith and Rees present a strong case that the cost–benefit and cost–risk ratios favoring robots over humans will only grow with time. But not all the reasons why we explore are rational. Strong political forces and more visceral, human desires will likely soon see astronauts on the surface of the Moon and, possibly, Mars.

Disclaimer: The views expressed in this review do not necessarily represent the views of the Jet Propulsion Laboratory.

Charles Beichman
Jet Propulsion Laboratory
Pasadena, California



NEW BOOKS & MEDIA

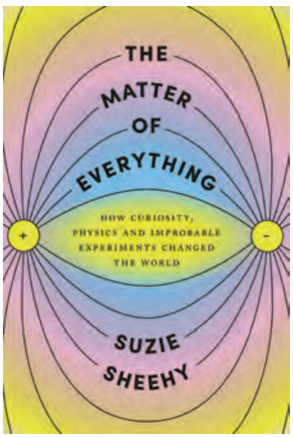
My Quantum Experiment

John Horgan
2023. Self-published; freely available online

Many of us had pandemic projects. Some got into baking sourdough; some started knitting. The science journalist John Horgan decided to learn quantum mechanics, and in *My Quantum Experiment*, he documents his quest to understand the famously strange theory. Despite making a name for himself as a prominent skeptic of so-called theories of everything, the iconoclastic Horgan had little formal training in any scientific field. He first began with self-study, using books like Leonard Susskind and Art Friedman's *Quantum Mechanics: The Theoretical Minimum* (2014) as his guide, and eventually enrolled in an undergraduate course on the topic, where he found several helpful study buddies. But the book is more than just a quantum diary: Interspersed with reflections on the theory's weirdness are Horgan's trademark ruminations on politics, love, and the meaning of life. —RD

The Matter of Everything

How Curiosity, Physics and Improbable Experiments Changed the World

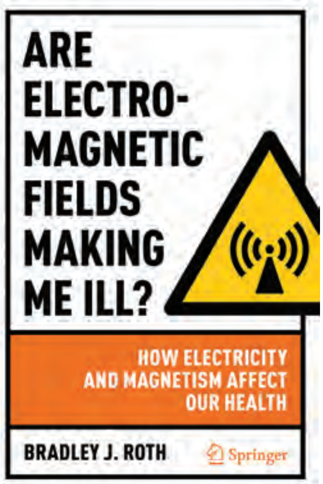


Suzie Sheehy
Knopf, 2023. $30.00

Computers, smartphones, TVs, MRI scanners, the Web—these are just a few of the technological achievements made possible by particle-physics research. In *The Matter of Everything*, the accelerator physicist Suzie Sheehy focuses on 12 of the most important physics experiments that have proven essential to our understanding of the world—from the detection of x rays in 1895 to the initial startup of the Large Hadron Collider in 2008. More than just a history of 20th-century physics, Sheehy's book highlights the scientists involved and their extraordinary ingenuity and collaborations. —CC

Are Electromagnetic Fields Making Me Ill?

How Electricity and Magnetism Affect Our Health

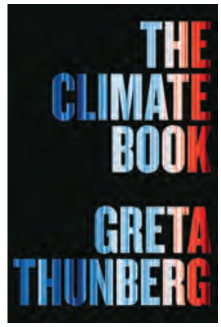


Bradley J. Roth
Springer, 2022. $29.99 (paper)

Aimed at a popular audience, this book—as the title indicates—examines the ways in which such devices as MRI scanners, high-voltage power lines, airport security scanners, pacemakers, and 5G cell phones affect the human body. Bradley Roth, an expert in medical physics, also examines the mysterious Havana syndrome, which was first reported by staff at the US and Canadian embassies in Havana, Cuba. Symptoms include fatigue, dizziness, and ringing in the ears. Some experts argue that microwave weapons are the cause of the illness. Although Roth is skeptical of that claim, he convincingly argues that if such weapons do exist, they should be easily detectable. —RD

The Climate Book

The Facts and the Solutions

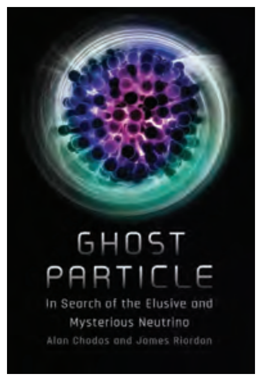


Greta Thunberg, ed.
Penguin Press, 2023. $30.00

An anthology of over 100 short essays on climate change and related issues, *The Climate Book* is the creation of the environmental advocate Greta Thunberg, who invited renowned scientists, science writers, and activists from around the world to share their expertise. Focusing on such topics as melting ice shelves, species extinctions, deforestation, and agricultural practices, the writers discuss the damage humans have done to the planet, what the repercussions are and continue to be for the climate, and what we can and should be doing about it. Graphs, charts, and photos illustrate the impactful text. —CC

Ghost Particle

In Search of the Elusive and Mysterious Neutrino



Alan Chodos and James Riordon
MIT Press, 2023. $32.95

Despite being the second most abundant particle after photons, neutrinos have nevertheless proved to be difficult to study because they rarely interact with matter. Yet because of that property, they may offer unique insights into how the universe evolved. In *Ghost Particle*, the physicist Alan Chodos and the science journalist James Riordon relate the fascinating history of neutrino research, which involves atomic bombs, the Cold War, and a retired gold mine. They explore neutrinos' importance to understanding astrophysics and cosmology as well as the potential applications of neutrino physics, such as monitoring nuclear reactors, probing Earth's geology, and even searching for alien life. —CC PT

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NEW PRODUCTS

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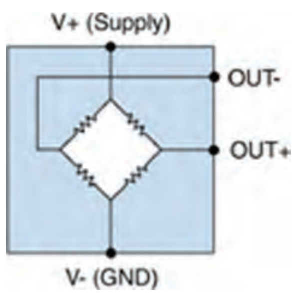
Andreas Mandelis

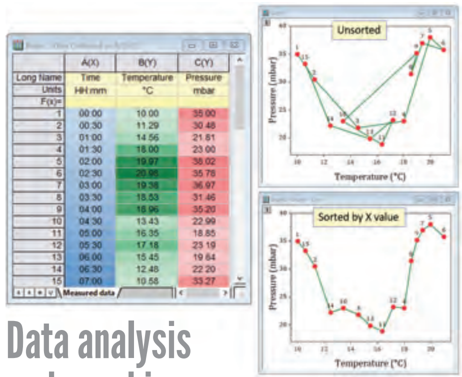
Integrated pump-motor technology

To diversify optimization choices, KNF has expanded its Digital Customization series by adding a new motor option. The DC-BI motor for diaphragm pumps offers a new ball-bearing configuration and the full integration of motor and housing. It relies on an advanced brushless DC electric motor developed in-house, and for maximum compactness and robustness, the motor, pump housing, ball bearings, and eccentric form one single unit. The newly developed housing improves the pump's heat management, especially under continuous heavy load. To extend the pump's lifetime, the size of the ball bearings has been increased and their placement optimized. Several of the company's micro gas pumps and liquid pumps can be customized with the new DC-BI motors. ***KNF Neuberger Inc**, 2 Black Forest Rd, Trenton, NJ 08691-1810, https://knf.com*

Magnetometer integrated circuit

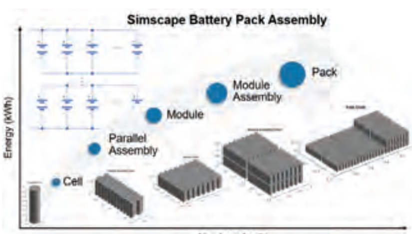


The ALT021-10E analog magnetometer from NVE has a sensitivity of 0.5 mV/V/μT, which the company claims makes it the world's most sensitive magnetometer integrated circuit. Based on NVE's ALT series tunneling-magnetoresistance technology, the new part can precisely measure fields from less than a microtesla to 250 μT. The differential bridge outputs are bipolar, meaning positive for a positive magnetic field and negative for an opposite-polarity magnetic field. The ALT021-10E features a large signal of 200 mV/V full-scale (typical), a flexible 0–14 V supply, 20 kΩ device resistance for low power, and an operating range from −40 °C to 125 °C. The ALT021-10E is suitable for various low-field sensing applications, including motion, speed, and position control; noncontact current sensing; and mechatronics and robotics. ***NVE Corporation**, 11409 Valley View Rd, Eden Prairie, MN 55344, www.nve.com*



Data analysis and graphing software

The 2022 version of Origin and OriginPro, OriginLab's data analysis and graphing software, adds more than 100 new features, improvements, and apps. Major upgrades have been made to the organization and management of an Origin project: Users can now add folder notes using rich text and preview the notes when hovering over a folder in the Project Explorer. Worksheet formatting, exporting, and viewing features have been enhanced, and new plotting features include support for plotting double-*y* graphs in a single layer. Methods have been added for smart skipping of symbols for large data sets and for performing automatic *x*-value sorting of data in line plots and line and symbol plots. An Angle Annotation tool adds a labeled arc in 2D graphs. LabTalk scripting upgrades include Script Window with syntax-coloring and Unicode support. New graph types include stacked 3D heat map and ternary vector; among new apps are Bootstrap Sampling, Pulse Fit, and Propagation of Error PRO. ***OriginLab Corporation**, One Roundhouse Plaza, Ste 303, Northampton, MA 01060, www.originlab.com*



Mathematical programming software

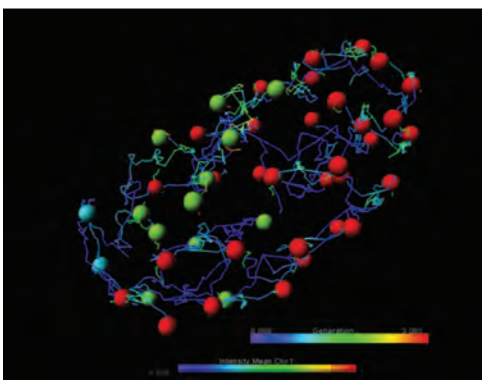
MathWorks has unveiled Release 2022b (R2022b) of its MATLAB and Simulink software. The release introduces Simscape Battery, which provides design tools and parameterized models that can be used to create digital twins, run virtual tests of battery-pack architectures, design battery management systems, and evaluate battery system behavior across normal and fault conditions. It automates creating simulation models that match desired pack topology and includes cooling-plate connections so electrical and thermal responses can be evaluated. The new Medical Imaging Toolbox provides apps, functions, and workflows for designing and testing diagnostic imaging applications, while the Deep Learning Toolbox lets users train predefined deep-learning networks on medical images. R2022b updates widely used MATLAB and Simulink tools such as AUTOSAR (Automotive Open System Architecture) Blockset; HDL (hardware description language) Coder; and the Fuzzy Logic, Model Predictive Control, and System Identification Toolboxes. ***The MathWorks Inc**, 1 Apple Hill Dr, Natick, MA 01760-2098, www.mathworks.com*

PCIe validation testing

According to Tektronix, its new TMT4 Margin Tester breaks new ground as a faster, easier approach to PCIe (peripheral-component-interconnect express) testing. The specialized tool for design and validation of PCIe Gen 3 and Gen 4 motherboards, add-in cards, and system development processes complements compliance testing systems that consist of oscilloscopes and bit-error-rate tests. It can uncover issues earlier in the design process before using traditional equipment to do an in-depth examination. The TMT4 tester's plug-and-play setup and easy-to-use interface deliver in minutes results that, up until now, required hours or days. Multilane testing capabilities significantly improve overall performance times by reducing the number of connection changes needed. Users at all levels of expertise can test PCIe devices across up to 160 combinations of lanes and presets in as little as 20 minutes at Gen 4 speeds. ***Tektronix Inc****, 14150 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com*

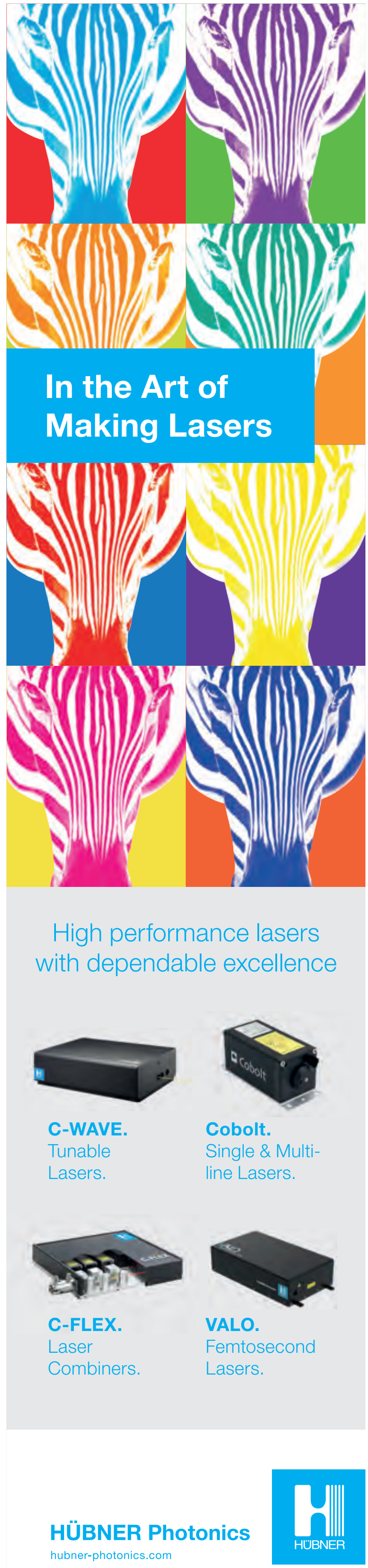
Software-defined test instrumentation

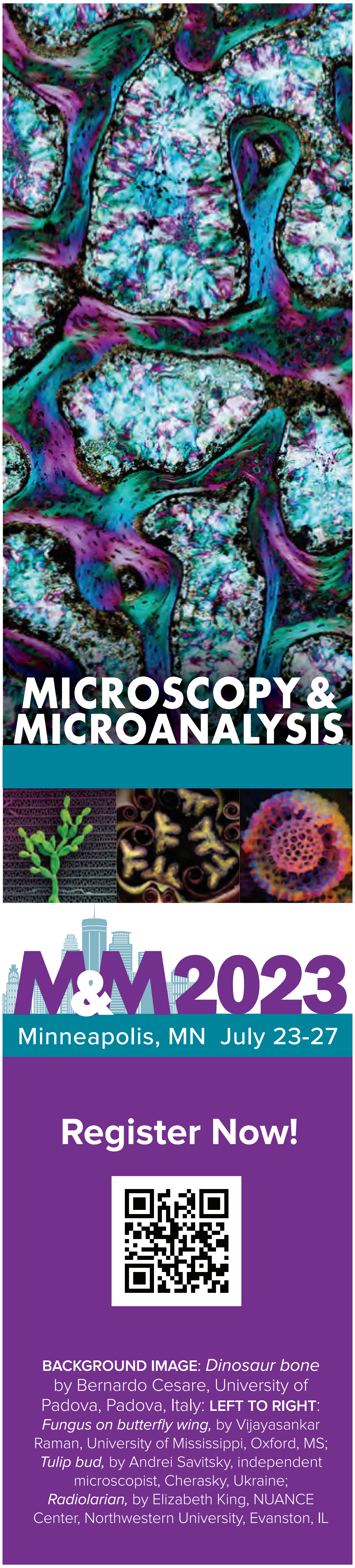
Liquid Instruments has upgraded its Moku:Pro and Moku:Go hardware platforms. Release 2.5 brings new capabilities that increase the functionality of the phasemeter, lock-in amplifier, frequency-response analyzer, and the company's Laser Lock Box to address more use cases in applications such as microscopy, spectroscopy, and quantum computing. With expanded application-programming-interface support for Multi-instrument Mode and Moku Cloud Compile, users can programmatically query and control advanced measurement configurations using Python, MATLAB, and LabVIEW. Those working on automated test systems can deploy and configure multiple instruments to a single device and perform tests with Multi-instrument Mode programmatically. Using Moku Cloud Compile, they can control custom digital-signal-processing blocks in an automated test environment. Moku:Go's lock-in amplifier can now be used in Multi-instrument Mode. ***Liquid Instruments****, 740 Lomas Santa Fe Dr, Ste 102, Solana Beach, CA 92075, www.liquidinstruments.com*

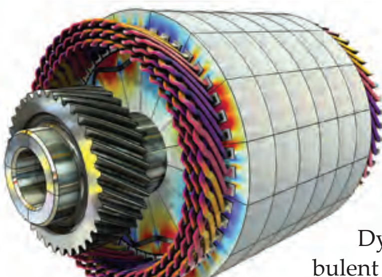


Software for microscopy image analysis

The latest release of Oxford Instruments' Imaris software for microscopy image analysis improves the speed of calculation and visualization of detected models. The filament tracer in the 10.0 version combines the versatility of an AutoPath intensity-based method with a machine-learning approach. According to the company, it provides the most flexible tool available for tracing a multitude of neuron types and can resolve within minutes various structures, such as neurons, dendritic spines, microglia, and blood vessels. Creating filament models is easy, even for inexperienced users, because they are guided via precisely designed wizards, with the result previewed after each step. Imaris 10.0 enables automated distance measurements between filamentous structures and other stained objects. It has been measured to be faster than its predecessor by a factor of five and easily handles much bigger data sets. ***Oxford Instruments plc****, Tubney Woods, Abingdon OX13 5QX, UK, https://nmr.oxinst.com*







Modeling and simulation software

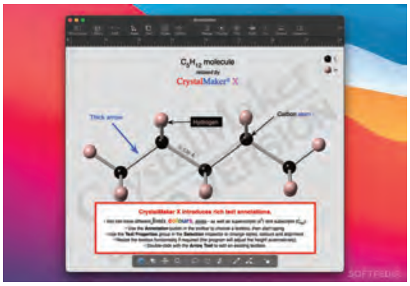
Comsol has launched version 6.1 of its Multiphysics software for creating physics-based models and simulation applications. The new release upgrades the fluid flow and mechanical simulation products. The Computational Fluid Dynamics Module now includes high-fidelity turbulent flow with detached eddy simulation, which yields accurate large eddy simulation with less computational effort. A new, fast method for mechanical contact is included in the Structural Mechanics and MEMS Modules. The Acoustics Module simulation environment is completed by functionality for analyzing the electrovibroacoustics of microtransducers and microacoustic systems. Additional tools for thermoviscous acoustics expand the software's capabilities for modeling speakers and microphones in consumer electronics. For users working on vehicle electrification, Comsol added to the Battery Design Module, including support for setting up thermal-runaway propagation models. In the AC/DC Module, new functionality for the rapid layout of motor windings and magnet arrays ensures a smooth workflow for electric motor design and analysis. ***Comsol Inc****, 100 District Ave, Burlington, MA 01803, www.comsol.com*

Signal-integrity simulation software

Keysight created its Electrical Performance Scan (EP-Scan) high-speed digital simulation tool to support rapid signal-integrity (SI) analysis for hardware engineers and designers of printed circuit boards (PCBs). EP-Scan performs electromagnetic simulation on signal nets and reports SI metrics such as channel return and insertion loss. It automates performance comparisons between different versions of a design and generates simulation reports that expedite verification prior to building costly physical prototypes. The only inputs EP-Scan requires are the layout geometry and substrate stack-up information for the PCB design. After users specify the desired nets for investigation, EP-Scan reports simulation results. Those include the characteristic impedance and delay of traces, return loss, insertion loss, and impedance time-domain reflectometry. By analyzing common fabrication formats such as ODB++, EP-Scan predicts how a design will perform before it's fabricated. ***Keysight Technologies Inc****, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Triode high-voltage power supply for thermionic SEM

Spellman High Voltage has added to its portfolio of triode high-voltage power supplies designed to drive thermionic scanning electron microscopes (SEMs). The EBM-TEGR offers digital communication, a rack-mountable 19-inch chassis, and higher output power on the accelerator and grid outputs. According to the company, its proprietary packaging and encapsulation technology deliver improvements in size, cost, and performance compared with other SEM power-supply offerings. The EBM-TEGR provides a high-precision, low-noise, ultrastable accelerator supply programmable up to −30 kV at 400 μA. This supply, together with floating filament and grid supplies using the accelerator as a reference, controls the beam. To drive the detector, which comprises photomultiplier-tube, scintillator, and collector-grounded outputs, the unit uses high-voltage outputs. The units are protected from overcurrent and overvoltage, arcs, and short circuits. OEM customizations are available. ***Spellman High Voltage Electronics Corp****, 475 Wireless Blvd, Hauppauge, NY 11788, www.spellmanhv.com*



Crystal-structure software

CrystalMaker has updated its software for visualizing crystal and molecular structures in research and teaching in chemistry, solid-state physics, materials science, mineralogy, and crystallography. Version 10.8 offers new functionality and enhanced ease of use. Smart autorotation lets users define rotation axes relative to their structure rather than the screen, which means they can manually rotate a structure spinning about a specific unit cell direction, zone axis, or chemical bond. A redesigned bend-selection interface allows users to enter a radial offset between the start and end of a "bend" and thereby define a nanoscale spiral instead of a nanotube. New commands have been added to view the structure parallel to, or perpendicular to, an existing selection: atoms, bonds, or a general selection. Other changes include calculation of the mean distance from a plane, faster "speedy sync," more responsive popover display, and revised three-body potentials. ***CrystalMaker Software Ltd**, Centre for Innovation & Enterprise, Oxford University Begbroke Science Park, Woodstock Rd, Begbroke, Oxfordshire, OX5 1PF, UK, www.crystalmaker.com*

Phase-noise analyzers

Rohde & Schwarz has improved its R&S FSPN dedicated phase-noise analyzer and voltage-controlled-oscillator (VCO) tester and its high-end R&S FSWP instrument that combines phase-noise analysis, VCO testing, and signal and spectrum analysis. Each instrument's performance is now faster and more accurate, and the sensitivity of each is enhanced by new hardware that includes upgraded DC sources with reduced noise levels. The capacitive screen features higher color intensity and better anti-glare properties, and the updated user interface supports multitouch features such as zoom. For very low-noise oscillators whose inherent noise is largely thermal at wider offsets, any potential cross-spectral collapse is now suppressed. Uniquely for this class of instrument, according to the company, both analyzers include test-sequence recording functions. With the newly introduced SCPI (Standard Commands for Programmable Instruments) command recorder, Rohde & Schwarz implements a function with phase-noise measurement equipment to record sequences of manual settings. It can be used to create easily repeatable test sequences, including synchronization. ***Rohde & Schwarz GmbH & Co KG**, Mühldorfstraße 15, 81671 Munich, Germany, www.rohde-schwarz.com* PT

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OBITUARIES

Peter Hale Molnar

Peter Hale Molnar, Distinguished Professor at the University of Colorado Boulder, died on 23 June 2022 in Lyons, Colorado. The recipient of the 2014 Crafoord Prize in Geosciences, he was a leading figure in the transformation of geology into a quantitative science. He was exceptional in the breadth of the fields he covered, which included plate tectonics, climate, seismology, tectonics, and geomorphology. He made profound contributions to the understanding of global tectonics and of the influence of tectonic processes on climate. Throughout his career, he insisted that geological phenomena, although often superficially complex, must in their essence be physically simple.

Born on 25 August 1943 in Pittsburgh, Pennsylvania, Peter had exceptional tenacity in all he undertook, which he attributed to both parents. His mother had a ruptured cerebral aneurysm when Peter was two, and his father had to take two jobs to pay the medical bills. An experimental physicist who eventually became executive vice president of Bell Labs, his father instilled in Peter rigor, respect for data, and the merits of simplicity. His mother's steadfast support, despite severe pain and partial paralysis, was echoed in Peter's support for countless younger colleagues.

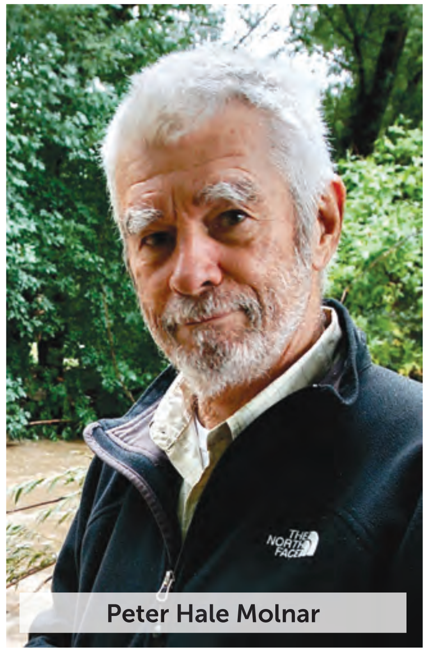
Peter obtained a degree in physics from Oberlin College in 1965 and a PhD in geophysics from Columbia University in 1970. His PhD was supervised by Jack Oliver, Bryan Isacks, and Lynn Sykes, and although it centered on plate tectonics, Peter became convinced that the field, then only a few years old, was stagnating, and he looked elsewhere for interesting questions. He soon found evidence that whereas the oceans obey the rules of plate tectonics, continents do not. The alignments of relative motions during major earthquakes had provided pivotal evidence that oceanic plates are rigid. In contrast, the major earthquakes in Asia show no such alignment. Instead, their principal axes of strain reveal a coherent pattern, such as would be expected if Asia were a deformable continuous medium.

Peter and Paul Tapponnier, in a collaboration starting in 1974, combined satellite imagery with meticulously reevaluated seismic data to show that deformation across most of eastern Asia represents a coherent response of the continent to India's penetration into its southern margin. The nature of the deformation depends on the elevation of the land surface: The high Tibetan Plateau is becoming thinner while its lower-lying surroundings are thickening. Peter argued that continents behave as fluids, flowing under gravity. Tibet is the pressure head that transmits, to the rest of Eurasia, the force that India applies to its southern margin. By making geological observations on scales of hundreds to thousands of kilometers and inextricably linking those observations to the underlying physics, that work demonstrated that the dynamics of continents are fundamentally different from those of the rigid oceanic plates.

At around the same time, a belief began to grow that the onset of the ice ages was caused by rapid uplift of mountain ranges. Peter showed that this belief was based on uncritical acceptance of it by some climate scientists, of misinterpretations by some geologists, and of data that were poor-to-false measures of surface uplift. That episode led Peter to focus on two questions, which were to preoccupy him for the rest of his life: What processes caused the global cooling that occurred in the past few million years, and what is the influence of large mountain ranges on the climate system?

Peter's modus operandi, once he had identified a problem, was to assemble a diverse group of talented (often early-career) scientists and initiate a meeting, preferably among mountains, to thrash out the means of a solution. The approach would lead to a string of papers with Peter's name buried in the middle of multinational lists of authors. It led to our present understanding of the Asian monsoon and to many other advances in both tectonics and climate. As a result of Peter's influence, many fields of geology—an observational science when he began his career—are now pursued in a rigorous and quantitative fashion.

Peter's door was always open, and he responded with excitement to any new result; an insight that particularly pleased him would elicit a stentorian "Holy cow!" that startled all in earshot. Visitors would leave his room usually smiling, often somewhat stunned, and always armed with scribbled equations and an extensive reading list drawn without apparent effort from Peter's encyclopedic memory. Those discussions could move a nascent study to a level that the visitor had not envisaged, and for which Peter would decline credit.



Peter Hale Molnar

Peter had a formidable exterior, but behind it, as even the newest collaborator found, was someone who enjoyed a glass of wine and a laugh. He relished the scenic and cultural opportunities that arose from studying tectonics all over the world and rejoiced in a large circle of friends and colleagues from around the globe. Peter faced cancer with his characteristic composure and tenacity, enjoying the mountains around his home for as long as he could, listening to classical music, and finishing papers. He sought tectonic beauty to the end and completed a final trip to the Galápagos Islands with close family and friends a few days before he died.

Philip England
University of Oxford
Oxford, UK
Roger Bilham
Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder

Roy Frederick Schwitters

Roy Frederick Schwitters, who served as director of the Superconducting Super Collider (SSC) project in Texas, died of cancer at his home on Orcas Island, Washington, on 10 January 2023.

An eloquent and dynamic physicist who played a major role in the 1974 discovery of the ψ particle at SLAC and subsequently led construction of the Collider Detector at Fermilab (CDF), Schwitters was selected to direct the SSC project in 1989. He led that increasingly contentious project until October 1993, when it was canceled by the US Congress.

Born on 20 June 1944 in Seattle and raised there, Schwitters developed an intense interest in physics during his undergraduate years at MIT, receiving his BS in 1966. He continued working in the laboratory of Louis Osborne, under whom he did his dissertation research on pion photoproduction and earned his PhD in 1971. His principal contribution to his thesis experiment (conducted at SLAC) was the development of a precision diamond target to produce polarized photons when struck by high-energy electrons.

That experiment brought Schwitters to the attention of Burton Richter, who hired him as a postdoctoral researcher on the SPEAR electron–positron collider then under construction at SLAC. In the process of working on the design and implementation of the SLAC–LBL (Lawrence Berkeley Laboratory) solenoidal magnetic detector, he determined how to surround the interaction point with cylindrical wire spark chambers to measure tracks of charged particles emanating from electron–positron collisions.

FERMILAB/AIP ESVA/PHYSICS TODAY COLLECTION

Roy Frederick Schwitters

During the data analysis of a 1974 experiment on the collider and detector, Schwitters recognized that two runs at 3.1 GeV were far out of line, with cross sections that were 5–7 standard deviations higher than in other runs at that energy. He and others convinced Richter to remeasure that energy region in greater detail during a November weekend and discovered an extremely narrow resonance at 3.105 GeV that they dubbed the ψ particle—soon identified as a charm–anticharm quark pair. That surprise discovery was "easily the most thrilling event of our scientific lives," recalled Schwitters.

After serving as an assistant professor and then associate professor of physics at SLAC, he joined Harvard University as a professor of physics in 1979, remaining in that position until 1990. During the 1980s Schwitters applied his deep understanding of collider–detector design to the CDF project, for which he led its construction and served as associate director and cospokesperson from 1980 to 1988.

In 1989 the Universities Research Association, manager of Fermilab, named Schwitters as the director designate in its successful application to become the SSC project's management and operations contractor. Building the gargantuan, multibillion-dollar proton collider involved project-management challenges unlike any that high-energy physicists had ever encountered. Because of the political challenges of securing sufficient funding, Schwitters began spending much of his time in Washington, DC, lobbying on the project's behalf.

After the SSC cancellation in 1993, Schwitters assumed a position full time as S. W. Richardson Regents Professor of Physics at the University of Texas at Austin, where he stayed until he retired in 2020. There he returned to experimental high-energy-physics research, focusing on B-meson physics. He also organized the Maya Muon project, which employed particle detectors sensitive to penetrating cosmic-ray muons to examine the innards of a Mayan pyramid in Belize for interior voids. In 1996 he joined JASON, a group of scientists that advises the US government on national security matters, chairing its steering committee from 2005 to 2011.

Schwitters was recognized with NSF's prestigious Alan T. Waterman Award in 1980 and shared the 1996 W. K. H. Panofsky Prize of the American Physical Society for his contributions to experimental particle physics.

An avid mountain climber, Schwitters served as a Mount Rainier guide during summers as an MIT undergraduate. In retirement he returned to the Pacific Northwest and Orcas Island, where he had deep family roots.

Schwitters will be remembered as one of the principal figures who led high-energy physics into the collider era and pioneered the design of hermetic 4π detectors, which surround as much as possible of the solid angle around the collision point. His contributions have already had a lasting historical impact.

Michael Riordan
University of California, Santa Cruz

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21 July 1938 – 19 July 2021

John Spence
24 April 1946 – 28 June 2021

Sow-Hsin Chen
5 March 1935 – 26 June 2021

Michael Wulf Friedlander
15 November 1928 – 29 April 2021

Lothar Werner Frommhold
20 April 1930 – 12 March 2021

Maurice Kleman
11 August 1934 – 29 January 2021

Maurice Barnett "Barney" Webb
14 May 1926 – 15 January 2021

Evans Vaughan Hayward
17 February 1922 – 2 March 2020

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Synthetic dimensions

Kaden R. A. Hazzard and Bryce Gadway

Novel geometries can be created using microwaves to couple the internal states of atoms or molecules and mimic movement in real space.

Objects move through three dimensions in space. But a wide range of experiments that manipulate atoms, molecules, and light can engineer artificial matter in ways that break even that basic law of nature. Such matter can behave as if it were extended to four or more spatial dimensions or restricted to just one or two, as determined by experimental design.

The techniques used by those experiments can control not only dimensionality but also spatial geometries and potential-energy landscapes. Even in one dimension, these abilities have made synthetic dimensions an exciting method to explore topological physics, where precise control of the landscapes is necessary. Frequently, synthetic dimensions are created in ultrasmall and ultracold systems, where the experiments provide powerful access to the hard-to-understand world of interacting quantum matter, which underpins fields as diverse as quantum gravity and solid-state physics.

To understand synthetic dimensions, it helps to distill physical theories into two basic ingredients—the set of states a system can occupy and the rules describing how to move between them. In classical mechanics, for instance, a state is composed of the positions and velocities of particles, and the rules are Newton's laws. Dimensionality is defined by those rules. Particles in one-dimensional systems can step only forward or backward, much like a tightrope walker. In three dimensions, they can also move up or down and right or left.

Synthetic dimensions refer to the degrees of freedom belonging to a single particle controlled in a particular way. The idea is simply to allow some set of states to play the role of spatial positions and then to apply controls—usually electromagnetic fields—that implement the desired rules of motion. That protocol creates a system that is mathematically equivalent to a particle moving in a new spatial dimension. And it provides novel capabilities for controlling geometry and motion.

Rydberg atoms

In this Quick Study, we focus on synthetic dimensions made with highly excited atoms, known as Rydberg atoms. Synthetic positions are created from the atoms' excited electronic states, while microwave-frequency radiation drives transitions between those states and dictates the rules for what motions are allowed. Those rules are mathematically equivalent to those obeyed by particles in a real lattice—for example, electrons moving in a crystal or molecule.

Figure 1 shows how electronic motion in a real molecule, such as polyacetylene, is equivalent to motion in a synthetic dimension created in a separate atom. The six carbon atoms (dark gray balls) in a fragment of polyacetylene are represented by six synthetic positions r—each one a Rydberg state. Think of those states as essentially identical to states of a hydrogen atom. The electron in the atom is excited so far from the nucleus that it effectively interacts with the nucleus and inner electrons as if they were a single point charge. We can thus label the states just as we would for hydrogen, with a principal quantum number n and an angular momentum ℓ. In recent experiments with Rice Uni-

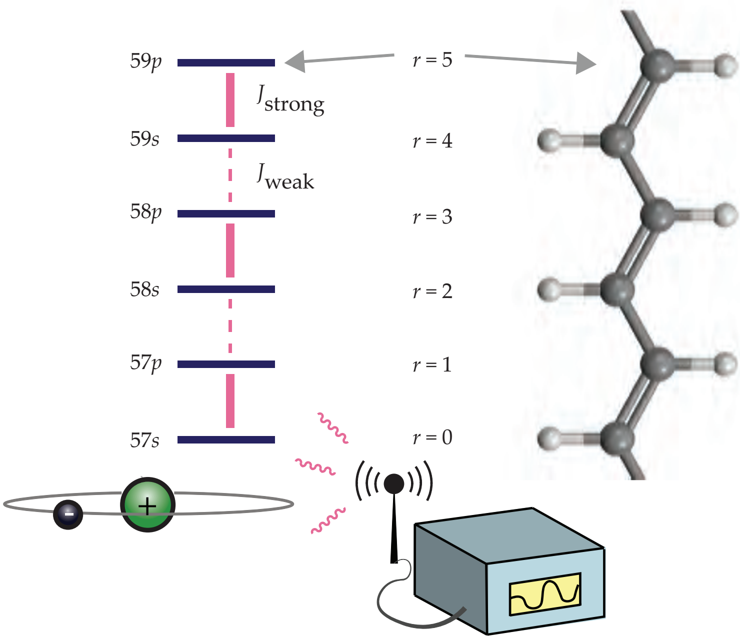

FIGURE 1. RYDBERG ATOMS as quantum simulators. Highly excited electronic states of strontium-84 atoms **(left)** that are cooled to nanokelvin temperatures act as position states r, and microwave fields drive transitions between them. States of the Rydberg atoms are connected in a one-dimensional geometry, and a staggered pattern of different tunneling strengths J mimics the lattice structure found in the organic conductor polyacetylene **(right)**. Dynamics in the synthetic dimension are mathematically equivalent to the electron moving between atomic sites in a real molecule.

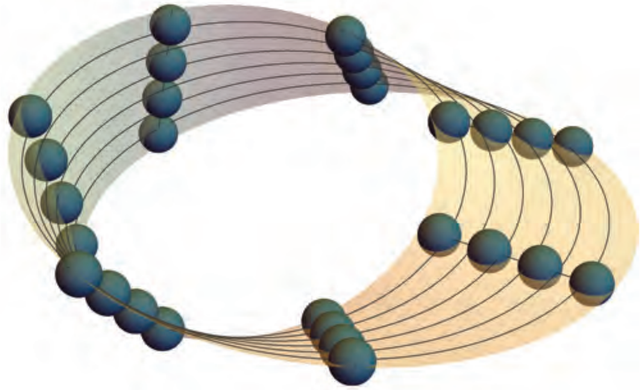

FIGURE 2. MÖBIUS MANEUVERS. Synthetic dimensions give experimentalists the tools to reproduce geometries that are difficult or impossible to create in real space. The famous Möbius-strip geometry, for instance, can be created by connecting the Rydberg energy levels (balls) with microwave-driven transitions (lines). The proper geometry emerges when one chooses an appropriate set of Rydberg levels and then drives transitions between them. Along the strip's width are transitions that change the angular momentum ℓ but keep the principal quantum number n fixed; and along its circumference are transitions that change both ℓ and n.

versity's Tom Killian and Barry Dunning, one of us (Hazzard) worked with a system of ultracold strontium atoms, using Rydberg states $n = 57$–59 and $\ell = 0, 1$ (that is, s and p) states.

In polyacetylene, electrons move between adjacent carbon atoms by quantum mechanical tunneling. The rates of that motion are slower (J_{weak}) or faster (J_{strong}), depending on whether the atoms are single or double bonded. (A so-called Peierls instability, or distortion, leads to the two distinct alternate bonding configurations in polyacetylene.) The equivalent processes in the synthetic dimension are created by microwave radiation driving transitions between adjacent Rydberg states. Importantly, because pairs of electronic levels are separated by different resonance frequencies, each tunneling rate can be controlled independently. The full lattice structure is formed by many transitions being driven at the same time.

The polyacetylene-inspired model, known as the Su-Schrieffer-Heeger model, harbors spatially localized states known as topological edge states at the boundaries of the molecule's chain. The presence of those states is not itself an exotic effect. Their energies, however, are robust to all local perturbations obeying a special symmetry of the model. And that protection against noise and disorder has made topology of great interest to condensed matter, materials science, and quantum information.

The suitability of the synthetic-dimensions approach to topological physics stems from its unique ability to create the precise configurations of tunneling elements necessary to realize topological lattice models and potential-energy landscapes. The general ease of performing state-resolved detection also allows for direct access to site-resolved measurements in the synthetic dimension. (See the article by Victor Galitski, Gediminas Juzeliūnas, and Ian Spielman, PHYSICS TODAY, January 2019, page 38.)

In the study by Killian and Dunning, those ingredients were combined to engineer protected boundary states and to directly image them through what one might call a single-site-resolved synthetic microscope. More generally, synthetic dimensions are appealing in being able to produce intricate tunneling arrangements and in allowing measurements of the populations of each site, potentially as a function of time.

The future of dimensions

The synthetic-dimensions concept is quite broad and has been implemented in ground-state atoms, Rydberg atoms, molecules, and a variety of architectures using light. While internal states often serve as the synthetic positions, as we described earlier, experimentalists can also use motional states, such as the quantized energy levels of an atom in a box, as synthetic states as well. In that case, transitions involve moving a whole atom between the eigenstates of an external potential—in contrast to electronic transitions driven between states of an atomic potential. Both electronic- and motional-state approaches are conceptually similar but differ in the length, energy, and time scales that each involves.

Some of the most notable achievements of synthetic dimensions include the direct study of protected edge states in topological models for neutral atoms and photons. Indeed, the capabilities to create rich tunneling arrangements and sharp edges follow naturally from the way that motion is induced through electromagnetic fields. Beyond those common capabilities, synthetic-dimension platforms have complementary strengths and limitations. Photons can access a nearly arbitrary number of states in, for example, a synthetic dimension formed by the frequency of light. But photons rarely interact strongly with each other. Rydberg atoms, by contrast, can strongly interact but are difficult to handle when coupling many states.

We expect the research field to grow, with improved coherence, larger numbers of states, and new capabilities for control. Improvements in the control of many different transitions, in particular, would allow researchers to explore more exotic phenomena—including geometries that are physically challenging to create in nature (see figure 2).

To date, most experiments have concentrated on single-particle physics and (nearly) noninteracting particles. But the deepest mysteries about quantum matter occur for systems of interacting particles, where new and poorly understood phases of matter can emerge. Those systems are generally difficult to computationally simulate. And the cost of simulating even simple models grows exponentially with the number of particles. Fortunately, synthetic dimensions can serve as an effective quantum simulator. One may engineer designer systems governed by the same physics as the system of interest—be it electrons in a material or quantum matter near a black hole—and explore its physics in a synthetic-dimensions experiment.

Additional resources

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Mauna Loa awakens

On 27 November 2022, Hawaii's Mauna Loa volcano on the Big Island began erupting for the first time in 38 years. A day later, a flight over the eruption captured this photo. It clearly shows a line of fissures, at an elevation of 3 km, from which lava flowed across the volcano's northeast rift zone. The eruption continued for about two weeks, with lava traveling some 20 km from the summit. The US Geological Survey observed an increase in the number of earthquakes beneath the volcano's cauldron-shaped summit and to the northwest roughly two months before the eruption began. The island's nearby Kīlauea volcano has been erupting since September 2021.

The two volcanoes appear to be connected underground by a deep, widespread network of pathways, according to a recently published paper by researchers from Caltech. Although previous studies have hypothesized that such a network may exist, the large data set the Caltech team analyzed showed enough seismic activity to map out a detailed plumbing system that connects Mauna Loa to Kīlauea, 34 km away. Future monitoring of volcanic activity may benefit from considering both volcanoes as part of a larger, interconnected system. (J. D. Wilding et al., *Science* **379**, 462, 2023; image courtesy of the US Geological Survey.) —AL

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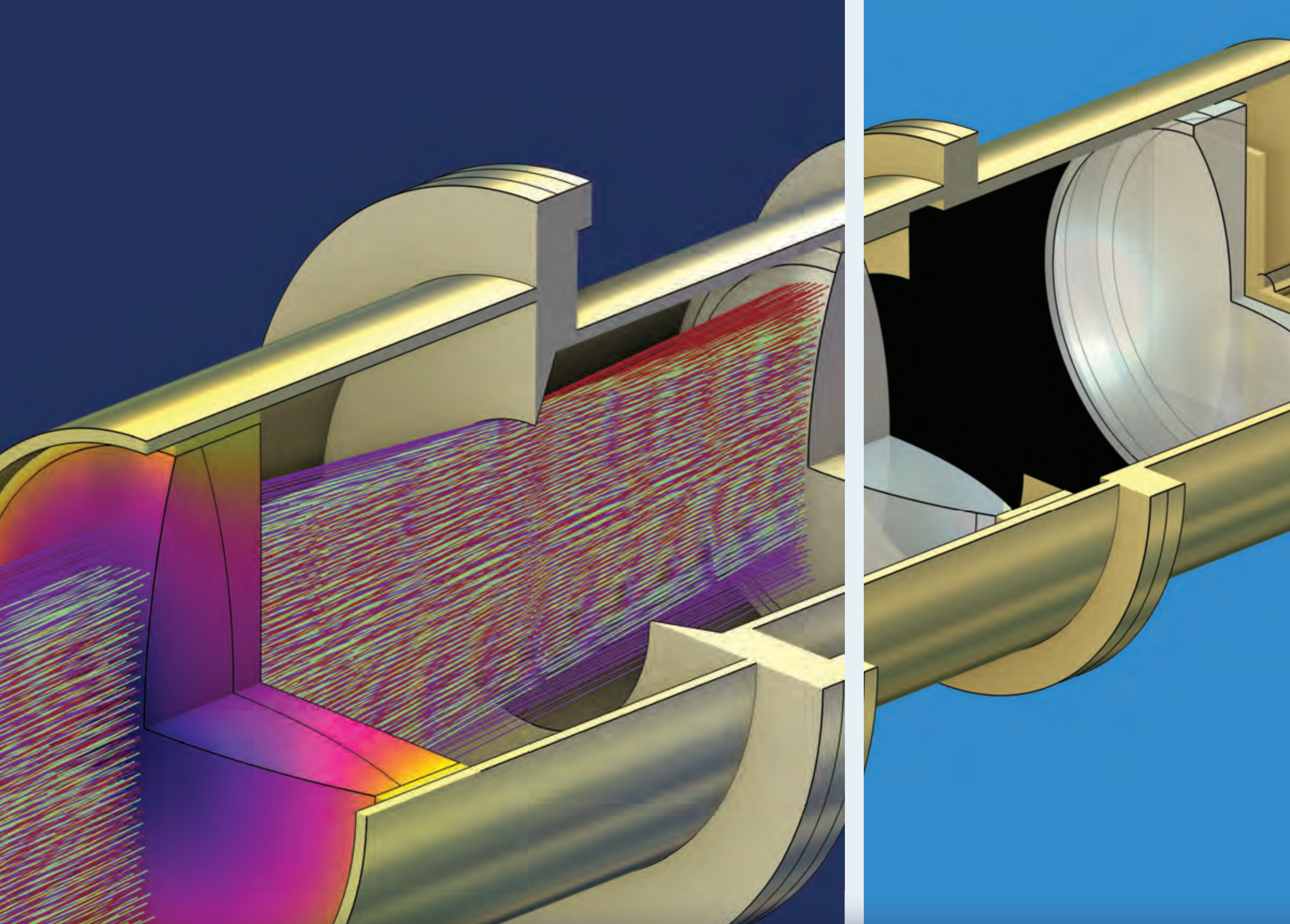

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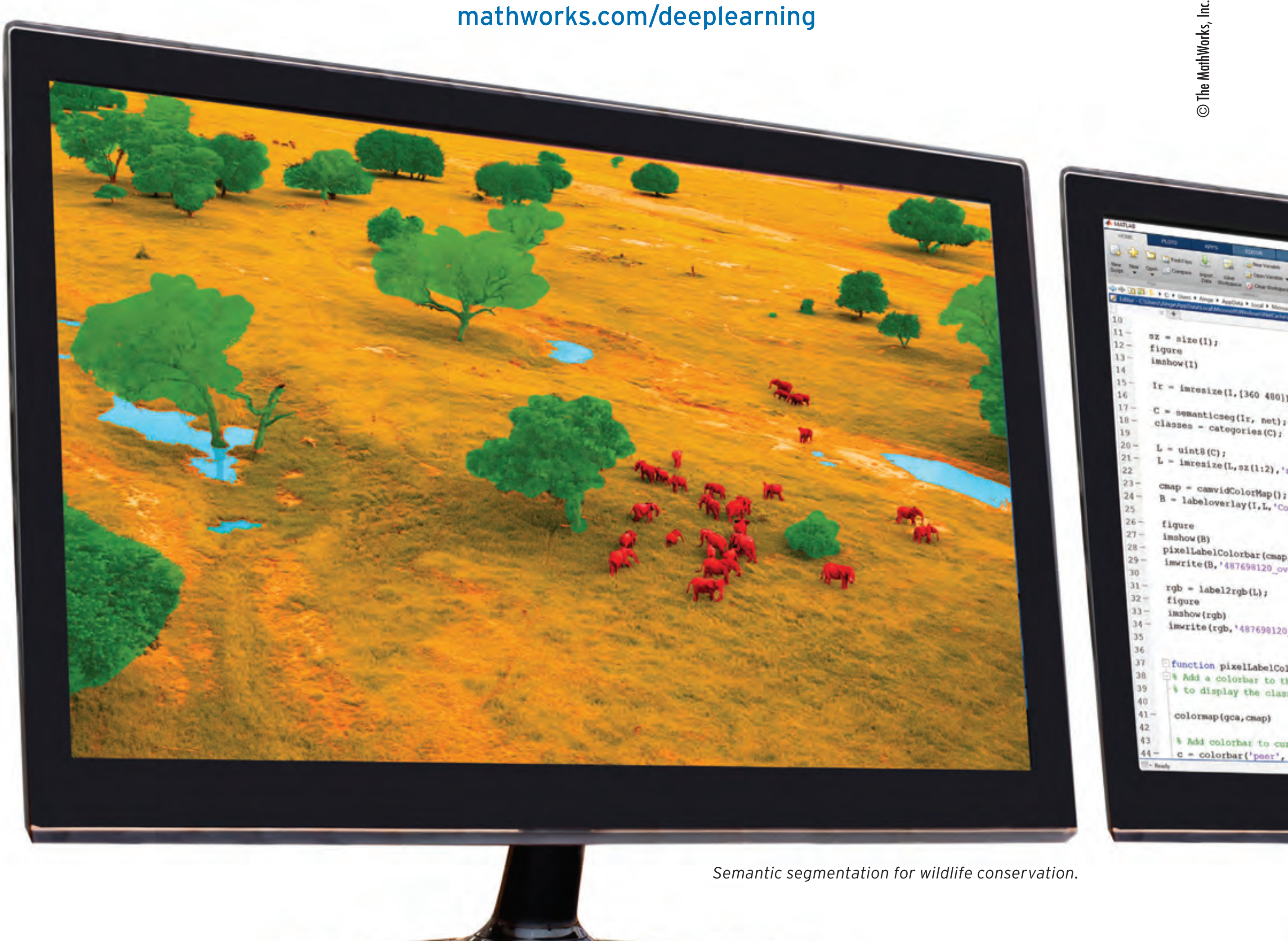

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