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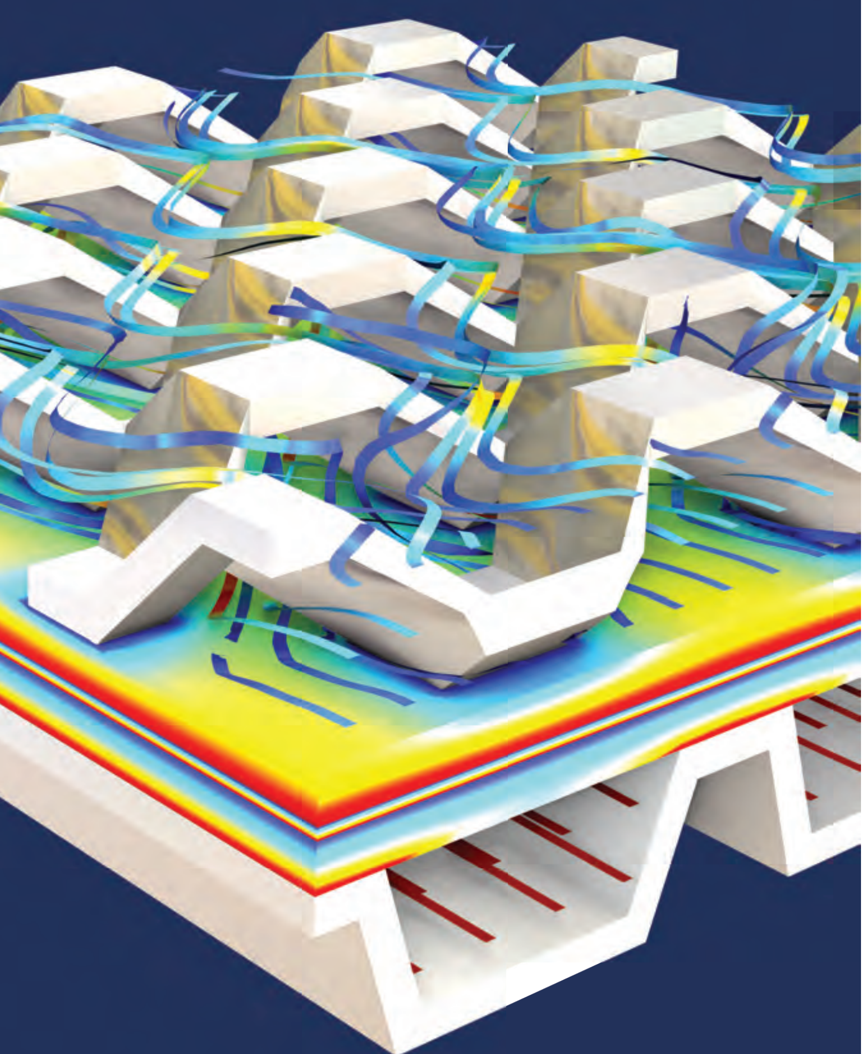

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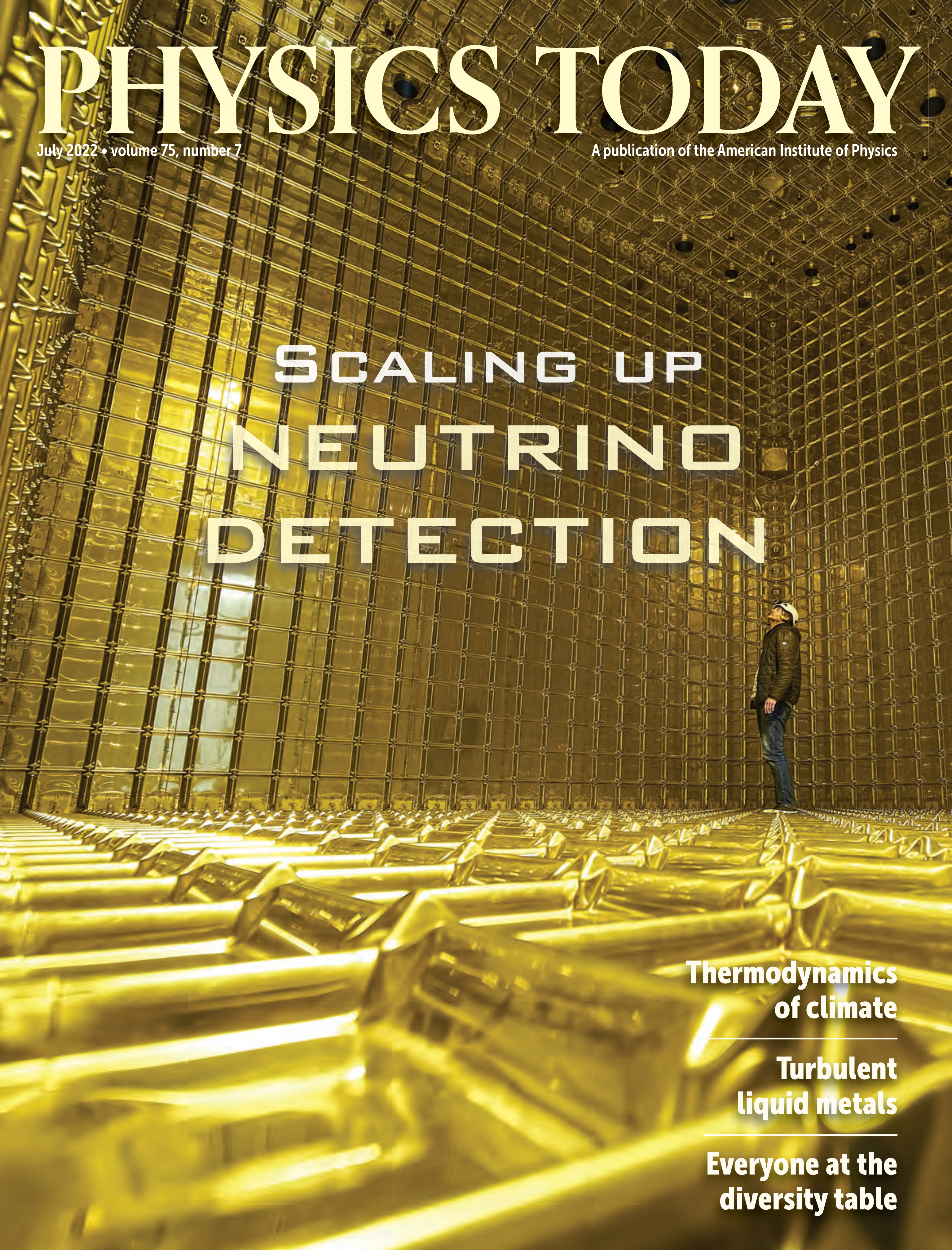

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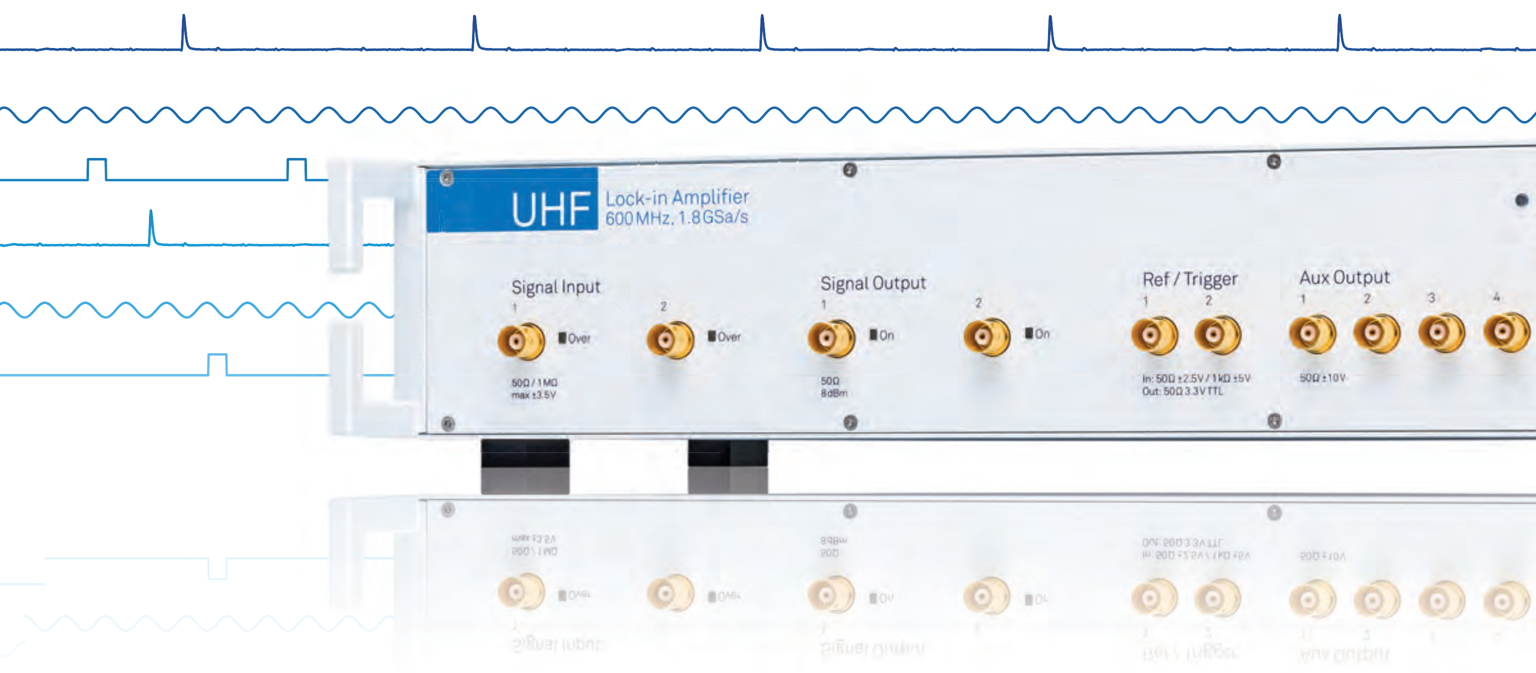

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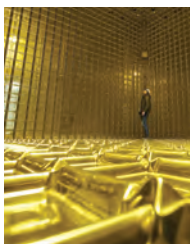

ON THE COVER: Before the Deep Underground Neutrino Experiment (DUNE) comes on line, the smaller two-detector protoDUNE program at CERN will test the underlying design. Seen here is the inside of one of protoDUNE's liquid-argon time-projection chambers; special lights that protect the photon-detection elements impart a gold hue. On **page 46**, Anne Heavey explores the numerous challenges to making the world's largest particle detector a reality. (Courtesy of Maximilien Brice/CERN.)

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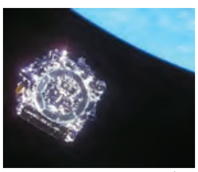

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MATHEW CRAWLEY

LGBT+ physicists

Several new surveys show the importance of a welcoming work environment for retaining LGBT+ physicists. "The absence of a negative climate is not sufficient to support LGBT people," says physics education researcher Ramón Barthelemy. "You have to have an actively inclusive community."

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SHAABAN KHALIL

Arab Physical Society

The newly founded Arab Physical Society aims to promote "excellence and creativity in the field of physics for the benefit of the Arab region and humanity." The organization already has more than 500 members. PHYSICS TODAY's Toni Feder speaks to some of its leaders about their priorities.

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Commentary

Why we need everyone at the diversity table

As an experienced consultant, I have learned that when I want to address homophobia and heteronormativity, I work with straight people. When I want to address sexism, I work directly with men. And when I want to dismantle racism, then I work directly with white people.

Members of empowered groups have the ability to create either just or unjust conditions. At the urging of those who are marginalized, empowered people have played integral roles in the struggles for social justice—be it the push for women's suffrage, the civil rights movement, or the fight for LGBT (lesbian, gay, bisexual, and transgender) rights.

Right now, as we continue to live through the COVID-19 pandemic, we need to remember that marginalized groups still face the effects of racism, sexism, classism, and ableism in society. We must also remember that we live in an age of political extremism—and in a time where racially motivated violence represents a serious threat to our nation.[1]

If members of the scientific community do not collectively seize the opportunity to stand in solidarity with one another and truly fulfill their roles as allies in struggles for equity and social justice, they stand to lose a great deal more than students in their courses and graduates from their programs. If we are all in agreement that human brilliance is spread evenly across all races, genders, classes, and abilities, shouldn't the community then do its part to ensure that students in the sciences in general—and physics in particular—experience its best efforts to include them?

Student groups, affinity groups, and employee resource groups and networks are crucial to the work of diversity, inclusion, and belonging. But they are not enough.

In my career, I have too often noticed that the very people marginalized groups need support from feel as if they have no place to turn to understand their role in the struggle for equity and social justice. Men will often tell me that they do not engage with women's issues because they are afraid to "say the wrong thing" or "make matters worse." Straight people will often share that they don't understand what all the letters in LGBT mean, and cisgender people will ask why everyone is putting pronouns in parentheses. Most dishearteningly, white people often have no idea where they fit into the racial dialog.[2]

Early in the pandemic, my spunky white personal trainer could not understand why I would risk my life to renew my vehicle registration. It befuddled her that I couldn't just "let it expire and ride." I realized that someone who cannot relate to the fear of being stopped for a routine traffic violation and possibly not living to talk about it needs a place to learn about that concept without consequence. Solidarity groups are needed for white people who are curious, concerned, or passionate about understanding racism and becoming anti-racist but have no idea where to begin.

Excellent diversity, equity, and inclusion programming does not condemn people who have underdeveloped understandings of race, sex, class, and ability. Rather, it invites, welcomes, affirms, and supports people who recognize that something is amiss but too

WHEN TAHAREE JACKSON, author of this commentary, taught at the University of Maryland in College Park, she invited students to discuss issues occurring inside and outside of the classroom during a check-in at the beginning of each class.

often feel clueless about how to help.

As you move forward in your quests to render physics a welcoming, inclusive, diverse, and equitable field, I urge you to turn away from spending time trying to change the groups you want to welcome and instead focus on trying to transform yourself. How can you alter your admissions practices, program norms, funding equations, and assessment practices? How can you modify your syllabi, courses, and learning opportunities? What can you do to ensure that opportunity is spread evenly across the racial, gender, class, and ability groups in your institution? And most importantly, how can your institution maintain its "core" while simultaneously becoming an equity-minded organization?

In what follows, I offer a few starting points for members of the physics community who are ready to do the work.

First, if you are a leader of any kind, ask yourself where you stand on issues of diversity. The tone you set as a leader will reverberate outward in ways you do not know.

The last research I conducted as a professor at the University of Maryland in College Park was a study of what motivated the teachers who do the best jobs at challenging oppression and supporting cultural differences to remain in classrooms. I found that the single most salient factor was the teacher's relationship with the highest-ranking leader in their building. Those leaders singlehandedly set the tone for how their subordinate faculty either embraced or eschewed the importance of diversity and equity.

The best leaders had varying levels of knowledge about diversity, equity, and inclusion, but they were all in full support of what their faculty wanted or needed to do to prioritize efforts to achieve them. They often vowed to "take the hit" in meetings with superiors, external stakeholders, and others who might push back.

Second, make sure that you are showing up to the diversity and equity dialog in the right identity. I have found that we encounter difficulty when white people who have experienced hardships such as poverty or discrimination because of their religion or parents' birthplace show up to the racial dialog not as white people but as *marginalized* white people. But when people who are white or pass as white enter conversations about race in one of those other identities, they miss the opportunity to take advantage of the power that their whiteness provides in the fight to dismantle racism.

It's the same for men. Are there men who face challenges of injustice and inequity? Yes. But when women need male allies to advocate for their presence as tenured faculty, to be the first authors on their papers, or to negotiate fair salaries for them, they need men to show up as *men* who are aware of the power their gender confers.

Third, make space for your students to share their stories. Some members of the scientific community possess a deeply dangerous sentiment that their work is somehow objectively outside the purview of social-justice issues, racism, inequity, and unfairness. I've noticed a serious hesitation among educators to discuss such topics in their classrooms.

But when I was attending Harvard University as a low-income student from a rural area, the biggest challenges I had to surmount had nothing to do with the one my peers found the most difficult: the curriculum. I found it much harder to deal with racist, sexist, classist classmates and faculty members than with my Moral Reasoning course.

When I was a student, the academics themselves were never the challenge for me. It was the sociopolitical context of my learning that always battered me, hampered me, and made my time in school far more arduous than it ever had to be. If professors, teachers, and scientists are actively shying away from discussing with students the issues that affect their lives in real time, then what kind of educating are they doing?

As a college professor, I began every class with a check-in. If students wanted to discuss racial tensions in and out of the classroom, the latest verdict of a high-profile case, or news from the White House, I made space for that. For them. For their stories.

I implore you to listen to your students whose voices long to be heard in class. I invite you to study your syllabi meticulously to see where people from different types of backgrounds are erased or fully present. I challenge you to look around your classroom and in your presentation slides for representations of not only the students who are in the room but also the students you say you so desperately want to attract. And most importantly, I encourage you to learn the history of yourself, your family, and your identities so you can juxtapose your stories with the new ones you absorb. We all have quite a lot to learn from one another's stories, and that's OK.

I have seen the value of welcoming all people to the struggle for diversity, equity, and inclusion, regardless of their identities or their hesitancies about joining.

We need *everyone* at the table. Thank you for showing up.

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LETTERS

Contributions to computed tomography

As I started reading the article on computed tomography (CT) by John Boone and Cynthia McCollough (Physics Today, September 2021, page 34), I expected to see Allan Cormack mentioned early on. Instead, only in box 1 is it noted that he shared a 1979 Nobel Prize with Godfrey Hounsfield. Cormack was the first to demonstrate the feasibility of x-ray CT through mathematical derivation and experimental validation. His investigations in that area, done with little or no funding, began in 1956 in South Africa, where he was assigned to a Cape Town hospital to oversee their radioactive sources. Observing how crudely radiotherapy planning was done at that time, he wondered if it would be possible to determine the internal inhomogeneities of each patient to improve their individual treatment plans.

In his 1964 paper, Cormack experimentally demonstrated the CT principle.[1] He built a hand-operated scanner to measure the attenuation of a cobalt-60 beam as it passed through an object along paths at various angles, referred to now as translate–rotate geometry and shown in figure 1a of Boone and McCollough's article. Using data collected over a two-day period, he reconstructed the scanned object's attenuation-coefficient profiles along several lines through the object and showed that, aside from some slight ringing artifacts, the reconstructed values matched the known values. Those profile plots demonstrated that he had achieved his goal of determining the attenuation values inside an object from its x-ray attenuation measurements.

Cormack, in his 1963 paper, presciently suggested the application of his work to two other modalities: positron emission tomography and single-photon emission computerized tomography, commonly referred to as PET and SPECT, respectively, which are frequently performed in the clinic today.[2] Prompted by an earlier suggestion by Robert Wilson that protons could be useful in medicine,[3] Cormack was especially interested in the promise of proton CT, which is currently being investigated for proton-therapy treatment planning.[4]

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I would like to add a historical footnote to the excellent article by John Boone and Cynthia McCollough in the September 2021 issue of Physics Today (page 34). The origins of computed tomography (CT) can be traced to William Oldendorf's pioneering work in the late 1950s and 1960s. Oldendorf was a professor of neurology at the UCLA School of Medicine when he developed a prototype of an automated tomographic device in which he used his son's electric train set, a phonograph turntable, an alarm clock motor, and other household items. It was the first demonstration of "a radiographic method of producing cross-sectional images of soft tissue by back-projection and reconstruction."[1]

In his 1961 breakthrough paper, Oldendorf laid out CT's basic concept,[2] which Allan Cormack later used to develop its underlying mathematics. In October 1963 Oldendorf received a US patent for a "radiant energy apparatus for investigating selected areas of the interior of objects obscured by dense material."[3]

The 1975 Albert Lasker Clinical Medical Research Award recognized the importance of Oldendorf's contributions to discoveries that enabled CT. He shared the prize with Godfrey Hounsfield, who with Cormack would receive the Nobel Prize in Physiology or Medicine four years later for "the development of computer assisted tomography."

Some have speculated that Oldendorf was on the original Nobel announcement but was removed at the last minute at the behest of certain members of the Nobel Assembly at the Karolinska Institute, which votes on the nominating committee's recommendations. It is possible some assembly members felt that the inclusion of a clinician would cheapen the award, making it appear overly pragmatic and thereby reducing its prestige.[4]

Oldendorf gave a lecture at UCLA shortly after the Nobel announcement was made. In it, he reviewed the work that earned him a Lasker and should have made him a Nobel laureate. Everyone who heard Oldendorf's presentation that day (myself included) came away convinced he was unjustly deprived of the pinnacle of scientific recognition. Readers wanting to learn more about Oldendorf's contributions to tomography and their historical context should consult his book on the topic.[5]

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▶ **Boone and McCollough reply:** We appreciate and agree with the comments from Steven Greenberg and Kenneth Hanson regarding our article, "Computed tomography turns 50." While writing it, we realized that so many people were involved in the development of modern computed tomography (CT), starting with Johann Radon in 1917, that we couldn't mention them all in our limited space. So we chose to mention only the few who were intricately involved early on in the clinical translation of CT—which is what the 50th anniversary celebrated. Many others could be mentioned for their contributions to CT technology, of course, and after our article was published, we received some wonderful anecdotes from those who were involved in the early days of CT.

We also learned that another, more comprehensive 50-year tribute[1] to CT was published around the same time as our Physics Today article. In summary, we concur with Greenberg's and Hanson's recommendations that many others deserve credit for CT.

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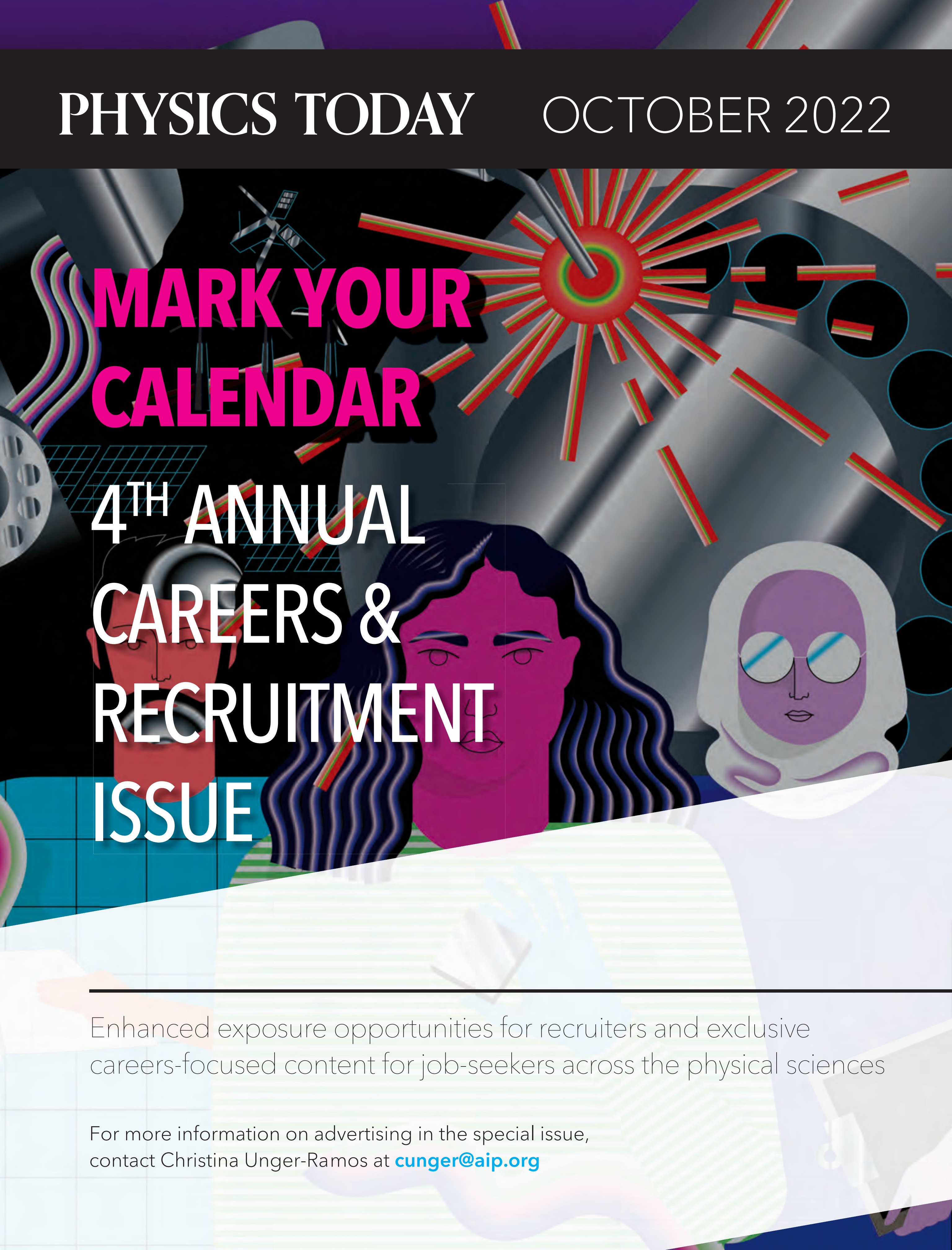
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Circulation collapses in turbulent liquid metals

The liquids' opacity makes it impossible to look at their flow structure. Instead, researchers listen to it.

Earth's magnetic field—useful not just for navigation but for shielding the planet's surface from the charged particles of the solar wind—owes its existence to the convective flow of the outer core. Heated from below and cooled from above, the churning liquid iron–nickel alloy hosts a self-sustaining dynamo in which electric currents and magnetic fields continually induce one another.

But the full picture is not so simple. The flow in Earth's core is almost certainly turbulent—and therefore chaotic, nonlinear, and hard to model. Observing the flow directly is impossible. And modelers get their simulations to output an Earth-like field only when they input material parameters, such as viscosity, that they know are wrong. (See the article by Daniel Lathrop and Cary Forest, Physics Today, July 2011, page 40.) Clearly, something is missing from researchers' understanding of liquid-metal turbulence.

Now Tobias Vogt, of the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in Germany, and colleagues have identified what may be an important piece of the puzzle. In a 64-cm-tall cylinder, shown in figure 1, they studied turbulent convection of a gallium-indium-tin (GaInSn) mixture that's liquid at room temperature.

What they found was completely unexpected. Instead of a stable large-scale circulation—one or a few big swirling vortices that fill the entire container and persist over time—they saw a constantly changing flow structure dominated by smaller, fleeting features.[1]

Until now, large-scale circulation has been considered an inevitable and ubiquitous feature of turbulent convection. Its absence in the HZDR liquid-metal experiments was not predicted by any theory. It's too soon to say exactly what Vogt and colleagues' observation means for understanding Earth's core and other planetary dynamos. But there could be profound implications for how turbulent liquid metals transport heat and momentum, especially at large length scales.

FIGURE 1. FELIX SCHINDLER, a PhD student at the Helmholtz-Zentrum Dresden-Rossendorf, assembles a cylindrical drum to be filled with liquid metal for turbulent convection experiments. (Photo by Tobias Vogt.)

Listen in

There are good reasons to think that turbulence in liquid metals is fundamentally different from turbulence in other fluids. Convective turbulence involves the interplay between the fluid's velocity field and its temperature field, so it's governed by the relative sizes of the features—vortices and thermal hot spots—that the fluid can sustain over time. For many fluids, the features are about the same size, but for liquid metals, the high thermal conductivity quickly washes out any small-scale temperature gradients. The difference is quantified by a dimensionless material property called the Prandtl number: on the order of 1–10 for typical liquids and gases, but just 0.03 for GaInSn.

Liquid metals are difficult to study in the lab. They're expensive, heavy, and hard to work with. They're also opaque, so the light-based methods used to study turbulence in other fluids (see, for ex-

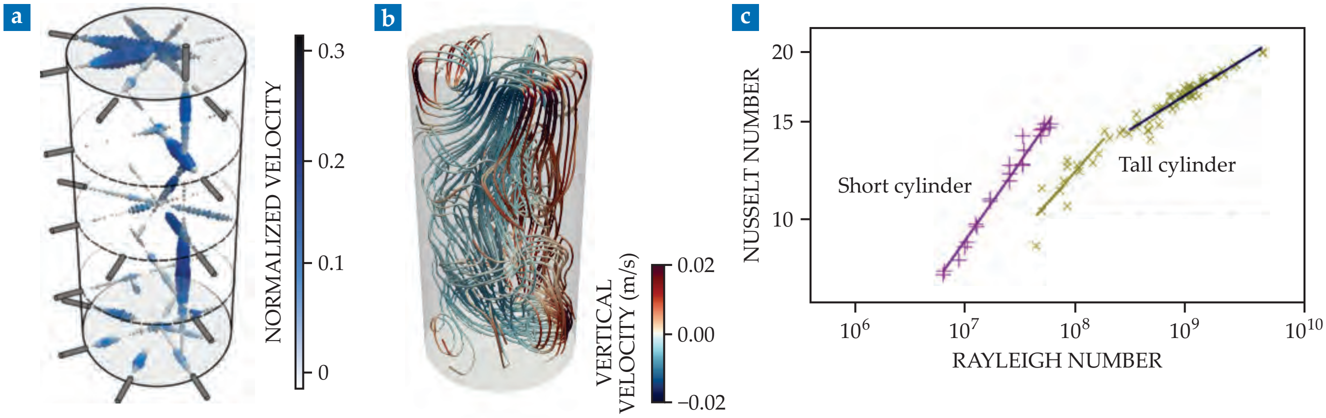

FIGURE 2. BREAKDOWN of large-scale circulation and heat transport in turbulent liquid metal. **(a)** Ultrasound Doppler velocimetry measured the fluid velocity profile along 17 straight-line beams. Tracking the data over time revealed that the flow consists of fast-changing, small-scale structures, not a single circulating cell. **(b)** Contactless inductive flow tomography confirmed the collapse of large-scale circulation. **(c)** A log–log plot of the Nusselt number (a measure of convective heat flow) versus the Rayleigh number (proportional to the temperature gradient) shows that heat transport unexpectedly levels off in the 64-cm-tall cylinder (green data). Measurements on a shorter cylinder (purple data), by comparison, show an expected power-law relationship. (Panels a and c adapted from ref. 1; panel b courtesy of Tobias Vogt.)

ample, the article by Leo Kadanoff, Physics Today, August 2001, page 34) are inapplicable.

But all is not lost. For decades the HZDR magnetohydrodynamics department has been working to develop, refine, and apply techniques for measuring velocity fields in liquid metals. In addition to turbulent convection and planetary cores, HZDR researchers are also interested in industrial applications—optimizing metallurgical processes and even exploring possibilities for liquid-metal batteries.

Light doesn't penetrate liquid metals, but sound does, so one of the HZDR team's go-to methods is ultrasound Doppler velocimetry (UDV): using ultrasound transducers to measure the velocity profiles of tiny acoustically reflective oxide particles that permeate the liquid metal. Technical limitations make it hard to deploy more than about 20 transducers simultaneously, and each one measures the profile only along a one-dimensional cut through the system, as shown in figure 2a. But the direct velocity measurements, especially when tracked over time, give the researchers some idea of the flow structure.

For a more complete picture, the HZDR team developed a complementary technique called contactless inductive flow tomography (CIFT). In a CIFT measurement, flowing metal is placed in a weak magnetic field—not strong enough to disrupt the flow but strong enough to induce eddy currents.[2] The currents generate their own magnetic field, which is measured with magnetometers surrounding the sample. By solving a sophisticated inverse problem, the researchers can convert their magnetic measurements into a reconstruction of the 3D flow.

Although CIFT potentially offers much more detailed insight into a flow structure, it's also a lot more work. So the researchers typically start their studies with UDV measurements and turn to CIFT only when they know it will be worth the effort. Vogt and colleagues' published analysis is based on their UDV studies. But in the time since they submitted their paper last year, they've begun some preliminary CIFT measurements, including the one shown in figure 2b. Both experimental techniques show the collapse of the large-scale circulation, with the liquid-metal flow devolving into smaller, fast-changing, incoherent structures.

Great heights

To classify different regimes of turbulent convective flow, another important dimensionless number is the Rayleigh number. Unlike the Prandtl number, which is an inherent property of the fluid, the Rayleigh number also depends on the experimental conditions and geometry: It's proportional to the container height to the fourth power times the overall temperature gradient. (Equivalently, it's proportional to the temperature difference across the system times the height cubed.) The temperature gradient is what drives the convection; to become turbulent, the flow needs to overcome resistance imposed by the fluid's viscosity and thermal conductivity, each of which introduces a factor of the height squared.

Earth's outer core is more than 2000 km thick, so its Rayleigh number is many orders of magnitude larger than can possibly be studied in a lab or simulated on any present-day computer. In their push to higher Rayleigh numbers, Vogt and colleagues chose to use a cylinder taller than it is wide, so they could make the best use of their costly and cumbersome GaInSn. In their previous work on convective turbulence, they'd always used containers as wide or wider than they are tall. All those systems—by necessity, much shorter than 64 cm—featured stable, large-scale circulation.[3]

To estimate how turbulence might behave in systems too large for a lab experiment, researchers look for trends as a function of the Rayleigh number. For a single experimental setup, they can obtain a range of Rayleigh numbers by varying the temperature difference across the fluid. Because liquid metals transport heat so easily, it's difficult for them to sustain large temperature gradients. But with the help of powerful heaters and coolers, Vogt and colleagues realized temperature differences from 0.25 K to 51.2 K across their tall cylinder, for Rayleigh numbers of 2×10^7 up to 5×10^9.

The key thermodynamic output is the Nusselt number, roughly the ratio of the amount of heat transported by convection to the amount that would have been transported by conduction alone if the fluid were at rest. For turbulent flows, the Nusselt number is greater than 1, even in liquid metals—despite the high thermal conductivity, the majority of heat is transported by convection. And as the Rayleigh number increases, so does the Nusselt number. The question is, how quickly?

For a given fluid and experimental geometry, the Nusselt number is usually a power-law function of the Rayleigh number with an exponent somewhere between about 0.2 and 0.5, depending on the system. If the scaling isn't well characterized by a single exponent, then it can often be described by a sum of terms with different exponents, with the effect that the dominant exponent increases with increasing Rayleigh number.[4]

But that's not what Vogt and colleagues observed. Rather, as seen in the green data in the log–log plot in figure 2c, they found a lower power-law exponent for higher Rayleigh numbers. For Rayleigh numbers below 2×10^8, the exponent was 0.22: on the low side, but within the expected range. But for higher Rayleigh numbers, the exponent dropped to 0.124—a lower value than had been predicted by any theory or observed before in any other experiment.

Scaling up

If the low-exponent power law could be extended indefinitely to higher Rayleigh numbers, it would suggest that Earth's core convection transfers far less heat than previously expected—and that it probably differs from expectations in other ways too. But far too many dots remain unconnected to confidently make such a simple extrapolation.

The HZDR researchers don't yet have a clear understanding of exactly what's going on at the Rayleigh numbers they observed, let alone at the ones they didn't. They tentatively attribute the change in power-law exponent at the Rayleigh number of 2×10^8 to a transition from a partially decoherent regime of turbulent flow to a fully decoherent one. But their observations of the turbulent flows are still too spotty to draw any solid conclusions.

Experimenters often turn to computer simulations to fill in the gaps in their measurements, but Vogt and colleagues don't have that option. A huge amount of computing power is necessary to simulate all the tiny vortices of high-Rayleigh-number, low-Prandtl-number flows. Meaningful results are possible only up to Rayleigh numbers of about 10^9. Vogt and colleagues' experiments are already past that threshold.

But with the confirmation that liquid metals' strange behavior is within experimental reach, the HZDR researchers are pressing on with their measurements. To push further into the unexplored regimes of turbulent liquid metals, they're in the process of setting up a new lab to perform experiments on liquid sodium. Despite that material's hazards, it's available in larger quantities—the researchers have 12 cubic meters of it ready to go—and has a Prandtl number an order of magnitude lower than GaInSn's.

Johanna Miller

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Magnetic field induces spatially varying superconductivity

Strontium ruthenate may exhibit an exotic superconducting state composed of electron pairs with nonzero momentum.

In 1957 the Bardeen-Cooper-Schrieffer (BCS) theory emerged as the first quantum mechanical model of what would become known as conventional superconductors. Below a critical temperature, the highest-energy electrons in those materials form pairs with antiparallel spins. Pairing up allows the electrons to act like bosons rather than fermions and condense into a collective state that moves without resistance. (See the article by Howard Hart Jr and Roland Schmitt, Physics Today, February 1964, page 31.)

But other models for superconductivity exist. In 1964, for example, Peter Fulde and Richard Ferrell and, independently, Anatoly Larkin and Yuri Ovchinnikov predicted that a large magnetic field could induce a different type of superconducting state.[1] Known as Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superconductivity, the state's parameters would vary periodically in space, unlike the homogeneous BCS state.

Direct evidence of FFLO superconductivity has long been elusive, however, in large part because the predicted state is unstable. A few materials, such as quasi-two-dimensional organics and the heavy-fermion system cerium cobalt indium-5, have shown some signatures of a potential FFLO state. Now Kenji Ishida of Kyoto University in Japan, his graduate student Katsuki Kinjo, and their colleagues have found the most direct evidence to date of the state.[2] Their observation of modulations in strontium ruthenate's spin density, illustrated in figure 1, points to inhomogeneous superconductivity.

Gaining momentum

The key difference between BCS and FFLO superconductivity is the response to magnetic fields. In the case of BCS, an applied magnetic field, if strong enough, twists the spins apart and destroys the material's superconductivity—a phenomenon known as Pauli pair breaking. An FFLO superconductor also eventually succumbs to pair breaking under the influence of a sufficiently strong field. But when subjected to slightly weaker fields, the FFLO gains its signature inhomogeneity.

To understand how, consider the simple band structure depicted in figure 2a. In the absence of a magnetic field, spin-up and spin-down electrons zip around with the same magnitude of momentum for a given energy (gray dashed curve). With the addition of a magnetic field, Zeeman splitting shifts the energy band of one spin upward and the other downward. The highest-energy spin-up electrons have different momenta from those of the highest-energy spin-down ones, and the resulting pairs adopt a nonzero net momentum, which creates spatial modulations in the superconducting order parameter and spin density.

Many superconductors, including most elemental ones, are well-described by BCS theory; finding materials suitable for an FFLO state has been a challenge. For starters, unlike robust conventional superconductivity, even dilute defects in the sample prevent the state's formation. So a candidate material must be quite pure and nearly perfectly crystalline. Its carriers must also undergo strong Zeeman splitting. Finally, the FFLO state requires high magnetic fields—higher fields than those at which superconductivity disappears in most materials as a result of induced vortex currents. So a suitable material must have Pauli pair breaking, rather than vortex formation, as the limiting factor on superconductivity.

Strontium ruthenate—Sr_2RuO_4 or SRO—is, in many respects, a promising candidate for FFLO superconductivity: It can be fabricated with few defects and possesses charge carriers with large effective mass, which produces large Zeeman splitting. Its layered structure, shown in the bottom left of figure 1, also can hinder vortex formation. Superconducting currents run primarily in the plane of each layer. (See the article by Yoshiteru Maeno, Maurice Rice, and Manfred Sigrist, Physics Today, January 2001, page 42.) Because electron pairs are effectively stuck in two dimensions, a magnetic field parallel to the plane fails to create the vortices that might otherwise disrupt the superconductivity before the FFLO state has a chance to form.

For many years, however, SRO was thought to be a spin-triplet superconductor, which has electron pairs with parallel spins. In 1998 Ishida's group was the first to produce NMR data that seemed to confirm that supposition. Spin-triplet superconducting pairs would be manipulable with magnetic fields, which makes them promising for spintronics and quantum computing. But they can't form an FFLO state. Zeeman splitting would have no effect on the net momentum of spin pairs pointing in the same direction.

After two decades of experiments in support of the spin-triplet interpretation, studies in 2019 and 2021 by Stuart Brown of UCLA and his colleagues reported NMR results that contradicted that picture.[3] (See Physics Today, September 2021, page 14.) The researchers argued that sample heating from the NMR pulses, negligible in most measurements, was enough to push the material out of the superconducting state in previous experiments. Brown and his colleagues employed low-energy pulses to reduce heating and found results that ruled out spin triplets. After that revelation, Ishida wondered if an FFLO state might be possible in SRO after all.

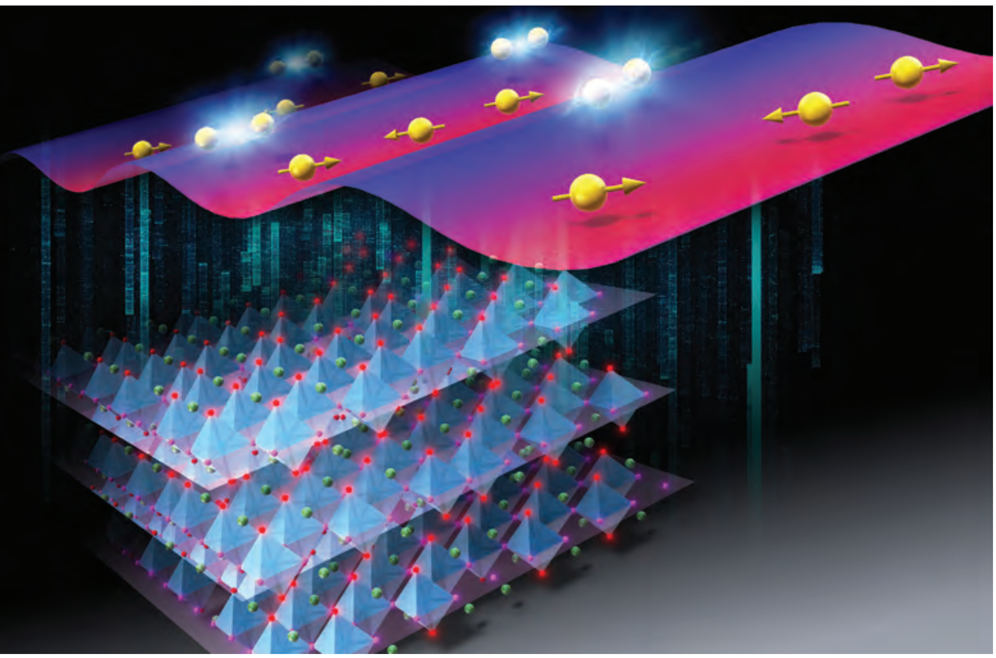

FIGURE 1. STRONTIUM RUTHENATE, illustrated in the bottom left, becomes superconducting at temperatures less than 1.5 K. The nature of that behavior has been the subject of excitement and debate since the mid 1990s. New results add another theory to the mix: an unusual and hard-to-find form of superconductivity whose order parameter varies spatially under the influence of sufficiently strong magnetic fields. Those variations, depicted by the sinusoidal surface at the top, take the form of regions of superconducting electron pairs and regions of high spin density that result from unpaired electrons. (Courtesy of Kenji Ishida.)

Seeing double

Ishida and his colleagues first replicated Brown's results.[4] They then used the same technique to examine SRO close to the critical magnetic field, above which the material returns to its normal state. The low-energy NMR pulses may prevent heating, but they also make the signal weak. So each spectrum took an order of magnitude longer than a typical NMR measurement. The researchers tested a range of temperatures from 70 mK to 1.6 K and magnetic fields up to 1.5 T.

The NMR spectra are given in terms of the Knight shift, which quantifies the NMR frequency shift. They indicate the electron-spin susceptibility in the vicinity of the probed nuclei, in this case oxygen-17. In its normal state, SRO has a certain, uniform spin susceptibility, with electrons and their accompanying spins spread out evenly. That state produces one NMR peak, as shown in black in figure 2b. In the homogeneous superconducting state at a low magnetic field, the Knight shift is lower because paired electrons with antiparallel spins reduce the material's spin susceptibility. Because the electron pairs are equally distributed across the material, the NMR spectrum still has one peak, albeit shifted.

Just below the critical field of 1.4 T, a second NMR peak appears, shown in the red spectra in figure 2b, that can't be explained by coexisting normal and superconducting phases. The researchers attribute the double peaks to spatial modulations in the spin density—periodic stripes of low and high electron-spin densities, illustrated in figure 1. As the second peak is at a slightly higher Knight shift than the normal state's peak, it suggests spin-dense regions between ones populated with electron pairs. Although spin-density waves and their accompanying multiple NMR peaks often arise in materials, they haven't been found before for superconducting electron pairs. The result thus strongly hints at an FFLO state.

Kinjo, Ishida, and their colleagues constructed a full phase diagram for the homogeneous and the FFLO superconducting

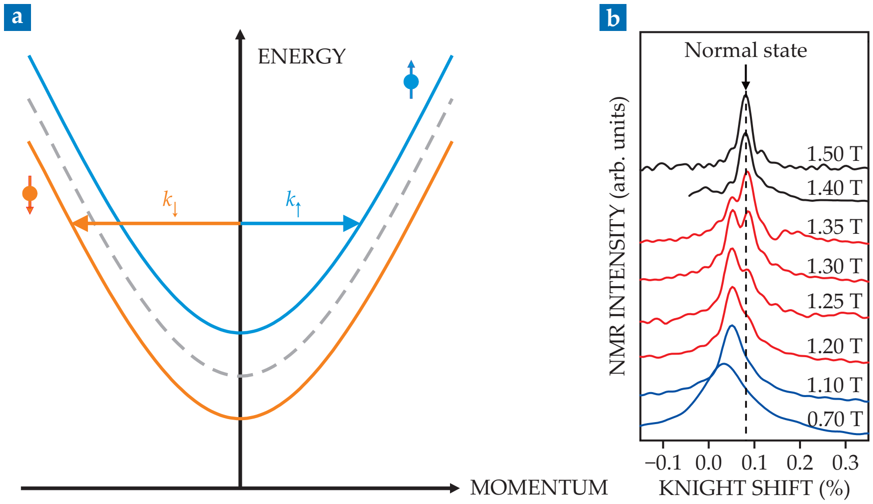

FIGURE 2. FFLO SUPERCONDUCTIVITY arises from Zeeman splitting. **(a)** In the absence of a magnetic field, spin-up and spin-down electrons have the same energies and momenta (gray dashed curve), so when the highest-energy electrons pair up in the superconducting state, the net momentum is zero. But in the presence of a magnetic field, spin-up (blue) and spin-down (orange) electrons take on distinct momenta *k*. When the highest-energy electrons pair to form an FFLO state, the pairs have nonzero net momentum and create spatial modulations in the spin density. **(b)** For strontium ruthenate at 70 mK, NMR measurements—given in terms of the Knight shift, which quantifies the NMR frequency shift—show the transition with increasing magnetic field from homogeneous superconductor (blue) to FFLO superconductor (red), characterized by double peaks, to nonsuperconducting (black). (Adapted from ref. 2.)

phases, with the FFLO occupying the high magnetic field, low-temperature region. The magnetic fields in their study were about a tenth of those necessary for previous FFLO candidates, which makes SRO a practical choice for future FFLO investigations.

Although encouraging, the new result isn't conclusive. The only definitive evidence would be an observation of spatial modulations in the superconducting order parameter through, for example, measurements of the superconducting gap—the small energy gap that opens when electrons pair up. That smoking gun could come in the future from scanning tunneling microscopy measurements.

Heather M. Hill

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Groundwater flows deep under Antarctic ice

Ice-dynamics models must be updated now that researchers have observed a thick layer of salty water in sediments beneath the West Antarctic Ice Sheet.

Some 70% of Earth's fresh water is stockpiled in Antarctica's ice. If it were all to melt, global sea level would rise by 58 m. Estimates of ice loss critically depend on such factors as the conditions at the base of an ice sheet and the stability of ice shelves that prevent the sheet from sliding into the ocean. (For more on Antarctica's ice shelves, see the article by Sammie Buzzard, PHYSICS TODAY, January 2022, page 28.)

Researchers have hypothesized that underground water may exist below the ice. If enough water melts at the ice sheet's bed, the friction between the ice and the land decreases, and the ice flows toward the ocean faster. For simplicity and with just a few observations, most glaciology simulations have modeled the basal meltwater as a thin layer that's a few millimeters to a few meters thick with an impermeable mass of bedrock below.

Reality, however, is most certainly different from those model assumptions. Take away the ice, and Antarctica has many of the same topographical features as any other continent, such as permeable valleys and impermeable rugged mountains. But the remote and harsh environment of Antarctica and the technical challenges of identifying water deep beneath the bed of the ice sheet have prevented glaciologists from observing any subglacial groundwater, aside from in a handful of nonglaciated regions at the ice's margins.[1]

Now Chloe Gustafson of the University of California, San Diego, and her colleagues have conclusively observed groundwater under the Whillans Ice Stream—a river of ice flowing from the West Antarctic Ice Sheet on land to the Ross Ice Shelf floating off the Siple Coast. Their new data indicate that the basin of groundwater contains an order of magnitude more water than previous estimates of subglacial hydrological systems.[2]

Into the field

To image subglacial groundwater, researchers have used seismometers and ground-penetrating radar. Although those methods have measured liquid water in the top few hundred meters, they aren't adept at observing the volume of water in deeper subterranean reservoirs. Radar signals attenuate because radio waves are easily absorbed by liquid water. And seismic-wave signatures are sensitive primarily to density variations, which limits how well those layers can be distinguished from one another.

In a 2017 feasibility study, two of Gustafson's coauthors—Kerry Key and Matthew Siegfried—found that a magnetotellurics (MT) approach should be capable of detecting groundwater more than a few hundred meters below Antarctic ice sheets.[3] Natural variations in electric and magnetic fields arise from the interaction of charged particles in the solar wind with Earth's conductive magnetosphere. Like all other time-varying electromagnetic fields, the ones in Antarctica are governed by Maxwell's equations and induce local secondary electromagnetic fields in ice, groundwater, rock, and other materials. MT sensors installed at the surface passively measure the resistivity of the secondary electromagnetic fields. High-resistivity glacier ice, for example, is easily distinguished from low-resistivity sediments whose pore space holds subglacial groundwater.

Although the MT approach is well established and has been used to study nonglaciated terrain over the past several decades, the method demanded some modifications for subsurface interrogations in Antarctica. Good measurements require electrodes to be well coupled to the surface. But snow on Antarctica's surface weakens that coupling, so Gustafson and her colleagues used temperature-insensitive titanium electrodes with a large surface area. On top of that, they applied an environmentally friendly buffer to the electrodes to amplify the resistivity signal further.

With their observational method in mind, Gustafson and her colleagues prepared for the fieldwork in West Antarctica. The area they visited is far from the permanent research stations in Antarctica, and the bitterly cold climate makes it and the rest of the continent accessible for just the three months of the Southern Hemisphere's summer. But measurements of the ice streams in West Antarctica would provide critical observations needed to accurately calculate ice velocities in models.

During the November 2018 to January 2019 field season in Antarctica, Gustafson and her colleagues installed a few dozen MT stations—one of which is shown in figure 1—on the Whillans Ice Stream. From the collected MT data and a passive seismic survey, the researchers discovered a sedimentary basin underneath some 800 m of ice.

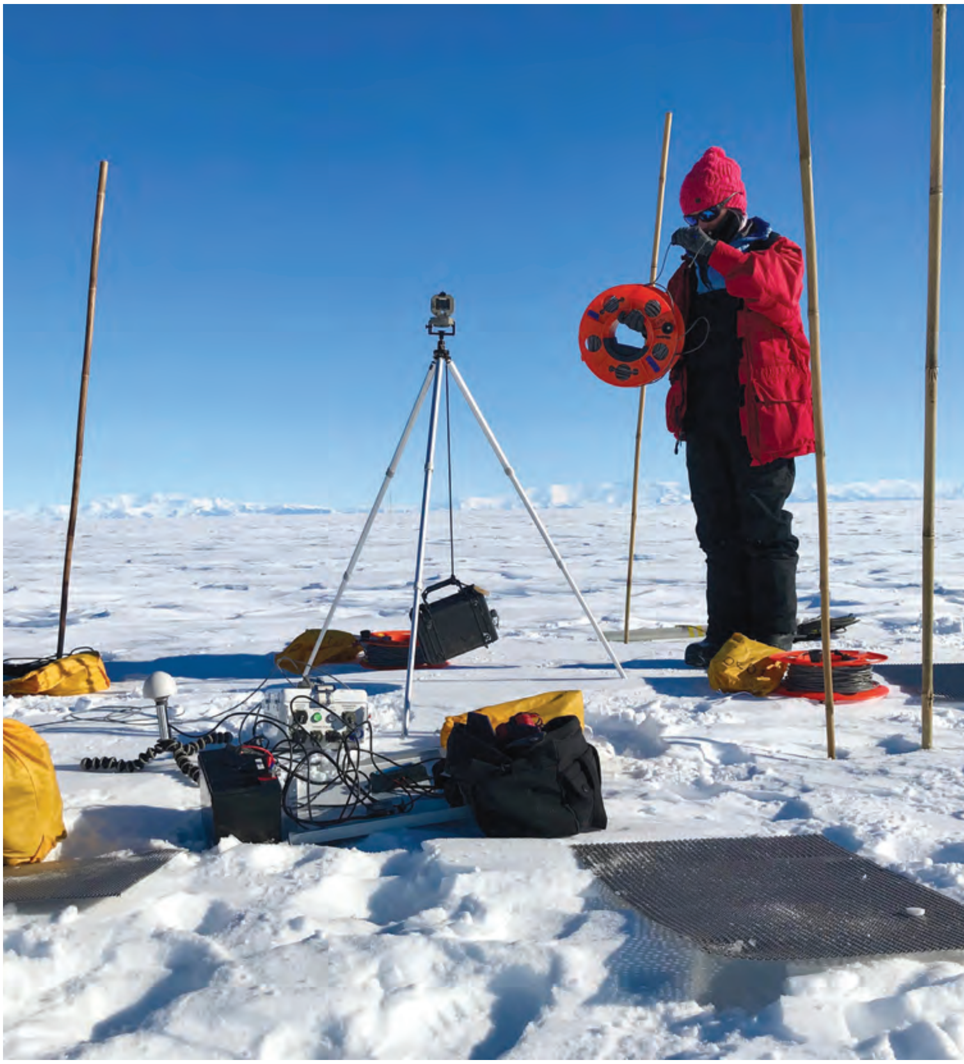

FIGURE 1. SEARCHING FOR GROUNDWATER. Chloe Gustafson sets up a magnetotellurics station for measuring the resistivity of the subsurface in West Antarctica. The dark titanium sheet in the foreground serves as an electrode: Its large surface area provides sufficient contact with the ground to measure the electrical resistivity of the land, ice, and groundwater. The instrumentation, installed during the 2018–19 field season, was placed inside a triple-walled box to protect it from snow drifts and ice accumulation. (Courtesy of Kerry Key.)

An ocean of groundwater

In that deep basin, the researchers found a subglacial water system. Figure 2 shows the electrical-resistivity results for the two regions of the ice stream that they focused on: the Whillans subglacial lake and the downstream area, known as the Whillans grounding zone, that connects to the ocean. In both locations, a layer of porous and permeable sediment extends

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some 2 km into the subsurface below the ice and is saturated with groundwater. All told, the volume of groundwater that Gustafson and her colleagues observed is at least an order of magnitude more than that found in the thin, shallow layer immediately below the ice stream's base.

To their surprise, the researchers learned that some of the groundwater was salty. The salinity increased with depth and had values approaching that of seawater. The MT measurements revealed that in the top few hundred meters of the basin below the ice sheet, fresh meltwater mixed with the saltier deep groundwater, a mixing whose existence had only been suggested theoretically.

The saltiness of the groundwater may be from seawater that infiltrated into the subglacial system 5000–7000 years ago when seawater advanced farther inland. Fresh water that subsequently melted from the glacier would have created the salinity gradient observed today.

Martin Siegert of Imperial College London says that the salty water could have also been added to the groundwater reservoir through a modern tidal-pumping mechanism. "We know that there are parts of the ice sheet in some parts of Antarctica with tidal ranges of six meters," he says. "The ice sheet gets lifted up and then slammed back down on its bed every single day because of the tides. So you've got all the water flowing in from underneath the ice shelves, the floating ice shelves, and then back out again. It's like a bellows effect." When asked about the tidal-pumping mechanism, Gustafson said, "It's certainly possible."

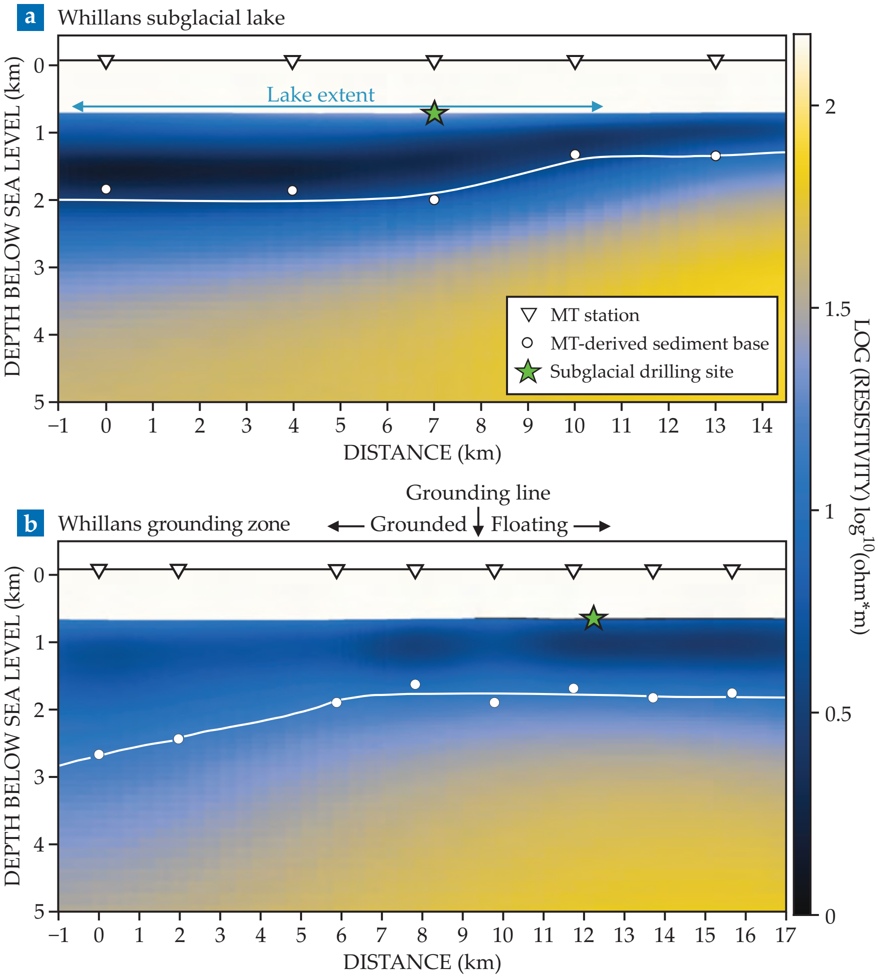

FIGURE 2. RESISTIVITY VARIATIONS measured by magnetotellurics (MT) stations were used to identify subglacial groundwater in West Antarctica. **(a)** The Whillans subglacial lake (dark blue) resides in the porous and permeable sediment beneath the ice (white) and above impermeable bedrock (yellow). The base of the sedimentary basin (white line) was estimated from the newly acquired MT data. **(b)** The downstream Whillans grounding zone contains the grounding line—the boundary between land and ocean. Previous studies that collected drill cores in the region (green stars) only recovered sediment from the top few meters below the ice. (Adapted from ref. 2.)

New observations, better models

Now that groundwater has been conclusively observed below the Whillans Ice Stream, the next step will be to incorporate the results into ice-flow models to determine to what extent the ice-sheet velocity is affected by subglacial groundwater. But how much the velocity would be affected by the groundwater is still an open question.

Some ice-sheet modeling on time scales of thousands of years has shown that as an ice sheet thins, the pressure release on the groundwater reservoir reverses the flow of water from a net-downward direction to net upward.[4] Evidence of overpressure has been observed before as unique seismic-wave signatures in bedrock off the coast of Martha's Vineyard. The observations likely originate from the retreat of the Laurentide Ice Sheet in North America as early as 2.5 million years ago. Gustafson says, "It can take thousands of years for the sediments to fully readjust to the pressure differential. So that's going to be something interesting to play around with in models of modern Antarctica."

Measurements of subglacial groundwater and their incorporation into ice-flow models will likely address some of the outstanding challenges in climate science (see the article by Tapio Schneider, Nadir Jeevanjee, and Robert Socolow, Physics Today, June 2021, page 44). The Whillans and other ice streams make up some 5% of Antarctica's surface area but are responsible for 90% of the ice flow. Tighter controls on the speed of ice streams will improve the estimates of ice mass balance and future loss.

Alex Lopatka

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PHYSICS TODAY

Whatever happened to cellulosic ethanol?

Technological immaturity, falling oil prices, overoptimistic investors, and regulatory uncertainty are blamed for the failure of a promising biofuel technology to perform as hoped.

Despite a decade and a half of big US federal investments in R&D and in pilot and demonstration plants, ethanol from noncrop biomass has yet to become a commercial reality in the US. Nor has that happened anywhere else in the world but Brazil.

Whether the technology can recover from the missteps of the past 15 years is an open question, but it has become ever more certain that sustainable biofuels are key to achieving global carbon neutrality by midcentury, according to the scientific consensus reflected in reports by the Intergovernmental Panel on Climate Change (IPCC) and other organizations.

"In order for biofuels to take their needed place in a sustainable world, the next decade has to be vastly more successful than the last," says Lee Lynd, an engineering professor at Dartmouth College who cofounded a failed cellulosic-ethanol startup named Mascoma. "We have got to do things differently, or from a climate change point of view, biofuels will have largely missed their opportunity."

Today, the US is by far the largest producer of ethanol, accounting for roughly 55% of global output. Nearly all of it is made from corn. The US renewable fuel standard (RFS), enacted in a 2005 statute and expanded two years later, requires petroleum refiners to blend ethanol into each gallon of the gasoline they sell. The RFS spurred the rapid growth of the corn-ethanol industry. Yet since the RFS for corn ethanol is capped at 15 billion gallons per year, there is little incentive for further expansion of the business. Another limitation on growth is the so-called blend wall, the 10% limit on the ethanol content of gasoline fuels that automakers have set for all but the small fraction of US vehicles that are flex-fuel, capable of burning ethanol content up to 85%. Ethanol advocates say the blend for conventional light-duty vehicles could be increased to 15% without harming drivetrains.

Roughly 40% of the annual US corn crop now goes to ethanol. Converting pasture or other lands to grow corn or other crops would result in the sudden release of large amounts of CO_2 from soils. That so-called carbon debt could take decades to pay back through photosynthesis by crops. The debt payoff time is debated in the scientific literature, but most analyses have identified that corn ethanol's life-cycle carbon intensity, including both CO_2 emissions and those associated with growing, is considerably lower than that of gasoline.

But John DeCicco, emeritus professor at the University of Michigan's Energy Institute, notes that the values that are assigned to land-use change in different models are arbitrary, and some studies have established a lower carbon-intensity value for gasoline.

The case for cellulosic

Cellulosic, or nonstarch, biomass—crop residues, wood waste, grasses, and other plant matter—has long been seen as a more sustainable raw material for ethanol production. Much of the biomass could come from lands unsuitable for agriculture, thus minimizing land-use impacts. Theoretically, cellulosic ethanol offers a much larger reduction in carbon intensity than corn ethanol—as much as 80% below gasoline's, depending on variables such as the feedstock used and the processing method, according to Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies full-life-cycle emissions model. The GREET model calculates corn ethanol's carbon intensity to be 44% below gasoline's.

In a series of 2016 studies collectively known as the "billion-ton report," the Department of Energy estimated that 500 million tons of nonstarch biomass could be harvested or collected annually in the US without adversely affecting ecosystems. DeCicco is skeptical of the finding, which he says is based on a lot of favorable assumptions. If cellulosic ethanol had actually taken off, he argues, it would have unleashed a wave of land-use conversions as large agribusinesses moved into the business of cultivating energy crops. "If they have an incentive to harvest biomass from switchgrass, miscanthus, or rapidly growing trees like aspens, they will seek to do that on the best land they can obtain."

The lignocellulose that composes the leaves and stalks of plants is considerably more difficult to break down to alcohol than the readily fermentable starch in corn; it requires specialized enzymes or thermochemical technologies. The 2007 RFS included a specific mandate for cellulosic ethanol, reaching 16 billion gallons by 2022. But lawmakers vastly overestimated the readiness of cellulosic

RAÍZEN

RAÍZEN'S PLANT in Piracicaba, Brazil, is the world's only commercial producer of cellulosic ethanol. Here, crushed sugarcane residue called bagasse is being loaded into the processing plant. Raízen plans to build 20 such plants by 2030.

technology, even as government and private money poured into R&D. The Environmental Protection Agency, which administers the RFS program, established a 2022 requirement for 630 million gallons of cellulosic biofuels.

DOE in 2007 established three bioenergy research centers at its national labs. A fourth center, headed by the University of Illinois at Urbana-Champaign, was added in 2017. In 2007, BP pledged $500 million over 10 years to fund an Energy Biosciences Institute, headquartered at the University of California, Berkeley. Chris Somerville, the institute's former director, says interest in biofuels fell in concert with plunging oil prices in 2014. "The bottom line is that to disrupt a cheap commodity business one needs to pay attention to all the sources of value. And to do that requires quite a lot of technical knowledge and know-how," he says. Large integrated oil companies such as BP could accomplish that, but "it will remain very challenging for startups to assemble the funds and technical abilities to do it."

DuPont, Poet-DSM, and Abengoa built commercial-scale cellulosic-ethanol plants in the mid 2010s with DOE cost-shared funding and loan guarantees. None remain in operation. One was mothballed, and two were sold and converted to produce biogas. As domestic production failed to materialize, the EPA has had little choice but to annually waive the cellulosic RFS requirement.

"DOE, who was sponsoring projects, was pushing very hard for them to be big," says Dartmouth's Lynd. "Technology providers had a very strong interest in saying, 'Look, the future is here, and we're ready to go today.'"

In the case of startups such as Mascoma, venture capitalists must share blame, Lynd says, for "inflating expectations way beyond the probable." During one meeting with investors, he recalls, "I stood up and said that what we're doing is not that different and not that good. Their response was, 'It doesn't have to be different or good—it just has to be first.' And the assumption was that the world would remain really excited about biofuels, and by God it was going to happen somewhere, and you just had to get there. But the world didn't remain that enthusiastic about biofuels."

The cellulosic-ethanol field, he says, "got overheated because each of the parties—the sponsors, technology providers, and investors—were all saying, 'Let's go big or go home,' and we ended up going home."

Bruce Dale, a chemical engineer at Michigan State University, says the challenges of gathering and processing the cellulosic feedstocks were seriously underestimated. "You have to have a guaranteed supply chain set up, know what kind of cellulosic material you're going to use, and know how much you're going to pay for it. In the US, we had sort of a technology, but no supply chain set up. There was no way to get large amounts of biomass delivered at defined qualities to the biorefinery."

Cellulosic material is inherently combustible, difficult to gather, and uneconomic to transport over distances greater than 80 kilometers, Dale says. It's also contaminated with rocks, soil, and other extraneous matter that tends to clog up machinery at the refinery. Fires in storage facilities were a regular occurrence.

Brian Davison, chief science officer at the Center for Bioenergy Innovation at Oak Ridge National Laboratory, says regulatory uncertainty also helped doom the commercial ventures. Poet-DSM blamed the instability of the RFS and other low-carbon credits such as California's Low Carbon Fuel Standard for the mothballing of its plant. "There was a year when the actual final value of the RFS wasn't announced until 18 months after the year began," he says. "It generally came in at a decent value, but the uncertainty was problematic. And the RFS would typically come up for a vote in Congress every year or two."

A success story

Brazil, with 27% of the global ethanol output, is the world's second-largest producer. There, sugarcane is the raw material; roughly half of Brazil's annual sugarcane crop is converted to ethanol each year. Vehicles in Brazil run either on a 25% ethanol mix or pure ethanol fuel. Raízen, a joint venture of Shell and Cosan, a Brazilian conglomerate, operates 26 plants producing sugar, ethanol, and biogas, and manufactured approximately 2.5 billion liters of ethanol and 3.8 million tons of sugar in the 2019–20 crop year. It began making cellulosic ethanol commercially in 2014, using sugarcane straw and bagasse, the pulp that remains once the juice is squeezed from the cane.

Mateus Schreiner Garcez Lopes, Raízen's global director for energy transition and investments, says that the plant uses technology licensed from Canada's Iogen and, after overcoming some challenges, has achieved production targets for the last three years. The company expects to open its second cellulosic facility next year, and it has committed to build a total of 20 such plants by 2030. Raízen recently completed an initial public offering to help finance its cellulosic expansion. "At this point, our bottleneck is the ability to build new plants," Garcez Lopes says.

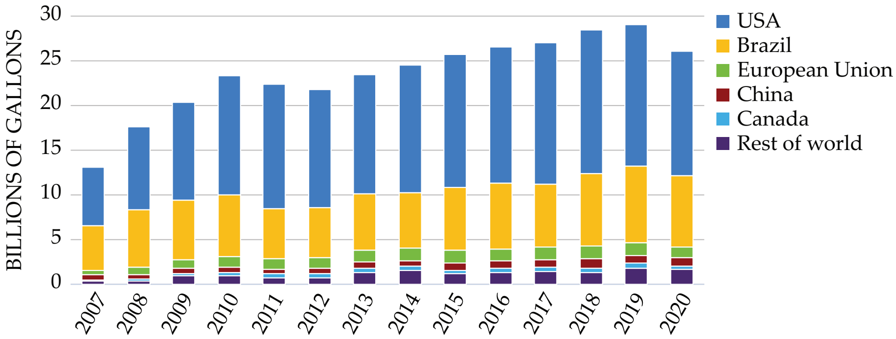
Raízen has an inherent advantage over US cellulosic-ethanol aspirants: Brazil's method of harvest brings the cellulosic feedstock together with the cane to the sugar mill. In the US, only the corn kernel is harvested; the remainder of the plant, known as stover, is left behind. Gathering and baling stover or other crop residues from the farm requires a separate harvest.

Lynd says the lower cost and pre-established supply chain for bagasse more than trumps the easier convertibility of corn stover. "And if you succeed at one plant in the US, you've still got to line up your feedstock for a second plant. In Brazil, if you succeed at one plant, there's 100 other plants you could do this at."

Raízen's entire output of cellulosic ethanol is exported to the US and Europe, where it fetches higher prices due to various RFS incentives. Though it's currently more costly to produce than conventional ethanol, Garcez Lopes says he expects that differential will disappear.

A bright future?

Some people have a perception that more ethanol won't be needed as electric vehicles become predominant, says Lynd. But that argument ignores the one-half of energy use in the transportation sector that can't be easily electrified: in aviation, heavy-duty trucks, and maritime shipping. "If you look at IPCC and [International Energy Agency] reports, biofuels are still a significant fraction, 10–20%, of the energy we need for 2050," says Davison. In fact, the median scenario of all 85 possible pathways considered by the IPCC to hold the global temperature increase to 1.5 °C above preindustrial levels by 2050 foresees a bigger role for biofuels than for wind and solar energy combined.



GLOBAL ETHANOL PRODUCTION. (Courtesy of the US Department of Energy, based on Renewable Fuels Association data.)

Ethanol can't be used directly for aviation fuel; more complex hydrocarbons are required. But ethanol can be an intermediate step for catalytic conversion to renewable aviation fuels. At least two US companies, LanzaTech and Vertimass, are nearing commercialization of sustainable aviation fuels derived from ethanol. LanzaTech licensed a process developed at Pacific Northwest National Laboratory; Vertimass licensed its technology from Oak Ridge National Laboratory, where it was codeveloped by Davison.

Other so-called drop-in fuels, such as renewable fuel oil for ships, and hydrogen production are potential growth areas for ethanol, says Garcez Lopes. The need is vast: Demand for aviation fuels will reach 400 million tons in 2030, he says, requiring five times the current global ethanol production.

"We are still very much interested in lignocellulosic conversion into biofuels," says a DOE official who declined to be identified. "The industry will take off in the very near future." There aren't many other good options for decarbonizing aviation fuel and other economic sectors that can't be electrified, he says.

Aviation fuels have been the focus of recent requests for proposals from DOE's Energy Efficiency and Renewable Energy office. On 1 June, DOE announced a $59 million solicitation for biorefinery and feedstock-development projects in support of sustainable aviation, diesel, marine, and rail fuels.

Lynd predicts that carbon dioxide removal will soon become the biggest driver of cellulosic ethanol and other biofuels. Photosynthesis in one form or another is the best way to remove CO_2 from the air, he says, and "the potential for biofuels in this capacity has been radically underestimated."

In biofuels that are produced efficiently, Lynd explains, 50–70% of the carbon content of the raw material is released and available for capture at the production site. Yet 40–70% of the feedstock's energy content remains in the fuel that's delivered to a vehicle. He cites a friend telling him that "biofuels are the only way we've figured out to have negative emissions and something other than negative-emissions [credits] to sell."

Dale is less optimistic about cellulosic biofuel's future. Biomass, he notes, can also readily produce methane. The existing natural-gas infrastructure and markets mean that incentivizing farmers to produce methane through anaerobic digestion of manure will be easier than motivating them to gather up crop stubble. While cellulosic ethanol wallows, biogas is already thriving, he says. "California is buying all it can get."

Dale, whose research currently focuses on sustainable agriculture, says US farmers could follow the example of counterparts in Italy who grow cover crops such as grasses after harvesting their grain or soybeans. In the spring, they harvest the grass, compress it, and allow it to ferment, producing biogas they burn to generate electricity. But in the US, he laments, "people are interested in these ideas, cover crops and so forth, but they don't think about harvesting them to make something farmers could sell."

David Kramer

Switzerland and the UK are relegated to sidelines of European research framework program

Scientists in those and other countries want science to be separated from politics.

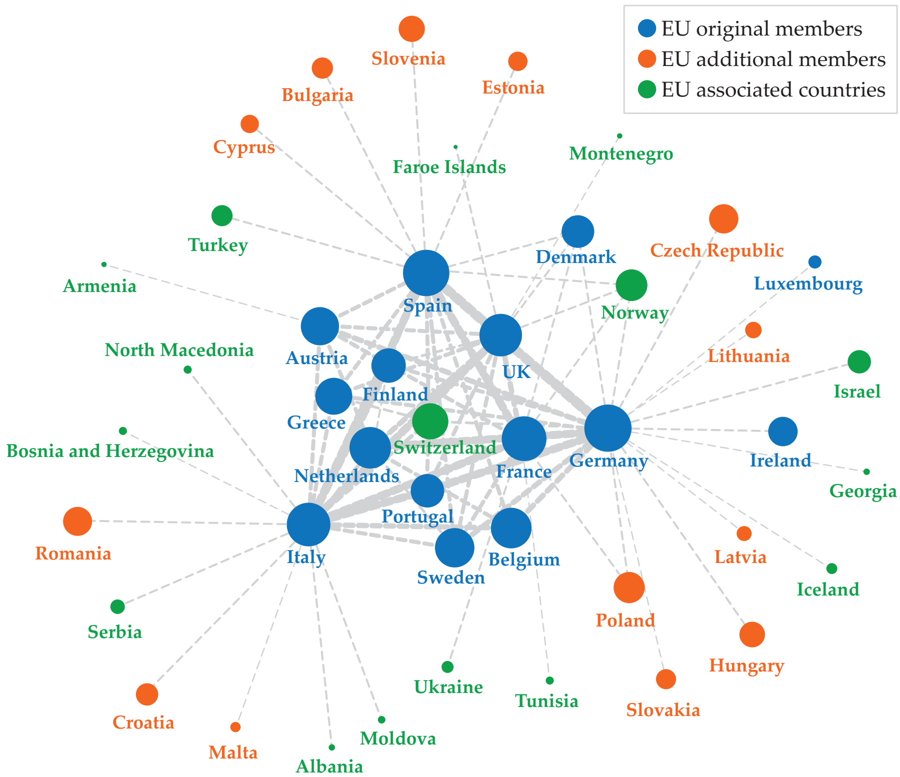
For the UK science community, participating in the research and innovation framework program of the European Union (EU) "may hang on how much fish France gets out of the English Channel," quips Vladimir Fal'ko, a condensed-matter theorist at the University of Manchester. "In Europe, things become political very quickly."

Political impasses have landed both the UK and Switzerland on the sidelines of Horizon Europe, the current €95.5 billion ($102 billion) framework program, which runs from 2021 through 2027. Negotiations between the UK and the European Commission (EC), the EU's executive body, have stalled over the Northern Ireland Protocol, which aims to satisfy the need for an open border for divided Ireland while also enforcing that border as a separation between the EU, to which the Republic of Ireland belongs, and the UK, of which Northern Ireland is a part. (See "Northern Ireland physicists face a unique post-Brexit situation" by Sarah Wild, Physics Today online, 3 May 2022.)

And in June 2021, the EC refused to negotiate with Switzerland—which has never joined the EU—about its association with Horizon Europe after that country pulled out of talks on bundling a bunch of bilateral agreements into one overarching agreement. The individual agreements span such issues as trade, agriculture, and access to social welfare and residency rights for EU citizens.

Scientists in the UK and Switzerland are dismayed to find themselves barred from full participation in Horizon Europe. They see the two countries' situations as intertwined, although the political contexts differ. The EU's hard line with Switzerland is interpreted by many as a signal to other countries in reaction to Brexit: Those who leave the EU don't get to pick and choose agreements with Europe à la carte.

The exclusion of Switzerland and the UK from Horizon Europe is bad for member states, too, says Robert-Jan Smits, president of Eindhoven University of Technology in the Netherlands. Previously at the EC, Smits ran the earlier EU framework program, Horizon 2020. "Without association, the possibilities for cooperating in easy and flexible ways are not there anymore. That is a blow for the fabric of cooperation that we have established over the years."



LINKS AMONG PARTICIPATING COUNTRIES are fostered by the European research and innovation framework program. Shown here is an overview of the strongest connections in Horizon 2020, the framework from 2014–20, based on 7500 collaborative projects in 2014–17. There were 28 European Union countries until the UK pulled out. Node size is representative of a country's participation in the framework program and the link thickness represents the number of collaborations. (Courtesy of the European Commission, Directorate-General for Research and Innovation.)

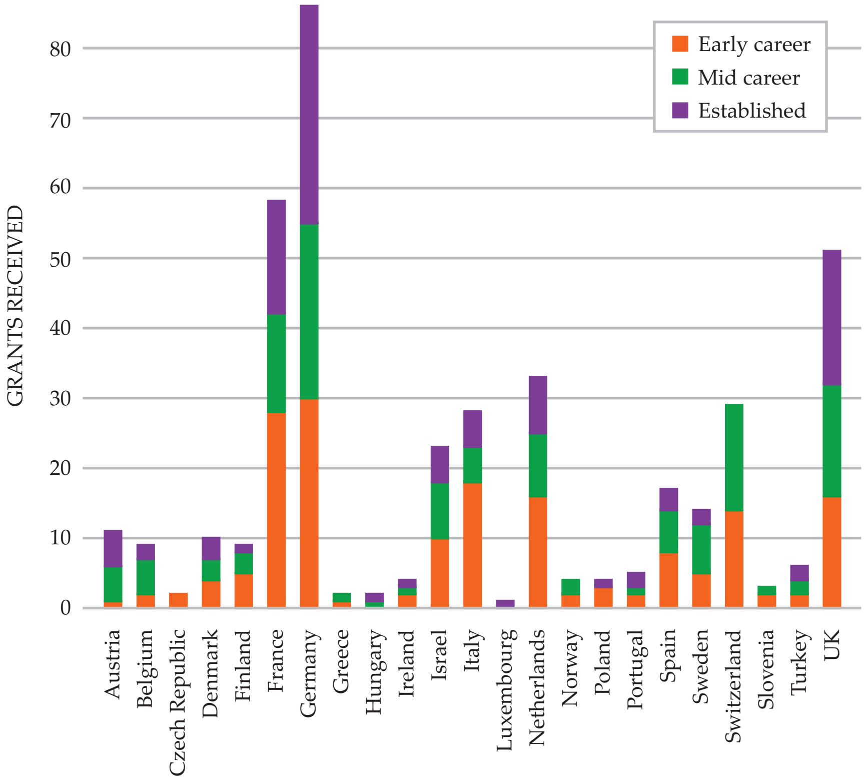
Cooperation and competition

Member and associated countries pay into the EU science and innovation framework according to their GDP, and grants are awarded competitively by the EC. The framework program includes postdoctoral fellowships, doctoral mobility opportunities, individual career grants, cross-border collaborations between industry and academia, and multinational collaborations.

Horizon Europe has five mission areas with goals set for 2030: adaptation to climate change, including societal transformation; cancer research, prevention, and treatment; healthy oceans, seas, and coastal and inland waters; climate-neutral and smart cities; and soil health and food. Examples of goals in those areas are cleaning marine and fresh waters, supporting the transformation of 100 cities toward climate neutrality, and achieving healthy soils across at least three-quarters of the EU. The current framework will continue the 10-year, €1 billion Quantum Technologies Flagship from Horizon 2020, but it is not launching new efforts in the same form.

All 27 EU member states and a dozen associated countries participate in the framework program. The associated countries include Israel, Norway, Turkey, and, until last year, Switzerland. Funded proposals from Israel, Switzerland, and the UK have often exceeded the monetary value of those countries' contributions.

New rules for the Horizon Europe framework program limit countries to getting out only as much money as they put in. But money is not the main benefit of participating, scientists say. Rather, the framework stimulates international collaborations, raises the level of competition, addresses global challenges, and strengthens science in Europe. Still, Smits notes the irony of top-performing countries consigned to the wings just when the EC is negotiating to admit far-flung countries into the framework program. Discussions are most advanced with Canada and New Zealand, he says. Australia, Japan, and South Korea are also interested.



NEARLY 20% OF AWARDS to individual researchers in the physical sciences and engineering in the 2021 call by the European Research Council went to researchers in the UK and Switzerland; the same was true across the life and social sciences and humanities. The successful applicants in those countries won't be funded by the ERC, though, because they are not currently associated with the Horizon Europe research and innovation framework program. (Compiled using data from the European Research Council.)

No longer leaders

Scientists in nonassociated countries can participate in more than half of Horizon Europe offerings. But individual grants are off limits, so researchers who want to go to Switzerland or the UK have lost access to the exchange programs. A suite of research grants spanning all career levels is also off the table for those countries. Most multinational projects are open, except in areas the EC deems strategic, such as quantum information and new space-propulsion systems.

The number of nonmember participants is often limited, sometimes to just one, notes Joël Mesot, president of ETH Zürich. "If someone else is already in, that's it." As nonmember participants in the framework program, researchers in Switzerland and the UK "have no rights to define projects," he continues. "We can't be the leader, and partners don't have to invite us to the table. It's a real problem."

Mesot notes that in 2014, Switzerland was excluded from the previous research and innovation framework program. The country was reinstated after more than two years. "We lost 30% of participation in collaborative projects," he says. Now, he continues, doubts over whether Switzerland will rejoin Horizon Europe mean "we are seen as unreliable partners, which is difficult for research consortia. It's a time of uncertainty for us and our partners."

"It's a disaster for collaborative projects," says Jean-Philippe Brantut, a tenure-track professor in the Laboratory for Quantum Gases at EPFL, the Swiss Federal Institute of Technology in Lausanne. "I have been contacted about joining international networks and had to say it won't work." The landscape in quantum technology moves quickly, he adds. "Because the field is growing, it's important to be there. Once a network has crystallized, if you are out, you are out."

Manchester's Fal'ko, who works on two-dimensional materials and played a significant role in the Graphene Flagship (see Physics Today, August 2021, page 20), says that after a while European colleagues "will see no benefit in working with [UK scientists] if we can't join their networks." If the UK doesn't participate in Horizon Europe, the best groups in the country will "automatically be damaged," he says. "It's not necessarily possible to find equally world-leading competencies in the UK to compensate for potentially broken links, as the strongest groups already have plans and commitments for the foreseeable future."

Compensation and confusion

For some researchers, the loss of access to prestigious European Research Council (ERC) grants for individuals represents the biggest hit. Both Switzerland and the UK were anticipated to be associated partners during the first call for proposals in Horizon Europe. By the time grantees were announced earlier this year, however, negotiations with Switzerland were stopped and those with the UK were dragging. Their downgraded status means researchers in those countries can't claim the awards—which came to nearly 20% of the total (see graph, page 26). Institutions in EU countries wooed many of them.

Both the Swiss and UK governments say they will compensate for the opportunities lost by ineligibility to participate in Horizon Europe. That includes stepping in to fund applicants who were awarded ERC grants in the first call. Switzerland is launching its own quantum initiative—to parallel the Horizon 2020 Quantum Technologies Flagship. And the government is offering to cover any ERC grant recipients from other countries who move to Switzerland and thereby lose their ERC funds. The UK is considering similar measures.

"Funding is easy to fix," says Brantut, whose ERC application last year was successful. "My colleagues who were not successful will now have the option to apply in Switzerland." But because the pool of applicants will be smaller, he says, the parallel grant "will not be nearly the career maker as an ERC grant." The domestic stand-in programs "can't replace the prestige," he adds.

"We are putting considerable effort to supporting researchers and to helping them navigate the red tape," says Jonathan Lamprecht, a scientific adviser for EU framework programs at the State Secretariat for Education, Research, and Innovation in Bern, Switzerland. "Some researchers don't realize they are able to participate in Horizon Europe." Lamprecht's colleague Brita Bamert stresses that "Switzerland's goal is to reenter Horizon Europe as soon as possible."

Researchers in the UK and Switzerland fear that exclusion from the European framework programs will degrade their communities. With fewer funding options, the system becomes more insular and less competitive, says Alberto Morpurgo, a University of Geneva experimentalist who works with graphene and other 2D materials. Fal'ko agrees: "I am afraid of the isolation. Access to fewer funding sources will also undermine our attractiveness to outside talent. And people who are mobile can and will move to Europe and continue their careers there."

"There's no benefit to the EU to cut ties with two of the communities with the best traditions in science and industry," says Didier Queloz, codiscoverer of the first exoplanet, who splits his time between the University of Cambridge and ETH Zürich. As an example, he notes that Europe aims to excel in artificial intelligence and quantum computing. "But it can't push if the best players are not playing leading roles—and the best people in AI and quantum computing are in the UK and Switzerland," he says. "By cutting ties, they remove horses from the carriage."

Stick to Science

On 8 February 2022, science leaders in Switzerland and the UK launched Stick to Science, an initiative that calls on politicians to disentangle science and politics—and to let their countries rejoin Horizon Europe independent of solving the broader disputes between them and the EU. More than 5500 individuals and 270 organizations across Europe have endorsed the initiative. "The signatories believe that collaboration in science, research and innovation in Europe is more important than ever as we face some of the world's greatest challenges," the Stick to Science website says. "Europe's position in the world would be stronger with robust research collaborations that contribute to a prosperous European research and innovation landscape."

It's important for politicians to hear the Stick to Science message, says Antoine Petit, chairman and CEO of the CNRS, and an early signatory. Cooperation between researchers in the UK and Switzerland with colleagues in EU member states will continue either way, he says. But without affiliation in Horizon Europe, institutions in the UK and Switzerland will likely put their efforts into scientific cooperations outside of Europe.

"You should not change a winning system," says Otmar Wiestler, president of the Helmholtz Association, Germany's largest network of research centers. The conflict in Ukraine could be an argument to separate R&D from the overarching negotiations between the EU and the UK and Switzerland, Wiestler says. The war will force Europe to reconsider economic issues, military readiness, energy, and international relations, he explains. "It's not the time for Europe to splinter more. We need to pull together."

Toni Feder PT

Originally Published in the Sept 2021 GradSchoolShopper Magazine

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

Find Your People and Grad Program at the 2022 Physics Congress

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

Samantha Pedek, 2022 Program Co-chair

Samantha Pedek

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

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

Networking at PhysCon was unlike any other professional development experience I had as an undergraduate physics student. The sheer number of like-minded people was daunting—hundreds of physics and astronomy undergraduates, representatives from graduate schools and summer research programs, employers from all over the country, and well-established professionals at the height of their careers were all under one roof for three days.

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

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

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

NETWORKING TIPS

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

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

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

BE AN SPS INTERN

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

www.spsnational.org/programs/internships.

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

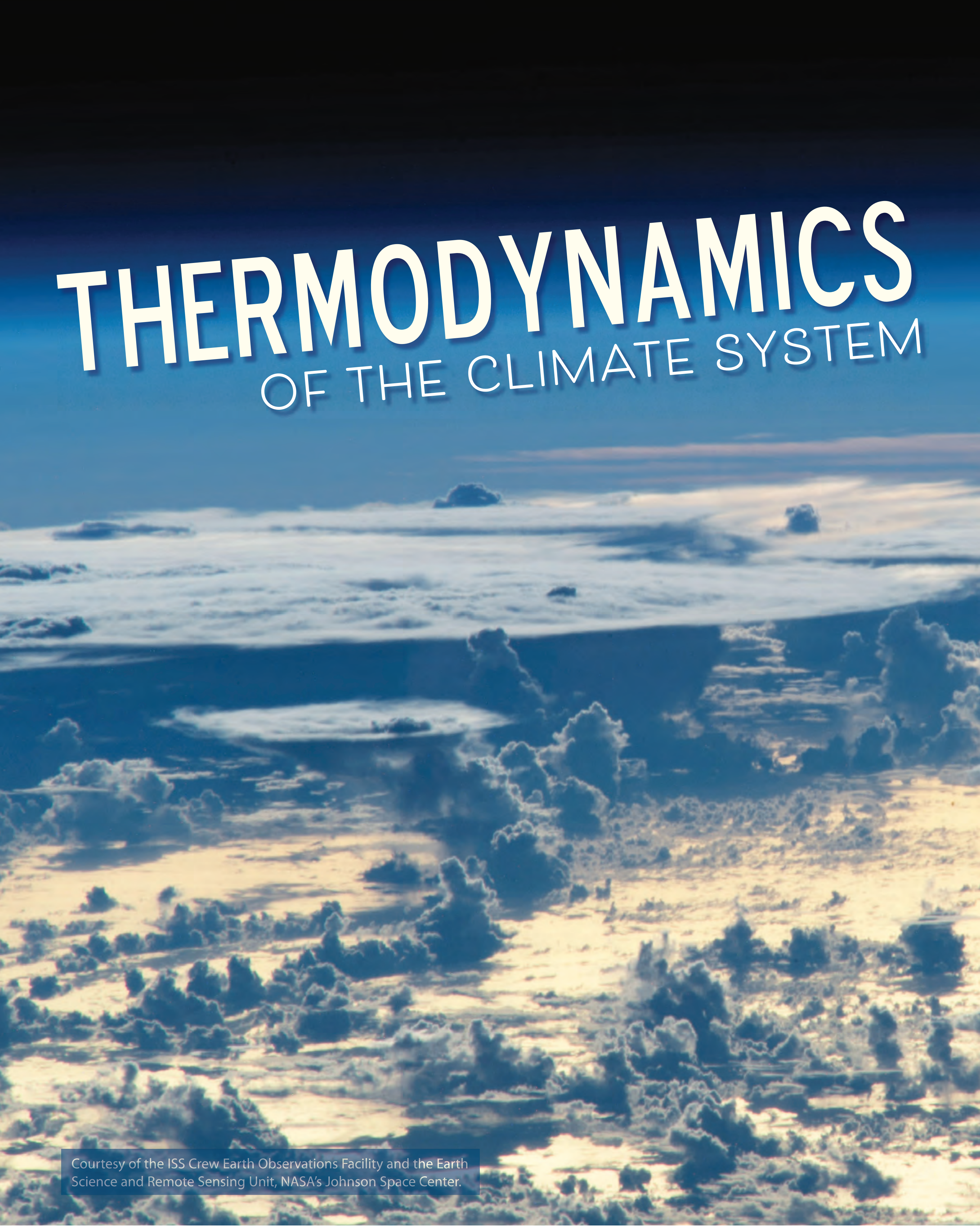
A more subtle opportunity to build your network as a young professional is to engage with attendees you don't already know, between events or at meals. Shuffling between workshops, plenaries, and banquets will be hundreds of people with lived experiences similar to yours. Be adventurous and sit at a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

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

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

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

THERMODYNAMICS OF THE CLIMATE SYSTEM



Courtesy of the ISS Crew Earth Observations Facility and the Earth Science and Remote Sensing Unit, NASA's Johnson Space Center.

Martin Singh is a senior lecturer in the Centre of Excellence for Climate Extremes at Monash University in Victoria, Australia. **Morgan O'Neill** is an assistant professor in the department of Earth system science at Stanford University in California. This article is based on the authors' recent article "The climate system and the second law of thermodynamics," published in *Reviews of Modern Physics* in January 2022.

Martin S. Singh and Morgan E O'Neill

To understand Earth's climate, think of it as a giant, planetary-scale heat engine that drives the circulation of the oceans and atmosphere.

Throughout its history, Earth has experienced vastly different climates, including "snowball Earth" episodes, during which the planet is believed to have been entirely covered in ice, and hothouse periods, during which prehistoric alligators may have roamed the Arctic. Recent anthropogenic greenhouse gas emissions are the cause of modern, rapid climatic change, which poses a growing hazard to societies and ecosystems.

The climate system comprises the fluid envelopes of Earth: the atmosphere, oceans, and cryosphere. Those constituents, along with the evolving surface properties of the solid lithosphere, are responsible for reflecting some and absorbing most radiation received from the Sun. The climate system is close to an energy balance at all times. The total energy doesn't significantly fluctuate in time because terrestrial radiation is emitted to space at approximately the same rate at which solar energy is absorbed.

Being in nearly exact energy balance with the universe allows Earth to have a relatively familiar climate tomorrow and a century from now. But over time, small deviations from a strict energy balance can induce massive changes in climate. Such small deviations are due to the diurnal and seasonal cycles, orbital variations—the Milankovitch cycles, for example (see the article by Mark Maslin, Physics Today, May 2020, page 48)—and internal forcings, such as anthropogenic emissions of carbon dioxide.

Another characteristic of Earth's climate—indeed, any planetary climate—is that it evolves irreversibly. Imagine watching a 10-second video of a field with a leafy tree on a sunny day. Would you notice if that video had been shown in reverse? Maybe not. Now imagine watching a 10-second clip of the same field and tree during a windy rainstorm. You could probably immediately assess whether the clip was run forward or backward in time. Some obvious tells stand out: Rain should fall toward the ground, and leaves should separate from, not attach to, the tree.

The climate system contains myriad irreversible processes, and on both a calm day and a stormy day they produce entropy. Like energy, entropy is a property of any thermodynamic system, and it can be calculated if one knows the state of the system. But unlike energy, entropy is not conserved. Rather, it is continuously produced by irreversible processes. Although physicists often consider ideal, reversible processes, all real physical processes are irreversible and therefore produce entropy.

In accordance with the second law of thermodynamics, irreversibility in the climate system permanently increases the total entropy of the universe. As in the case for total energy, though, the total entropy in the climate system is relatively steady. That's because the climate is an open system that receives much less entropy from the Sun than it exports to the universe (see box 1). The difference between what is imported and what is exported is produced locally, through friction, mixing, or irreversible phase changes.

Although the climate is approximately steady, it is far from thermodynamic equilibrium, which would be a very cold and boring state with no motion. Instead, the climate system may be thought of as an engine, fueled by the unequal distribution of solar radiation incident upon it. It is those gradients in energy, and the resulting gradients in temperature and pressure they produce, that allow the wind to blow.[1]

Climate system as heat engine

The concept of a heat engine is familiar to engineers and students of thermodynamics. Through the transport of heat from a hot reservoir to a cold one, a heat engine produces mechanical energy that may then be used to perform useful work. Examples include steam engines, internal combustion engines, and power plants. When run in reverse, a heat engine becomes a refrigerator or a heat pump.

The efficiency of the engine provides information about how much work it can produce for a given heat input. A remarkable consequence of the second law of thermodynamics is that a theoretical upper limit to that efficiency exists, and it may be expressed as a simple function of the temperatures T_H and T_C of the hot and cold reservoirs:

$$\eta_C = \frac{T_H - T_C}{T_H}.$$

Named the Carnot efficiency after the scientist who first derived it,[2] η_C determines the maximum possible work any heat engine can perform on an external body. It is achieved by a closed, reversible (ideal) engine, known as a Carnot engine (see figure 1a). Real heat engines can never truly reach the Carnot efficiency because their work output is limited by irreversible processes (see figure 1b). The output of an internal combustion engine is limited, for instance, by frictional losses between the pistons and cylinders and by conductive losses to the surroundings.

The climate system is essentially a giant planetary-scale heat engine. It is heated by the absorption of solar radiation and cooled by the emission of radiation to space (see figure 1c). The heating is largest at the warm tropical surface, while the cooling occurs primarily in the colder troposphere and is weighted toward higher latitudes. The planetary heat engine transports heat from the warm surface source to the colder tropospheric sink by the flows of the atmosphere and oceans.

But how do climate scientists characterize the work performed by the planetary heat engine? Earth cannot push on any external body, and in the framework of a classic heat engine, its work output is identically zero! The oceans and atmosphere do, however, perform work on themselves and each other, and that work generates the familiar winds and ocean currents that scientists observe. For climate scientists, useful work is that used to drive atmospheric and oceanic circulations.

Because the work performed by the planetary heat engine is internal to the engine itself, its efficiency is not limited by the Carnot efficiency. Rather, the climate system can, in principle, recycle some of the heat produced by the frictional dissipation of winds and ocean currents and increase its maximum efficiency to a value

$$\eta_P^{max} \approx \frac{T_H - T_C}{T_C},$$

which is similar to the Carnot efficiency, except that the temperature in the denominator is replaced by that of the cold sink.[3] The maximum planetary efficiency occurs when all available energy is used to drive atmospheric and oceanic currents and when the dissipation of those currents is concentrated at the warm source—for instance, through friction with Earth's surface. As we shall make clear, Earth's heat engine operates far from that limit.

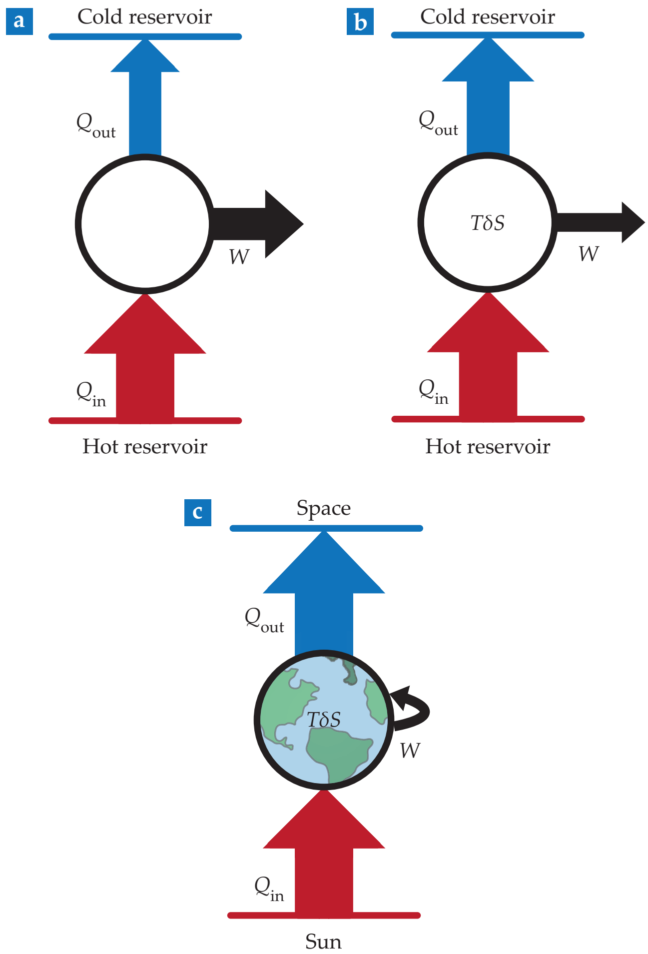


FIGURE 1. CLIMATE AS HEAT ENGINE. A heat engine produces mechanical energy in the form of work W by absorbing an amount of heat Q_{in} from a hot reservoir (the source) and depositing a smaller amount Q_{out} into a cold reservoir (the sink). **(a)** An ideal Carnot heat engine does the job with the maximum possible efficiency. **(b)** Real heat engines are irreversible, and some work is lost via irreversible entropy production $T\delta S$. **(c)** For the climate system, the ultimate source is the Sun, with outer space acting as the sink. The work is performed internally and produces winds and ocean currents. As a result, $Q_{in} = Q_{out}$.

Along with doing work, atmospheric and oceanic circulations are important in setting the spatial cloud and temperature distribution on Earth. As a result, the winds and currents driven by the planetary heat engine affect both its efficiency and the amount of heat that it transports. Those effects lead to an important feedback that regulates the climate: The work performed by the planetary heat engine acts to reduce the temperature gradient that drives it.

Such behavior complicates the analysis of Earth's heat engine, but it also raises tantalizing questions of planetary climate dynamics. What sets the efficiency of the planetary heat engine? Has it changed in the past, and will it change in the future? How does the operation of the planetary heat engine affect the everyday weather?

Irreversible processes

The work performed by the planetary heat engine produces in the atmosphere and oceans eddies of vastly varying scale and intensity, including tiny ripples on the ocean surface and violent winds in a tropical cyclone. Turbulence deforms such eddies into new shapes and patterns until viscosity ultimately dissipates their kinetic energy into heat. The resultant cycle of energy production and dissipation, beautifully described in 1955 by Edward Lorenz,[4] implies a balance between work and frictional dissipation in the climate system.

The presence of friction does not necessarily limit the planetary heat engine's efficiency. In fact, the heat engine approaches its maximum efficiency when the frictional dissipation of winds and ocean currents is the dominant irreversible process. But other irreversible processes in the climate system compete for the available energy, as shown in figure 2. For example, heat conduction—that between the surface and atmosphere and that caused by molecular diffusion in the oceans and atmosphere—reduces the planetary efficiency just like conductive losses do in an internal combustion engine. Absorption, reflection, and emission of radiation are also irreversible processes, although they are generally not considered in discussions of the planetary heat engine (see box 1).

On Earth, an additional class of irreversible processes represents by far the most important control on the planetary heat engine. Those processes exist because of an aspect of Earth's climate that makes it habitable for life: the presence of an active hydrologic cycle.

Consider the path of a parcel of water from the ocean surface through Earth's hydrologic cycle. Heated by the Sun, the parcel initially enters the atmosphere by evaporating into the air. Like the drying of a wet shirt on a clothesline, that process of evaporation is irreversible. In its gaseous form, the parcel is at the mercy of the winds, swirling through the atmosphere and mixing with the air around it. Eventually the parcel is drawn into an updraft, cooling as it rises, until it condenses into tiny droplets in the saturated core of a cloud.

If it reaches high enough altitude, the parcel encounters subfreezing temperatures of the upper atmosphere and the droplets spontaneously and irreversibly freeze. As the frozen droplets grow, they begin to fall, first as snowflakes and later as raindrops. As they fall, the droplets irreversibly lose gravitational potential energy and partially evaporate as they pass through subsaturated air.

The various irreversible processes in the hydrologic cycle limit the work performed by the planetary heat engine. The effect may be quantified by considering the contributions of those processes to the irreversible entropy production of the climate system. Although such contributions are difficult to constrain observationally—an exception is the dissipation caused by falling precipitation, which may be estimated using satellites, as shown in figure 3—one may use models of the climate system to estimate their magnitude.

In 2002, Olivier Pauluis and Isaac Held used such an approach to demonstrate that irreversible processes associated with the hydrologic cycle,[5] including phase changes, mixing, and precipitation, account for most of the irreversibility in the atmosphere and in Earth's climate system more broadly (see figure 2). Those so-called moist processes limit the entropy production associated with frictional dissipation, and they reduce the planetary heat engine's efficiency. Indeed, moist

Box 1. Entropy of radiation

Like matter, radiation obeys the second law of thermodynamics. The concepts of entropy and irreversibility are therefore just as relevant to photons as they are to atoms and molecules. But although the second law was developed for matter using the techniques of classical thermodynamics by Sadi Carnot,[2] Rudolf Clausius,[15] and others in the middle of the 19th century, a full account of the entropy of radiation had to wait for Max Planck's theory of heat radiation.[16] According to Planck, the entropy carried by a beam of radiation is dependent on its frequency spectrum, angular distribution, and polarization. A given amount of radiant energy carries the greatest amount of entropy when it is low frequency, isotropic, and unpolarized.

Earth scrambles a focused beam of solar radiation into a diffuse beam made of reflected solar radiation and terrestrial radiation at much lower frequency. As such, the radiative interactions, including absorption, emission, and reflection, are irreversible on Earth and contribute to the planet's entropy production. A simple analysis of that production allows one to quickly reject the notion—sometimes seen in contemporary discussions of global warming—that the greenhouse effect is in violation of the second law of thermodynamics (see the article by Raymond Pierrehumbert, Physics Today, January 2011, page 33).

In fact, irreversible entropy production by radiative processes is the dominant source of irreversibility on the planet. Most studies of the second law applied to Earth, however, consider only matter (atoms and molecules) to be a part of the climate system, whereas radiation (photons) is considered a part of the surroundings. In that view, radiation is treated as an external and reversible heat source or sink, and the irreversibility of radiative processes does not enter discussions of the planetary heat engine.

processes exert a profound influence on various atmospheric circulations, including individual clouds and the global circulation.

Drivers of global circulation

Imagine it's late morning in a tropical paradise. The Sun is starting to heat the ground and produce warm, rising bubbles of clear air known as thermals. Those thermals are replaced by slowly sinking air that has lost energy because of radiative cooling. Such vertical exchanges, or circulations, of air are a local version of the planetary heat engine, and climate scientists expect the work done by such dry thermals to scale with the surface heating rate.

Later in the day, the surface has warmed sufficiently to make stronger thermals. They can reach and exceed the lifting condensation level, where the water vapor in the air cools enough to condense as liquid water. That process introduces a phase change. The presence of a hydrologic cycle means that rising air can be seen as it forms clouds, and the clouds themselves indicate a local dominance of irreversible entropy production from moist processes.

If the system is defined to include both clouds and the surrounding, slowly sinking air, the total work available to drive motions can potentially be much smaller, and it no longer scales with the surface heating rate. Instead, the updrafts in clouds decouple from the heating rate, and their properties depend on microscopic details of cloud processes, such as the speed at which raindrops fall through the air and the rate at which moist, cloudy air is mixed into the dry surroundings at the cloud edge.

One can think of a developing cumulus cloud as a heat engine that does work on itself and the surrounding atmosphere. But not all clouds behave like a heat engine. Imagine, for example, a thin sheet of cirrus (an ice cloud) high in the atmosphere that is simply being advected by the wind. No potential energy is being released to perform work on the surroundings.

The heat engine analogy of a single cloud, however, can be usefully applied to organized clusters of convective clouds, which can take the form of thunderstorms, midlatitude storms, and tropical cyclones. Also known as hurricanes and typhoons, tropical cyclones in particular have long been conceived of as Carnot heat engines (see the Quick Study by Kerry Emanuel, Physics Today, August 2006, page 74). In reality, those storms are irreversible and extremely inefficient.

On global scales, the atmospheric circulation is driven by the differential heating associated with the Sun's angle. It man-

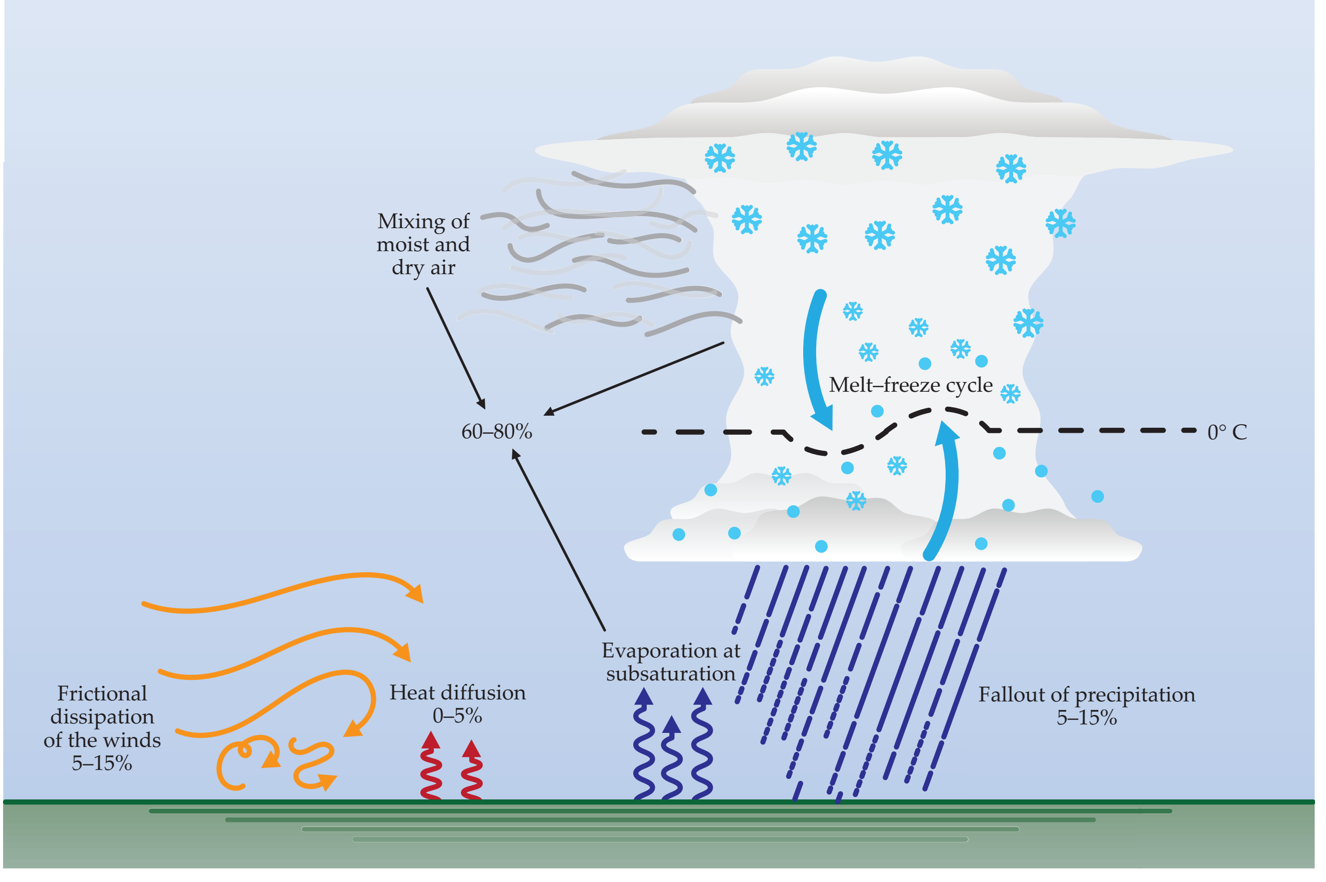


FIGURE 2. IRREVERSIBLE PROCESSES in the atmosphere. Neglecting radiative processes (not shown here), the largest sources of irreversibility in the atmosphere are those associated with the hydrologic cycle: evaporation, the mixing of moist and dry air, and the melt–freeze cycle (60–80% collectively), and the fallout of precipitation (5–15%). Those contributions limit the entropy generated by frictional dissipation of the winds (5–15%), which ultimately places a limit on the work performed by the atmospheric heat engine in generating circulations. Percentages are estimated based on global climate simulations[12] and idealized high-resolution simulations.[8]

Box 2. Heat engines on other planets

The gross characteristics of Earth's climate are unique to its rotation rate, planetary and orbital radii, mean temperature, and water content. Other planets in our solar system or in orbit around other stars have dramatically different climates. Earth's heat engine is one example of a wide range of possibilities on planets with fluid envelopes. The giant planets (Jupiter, Saturn, Uranus, and Neptune), for example, are all presumed to have water clouds, but they likely also have ammonia, ammonium hydrosulfide, and hydrogen sulfide clouds. Saturn's moon Titan has an active hydrologic cycle with methane clouds and rain (see the article by Ralph Lorenz, Physics Today, August 2008, page 34). The presence of exotic condensation and evaporation suggests that those planetary heat engines are highly inefficient and produce considerable entropy via the whole suite of irreversible processes.

Other surprising differences exist between the climates of Earth and its neighbors. Take Mars, for example. Other than a carbon dioxide cycle that deposits its snow on the winter pole and the occurrence of wispy water–ice clouds near the equator, Mars's thin atmosphere is extremely dry. One might assume that it could thus be relatively efficient, given the lack of a planetary-scale hydrologic cycle. Mars, however, has periodic, planetary-scale dust storms, which represent a major source of drag inside the atmosphere. Settling dust reduces the atmosphere's gravitational energy and converts it directly into internal energy. The process reduces the efficiency of the Martian heat engine.

Another curiosity is the lack of a known, well-defined bottom boundary on the giant planets. On rocky planets like Earth, the frictional surface is the primary source of dissipation of winds. What sets the brakes on the winds of giant planets if their fluid envelopes just get denser on the way down? Hypotheses include wave breaking and magnetic field effects.

Observations demonstrate that Earth is close to entropy and energy balance at all times. That need not be true of other planets. Jupiter, Saturn, and Neptune are all losing more heat to space than they receive from the Sun, which indicates that they are still cooling and shrinking over time. Just as energy balance is not an inevitable planetary characteristic, the same holds true for the entropy budget: Those gas giants could also be losing net entropy to space. That would be consistent with the second law of thermodynamics because planets are open systems.

ifests as large overturning cells and jet streams. All planets in orbit around a star are heated most strongly at any given moment at the substellar point, where the planet's surface is directly perpendicular to the star's radiation. Because Earth's day is short relative to its orbital period around the Sun, the planet is primarily warmed in the tropics (±30° latitude), and that heat is redistributed by the oceans and atmosphere toward the poles. The polar regions therefore lose more radiation to space than they receive from the Sun. For the global circulation, the characteristic input and output temperatures of the planetary heat engine are controlled by two temperature gradients: the surface-to-upper-atmosphere gradient and the equator-to-pole gradient.

Climate scientists quantify the efficiency of the global circulation, which, as we have seen, is a strong function of the moist, irreversible processes occurring within it. One of the most robust theoretical predictions of climate change is that the total amount of water vapor in the atmosphere will increase with warming—by about 7% per kelvin.[6] If the magnitude of moist processes also increases with the vapor content, scientists might expect the climate heat engine to become less efficient on a warmer planet. A study of global climate models shows that, indeed, the mechanical efficiency of simulated future climates may go down and decrease the net energy available to drive winds.[7] More detailed modeling on local scales, however, shows the opposite.[8] Which one is right? And what does it

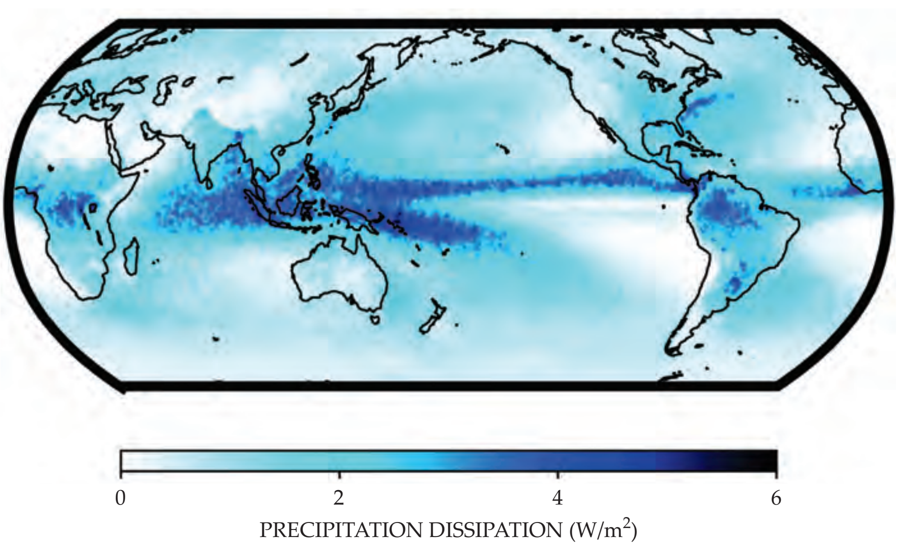


FIGURE 3. FALLING PRECIPITATION. One of the most important sources of dissipation in the atmosphere occurs when raindrops fall, a process that reduces their gravitational potential energy. Using satellite information from NASA's Global Precipitation Measurement mission, we estimated the dissipation for the years 2015–20 with the method outlined in reference 13. The largest dissipation rates occur where precipitation rates themselves are highest—in the tropical western Pacific Ocean and in a band around the globe known as the intertropical convergence zone.

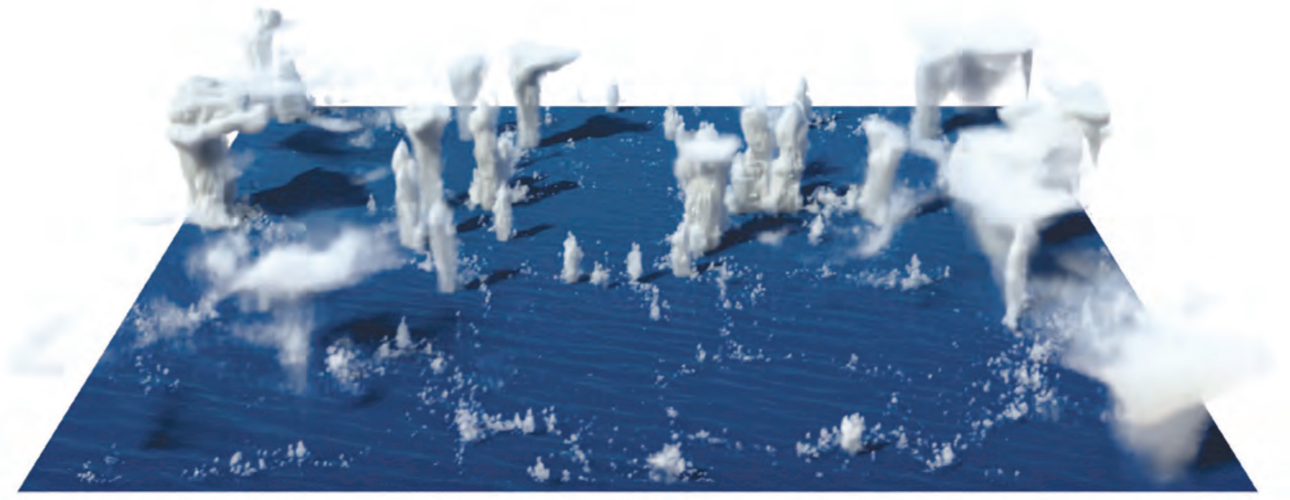


FIGURE 4. NUMERICAL MODELS are crucial for conducting climate research and estimating irreversible processes in the atmosphere and oceans. This image is a snapshot of clouds from an idealized high-resolution simulation made with the System for Atmospheric Modeling.[14] The simulation spans a 100 x 100 km^2 region of ocean using a horizontal grid size of 250 m. It captures many details of cloud morphology, including the tiny boundary-layer clouds that form a ring in the foreground of the image and the wispy cirrus clouds in the extreme bottom right. Processes that produce entropy irreversibly—such as mixing, evaporation, and the falling of raindrops—are not resolved and must be estimated through submodels called parameterizations.

mean for Earth's future climate? Those are outstanding questions in climate science; answering them requires fundamental advances in scientists' ability to model irreversibility in the climate system.

Modeling irreversibility

Models of the climate system come in various forms, such as general-circulation models that simulate the entire atmosphere or ocean and detailed large-eddy-simulation models that capture processes associated with individual clouds (see figure 4). Such models are used in numerous ways, such as forecasting the weather and probing the climate of alien worlds, as discussed in box 2. Regardless of their application, the general characteristics of climate models remain the same. The atmosphere or ocean is discretized, and a set of equations representing physical laws, such as conservation of mass, momentum, and energy, is numerically solved on the model grid.

Since weather and climate models are based on fundamental physics, one can naturally expect them to satisfy the second law of thermodynamics. Indeed, analysis of the entropy budget of climate models has allowed scientists to probe the climate system's irreversibility far beyond what observations alone would allow. Such studies have shed light on the role played by moist processes in governing how Earth's planetary heat engine may respond to climate change.

A challenge in climate modeling is representing processes that act on scales smaller than the model's grid length. For example, the large-eddy simulation represented in figure 4 has a horizontal grid spacing of 250 m. It can resolve the air movements of a given cloud, but it cannot resolve processes at smaller scales in, for example, turbulence that leads to irreversible mixing or the formation of individual raindrops. The effect of those subgrid processes must be accounted for using submodels called parameterizations.[9]

Beyond classical thermodynamics

So far, we have remained largely in the world of classical thermodynamics, having explored the conceptual model of the climate system as an irreversible heat engine. The second law of thermodynamics and the idea of irreversibility, however, may be interpreted more generally.[10] The field of statistical mechanics, for example, has proven valuable to the study of certain long-lived flow phenomena in our solar system, such as Jupiter's famous Great Red Spot and Earth's stratospheric polar vortices.

Such problems require that researchers discard the heat engine model entirely and consider the system of interest as thermodynamically isolated and in contact with a single thermal reservoir rather than two. One can then generalize the concept of entropy to be a measure of the number of microscale arrangements of fluid particles that produce a given large-scale fluid behavior. By maximizing this Boltzmann entropy, scientists find the most likely long-term structures of the flow.

Although the Boltzmann entropy is widely known to provide the equilibrium distribution of molecular speeds in an ideal gas, it predicts counterintuitive and stunningly beautiful behavior, such as jets and vortices, when applied to planetary fluid envelopes. That's because high-Reynolds-number fluids that are dominated by stratification and rotation, which characterize most planetary fluid envelopes, exhibit quasi two-dimensional behavior that leads to an upscale energy cascade.

Instead of producing ever-smaller eddies that are lost to viscosity, 2D turbulence produces ever-larger structures that persist in time. Two-dimensional fluids pose a particular challenge theoretically because they conserve an infinite number of variables, which substantially constrains their evolution. That technical challenge was surmounted by the Robert-Sommeria-Miller (RSM) theory. (See the review in reference 11.)

The RSM theory and related statistical mechanical treatments of fluid flow provide a method to retrieve the long-time steady solutions for an inviscid fluid. But all real fluids have viscosity, and any real steady-state jet or vortex must be at least weakly forced because it is at least weakly damped by dissipation. It is remarkable then that some examples of real, large-scale vortices in the solar system can be predicted by inviscid theory for flows in thermodynamic equilibrium.

How can climate scientists reconcile a conceptual model of a planetary heat engine, which requires a temperature gradient to induce an overturning circulation, with the fact that observed large-scale vortices can be predicted by models that forbid temperature gradients? Tropical cyclones certainly have an important overturning circulation that responds to surface heating and upper-level cooling, but the much larger stratospheric polar vortex does not: It is a 2D phenomenon that is amenable to description using Boltzmann entropy. The most useful interpretation of the second law of thermodynamics is evidently feature-dependent in the climate system.

The swirling, circulating components of a planetary climate continue to inspire and confound. Understanding the drivers of a climate requires using a hierarchy of conceptual, analytical, and numerical models. Climate scientists have had to be creative and borrow from statistical mechanics, economics, and other fields to make sense of a spectacularly complex moving target. Amid a period of rapid anthropogenic climate change, it is more important than ever to make sure that climate science is accessible to the broadest possible coalition of researchers.

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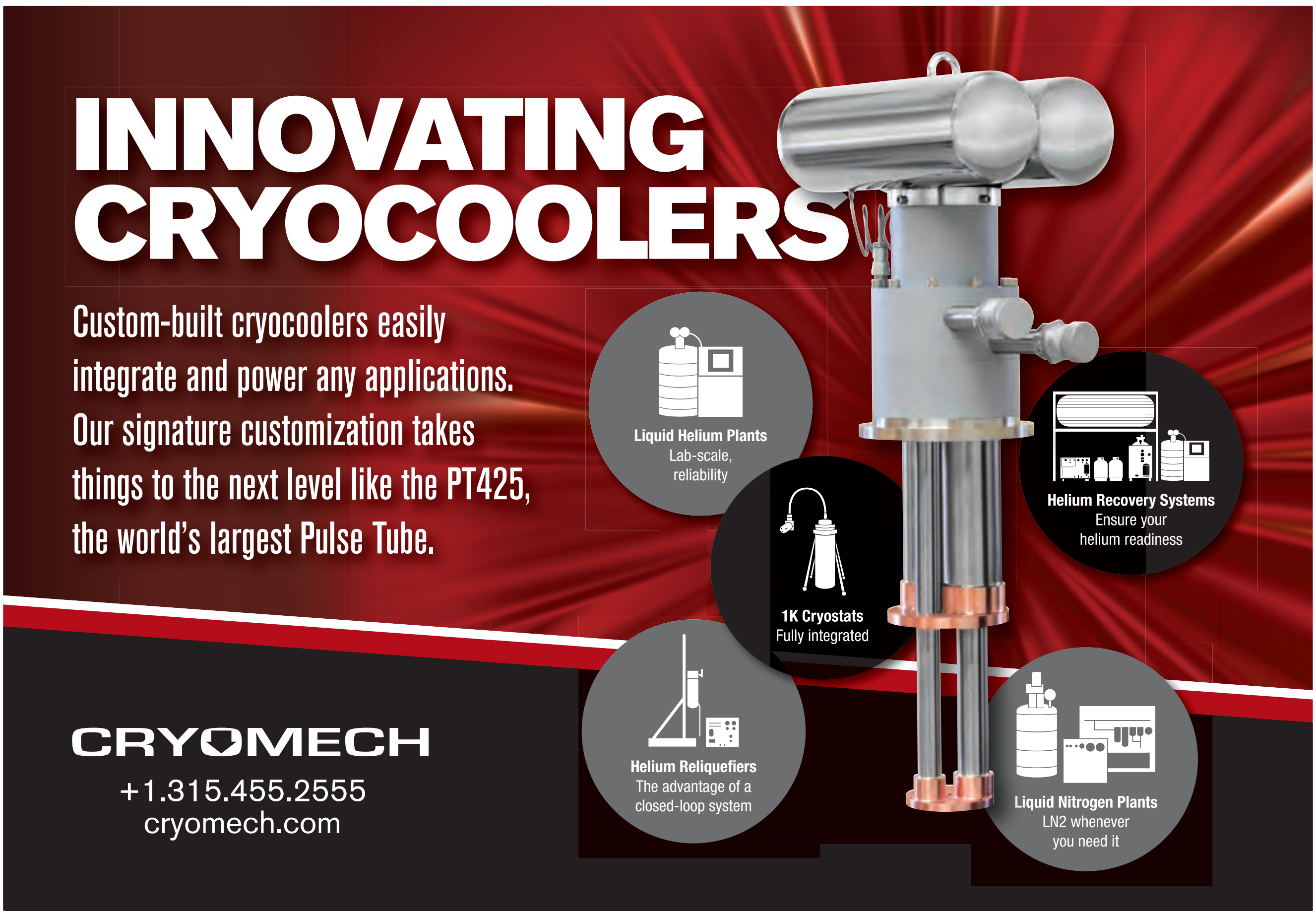
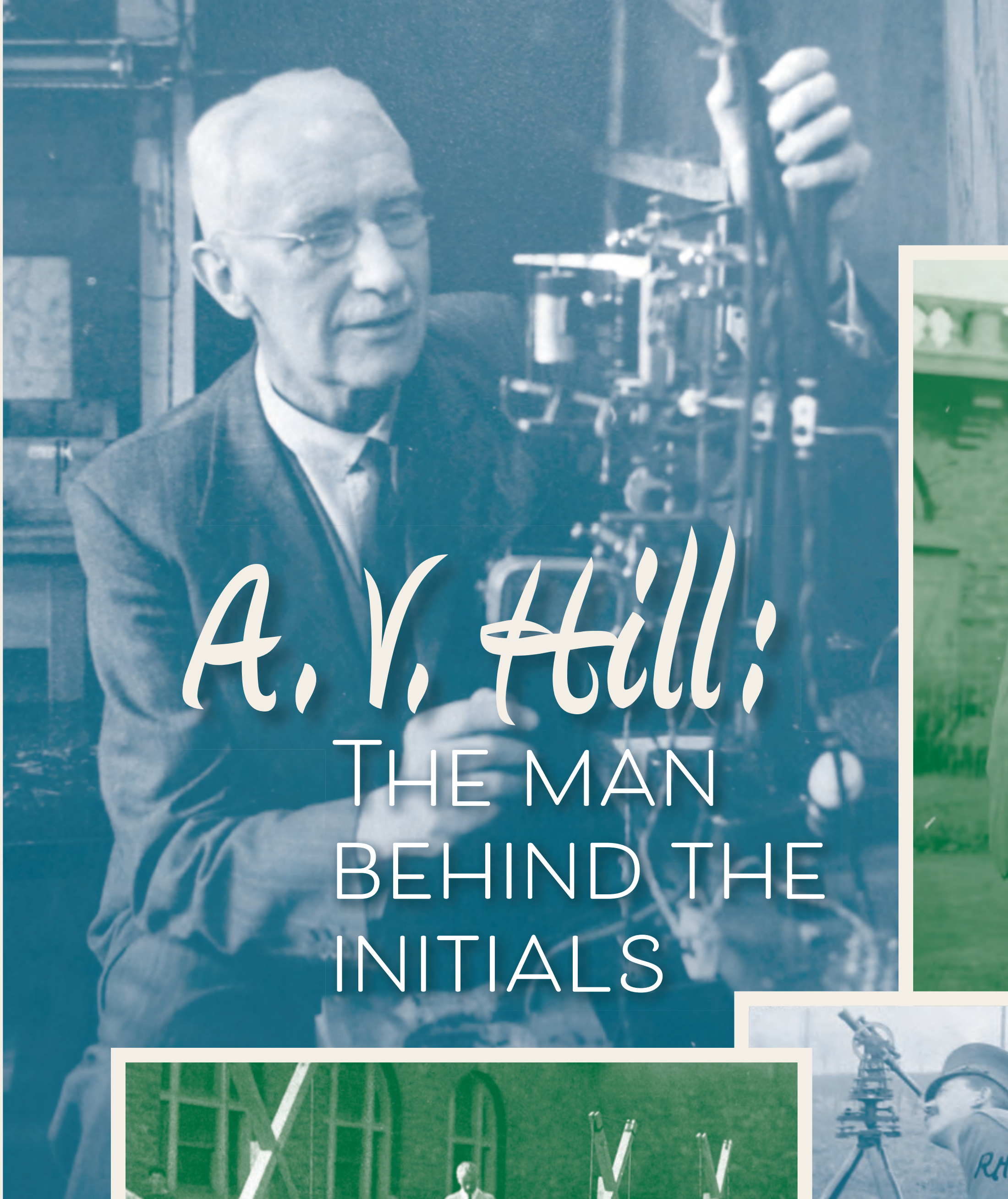
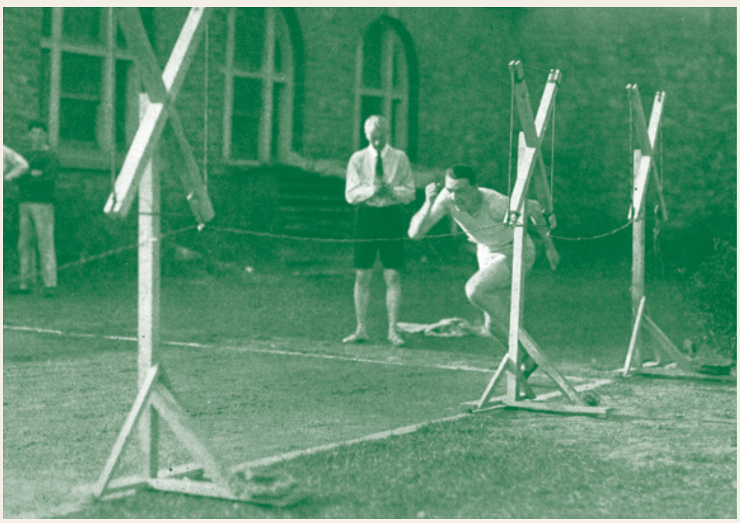


A. V. Hill: The man behind the initials





Clockwise from top left: A. V. Hill in his laboratory in 1948; with a sprinter wearing a Douglas bag to measure his oxygen consumption; with the physicist Ralph Fowler (left), testing their prototype aircraft-position finder during World War I; and measuring a sprinter's acceleration at Cornell University in 1927. (The top two and bottom left images are courtesy of Nicholas Humphrey, and the bottom right image is courtesy of Nicholas Humphrey and the Churchill Archives Centre.)

Andrew Brown is a retired radiation oncologist. He has previously published biographies of James Chadwick, John Desmond Bernal, and Joseph Rotblat. *Bound by Muscle*, his book about A. V. Hill and Otto Meyerhof, will be published by Oxford University Press later this year.

Andrew Brown

The Nobel Prize winner was one of the founders of biophysics. He also helped rescue thousands of academics from Nazi-dominated Europe and contributed significantly to UK defense efforts in World War II.

The morning he received word he would receive a share of the 1922 Nobel Prize for Physiology or Medicine, A. V. Hill rode to University College London (UCL) on his sidecar motorbike. Enthusiastic students carried him around the quadrangle before assailing Hill's distinguished predecessor as UCL's professor of physiology, Ernest Starling, in his laboratory. Because Hill's interests ranged far beyond the field's traditional boundaries, Starling had once joked that he did not know any physiology. The students taunted him with that remark, but Starling refused to give up the joke, exclaiming, "He doesn't know a damned word!"[1] All kidding aside, Starling held his successor in high esteem: When recruiting Hill to UCL, he accurately predicted that Hill would become the "most important person in the physiological world."[2]

Archibald Vivian Hill (1886–1977) was a physiologist, military scientist, and humanitarian. To most of his colleagues, family, and friends, he was known simply as "A. V." A central figure in UK science during the first half of the 20th century, Hill was also a prominent member of the international community. In the 1930s, he became an outspoken critic of fascism and was a cofounder, and subsequently the effective leader, of the Academic Assistance Council, which helped Jewish and anti-Nazi academics flee Germany and, later, Nazi-occupied Europe. In 1940 he laid the groundwork for the crucial Tizard Mission to the US and was elected as a member of Parliament (see figure 1). He extended his research beyond laboratory work on frog muscle to study the physiology of exercise in humans and became a pioneer in the new subject of biophysics.

Early life

After her marriage collapsed, Hill's mother, Ada, raised her two children alone. A. V. was competitive as a youngster and collected a series of scholarships that underpinned his education. The first was awarded to attend Blundell's School, a boarding school in Devon in southwestern England, where he excelled both academically and as a sportsman. Scholarships allowed him to attend Trinity College at Cambridge University, where he studied mathematics. He placed third in the famously grueling Wrangler exams in 1907.

Despite that success, the leading exam

coach of the era, R. A. Herman, cautioned Hill that he did not believe the student would make the grade as a mathematician. Although Hill never lacked self-confidence, he was realistic about his limitations and took Herman's opinion to heart. He discussed alternatives with his tutor, the physiologist Walter Fletcher, and decided to follow Fletcher into that field. Hill graduated with first-class honors in physiology in 1909 and, with fresh scholarship support, immediately embarked on a research career. In 1913 he married into the Cambridge academic aristocracy: Hill's bride, Margaret Keynes, was the daughter of the chief administrator of the university and the younger sister of the economist John Maynard Keynes.

Physiology

In those days, physiology included the subjects that would now be termed embryology, histology, biochemistry, and pharmacology. The chief of the overcrowded physiology department was John Langley, who had succeeded the department's founder, Michael Foster. When Foster arrived at Cambridge from the Royal Institution in 1870, his working space consisted of one room with three tables. A purpose-built physiology laboratory would not be constructed until 1914. Despite the modest quarters, the group assembled by Foster and then Langley was highly talented. As Hill recalled, "There were probably more great physiologists there to the square yard than in any other place, before or since; and not only because there were so few square yards."[3]

FIGURE 1. A. V. HILL (right) on his first day as a member of the UK Parliament in 1940. (Courtesy of Nicholas Humphrey and the Churchill Archives Centre.)

Most of the physiologists at Cambridge, including Fletcher, were medical doctors, but Langley, like Hill, started his undergraduate life studying mathematics. A noted histologist, Langley conducted microscopic studies that distinguished sympathetic and parasympathetic nerves and clarified the structures of what he named the "autonomic nervous system." By the time Hill arrived in the department, Langley had turned his attention to the effect of such drugs as nicotine and curare on muscle stimulation. He had convinced himself that the drugs were effective because they combined directly with what he called "receptive substances" in muscle cells.

Langley wanted to find new evidence to support that theory, which his colleagues were skeptical of. One powerful approach would be to uncover the energetics of those reactions, and that was the task he set Hill. Perhaps Langley believed that Hill's mathematical prowess would allow him to succeed. In a remarkably short period—only a week or two—Hill immersed specimens of frog abdominal muscle in solutions with varying concentrations of nicotine at different temperatures. Observing the time course of the contractions, Hill discovered that the muscle fibers relaxed completely when the nicotine solution was washed off. He found that both the contraction and relaxation phases could be accurately represented by two simple exponential functions.

Hill posed the question as to whether those curves could reflect a physical process in which the degree of contraction is due to nicotine passively diffusing into the muscle fibers, or whether his experimental results comported with Langley's hypothesis that the nicotine undergoes a chemical reaction with a receptive substance. In his first paper, published in December 1909, Hill argued that his experiment was "very strong evidence in favour of the hypothesis of a [chemical] combination between nicotine and some constituent of the muscle."[4]

He was always modest about that paper, but when his distinguished colleague and friend Bernard Katz read it closely while writing Hill's obituary for the Royal Society's *Biographical Memoirs*, he identified two important features buried in the main mathematical argument. As Katz pointed out, it was the first kinetic description of drug–receptor interaction, and it foreshadowed the 1913 discovery of the Michaelis–Menten equation, which deals with the reversible reactions of enzymes on substrates and is perhaps the most famous formula in all of biochemistry. Katz also showed that Hill anticipated Irving Langmuir's 1918 paper on the adsorption of gases on metal surfaces. His reassessment of Hill's first publication has gained general acceptance: It is regarded as foundational in both receptor theory and quantitative pharmacology.

Hemoglobin

Two significant papers on hemoglobin followed within weeks. The first was an experimental study conducted with Joseph Barcroft, who had invented a manometer for measuring blood gases. He and Hill proved beyond doubt that the reversible union of oxygen with hemoglobin is a chemical reaction and that "the velocity of dissociation of oxyhæmoglobin obeys an equation derived from the laws of mass action, and has a high temperature coefficient."[5]

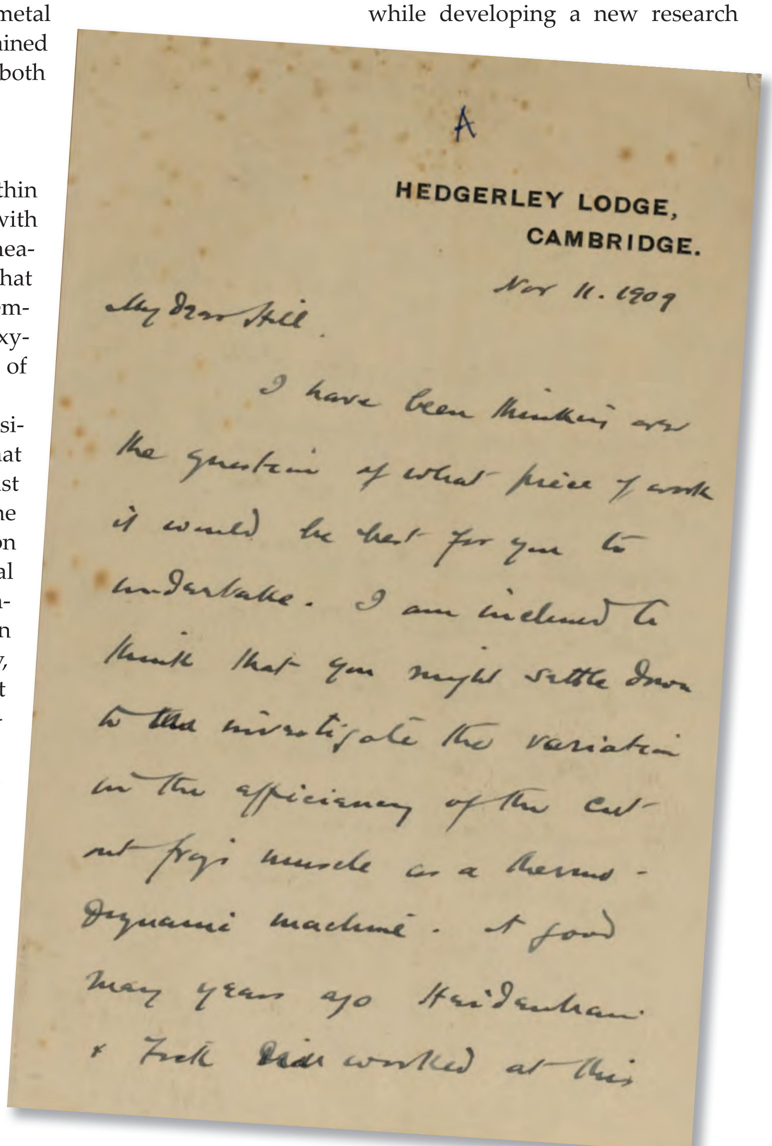
The second paper, delivered at a meeting of the Physiological Society in London, analyzed the Bohr effect. That phenomenon was discovered in 1904 by the physiologist Christian Bohr (the father of Niels), who noticed the S-shaped curves that arise when the percentage saturation of hemoglobin with oxygen is plotted against the partial pressure of oxygen. Bohr observed that the oxygen-dissociation curves shift to the right as the concentration of carbon dioxide in the blood increases. Consequently, at higher levels of carbon dioxide, hemoglobin does not readily take up oxygen, which means that more is available to the tissues.

Hill's paper derived a simple power equation, which he fitted successfully to published dissociation curves of hemoglobin in different chemical solutions. If the "Hill coefficient," as it later became known, is greater than one, a positively cooperative reaction occurs, in which a macromolecule such as hemoglobin shows an increasing affinity for binding a ligand like oxygen after the initial link is made. The Hill equation has proven widely useful in pharmacology, physiology, and molecular biology.

Despite the brilliance of the two hemoglobin papers, Langley was particularly captivated by Hill's first paper on frog-muscle contractions. Writing to Hill on 11 November 1909, Langley encouraged him to "settle down to investigate the variation in the efficiency of the cut-out frog's muscle as a thermodynamic machine" (see figure 2). Hill considered that letter to be so important to his scientific development that, later in life, he glued it to the inside cover of a bound collection of his papers.

Hill's chosen biological specimen, a thin slice of frog sartorius muscle, was dwarfed by his physical apparatus of galvanometers, thermocouples, novel electric circuits, and a rotating recording drum. He soon discovered that the frog muscle produced heat not only during stimulated contraction but also during the recovery phase. He realized that he was observing physical evidence of the underlying metabolic processes and concluded in a paper published in the *Journal of Physiology* in January 1911 that "the muscular machine is concerned with the transformations of chemical energy into the potential energy of increased tension." That was the start of 50 years of studying similar phenomena. It would be the basis for his 1922 Nobel Prize.

Hill took the chair in physiology at the University of Manchester in 1920, where he continued his frog-muscle studies while developing a new research



A

HEDGERLEY LODGE,
CAMBRIDGE.

Nov 11. 1909

My dear Hill.

I have been thinking over the question of what piece of work it would be best for you to undertake. I am inclined to think that you might settle down to the investigate the variation in the efficiency of the cut-out frog muscle as a thermo-dynamic machine. A good many years ago Heidenhain & Fick had worked at this

FIGURE 2. IN THIS LETTER, dated 11 November 1909, the physiologist John Langley suggested to Hill that he "settle down to investigate the variation in the efficiency of the cut-out frog's muscle as a thermodynamic machine." (Courtesy of the Churchill Archives Centre.)

topic: the physiology of human exercise. Wearing Douglas bags on their backs that collected their expired air for analysis, Hill and his junior colleagues also measured their blood gases immediately after energetic runs. At sprinting speeds, they noticed that they incurred "oxygen debts" in their blood that rapidly increased and eventually prevented further effort. They were forced to repay the debt by consuming a huge volume of oxygen during subsequent rest. The term "oxygen debt" has since entered everyday speech, although other factors such as increased temperature and steroid levels are also involved.[6]

Military defense expert

Hill was called up for army service at the start of World War I in 1914. His schoolboy talent for shooting meant he was soon training men bound for the trenches. In January 1916, he received an invitation from Horace Darwin—a son of the naturalist, Charles—to come to London to discuss a new project. Darwin oversaw the Anti-Aircraft Experimental Section of the Munitions Inventions Department, a UK governmental agency founded in 1915 to develop new military technologies.[7] He wanted Hill to study methods for accurately plotting the position of planes so that they could be shot down by artillery.

On the reluctant recommendation of Godfrey Harold Hardy, the mathematics don at Trinity College, Hill recruited the physicists Ralph Fowler and Edward Milne. The anti-aircraft group quickly expanded and moved to a naval base in Portsmouth, England, where they became known as Hill's Brigands. Under Hill's inspirational leadership, the brigands made numerous discoveries about the practicalities of antiaircraft fire and made the first rigorous mathematical analyses of artillery trajectories.[8]

As an imaginative experimenter who effectively directed a team and convincingly addressed problems in the field, Hill impressed senior military and government figures with his leadership qualities and his systematic approach. His brigands were among the first exponents of operational research. Fowler became the sole theoretician at the Cavendish Laboratory in the 1920s and would supervise dozens of doctoral students, including Paul Dirac. With Hill's support, Milne became a leading astrophysicist and cosmologist during the interwar period.

Scientists at the Air Ministry remembered Hill's wartime contributions in summer 1934 when they realized England's vulnerability to attack from the skies. Although the national mood was lifting as the country began to recover from the Great Depression, Winston Churchill rebuffed any such optimism in a fierce speech from the parliamentary back benches that warned about the threat from the expanding German Luftwaffe.

The message was reinforced by Churchill's good friend, the Oxford physicist Frederick Lindemann, in an August 1934 letter to the *Times* of London. After a lunch with Hill at which the notion of using "death rays" against pilots was discussed, Harry Wimperis, the director of research at the Air Ministry, wrote to the secretary of state for air suggesting that a defense committee be established under the chairmanship of Henry Tizard (see figure 3). Tizard went to work immediately and included two independent scientists on his committee: Hill, whom he had known since 1916, and the physicist Patrick Blackett.[9] Churchill successfully pressed for Lindemann to be added to the committee (see figure 4).

Although Lindemann and Tizard had been friends since before the Great War, Lindemann's addition to the Tizard committee destroyed its collegial spirit. He had a caustic personality and, worse, he disagreed with the committee's emphasis on developing radar. Instead, as Hill later wrote in a 1960 letter to Lindemann's biographer, the cantankerous physicist advocated a "fantastic scheme for dropping bombs, hanging by wires on parachutes in the path of attacking aircraft." As a result Blackett and Hill resigned, but a new Tizard committee was soon formed, one which included them but not Lindemann.

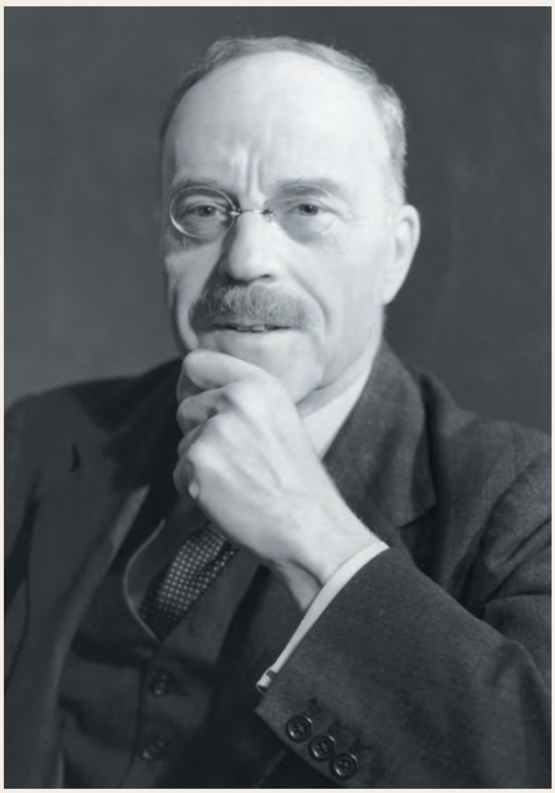


FIGURE 3. HENRY TIZARD, pictured here in 1942, led the UK air defense committee that championed the development of radar in the 1930s. (Photograph by Howard Coster, courtesy of the National Portrait Gallery, London.)

Anti-fascism

When he delivered the opening address to the International Physiological Congress in Rome in 1932, Hill shared the stage with Benito Mussolini and seemed to enjoy the encounter. Nevertheless, Adolf Hitler's assumption of power in Germany in early 1933—which quickly led to unchecked anti-Semitism and the violent repression of all political opposition—filled Hill with foreboding. The Nazis quickly enacted a new law in April 1933 to "reform" the civil service. The law called for the dismissal of civil servants who had at least one Jewish grandparent or who opposed the Nazi regime. (An exception was initially made for Jews who fought for Germany in World War I.) Because all German universities were public institutions, the law had an immediate and deleterious effect on science.

Within one month, a relief organization to support German intellectuals began to take shape in the UK. The Academic Assistance Council (AAC), as it was termed, was largely the work of two men:

FIGURE 4. FREDERICK LINDEMANN'S caustic personality led to the temporary collapse of Henry Tizard's air defense committee. Lindemann (far left) is pictured here with Winston Churchill (with cigar) observing antiaircraft exercises. (Photograph by W. G. Horton, courtesy of the Imperial War Museums.)

the economist William Beveridge and the peripatetic physicist Leo Szilard. But Hill was soon drawn into the planning—he became a founding member and the organization's first vice president.

In November 1933, Hill gave the Huxley Memorial Lecture at the British Association for the Advancement of Science, in which he warned that the "coercion of scientific people to certain specified political opinions, as in Russia, Germany or Italy, may lower the standard of scientific honesty and bring science itself into contempt." A summary of the lecture was included in *Nature*,[10] which both inspired many repressed scientists in Europe and caused fury among Nazi party members.

Johannes Stark, the newly appointed head of the Imperial Institute of Physics and Technology in Berlin, took offense at Hill's accurate assertion that over a thousand scientists had been dismissed due to the Nazi law. In a brazen reply, which also appeared in *Nature*, Stark denied that anti-Semitism was a deliberate Nazi policy and that there were more than a few thousand people held in concentration camps. He accused Hill of mixing science with politics. In a rebuttal, Hill dismissed Stark as an absurd anti-Semite and appealed for *Nature* readers to donate to the AAC.[11]

For many years, Hill was the essential executive at the AAC, which in 1936 was renamed the Society for the Protection of Science and Learning and is now known as the Council for At-Risk Academics. Much of the day-to-day responsibility for academic refugees and their families was unselfishly undertaken by the AAC's assistant secretary, Esther Simpson. She and Hill's largely unsung efforts led to salvation for more than

HILL AND CRICK

Francis Crick started a PhD in physics at University College London in the late 1930s, but his studies were interrupted by the outbreak of World War II. After the war, as he wrote in a May 1947 letter to Hill, he began to feel "a strong, though uninformed inclination to some form of bio-physics." Hill invited Crick for an interview and told him he needed to learn some basic biology. Crick was not interested in muscle research, so Hill advised him to go to Cambridge, which he did in fall of 1947.

About 18 months later, Crick wrote to Hill that he had "looked more closely into x-ray analysis" and found it to be easier than he had anticipated. "I think I have the sort of brain which enjoys puzzles of this sort," he said. Crick applied successfully to join Max Perutz's Cavendish Laboratory group, which was studying protein structure. Crick's assertive personality and genius for x-ray crystallography was too much for William Lawrence Bragg, the Cavendish director. He wrote to his old friend Hill:

> There is a young man working here, in Perutz's team, who I believe at one time was a protégé of yours and advised by you to take up biophysics. This is Crick. . . . He is working for a Ph.D. here, though he is 35, because the war stopped him trying before. My worry is that it is almost impossible to get him to settle down to any steady job and I doubt whether he has got enough material for his Ph.D. which should be taken this year. Yet he is determined to do nothing but research and is very keen to hang on here. With a wife and family he ought to be looking for a job. I think that he overrates his research ability, and that he ought not to count on getting a job with no other commitments. Are you interested in his career enough to wish to discuss it?[18]

Hill was interested enough to immediately reassure Bragg that Crick was worth keeping. Almost exactly one year later, Crick and James Watson announced the discovery of DNA's double-helix structure.

2000 scholars, including numerous future fellows of the Royal Society of London and Nobel laureates.[12]

The Tizard Mission

In November 1935, Hill was appointed biological secretary of the Royal Society. By 1938, with war clouds on the horizon, Hill and other society officers began to compile a detailed registry of scientists and engineers whose services might be needed in wartime. Impressed by that effort, Tizard asked Hill in early 1940 to visit Washington, DC, as an ambassador for science. Hill readily agreed, and, upon his arrival that March, quickly established a good relationship with the UK ambassador.

Hill met with such leading scientists as Szilard and Enrico Fermi as well as the science administrator Vannevar Bush. He established contacts in Canada and attended the annual conference of the American Philosophical Society in Philadelphia. After that, he returned to DC for the annual meeting of the National Academy of Sciences. He made lists of US Army and Navy officers and organized names of engineers and physicists by the companies they worked for. He was impressed with the availability of young engineers in the US.

After one month in the US, Hill informed Tizard that the US military had paid little attention to radar, although strong commercial interest was developing. He argued that the US would quickly catch up and advised the UK government to "be frank, generous and immediate" in sharing the fruits of their radar research.[13] Although Tizard was convinced by Hill's arguments, he faced considerable resistance in UK military and government circles. But Churchill eventually agreed, and later that summer a black box of gadgets arrived in the US. Among the objects in the box was a prototype cavity magnetron, which enabled development of the centimeter-wavelength radar that proved vital to the Allied war effort.

The Tizard Mission, as it became known, was a triumph in establishing technical cooperation between the UK and US.[14] Although Hill did not take a direct role, it is hard to imagine that the mission would have happened without his ceaseless efforts during the first half of 1940.

FIGURE 5. A. V. HILL with the Indian chemist Shanti Bhatnagar. Hill's 1945 report on the state of science in India helped determine science policy during the period leading up to Indian independence. (Courtesy of Nicholas Humphrey and the Churchill Archives Centre.)

India

Just before going to North America, Hill took the oath of allegiance to the crown as a member of Parliament for the Cambridge University constituency. (Until university constituencies were abolished in 1950, several institutions of higher education were represented directly in the House of Commons; the voting body for each university constituency consisted of the respective university's graduates. Isaac Newton, for example, was briefly a member of Parliament for Cambridge University.) Hill was elected as an Independent Conservative and, in a widely circulated memo, explained his reason for serving: "Practically none of the political leaders of the country have any personal acquaintance with science or technology."[15] As he said, he aimed to make a nuisance of himself in Parliament, which he consistently did by deploring the treatment of refugees from enemy countries, attacking the government over its prosecution of the war, and, when he felt it was necessary, openly criticizing Churchill.

In early summer 1943, the Indian government invited Hill to visit, assess the state of scientific research, and advise how it might be harnessed for future development. Given the contentious state of politics on the subcontinent, Hill decided to undertake the task under the auspices of the Royal Society rather than as a member of Parliament. After several hops by flying boat, he arrived in Delhi and stayed in India for five months. His tour of universities, hospitals, schools, and factories was arduous, but his natural openness and friendly nature allowed him to quickly gain the confidence of new acquaintances (see figure 5). Hill gave lectures, compiled voluminous notes, and gave a broadcast on All India Radio.

In his report to the Indian government,[16] he recommended the establishment of an All-India Medical Centre and suggested creating a central department to oversee scientific research in the areas of medicine, industry, agriculture, natural resources, engineering, and war. Many of his ideas were adopted quickly, but Hill worried that India was living on the edge of a precipice because of disease, malnutrition, and population growth. He feared that internal strife or a disease outbreak like the 1918 influenza pandemic would produce a major catastrophe.

Biophysics

On his return from India in 1944, Hill became engrossed in a Royal Society project on postwar needs. He was a strong proponent of biophysics and other interdisciplinary subjects. That December he circulated a memo arguing for the creation of a biophysics institute, in which he asserted that physical techniques such as radioactive labeling and electron microscopy should be adopted in the biological sciences.[17] The memo proved influential, and he succeeded in securing a substantial grant in 1945–46 from the Rockefeller Foundation to start a biophysics department at UCL.

He persuaded Katz, a German Jewish refugee neurophysiologist who had studied with him in the 1930s, to accept the position of assistant director. Katz spent the war serving in the Royal Australian Air Force, in charge of a team running mobile radar units in New Guinea, where he gained much practical experience in electronics. The same was true for Hill's son David, his nephew Richard Keynes, and their Cambridge neurophysiologist friends Andrew Huxley and Alan Hodgkin. Hill regarded them all as physicists by nature who happened to have biological experience and knowledge.

Hill also placed journal advertisements that targeted young physicists coming out of the armed services who were thinking of switching to biology. Two notable recruits were Eric Denton, who later became the head of the Marine Biological Association's laboratory in Plymouth, England, and J. Murdoch Ritchie, who chaired Yale University's pharmacology department for many years. The one who got away was Francis Crick, who nevertheless owed his career start to Hill (see the box on page 43).

Although Hill continued to tinker in his UCL lab for years after World War II, he spent much of his time repeating previous experiments. His style as a physiologist was analogous to the empirical bent of Ernest Rutherford's school of physics, and he was slow to accept new theories such as the sliding-filament model of muscle contraction. Nevertheless, his popularity among his colleagues and the gratitude of those he helped to rescue from Nazi-occupied Europe brought him more accolades with each passing decade. Katz, one of those refugees, fittingly described Hill in a 1996 autobiographical essay as the "most naturally upright man" he had ever encountered.

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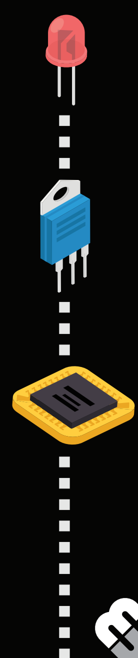

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Building a ship in a bottle for NEUTRINO SCIENCE

Anne Heavey

In a former gold mine in South Dakota, an international particle-physics experiment will delve into the unexplained matter–antimatter imbalance that gave rise to the universe.

The ore pass at the Sanford Underground Research Facility in South Dakota. (Courtesy of Sanford Underground Research Facility, CC BY-NC-ND 4.0.)

Anne Heavey is a senior technical editor at the Fermi National Accelerator Laboratory in Batavia, Illinois.

The Deep Underground Neutrino Experiment (DUNE) will be the world's largest cryogenic particle detector. Its aim is to study the most elusive of particles: neutrinos. Teams from around the world are developing and constructing detector components that they will ship to the Sanford Underground Research Facility, commonly called Sanford Lab, in the Black Hills of South Dakota. There the detector components will be lowered more than a kilometer underground through a narrow shaft to the caverns, where they will be assembled and operated while being sheltered from the cosmic rays that constantly rain down on Earth's surface.

For at least two decades, the detector will be exposed to the highest-intensity neutrino beam on the planet. The beam will be generated 1300 km away by a megawatt-class proton accelerator and beamline under development at Fermilab in Batavia, Illinois. A smaller detector just downstream of the beamline will measure the neutrinos at the start of their journey, thereby enabling the experiment's precision and scientific reach.

A whale of a problem

Imagine the following picture proposed by André de Gouvêa, a physicist at Northwestern University: atoms so big that each of their protons and neutrons is the size of a blue whale. Along with a pod of whales as a nucleus, he chose rabbits as the electrons. In a volume filled with the whale–rabbit element—whimsically named *cetaceacuniculium* by borrowing from the Latin words for whale and rabbit—each atom would be tens of thousands of kilometers across. Neutrinos, on the other hand, would be but fruit flies passing through, unaware of and unaffected by the other objects in the vast, largely empty space. So how do we even know neutrinos exist? Furthermore, why do we think they might be of any importance?

The existence of neutrinos has been demonstrated by many experiments, and particle physicists have been steadily accumulating clues about the neutrino's role in the domination of matter over antimatter in the early universe (see Physics Today, June 2020, page 14). DUNE researchers are developing and testing ever-more-sensitive and high-precision technologies to understand and elucidate how the neutrino may have been instrumental at that crucial juncture.

DUNE and its associated home, the Long-Baseline Neutrino Facility (LBNF), are hosted by Fermilab and make up the LBNF/DUNE megaproject. DUNE brings together more than 1300 scientists and engineers from more than 30 countries. LBNF/DUNE is conceived around three instruments: a megawatt-class proton accelerator and beamline at Fermilab that is engineered to generate what will be the highest-intensity neutrino beam ever built and two ultrasensitive detectors to pick up neutrinos' signals and measure their properties. The near detector will be constructed at Fermilab, just downstream of the beamline. The far detector will reside at Sanford Lab. The LBNF/DUNE baseline—the separation between the neutrino source and the far detector—is 1300 km (see figure 1).

Launched in early 2015 and built on designs developed for two earlier projects,[1] DUNE is scheduled to start taking data in the late 2020s. While some researchers are preparing for the physics studies themselves, other members of the LBNF/DUNE enterprise are wrestling with practical complications: the experiment's sheer scale, the delicacy and precision of its components, the decade-plus duration required for construction, and the logistics of moving items and people around the world. Some of the challenges are unique to LBNF/DUNE, whereas others are shared, at least to a degree, by other neutrino experiments and even more broadly across high-energy physics. The fact that DUNE will proceed despite those challenges conveys the importance that scientists place on understanding the universe's fundamental properties.

A mysterious asymmetry

It is not obvious that neutrinos—or people, for that matter—should be here at all. If just after the Big Bang the still-tiny universe contained equal amounts of matter and antimatter, why didn't it simply self-destruct? If every matter particle were the perfect mirror image of its antiparticle, with opposite charge and reversal of left and right, the mutual annihilation should have been complete.

Some aspect of the matter–antimatter symmetry must therefore not be working as expected. The unanticipated behavior, without which matter could not have beat out antimatter, requires that nature violate charge conjugation–parity (*CP*) symmetry, which says that the laws of physics must act the same on a particle whose charge is reversed and

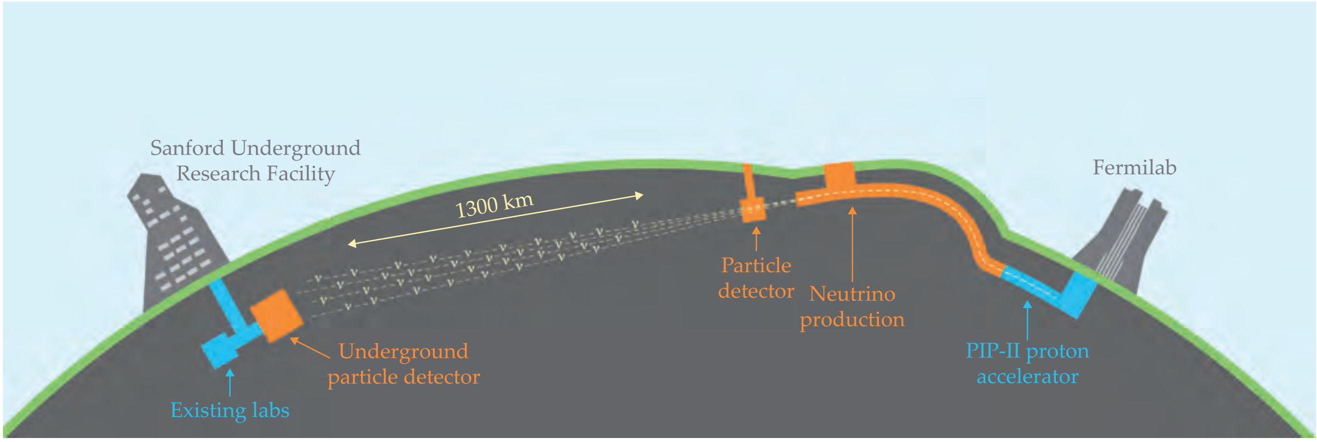


FIGURE 1. A NEUTRINO BEAM traveling from Fermilab in Illinois to the Sanford Underground Research Facility in South Dakota lies at the heart of the Deep Underground Neutrino Experiment. Two detectors set 1300 km apart will look for oscillations between neutrino states. (Adapted from an illustration courtesy of Fermilab.)

whose coordinates are inverted. Particle-physics experiments have found *CP* violation in processes involving quarks, but not to a level that would account for the extraordinary matter–antimatter asymmetry in the universe today—at least not according to the standard model in its current form.[2] So what else might contribute to the asymmetry?

Leptons—non-quark-based particles that include electrons, muons, and neutrinos—might be the culprits. Paramount among DUNE's potential discoveries is evidence of *CP* violation in the lepton sector, which could indicate that neutrinos hold the key to the matter–antimatter symmetry.

Neutrinos were postulated by Wolfgang Pauli in 1930 to solve an apparent breach of energy-conservation laws in radioactive decays. A quarter century later, the first of what turned out to be three types, or flavors, of neutrinos was discovered (see figure 2). Subsequent experiments revealed all three flavors, each of which corresponds to a charged lepton, and they showed that a neutrino can transform from one flavor into another as it travels. The process, known as oscillation, occurs over a wide range of distances and depends on the energy of the source neutrinos (see Physics Today, December 2015, page 16). The LBNF/DUNE beamline is designed to produce neutrinos that span the energy range of a few hundred MeV to a few GeV and that oscillate over more than a thousand kilometers, corresponding to the experiment's baseline.

The physics behind neutrino oscillations implies that each neutrino flavor state is a mixture of three mass states. The determination in 1998 that the neutrino—assumed massless, and in fact defined as such for decades—definitively has mass was one of the most important fundamental particle-physics discoveries of the late 20th century.[3]

Tiny escape artists

Neutrinos, so named because they are electrically neutral, have the smallest masses of the pantheon of elementary particles. They interact with matter only through gravity and the weak nuclear force. Weak interactions have a strength about one-tenth of a trillionth that of electromagnetic ones, and they're best known as a mechanism for radioactive decay.

Because neutrinos encounter little if any resistance, they are the first particles to escape from deep inside active stars, collapsing stars, and, originally, the Big Bang. They travel through the universe virtually unimpeded, carrying information that no other particles can. For example, in 1987, the Kamiokande-II experiment in Japan captured a telltale spray of neutrinos escaping from a supernova.[4] (See the article by Masa-Toshi Koshiba, Physics Today, December 1987, page 38.) Study of that signal has led to a greater understanding of supernova dynamics—one that DUNE hopes to build on.

It's clear that observing enough neutrino interactions to make definitive discoveries requires a huge detector mass. Also necessary are copious neutrinos, a long data-collection period, and sensitive detection elements. Furthermore, no known technology can directly detect a neutrino; experiments rely on gathering enough information from particles created in each neutrino interaction to reconstruct that interaction and tease out evidence that a neutrino initiated it. That process requires a detailed understanding of the sought-after experimental signatures: the unique products of physically allowed decays in concert with the detector elements' responses.

When a neutrino interacts with a target particle via the weak force, the two particles exchange either a neutral Z^0 or a charged W boson.[5] In the exchange of a Z^0, the neutrino transfers some of its energy to the target particle and continues on, accompanied by other particles created in the collision.

If the energy of the incoming neutrino is high enough, though, it can exchange a W boson with the target particle. In that case it transforms into its detectable partner lepton—an electron, muon, or tau—and acquires a charge in the process. The transformation requires the incoming neutrino's energy to be somewhat higher than the rest mass of its partner lepton: more than 0.5 MeV for an electron, roughly 50 MeV for a muon, and several GeV for a tau. The target particle's charge also changes, in observance of charge-conservation laws, which effectively changes it into a different particle. Somewhere between 0 and 10 secondary particles are created out of the interaction's energy.

When a neutrino interacts with a nucleus, it may interact with the whole thing, with a single nucleon, or even with just one quark. The probability of each depends on the energy of the incoming neutrino. The particles produced in the collision can tell the story, but coaxing it out of them is one of the most significant challenges of neutrino physics.

A particle detector picks up, digitizes, and processes an as-

FIGURE 2. THE COWAN–REINES EXPERIMENT confirmed the existence of neutrinos in 1956. Clyde Cowan (far left) and Frederick Reines (far right) used large tanks of water to detect electron antineutrinos produced by a nearby nuclear reactor. (Photo from LANL/Science Source/Science Photo Library.)

semblage of signals in a time frame associated with a single interaction. Later, a set of reconstruction algorithms uses the data to work backward and determine the parameters of the interaction. The same is true for all particle experiments, but it presents a particular challenge for long-baseline experiments like DUNE, whose beamlines produce neutrinos in the 500 MeV–5 GeV range. Neutrinos with energies below that range tend to interact with the entire nucleus, whereas neutrinos above that range tend to interact directly with quarks. The transitional range used by DUNE, however, presents a complicated mix of interactions. Although the researchers would have preferred that the experiment operate in a more straightforward energy range, constraints on the baseline and the neutrino beam needed to achieve the physics goals forced researchers to work in that awkward transitional range.

Beam building

You can't steer a neutrino. You can't push or pull one either. To create a neutrino beam, you need to start with another beam made of more controllable—that is, charged—particles, such as protons, and then accelerate them to nearly the speed of light and smash them into a target. That process creates oodles of other particles, many of which will decay into neutrinos.

At Fermilab, a chain of particle accelerators produces pulsed beams of relativistic protons grouped in tightly compressed bunches. To generate the high-intensity beam needed for DUNE, a new state-of-the-art superconducting accelerator, known as the Proton Improvement Plan-II or PIP-II, was installed at the start of the chain.[6] The protons head from there to the booster and the main injector, where they reach energies of 120 GeV. At that point, the new LBNF/DUNE beamline will extract protons, steer them toward the near and far detectors, focus and align the beam, and smash it head-on into a target the diameter of a pencil.

The charged particles created in the collisions will be tightly focused before they decay so they produce a narrow, intense neutrino beam in the direction the parent particles were steered—namely, toward the detectors. Other particles created in the decay get absorbed in tons of concrete and steel shielding. The shielding poses no barrier to the neutrinos because, recalling *cetaceacuniculium*, nothing really does. The vast majority of the neutrinos pass right through the near detector, through the 1300 km of earth, through the far detector, on through more earth, and finally out into space, oscillating the entire way. Only a tiny fraction will interact with the detectors.

Like neutrinos themselves, the challenges of designing and building neutrino experiments come in various flavors. Detectors are often located in quite inconvenient, if not downright inhospitable, places—for example, underneath mountains or deep in former mines—to shield them from sources of such unwanted interactions as cosmic rays. Because of the volume of material required, neutrino detectors have even been installed deep in the sea and at the South Pole (see, for example, Physics Today, May 2013, page 14), where the surrounding water or ice serves as the target medium.[7]

Scientists have invented a host of neutrino detection methods

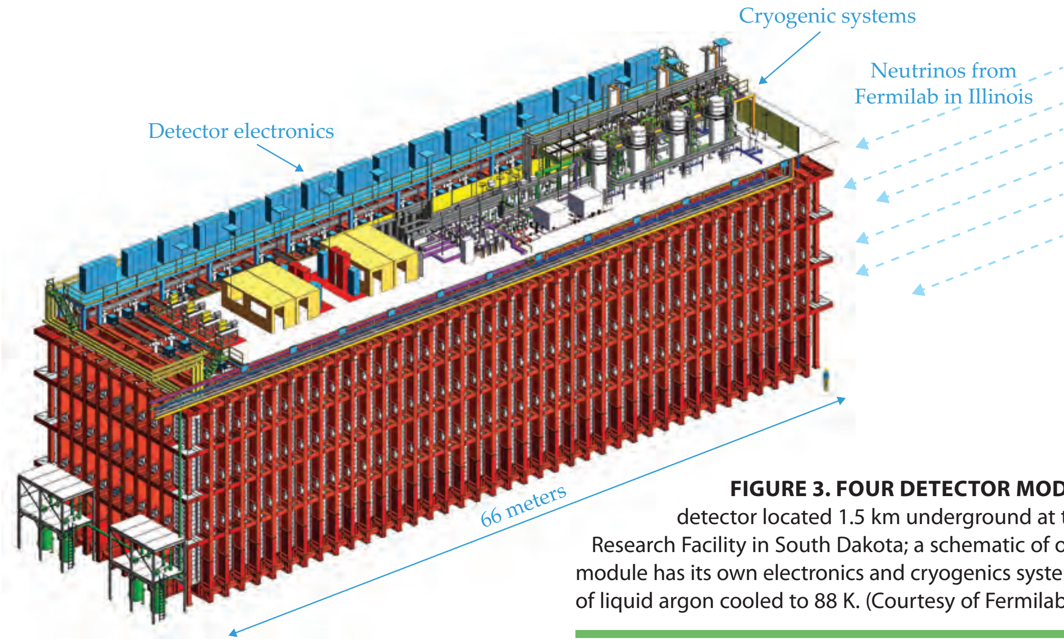


FIGURE 3. FOUR DETECTOR MODULES will make up the far detector located 1.5 km underground at the Sanford Underground Research Facility in South Dakota; a schematic of one is shown here. Each module has its own electronics and cryogenics systems to keep its 17 000 tons of liquid argon cooled to 88 K. (Courtesy of Fermilab.)

over the past several decades. They've built distinct types of detectors with various experimental goals as new discoveries have been made and new measurements have been sought that required different features and capabilities. To measure low-energy solar neutrinos, for example, a detector needs a low energy threshold. Astrophysical neutrino measurements typically require precise angular resolution. Beam neutrino-oscillation experiments like DUNE require an intense supply of neutrinos of a known flavor that travel a given distance; they also rely on excellent particle-identification and energy-measurement capabilities. Some à la carte features can be added to a detector, but the number that can be included in a particular experiment is limited.

Another aspiration of DUNE's is capturing a core-collapse supernova's neutrino burst—a roughly 10-second initial outpouring of neutrinos that precedes the collapse. To do so, the detector must be quite robust. It can't afford to be off-line for more than rare and brief maintenance periods because such a neutrino burst could come at any time. The detector must also be able to handle the data deluge that a supernova event would generate—potentially terabytes of data within a window of only a few seconds.

DUNE's far detector will be a liquid-argon time-projection chamber (LArTPC; see the box on page 51 for more about its principle of operation). LArTPCs are enormous vats of cryogenic liquid argon outfitted with components that generate an electric field across the liquid volume and elements for detection. When charged particles emerge from a neutrino interaction with an argon nucleus, they ionize other argon atoms, and the liberated electrons drift under the electric field's influence to a finely segmented collection plane. Also, because liquid argon is a profuse scintillator, electron detectors are usually supplemented with photosensitive elements for light detection.

The LArTPC's fine segmentation enables efficient distinction between actual signal events and uninteresting background interactions. Two key factors affect an LArTPC's performance: the purity of the liquid argon and noise on the readout electronics. Impurities, such as oxygen and water, tend to swallow up the drifting electrons, thereby attenuating the signal's charge over long drift lengths and reducing the signal strength. Noisy electronics reduce the signal-to-noise ratio, making it harder to separate the two.

Down-to-earth challenges

Coveralls, helmet, boots, headlamp, check. It was October 2018 and I was ready to descend deep into the underground labyrinth of the former Homestake gold mine in Lead, South Dakota, now home to Sanford Lab and its ultrasensitive science experiments. It was here, starting in the late 1960s, that a team led by Ray Davis Jr, a physicist at Brookhaven National Laboratory, undertook the neutrino experiment that famously observed only a third of the electron neutrinos expected from the Sun.[8] That discovery bolstered the theory of neutrino oscillations initially proposed by Bruno Pontecorvo in 1957 and eventually led to two Nobel Prizes in Physics. A share of the 2002 prize was split by Davis and Masatoshi Koshiba for their initial detections of cosmic neutrinos; the other was shared by Takaaki Kajita and Arthur McDonald in 2015 for conclusively demonstrating the phenomenon. Tagging along with a group of visiting particle physicists, I would get a glimpse of the historic site being prepared for DUNE.

The spaces for the DUNE far detector at Sanford Lab, which is planned to include four LArTPC modules (see figure 3), require excavation of about 800 000 tons of rock—or the equivalent mass of about eight aircraft carriers, as Chris Mossey, a retired US Navy admiral and now LBNF/DUNE-US project director, likes to describe it. The excavation at Sanford Lab will create two detector caverns, each three stories high and 145 m long that will house two modules, and a central utility cavern 190 m long. The total volume is around 250 000 cubic meters, the equivalent of about 100 Olympic-size swimming pools. Cavern excavation began in spring 2021 following an extensive renovation of the 1930s-era Ross Shaft—the same shaft my companions and I used on our visit—that connects the underground site to the surface at Sanford Lab. Rock travels up the 4 m × 6 m shaft and then along a newly constructed conveyor that deposits it into a large, open former mining area.

The reasons for choosing that location include the geotechnical strength of the rock at the underground site, the capacity of the Ross Shaft elevator, constraints on excavation so deep underground, and the internal and external forces that act on an insulated steel container, called a cryostat, filled with a heavy liquid. Each module will be assembled of still smaller detector elements that will fit either in or under the 4 m × 1.5 m cage or in one of the two roughly 1.5 m × 1.2 m skip compartments in the shaft. The detector's construction is reminiscent of a ship in a bottle. Together the four modules will contain nearly 70 000 metric tons of liquid argon. At least 40 000 metric tons will be in the instrumented, usable volumes of the LArTPCs from which data from particle interactions will be recorded and sent out to a data acquisition system.

Keepin' it cool

Delivery, handling, and storage of the vast quantity of liquid argon required will take a few years and serious planning. Many questions needed to be answered, including the following: What is the total capacity of the vendors within trucking distance? How many tanker trucks will be needed, and over what period of time? How will the undertaking affect the local community? How will weather, or the annual Sturgis Motorcycle Festival, affect deliveries? What is the best way to transfer the argon underground? How much storage is needed in case a delay arises in preparing a cryostat?

The cryogenics team will likely need to coordinate three or four vendors that, together, will make about 1000 deliveries per detector module. The argon will arrive in 20-ton-capacity tank trucks over a period of roughly a year. From the interstate highways, the trucks—at least 25 each week—will wend their way into the Black Hills, through the small town of Lead, and finally up a steep hill to the argon receiving station at the Ross Shaft headframe. To get a scale of the undertaking, add to that the delivery of cryostat and detector components, then multiply by four.

Transferring liquid argon at 88 K directly down the Ross Shaft would require insulated piping and a set of pressure stations along the way. Instead, equipment will vaporize the argon at the surface, send it down through uninsulated pipes, and recondense it underground.

Once a detector is fully installed inside a cryostat, the interior must be made free of all debris and loose material that could contaminate the argon. At that point, the cryogenics system will introduce the purified heavier-than-air argon vapor at the bottom so it can slowly push the air up and out. The purge will be repeated 10 times to reduce contamination levels in the cryostat and piping to a few parts per million before the cooldown can start.

To cool the cryostat volume, atomizing sprayers will introduce liquid argon at the top of the cryostat and let gravity and convection distribute it. When the interior reaches 90 K, the system will begin to fill the cryostat with purified liquid argon—a yearlong process during which the deliveries must keep up with the fill rate. Recirculation and constant purification processes kick in when the liquid depth reaches about 1.5 m. A minuscule but unavoidable heat ingress leads to a very slow, constant evaporation of the liquid, which, in turn, leads to the need for a continuous vapor recovery and reliquefaction process.

Those cryogenic processes, some of which must operate for the lifetime of the detector, call for an industrial-scale cryogenics

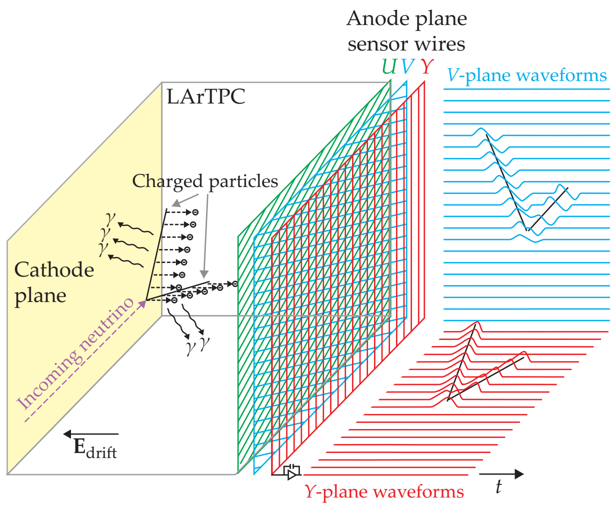
LArTPC OPERATING PRINCIPLE

In its most basic configuration, a liquid-argon time-projection chamber (LArTPC) consists of a cathode plane (left) at a high negative voltage and a grounded anode plane (center) that is parallel to it and some distance away. Both are immersed in liquid argon, and together they establish an electric field across the liquid volume.

When a neutrino interacts with an argon nucleus, high-energy charged particles emerging from the interaction liberate electrons in the liquid argon. The electric field pushes the electrons toward the anode and draws the positive ions toward the cathode. The diagram, adapted from reference 9, depicts the DUNE design in which the anode is made up of planar arrays of sensor wires strung at different angles relative to each other; the wires in each plane are spaced a few millimeters apart.

Just like any charge moving in the vicinity of a conductor, drifting electrons create signals on the induction plane wires, *U* and *V*, as they pass. Once the electrons reach the inner collection plane, *Y*, they produce signals on its wires, too, and are absorbed. The signals from the three wire planes are captured by the readout electronics. Photons produced in the interaction are also captured by a separate photon detection system and provide a time stamp for each event.

Specialized software processes the signals to reconstruct a time-evolving stereo projection of the pattern produced on the wire planes (right) that reveals the location, time, and characteristics of the original neutrino interaction in the liquid. See reference 9 for more details.



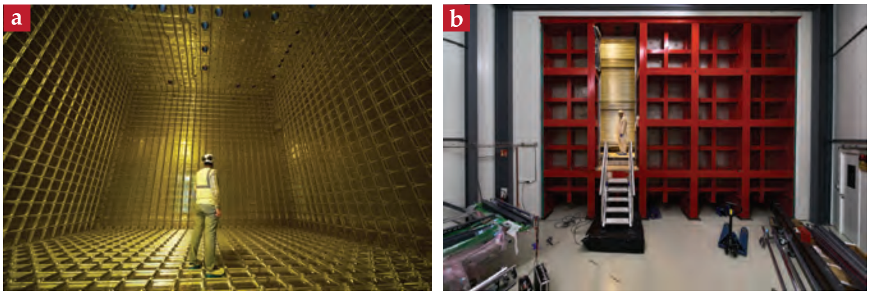


FIGURE 4. PROTOTYPE DETECTORS built at CERN for the Deep Underground Neutrino Experiment were just 1/20th the size of the final planned detector, but when completed, they were the largest liquid-argon time-projection chambers ever made. **(a)** Prototype components were installed in this inner stainless-steel membrane and immersed in liquid argon. The gold color is an artifact of the lights used to protect the photon detectors during installation. **(b)** A red steel outer structure supports the multilayer insulated cryostat. (Courtesy of CERN/Maximilien Brice/Julien Marius Ordan.)

system. DUNE will not be a test bed for any of the systems; all those being implemented have been extensively tested and used in industrial environments. The creativity is in identifying solutions that are as standard as possible, meet the performance requirements, and—importantly—fit down the shaft.

All the components that go into a detector must be thoroughly tested under conditions similar to actual operating conditions. Furthermore, constructing, transporting, assembling, and installing precision components at the size and scale required for the DUNE detector modules requires careful planning and rehearsal. Prototyping has therefore been integral to DUNE's strategy for success. In addition to earlier, smaller prototypes, the DUNE collaboration has constructed and operated two 1/20-scale prototypes at CERN over the past three years (see figure 4). The prototypes used different LArTPC designs and were both instrumented with a small number of full-scale detector components. When installed in cubic cryostats nearly 6 m on a side, the devices became the largest LArTPCs built and operated to date, barely beating out the narrower ICARUS detector at Fermilab for the distinction.

The far-detector prototyping effort has validated the technology and the performance of the detection components in liquid argon, and it has demonstrated excellent control over argon purity and signal-to-noise ratio. Comparing the carefully choreographed assembly and installation of the prototype to a Fred Astaire dance number, installation of the full-size detector will require the team to execute the moves not just 20 times over for each of the four modules and 1450 m underground but, like his partner Ginger Rogers, backward and in high heels—down shafts, through excavated corridors, and around obstacles.

The near detector

At Fermilab, just downstream of the neutrino source, the near detector—a smaller hybrid neutrino detector—will be installed in a shallow underground cavern. It is composed of three subdetectors, one of which is an LArTPC whose readouts can undergo apples-to-apples comparisons with those from the far detector. Together the far and near detectors allow the experiment to take full advantage of the 1300 km separation, which is optimal for observing *CP* violation through neutrino oscillations.[1] The near detector will provide information crucial to interpreting the measurements made in the far detector and reducing their uncertainties, and it will also perform some independent physics studies.

Since the neutrino beam will be much narrower and therefore more intense at the near detector than at the far detector at Sanford Lab, both the LArTPC and a subdetector optimized for other studies will be able to move off the beam axis to sample different neutrino energy spectra in the beam and enable further comparisons. The third subdetector, a beam monitor, will measure variations in the beam via the products of the relatively copious neutrino interactions that take place in its volume. The beam monitor remains fixed in the beam path, where it is most sensitive to those variations.

When all three subdetectors are placed end to end along the beam axis, they fit into a space 50 m long, 19 m wide, and 10 m high—about a quarter the size required for one far-detector module. And, like the far detector, all the systems must undergo prototyping regimens, albeit at an appropriately smaller scale.

The far detector will need to collect a few thousand neutrino interactions to reach the measurement precision that will allow DUNE to accomplish its ambitious physics goals. Given the size of the far detector, the intensity of the neutrino beam, and the expected interaction rate, the experiment is planned to operate for about 20 years.

Many physicists will spend significant fractions of their careers devoted to DUNE during that time—monitoring the near and far detectors, fixing or upgrading things as needed, and analyzing the data. Accelerator physicists will keep the beam running smoothly. Many scientists, engineers, computing specialists, technicians, and project management professionals have already spent years planning and developing the experiment. Everyone involved is looking forward to witnessing the transformative discoveries that DUNE promises.

I'd like to thank Steve Brice, Chris Mossey, Elizabeth Worcester, and David Montanari for particularly useful discussions in the development of this article.

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PT

H. O. HAVEMEYER COLLECTION/BEQUEST OF MRS. H. O. HAVEMEYER/1929/PUBLIC DOMAIN

THE OCEAN, depicted here by Hokusai in his famous early-19th-century print *The Great Wave off Kanagawa*, remains one of the least understood environments on Earth. This copy of the print is held by the Metropolitan Museum of Art in New York.

Even underwater, money talks

Science on a Mission
How Military Funding Shaped What We Do and Don't Know About the Ocean
Naomi Oreskes
U. Chicago Press, 2021. $40.00

The older I get, the stranger it seems to me that my undergraduate education in physics and astronomy included virtually no instruction in fluids. I suspect I am not the only physicist who feels that way. But there is another lacuna in my education, which I was unaware of until reading Naomi Oreskes's new book, *Science on a Mission: How Military Funding Shaped What We Do and Don't Know About the Ocean*: The role of physicists in oceanography.

Ostensibly a text that uses oceanography as a vehicle to think through the military's role in science, *Science on a Mission* also serves as a history of how physicists helped create the field of modern oceanography. The result is a book that will be of interest to both historians and scientists.

Oreskes is clear from the start about the question her book addresses: "What difference does it make who pays for science?" The conclusion we are led to is inevitable: Money matters. But, as we learn along the way, so do the personalities and motivations of those doing the science. As with all scientific achievements, understanding the physical structure of the universe inside our oceans is a tale filled with false starts, compelling but wrong ideas, strong personalities, and political imperatives.

To tell the full story, Oreskes spends time explaining the scientific ideas under consideration at various points of historical significance. Examples of such moments include major geopolitical events like the end of World War II, but also critical junctures within the scientific community itself, such as changes in the funding sources and challenges to the leadership at major research facilities like the Scripps Institution of Oceanography. In other words, Oreskes's history is—happily—not discovery oriented but focused on highlighting the way scientific work was shaped by its political and economic environments. The book closes with a helpful look at oceanography's turn toward climate change research and nonmilitary funding sources.

Oreskes does not take any shortcuts with the science. Indeed, *Science on a Mission* is so detailed in its descriptions of technical ideas that there were moments when I began to feel impatient. But those feelings were significantly tempered when I recognized that Oreskes has performed an enormously important service to the community: Anyone who really wants to understand Cold War–era oceanography now has a definitive text to turn to. Not only does the book provide extensive explanations of the plethora of ideas that have circulated about one of the least understood environments on Earth, but the bibliography alone is a significant contribution that will be useful to scholars in the field.

It would have been helpful for the book to open with a cast of characters as part of its front matter, because there are so many key players that come up repeatedly across its hundreds of pages. Indeed, picking up the book requires a serious commitment: The main text consists of 502 pages spread across nine chapters, to which 145 pages of notes are appended. The font is also on the smaller side, which is to say the text is dense. The endnotes are long but often interesting. To put it bluntly: The book is long, and it took me a while to get through it. At times I got lost reentering the text, and readers who have a hard time tracking complex and large amounts of information would have been better served if Oreskes had broken the content into more, shorter chapters.

Ultimately, the task of *Science on a Mission* is to describe how the military's financial prowess affected what we know about the ocean and how we came to know it. And the text succeeds in that mission. But it is so much more than that. What shines through is Oreskes's utter fascination with the community she decided to study. On some pages it almost felt like I was reading not just history but an actual ethnography.

Science on a Mission makes a strong case for thinking in terms of not just money but power. Oreskes demonstrates that big personalities with sufficient social capital can be incredibly influential—and can even determine how and when military funding produces specific scientific outcomes. Moreover, regardless of whether she intended it, Oreskes makes a strong case for why histories of physics must now encompass oceanography.

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To minimize interference in the radio spectrum, the National Radio Astronomy Observatory employs a fleet of electronics-free vintage cars, such as the Checker Marathon pictured here, for site maintenance.

JAREK TUSZYŃSKI/CC BY-SA 3.0

The golden age of radio astronomy

Open Skies
The National Radio Astronomy Observatory and Its Impact on US Radio Astronomy

Kenneth I. Kellermann, Ellen N. Bouton, and Sierra S. Brandt

Springer, 2020. Open access ($59.99 print)

Although it originated in the 1930s, radio astronomy reached maturity during the latter half of the 20th century. One of the major sites of radio astronomy during that period was the US National Radio Astronomy Observatory (NRAO). In *Open Skies: The National Radio Astronomy Observatory and Its Impact on US Radio Astronomy*, Kenneth Kellermann, Ellen Bouton, and Sierra Brandt tell the story of that august institution, warts and all: from the NRAO's genesis in the mind of NSF's first director, Alan Waterman; through the growing pains it faced during its early years; to its current status as a world-class radio astronomical facility.

A weighty tome of over 600 pages, the book begins with three chapters describing the early history of radio astronomy before delving into the NRAO's history in chapter 4. In that section, the authors introduce us to the first radio telescope erected at the NRAO's site in Green Bank, West Virginia: a 30 MHz interferometer that saw first light a year before the Green Bank site officially opened in October 1957.

From the start, the plan was to erect 85-foot and 140-foot radio telescopes at Green Bank. But a turf war quickly broke out between two committees involved with the observatory's design. Even after they agreed on the size of the larger telescope—140 feet—there were heated arguments about the type of mounting to be used and the surface accuracy of the parabola. Construction of the 140-foot telescope wasn't finished until 1965, five years later than planned.

While that project was stalled, the NRAO managed to secure about $1 million in funding from NSF for a simple 300-foot radio telescope with an inexpensive altazimuth mounting. Funding was approved in 1961, and in record time the 300-foot telescope was finished. The NRAO finally was an international-class radio astronomical facility.

Given the focus on instrumentation, people, and politics, *Open Skies* contains little discussion of the major research accomplishments of the NRAO and its staff. Nevertheless, the authors highlight a few examples of scientific discoveries made at Green Bank, including supernova remnants, planetary nebulae, radio galaxies, and quasars. They also discuss the discovery of radio recombination lines and interstellar molecules.

Perhaps the most famous NRAO instrument is the Very Large Array (VLA), discussed in chapter 7. It comprises 27 mobile parabolas, each 25 meters in diameter, which are arranged in a Y-shape at a radio-quiet site outside Socorro, New Mexico. Construction of the VLA began in late 1972, and in July 1980—18 years after it was first proposed—the VLA was fully operational. It was not only the most powerful radio telescope in the world but also the most complex one ever built.

Another area of radio astronomy for which the NRAO is justly famous is very long baseline interferometry (discussed in chapter 8), which involves electronically linking separate radio telescopes located across Earth, and even in space, to achieve resolutions that greatly exceed those possible using optical telescopes. Canadian and US radio astronomers (including Kellermann) were the early pioneers in that exciting new field.

Although the NRAO had from its founding intended to acquire a very large antenna, after the 140-foot debacle they couldn't find support for such a program. But on 15 November 1988, the 300-foot telescope at Green Bank suddenly collapsed—fortunately with no loss of life. Senator Robert Byrd of West Virginia used the collapse, which the media described as a disaster, to lobby successfully for a replacement antenna. The result was a new 100-meter radio telescope, called the Green Bank Telescope, whose story is related in chapter 9.

Chapter 10 describes the NRAO's first telescope dedicated to millimeter-wave radio astronomy, a 36-foot parabola sited in a dome at Kitt Peak National Observatory near Tucson, Arizona. It practically single-handedly gave rise to the field of astrochemistry. That chapter also discusses the NRAO's role in the planning of the internationally run Atacama Large Millimeter/Submillimeter Array in Chile.

The final chapter in the book covers the NRAO's contributions to 21st-century radio astronomy. It offers reflections on the love-hate relationship between the NRAO and university-based radio astronomy programs, the philosophical differences between the NRAO and optical astronomers at the Kitt Peak National Observatory, patterns of conflict and collaboration in US radio astronomy, and the management of frequency spectra. The authors round out the book by discussing the most ambitious international radio astronomy project ever devised: the Square Kilometre Array, currently under construction in Africa and Australia.

Well researched and well illustrated, *Open Skies* contains copious references at the end of each chapter for those wanting to learn more. It is also an open-access book, which means that the digital edition is freely available for anyone to download and read. Although it focuses on the US, *Open Skies* places the NRAO's achievements in both a domestic and an international context. For those wanting to know about the development of post–World War II radio astronomy—and not just about the NRAO—*Open Skies* is essential reading.

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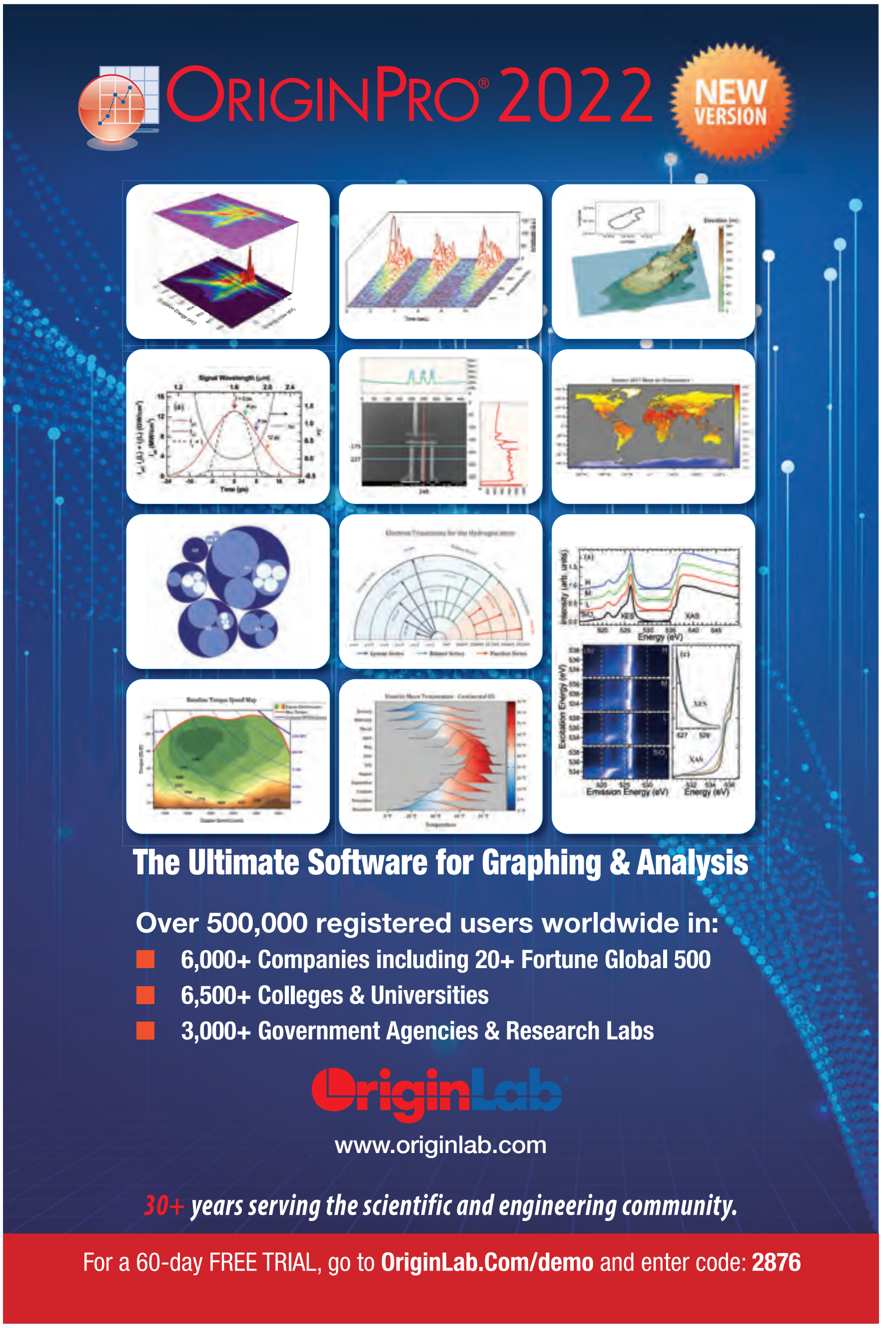
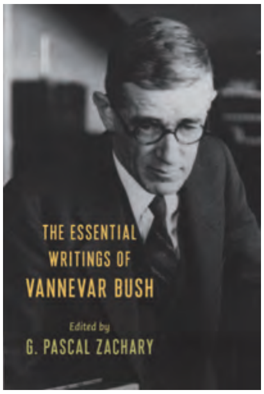


NEW BOOKS & MEDIA

The Essex Serpent

Anna Symon, lead writer
Apple TV+, 2022

The age-old conflict between science, reason, and faith comes to a head in *The Essex Serpent*, an atmospheric six-part TV adaption of Sarah Perry's best-selling 2016 novel. In the late 19th century, a massive earthquake hits the east coast of England, and rumors abound that a mysterious sea serpent has been seen in the waters. Recently widowed Cora Seaborne (Claire Danes), along with the local pastor, William Ransome (Tom Hiddleston), decide to investigate whether the serpent is a real dinosaur or something more ordinary. Local villagers, however, are certain it's a nefarious creature from hell. Beautifully shot in Essex, England, the series captures the awe and enthusiasm for science at a time when it seemed that new discoveries were occurring daily. —PKG



The Essential Writings of Vannevar Bush

G. Pascal Zachary, ed.
Columbia U. Press, 2022. $120.00

Perhaps no individual had a greater impact on postwar US science policy than Vannevar Bush, an engineer and administrator whose advocacy for governmental support of science—famously expressed in the 1945 report *Science: The Endless Frontier*—laid the groundwork for the founding of NSF. Edited by G. Pascal Zachary, this volume collects over 50 letters, memos, and essays dating from the 1920s to the 1970s. The texts discuss inventions like Bush's proposed "memex," a desk-based microfilm reader that presaged the World Wide Web, and major issues like the Cold War arms race, which Bush futilely tried to slow. Readers will likely be impressed by his prescience. As early as September 1944, for example, Bush predicted that another advanced nation could construct an atomic weapon within three to four years. Sure enough, the USSR tested its first bomb in 1949, a little over four years after the Trinity test. —RD PT

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The Stavropoulos Center for Complex Quantum Matter at the Department of Physics and Astronomy of the University of Notre Dame invites applications for a **tenure-track faculty position in materials discovery**. The successful candidate will demonstrate the capacity to lead research projects in materials synthesis and characterization of novel quantum materials and have experience with multiple crystal growth techniques.

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Andreas Mandelis

High-speed Roots pumps

Pfeiffer Vacuum has extended its HiLobe series by adding Roots pumps that can handle pumping speeds up to 13 600 m^3/h. The pumps are suitable for a range of low and medium vacuum applications. Those include the rapid evacuation of large enclosures such as load-lock chambers and vacuum furnaces, leak detecting, electron-beam welding, and freeze-drying and coating. Compared with conventional Roots pumps, the new pumps have energy-efficient drives and optimized rotor geometries that reduce energy costs by more than 50% and shorten pump-down times by about 20%, according to the company. The pumps are hermetically sealed and have a maximum integral leak rate of 1×10^{-6} Pa m^3/s. The elimination of dynamic seals means the pumps need maintenance only every four years. Intelligent interface technology ensures optimal process adjustment and condition monitoring. ***Pfeiffer Vacuum Inc**, 24 Trafalgar Sq, Nashua, NH 03063, www.pfeiffer-vacuum.com*

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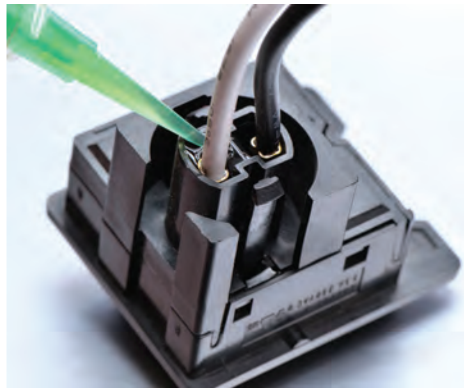

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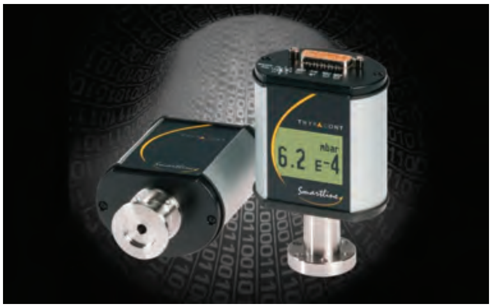
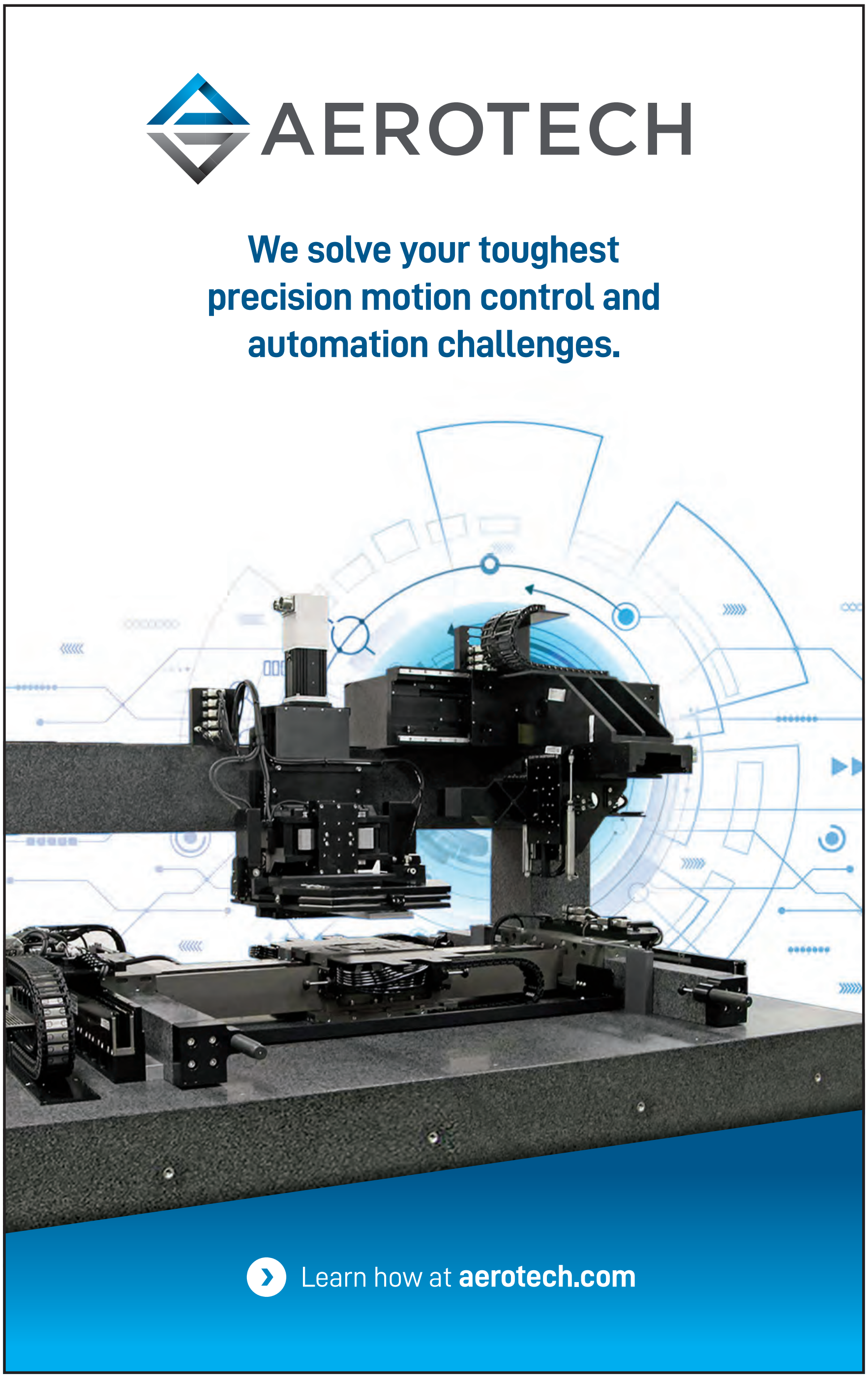


Vacuum transducer that supports predictive maintenance

According to Thyracont Vacuum Instruments, it is the first manufacturer of vacuum measurement technology to offer transducers that comply with the Open Platform Communications Unified Architecture, a data-transfer standard for industrial communication. OPC UA allows safe data transmission from machine to machine or machine to PC, independent of manufacturer, programming language, and operating system. All vacuum transducers of the company's Smartline product family with an RS485 interface will provide further parameters to support predictive maintenance, the proactive servicing of machines and appliances. To better plan service intervals, order spare parts, and optimize system run times, users can check the degree of sensor wear or corrosion, the time of the last adjustment, and the operation hours. ***Thyracont Vacuum Instruments GmbH***, *Max-Emanuel-Str 10, 94036 Passau, Germany, https://thyracont-vacuum.com*



Compound-semiconductor characterization

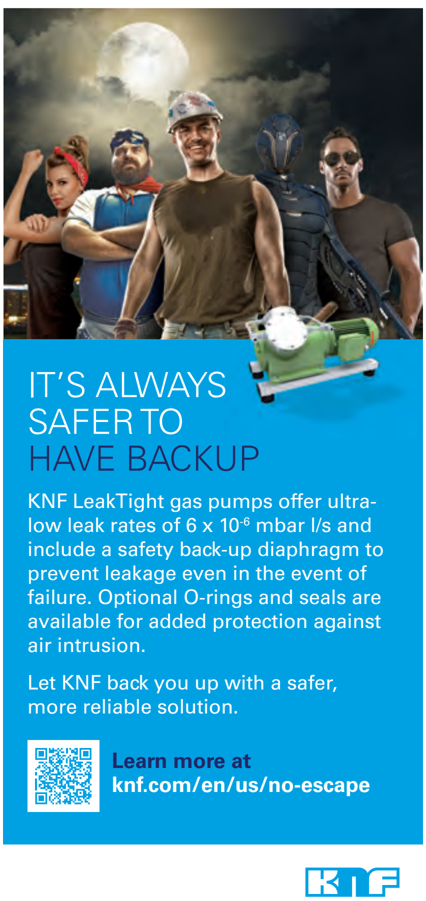
Semilab now offers its MBM-2201 semiconductor metrology system for the RF gallium nitride device market. MBM-2201 can characterize the charge carrier mobility and density and the sheet resistance of compound semiconductors with high-resistivity substrates on the entire surface of samples up to 200 mm in size. It features a small footprint, an ISO Class 1 clean-room design, and a fully automated wafer-handling capability, and delivers higher performance compared with its predecessor in the form of wider sheet resistance and mobility ranges, improved stability, and high sampling frequency and throughput. The MBM-2201's noncontact, nondestructive measurement method allows sample wafers to be sold after measurements. ***Semilab USA LLC***, *12415 Telecom Dr, Tampa, FL 33637, https://semilab.com*

Pulse-tube cryocooler

To enable dry dilution refrigerators to achieve temperatures down to millikelvin levels, Cryomech designed its PT310 pulse-tube cryocooler to deliver its optimum heat-lift performance at 3 K: It offers 1 W at 3 K and 35 W at 35 K. The remote-motor version, the PT310-RM, offers 0.9 W at 3 K and 32 W at 35 K. The base temperature is 2.3 K, and the cool-down time to 3 K is 60 minutes. The new cryocooler has the same envelope as the company's PT425 model, which makes it easy to transition to the next generation of dilution refrigerators. The unit is run with the CPA1114 compressor and is available with an integrated or remote motor. According to the company, the PT310's performance enables users to advance their refrigeration technology, which is at the heart of quantum computing developments. ***Cryomech Inc****, 6682 Moore Rd, Syracuse, NY 13211, www.cryomech.com*

Vacuum process analyzers

Hiden Analytical has introduced its HPR-30 series quadrupole analyzers for fast-response, high-sensitivity analysis of gas and vapor species. Applications for the bolt-on vacuum process analyzers include leak detection, contamination monitoring, process trend analysis, and analysis of high-mass species and precursors used in atomic layer deposition and metal–organic chemical vapor deposition. The standard mass range is 200 amu; versions up to 1000 amu are available. Multiple sampling configurations suit a full range of process-pressure and vacuum-system-geometry requirements. Those include versions with single or multiple sampling inlets and unheated or heated models to allow sampling of volatile species. For pulsed deposition processes, 50 ns time-resolution measurements are offered. ***Hiden Analytical Inc****, 37699 Schoolcraft Rd, Livonia, MI 48150, www.hidenanalytical.com* PT



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Michael Ellis Fisher

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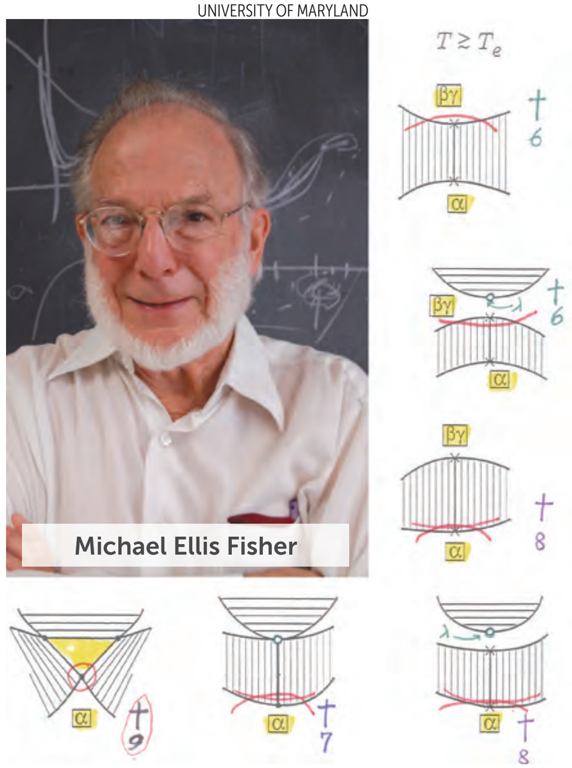

Michael Ellis Fisher

Michael Ellis Fisher, a Distinguished University Professor Emeritus at the University of Maryland, was born on 3 September 1931 in Trinidad and Tobago and passed away on 26 November 2021 in Silver Spring, Maryland.

A chemist, a physicist, a mathematician, an expert instructor in Spanish (flamenco) guitar, and an amateur artist whose skills spilled over into his expressive slides (see examples at right) and detailed edits, Michael was, in essence, a polymath. His long and productive career in theoretical statistical physics includes an astonishing 400-plus publications. He was a British Royal Air Force officer at a young age and produced his thesis and first publications—regarding analog computers—in that capacity.

Michael received his BS from King's College London in 1951 and his PhD in 1957 with Donald MacKay. He continued at King's College to focus on statistical mechanics with collaborator Cyril Domb. Michael held a progression of positions: research fellow, lecturer, reader, and, finally, professor. He moved to Cornell University in 1966 as Horace White Professor of Chemistry, Physics, and Mathematics. Twenty-one years later he went to the University of Maryland. At all those institutions, he had a significant impact.

Michael's most notable contributions include a number of scientific advances. In an early paper, "Magnetism in one-dimensional systems—the Heisenberg model for infinite spin," published in the *American Journal of Physics* in 1964, he presented an exact solution for the phenomenon. That same year his paper "Correlation functions and the critical region of simple fluids" in the *Journal of Mathematical Physics* introduced the critical exponent η. It is fundamental in critical point scalings as one varies the dimension of the system.

In 1967 Michael extended the droplet or cluster theory of condensation and predicted that there is an essential singularity at the condensation point, suggesting complex possibilities that were the basis for many subsequent studies by others. With Kenneth Wilson in 1972 in *Physical Review Letters*, he published the groundbreaking paper "Critical exponents in 3.99 dimensions," which helped Wilson earn the 1982 Nobel Prize in Physics. Michael's other important works include the 1974 *Reviews of Modern Physics* article "The renormalization group in the theory of critical behavior."

As a professor at Cornell and Maryland and at scientific meetings through the years, Michael had a substantial presence. To quote an anonymous source: "He was loved by many and feared by more." On one occasion, Michael attended a talk on new advances on superfluids given by one of us (Lathrop) and then grad student Gregory Bewley (now a faculty member at Cornell). After the talk, Bewley said, "That went terribly." Lathrop corrected his observation: "You don't understand, Greg. We had Michael's full attention; he likes what he has seen."

Michael received many awards and accolades. Among them were the 1971 Irving Langmuir Award in Chemical Physics and the 1995 Lars Onsager Prize, both from the American Physical Society; the 1983 Boltzmann Medal of the International Union of Pure and Applied Physics; and a 2005 Royal Medal from the UK's Royal Society.

With Wilson and Leo Kadanoff, Michael received the Wolf Prize in Physics in 1980. In its citation, the Wolf Foundation described him as "an extraordinarily productive scientist, and one still at the height of his powers and creativity" and said that "Fisher's major contributions have been in equilibrium statistical mechanics, and have spanned the full range of that subject. He was mainly responsible for bringing together, and teaching a common language to, chemists and physicists working on diverse problems of phase transitions."

Michael's mentorship at all levels—K–12 students; undergraduate, graduate, and postgraduate students; and junior and senior faculty members—is difficult to capture here. As a fierce proponent of the scientific method, ethics, and education, he was at times very patient with students and would at other times sharply question colleagues. He gave brilliant advice, and his impact with regard to that and his scholarship was as consistent as his humanity. To quote one mentee: "He invested so well in his students that they now pass along the same messages to those they teach."

As for his character, Michael was an aggressive questioner and a fierce debater. And he was someone you could trust with your life. Michael Ellis Fisher's intellectual legacy will echo through the generations in chemistry, mathematics, and physics in ways that are hard to measure.

Daniel P. Lathrop
Ellen D. Williams
University of Maryland
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Sean Carroll (seancarroll@gmail.com) is the Homewood Professor of Natural Philosophy at Johns Hopkins University in Baltimore, Maryland, and a member of the Fractal Faculty at the Santa Fe Institute in New Mexico.

Addressing the quantum measurement problem

Sean M. Carroll

Attempts to solve the problem have led to a number of well-defined competing theories. Choosing between them might be crucial for progress in fundamental physics.

What precisely happens when a quantum measurement is performed? That's the quantum measurement problem, in broad strokes. There are optimistic folks, like David Mermin (see Physics Today, June 2022, page 62), who believe there is no measurement problem, but that's because they think they know the answer to it. Unfortunately, despite almost a century of effort, no one solution has been completely accepted by a majority of physicists. The fairest thing is to admit that the measurement problem is still with us.

The awkwardness of the measurement problem is only enhanced by the undeniable empirical success of textbook quantum theory. According to that treatment, quantum systems are described using wavefunctions. Wavefunctions evolve according to the Schrödinger equation, at least when the system is not being observed. Upon measurement, the wavefunction collapses to an eigenstate of the measured observable.

That textbook version of quantum mechanics fits a wide variety of data, but it clearly isn't the final answer. It is too vague and ill-defined to qualify as a rigorous physical theory. What exactly is a "measurement"? What kind of system is allowed to make a measurement, and when precisely does it happen? Are measuring apparatuses and observers themselves quantum systems? Do measurements reveal a pre-existing reality, or bring the world into existence?

Any plausible approach to the foundations of quantum mechanics would have to provide definite answers to those questions.

Lines of attack

The issue is not that no plausible solutions to the measurement problem exist, but that several reasonable lines of attack are available, all of which come with obvious drawbacks. In particular, each seems to demand a significant leap away from our traditional intuitive view of the world. Perhaps that is to be expected—quantum mechanics differs profoundly from classical mechanics—but opinions vary about which leaps are worth taking and which are just too wild to countenance.

One strategy, descending from Niels Bohr and Werner Heisenberg, is to take the notion of measurement as central, rather than as an annoying technicality. The basic focus of analysis is not the physical world itself, but rather a set of agents within it, and the experiences and knowledge that those agents accrue. That approach is known as epistemic, because the wavefunction doesn't represent physical reality but is simply a device for tracking what agents know about it. The Copenhagen interpretation falls into this category, as does the QBism approach favored by Mermin and others (see the Commentary by Mermin, Physics Today, July 2012, page 8).

The idea that physics isn't about objective reality, but about the experiences of agents, would certainly be a dramatic shift. It seems counter to the general progression of science, which has acted to remove human beings from a central role in the workings of the universe. More substantively, one would still presumably like a rigorous mathematical definition of what the physical world really is, and for that matter what agents are. But perhaps the radicalness of that change in perspective is simply what quantum mechanics demands of us.

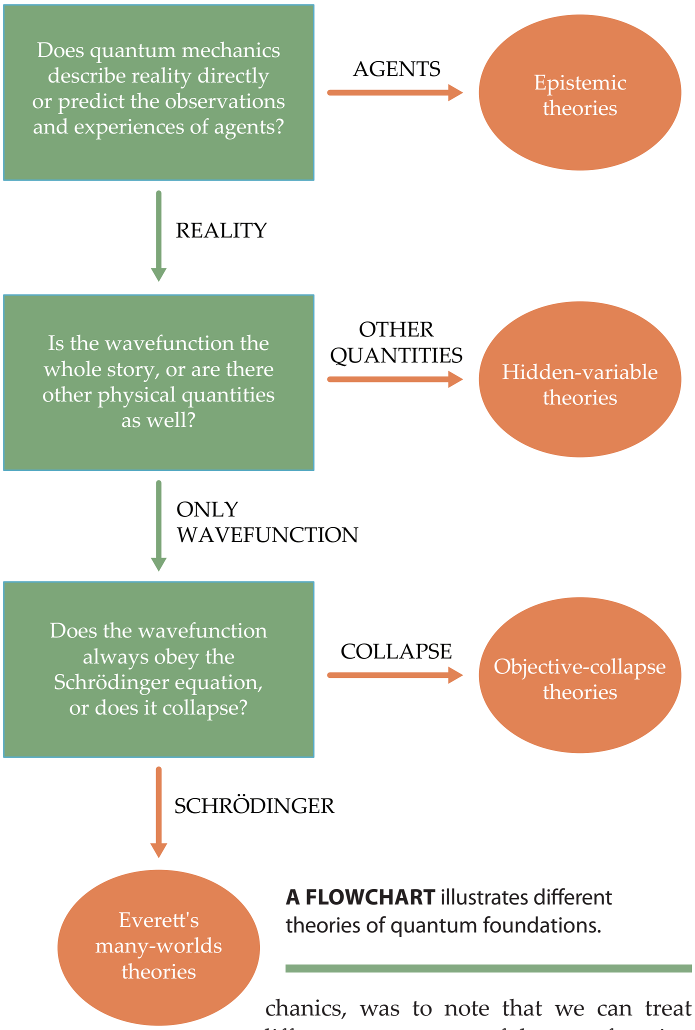
It's not the only option, however. A second strategy is to posit that the wavefunction represents reality, entirely and exactly—an ontic rather than epistemic role. The wavefunction of an electron interferes with itself when it passes through a double-slit experiment; that kind of behavior seems characteristic of physical stuff, not of a knowledge representation. For that matter, things like the solidity of materials are explained in terms of the energies of wavefunctions of atoms; again, a very stuff-like property for something to have.

But we don't see wavefunctions when we measure properties of quantum systems. We see specific values of the quantity being measured. That's what inspired quantum pioneers to think differently. How can we explain that feature if the world is nothing but wavefunction?

Life in a superposition

One bold version of the ontic strategy is to simply erase all of the textbook rules pertaining to observation. Remove measurements from the formalism entirely, accept that the wavefunction describes reality fully, and insist that all it ever does is obey the Schrödinger equation. From those postulates we find that a measuring apparatus does not collapse the state of a measured system; rather, it becomes entangled with it. When an electron's spin is measured, one component of the universal wavefunction describes the electron as spin-up and the observer as having measured it as such, while another component does the same for spin-down. Both components continue to exist if we simply take the Schrödinger equation at face value.

The problem with that perspective is that we never *feel* like we're in a superposition; empirically, we report definite measurement outcomes. The solution proposed by Hugh Everett, founder of the many-worlds interpretation of quantum me-



A FLOWCHART illustrates different theories of quantum foundations.

chanics, was to note that we can treat different components of the wavefunction as distinct, noninteracting worlds. Modern decoherence theory puts meat on those bones, explaining how worlds are chosen and why they never interact.

Problems, no doubt, remain. How do you recover the Born rule—the probability that an outcome is given by its amplitude squared—if every outcome comes true in some branch? At a more philosophical level, are we really prepared to accept the existence of countless copies of ourselves, living in slightly different worlds? That approach is arguably as metaphysically dramatic as putting agents at the center of our theories of physics.

Yet another tactic is possible—still accepting that a wavefunction exactly represents reality, but denying that it always obeys the Schrödinger equation, and instead introducing genuine collapses into the dynamics. Rather than invoking measurements, however, we can allow such collapses to be spontaneous (every particle has a probability per unit time of suddenly localizing) or triggered (collapse happens when branches of the wavefunction become sufficiently distinct). In either case the collapse is imagined to be genuinely stochastic, with frequencies that recover the Born rule.

In effect, those objective collapses prune off the extra worlds implied by Everett's approach. At the same time, doing stochastic violence to the deterministic beauty of the Schrödinger equation might seem *ad hoc*, as is the choice of what the wavefunction collapses to. The good news is that such modifications are generally experimentally testable, though the experiments generally involve keeping large numbers of particles in a coherent superposition.

Hidden variables

The last strategy could be thought of as a middle ground: Accept that the wavefunction is part of reality, but not the whole thing, and not the part we see when we perform a measurement. We see particles, in this view, because particles exist as distinct entities, in addition to the wavefunction. Those extra degrees of freedom are known as hidden variables, even though they are what we observe. The wavefunction acts as a "pilot wave," guiding particles into the right positions to be measured. That guidance is a nonlocal effect, which allows such theories to be compatible with Bell's theorem. Louis de Broglie pioneered the approach, and it has been championed by David Bohm and John Bell.

Pilot-wave theories, like objective-collapse theories, seem a bit contrived. The wavefunction guides the particles, but the particles exert no influence on the wavefunction whatsoever. Perhaps more worryingly, it is hard to generalize that strategy from theories of particles to more modern quantum field theories, and much harder still to imagine how quantum gravity might ultimately be incorporated. Needless to say, proponents of the approach have ideas about addressing those problems, as do partisans of the above theories for the problems of their own.

So there are a number of different approaches to the quantum measurement problem, all of which are legitimately distinct and well-defined physical theories. (And there are others we don't have space to mention.) But at the end of the day their experimental predictions are seemingly identical, or pretty close to it. Should we care?

Yes, we *should* care, because physics isn't finished. As Richard Feynman noted, theories can be formally equivalent but psychologically different. As we try to construct more comprehensive theories of grand unification, quantum gravity, and emergent spacetime, the ideas we come up with might be strongly influenced by our attitude toward quantum foundations. Questions that seem hardly worth addressing in one approach might merit intense concern in another.

Besides, are we sure that those approaches are experimentally equivalent? My own view is that the theories are not quite developed enough, and we haven't yet put sufficient effort into understanding them, to say for sure. Only by knowing exactly what the options are and how they fit in with the rest of physics can we be certain. There might be new experiments that we haven't thought of, which could distinguish between them. And that is what physics is all about.

Additional resources

▶ S. Carroll, *Something Deeply Hidden: Quantum Worlds and the Emergence of Spacetime*, Dutton (2019).
▶ T. Maudlin, *Philosophy of Physics: Quantum Theory*, Princeton U. Press (2019).
▶ T. Norsen, *Foundations of Quantum Mechanics: An Exploration of the Physical Meaning of Quantum Theory*, Springer (2017).
▶ D. Wallace, *The Emergent Multiverse: Quantum Theory According to the Everett Interpretation*, Oxford U. Press (2012). PT

BACK SCATTER

Where rivers jump

The location of a streambed drifts over time as the water carried downstream erodes the surrounding land. Sometimes that gradual process is superseded by an avulsion—an abrupt jumping of the stream from one channel to another. Avulsions are rare, typically happening once every few decades at most, but they've been linked to historical floods. The consequences were devastating for civilizations that relied on the crops destroyed by those floods. This photo—from optical data collected by some of the European Space Agency's Sentinel satellites—shows the avulsion of the Pemali River in Indonesia. In 2006, almost 5 km upstream of the Java Sea, the river jumped from the longer right-hand path to the left-hand one.

Sam Brooke and Vamsi Ganti of the University of California, Santa Barbara, and their colleagues identified three categories of avulsions in a database they created from 50 years of global satellite imagery. The Pemali's jump falls into a category in which avulsions take place in a stream's delta and in a region known as the backwater zone, which is characterized by nonuniform flows. Although today's global supply chains better protect people from crop losses in a single location, avulsions can still threaten lives and property. Brooke, Ganti, and colleagues find that increasing flood frequency and sediment quantity, driven by climate change and people's engineering of the land surface, will affect avulsions. Their analysis offers a means to predict where they may occur in the future. (S. Brooke et al., *Science* **376**, 987, 2022; image courtesy of Sam Brooke and Vamsi Ganti.) —AL

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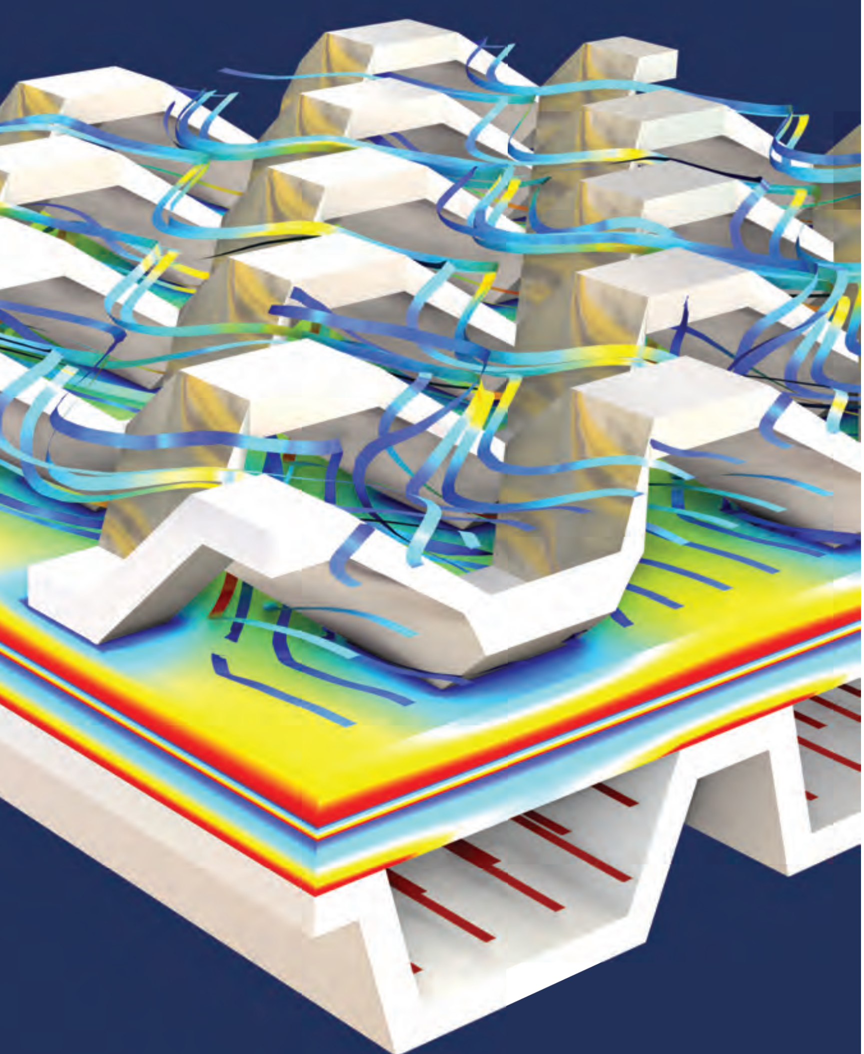

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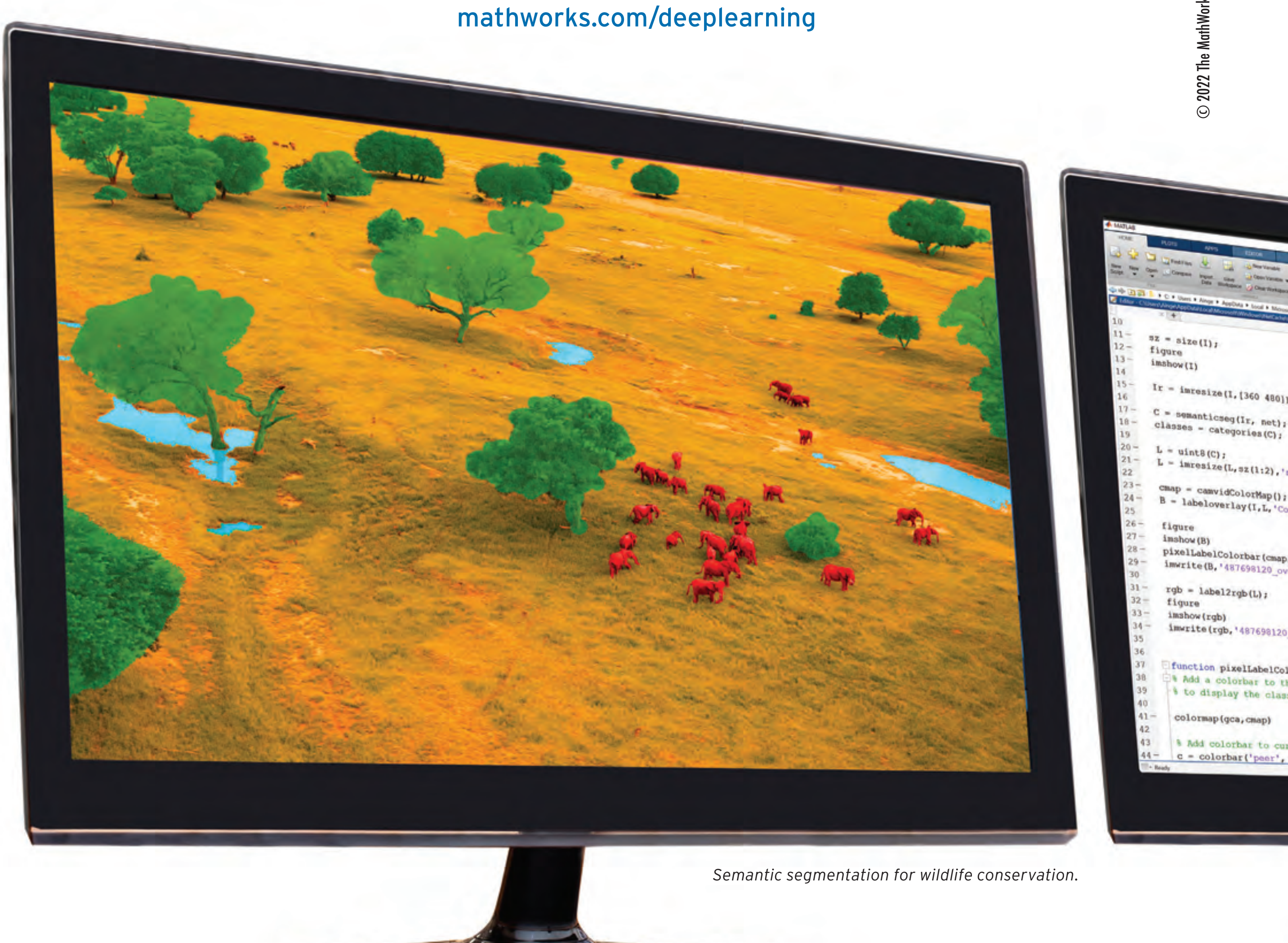

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