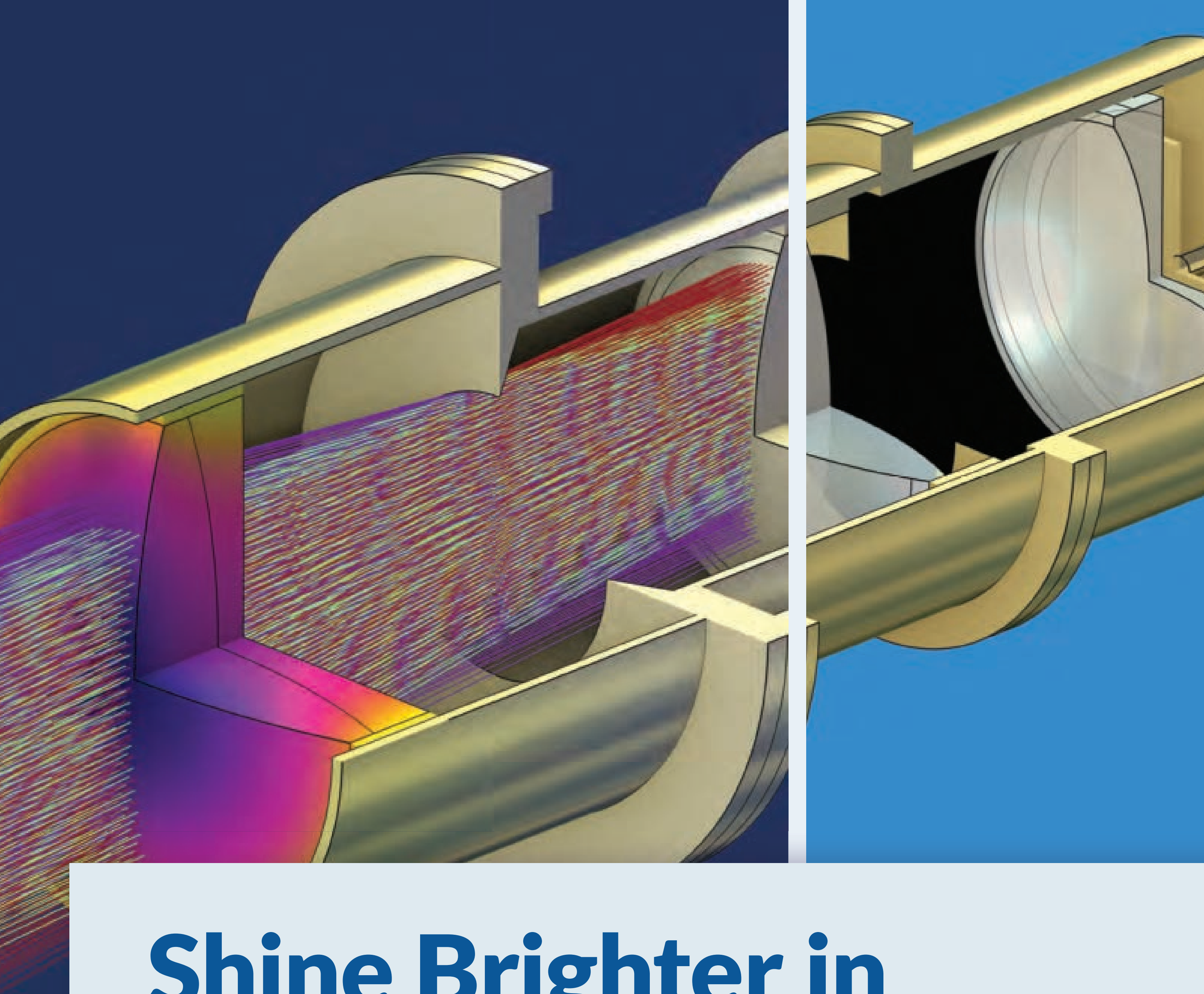

PHYSICS TODAY

November 2023 • volume 76, number 11

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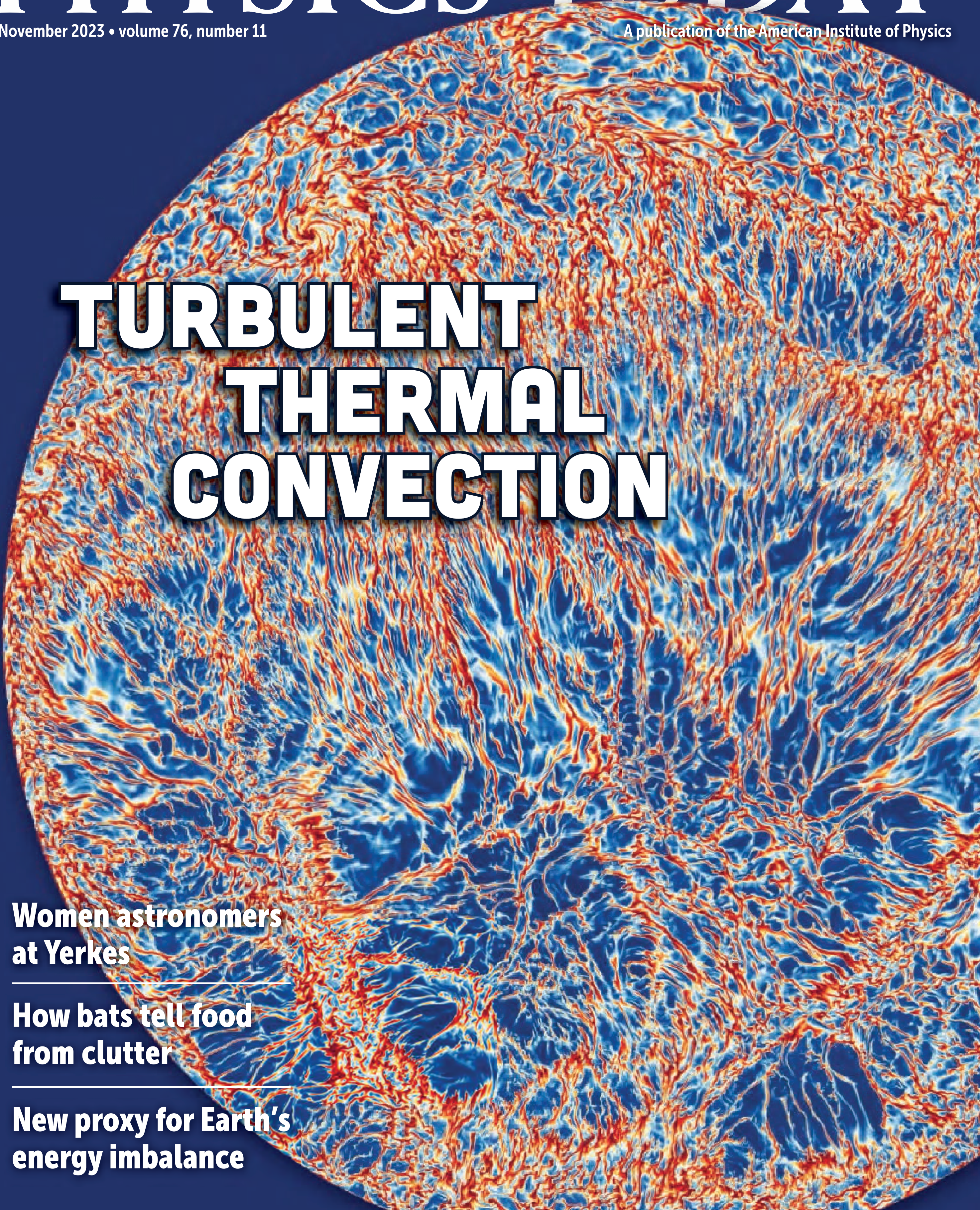

TURBULENT THERMAL CONVECTION

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How bats tell food from clutter

New proxy for Earth's energy imbalance

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Tenure-Track Position in Experimental Condensed Matter Physics at the Assistant Professor Level

The Department of Physics and the College of Liberal Arts and Sciences (LAS) at the University of Illinois Chicago (UIC) invite applications to fill a tenure-track position in experimental condensed matter physics at the Assistant Professor level. The emphasis of this search is to strengthen the department's efforts in experimental materials and condensed matter research in the areas of quantum, superconducting and topological materials. The anticipated start date is Fall 2024.

The materials and condensed matter research faculty in the Department of Physics at UIC conduct experimental and theoretical research on a wide range of functional and complex materials, including energy-relevant, quantum, topological, superconducting and strongly-correlated systems. A successful candidate is expected to build a highly visible research program focusing on areas such as materials synthesis and the characterization of heterostructures, interfaces, low-dimensional/2D materials or quantum engineered lattices. Expertise in characterization approaches, such as X-ray diffraction, electron or neutron scattering, Raman spectroscopy, transport, or scanning probe microscopy is highly desirable. The successful candidate should be able to collaborate with existing condensed matter theory and experiment groups in the Physics Department. A description of the research programs in the Department of Physics can be found at phys.uic.edu.

UIC has strong computational and characterization core facilities, including a high-performance computing cluster and aberration-corrected electron microscopy facilities (**www.rrc.uic.edu**). The proximity to Argonne National Laboratory opens the possibility to perform material characterization at the Advanced Photon Source, such as angle-resolved photoemission and x-ray diffraction/spectroscopy experiments.

Please go to **https://uic.csod.com/ux/ats/careersite/1/home/requisition/6938** to complete an online application. Required documents to be uploaded include a CV, publication list, concise statements of research and teaching interests, and of perspectives on and commitment to diversity, equity, and inclusion. The minimum qualification for the position is a Ph.D. in physics or in a related field. Applicants that are confirmed to meet the minimum qualifications will be requested to provide contact information for at least three reference letters. Applications must be completed by November 15th, 2023 to receive full consideration. Final authorization of the position is subject to availability of funding.

UIC is a Research I public university in the heart of Chicago. It is the largest university in the Chicago area with over 30,000 students, 16 colleges, one of the nation's largest medical schools, and one of the most diverse student bodies. For additional information, please refer to UIC's Home Page at **www.uic.edu** and the College of Liberal Arts and Sciences at **www.las.uic.edu**.

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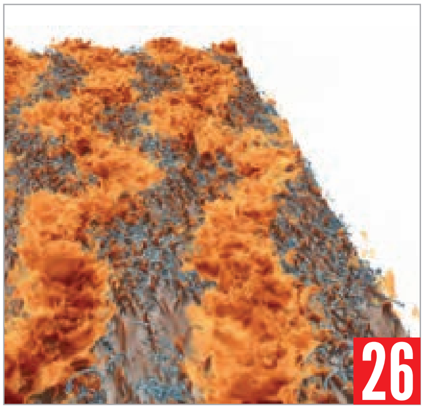
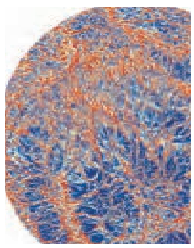


FEATURES



ON THE COVER: This cross-sectional snapshot from a simulated cylindrical cell shows the temperature in turbulent Rayleigh–Bénard convection, the flow of fluid heated from below and cooled from above. Tiny plumes of rising (red) and sinking (blue) fluid are visible in the snapshot, taken close to the cylinder's lower, warm plate. For more details on strongly turbulent convection, turn to the article by Detlef Lohse and Olga Shishkina on **page 26**. (Simulation courtesy of Richard Stevens and Roberto Verzicco.)

Recently on PHYSICS TODAY ONLINE

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US NAVAL RESEARCH LABORATORY

Titus Pankey

In 1962 Titus Pankey proposed a mechanism that explained the light curves of type Ia supernovae, the stellar explosions that are now used to track the universe's expansion. Camryn Bell and Matt Caplan profile the late Howard University researcher, who was among the first 10 Black physics PhD holders in the US.

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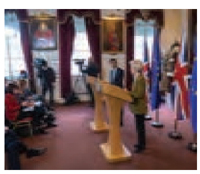

NO. 10 DOWNING STREET

UK rejoins Horizon

A recent agreement ensures that after a three-year hiatus, the UK will rejoin Horizon Europe, the €95.5 billion ($101 billion) framework for research and innovation in the European Union. Toni Feder talks to researchers in both the UK and the EU who are eager to resume their collaborations in January.

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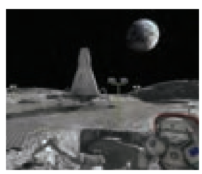

PAVER CONSORTIUM

Lunar paving

The roads of future Moon bases could be paved with lunar dust that is zapped into bricks, a new study suggests. In a lab demonstration, researchers used a laser to melt synthetic regolith, which then hardened into a robust composite. Focused sunlight could do the job of the laser on the Moon, the researchers say.

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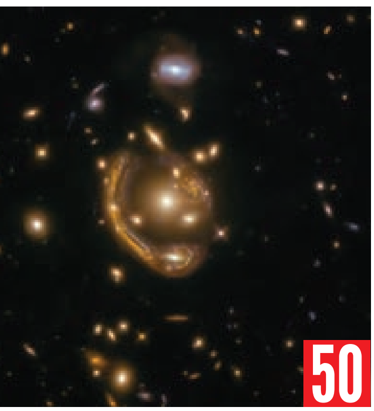

DEPARTMENTS

SUBSCRIPTION QUESTIONS? +1 800 344-6902 | +1 516 576-2270 | **ptsubs@aip.org**

Editor-in-chief
Richard J. Fitzgerald *rjf@aip.org*

Art and production
Freddie A. Pagani, art director
Cynthia B. Cummings, photographer
Nathan Cromer
Abigail Malate
Lorien Williams

Editors
Ryan Dahn *rdahn@aip.org*
Laura Fattaruso *lfattaruso@aip.org*
Toni Feder *tf@aip.org*
Abby Hunt *ahunt@aip.org*
David Kramer *dk@aip.org*
Alex Lopatka *alopatka@aip.org*
Johanna L. Miller *jlm@aip.org*
Gayle G. Parraway *ggp@aip.org*
Jennifer Sieben *jsieben@aip.org*
R. Mark Wilson *rmw@aip.org*

Online
Andrew Grant, editor *agrant@aip.org*
Greg Stasiewicz *gls@aip.org*

Assistant editor
Cynthia B. Cummings

Editorial assistant
Tonya Gary

Contributing editor
Andreas Mandelis

Sales and marketing
Christina Unger Ramos, director *cunger@aip.org*
Bonnie Feldman
Unique Carter
Krystal Amaya
Kelly Winberg

Address
American Institute of Physics
One Physics Ellipse
College Park, MD 20740-3842
+1 301 209-3100
pteditors@aip.org

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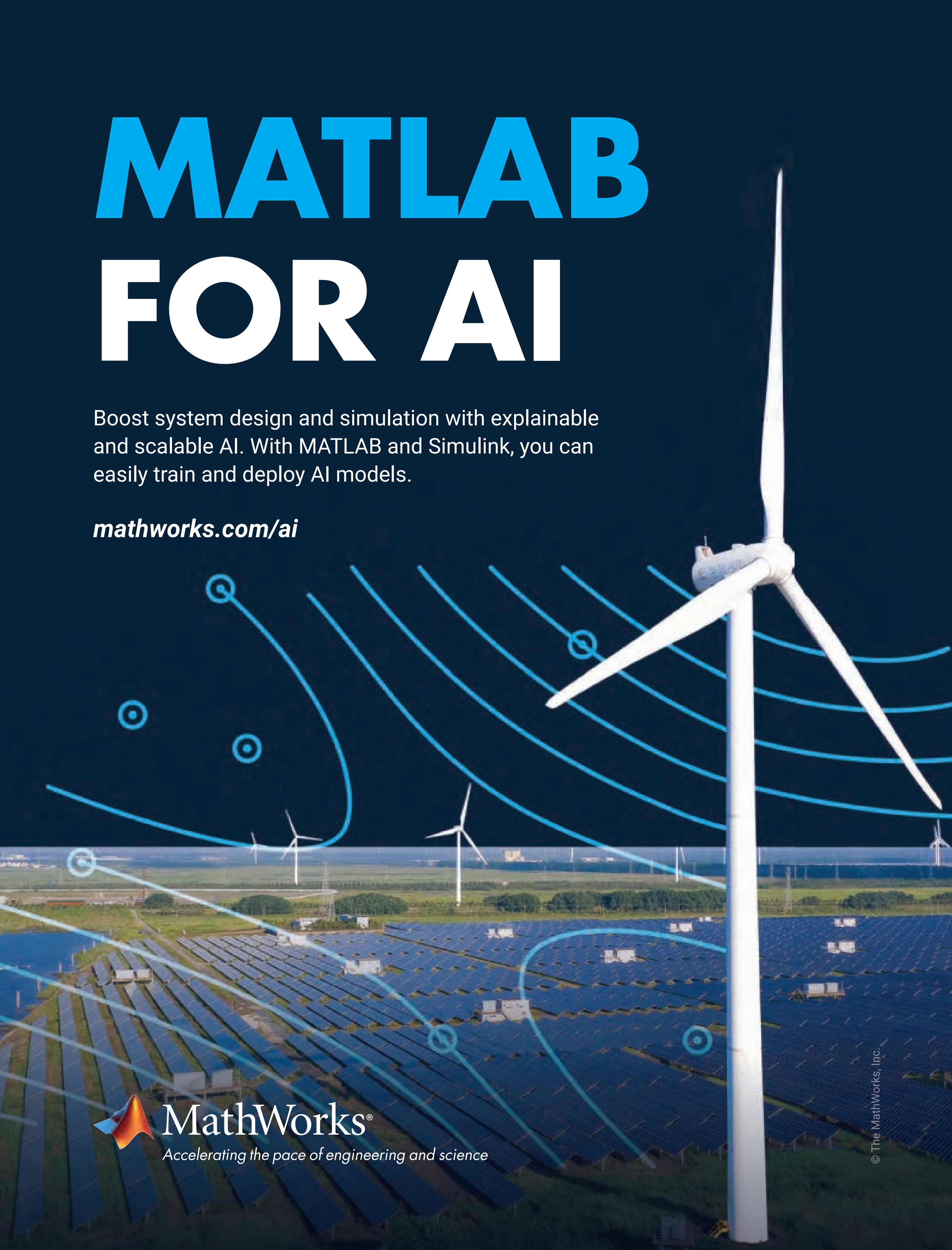
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The clean-energy challenge redux


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For a publication that covers a field so important to energy-conversion technologies, I find it interesting that the recent conversations about "clean energy" in PHYSICS TODAY seemed focused on whether we can produce enough of it. That issue came to my attention while reading David Kramer's "Electrification of cars and trucks likely won't disrupt the grid" (PHYSICS TODAY, April 2022, page 22) and the subsequent discussion in the April 2023 issue (page 11). Kramer substantiates the assertion in his headline with a quote from National Renewable Energy Laboratory research team leader Matteo Muratori: "Utilities are excited. Selling more electricity is their business. . . . We build new industrial facilities, new hospitals, and new schools, and they make sure the electricity is there to support those needs."

A missing piece in the discussion has been a proposal to use less energy.

Generally speaking, traveling by rail is less energy intensive than by car or airplane. I live out in the country and have an electric car. But 100 meters from my doorstep lies an abandoned train platform that was active 60 years ago, and the train could have taken me to the city in less time than I can drive there now. And while my recent flight to a conference in Chicago took only three and a half hours in the air, when I factored in time spent heading to the airport, going through security, waiting for the flight, taxiing on both ends, and grabbing a shuttle into town, the trip consumed a bit over 10 hours in total. Had I taken a high-speed train traveling at 300 kilometers per hour, it would have taken nearly the same amount of time from city center to city center—and I would have been able to work, eat, and sleep at my leisure.

Europe understands that, and consequently many of its countries have constructed thousands of kilometers of high-speed rail throughout the landscape. Meanwhile, the US lacks even one fully high-speed line—currently the Amtrak Acela, between Boston and Washington, DC, is the one train that can reach high speeds, but only on parts of its route. Nonetheless, people buying vehicles have the option to choose among many "all-electric" SUVs, pickups, and other types of cars—some of which have more than a thousand kilograms of batteries, along with synthesized motor sounds you can turn on should you miss the rumble of an internal combustion engine.

It's time to include the principles of energy conservation into the discussions about decarbonizing our economy.

Michael Stocker
(mstocker@ocr.org)
Ocean Conservation Research
Lagunitas, California

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

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In their letters in the April 2023 issue of PHYSICS TODAY (page 11), Mike Tamor and Arthur Williams raise valid points about the difficulties of meeting the energy needs of a future world trying to wean itself off carbon-based fuels. As good physicists do, they see a problem and soberly evaluate potential solutions.

But figuring out how to meet energy needs in a future carbon-free economy is not the same as solving a classic physics problem. In classic physics problems, we accept that we cannot do anything about the laws of nature; we can at best try to understand those laws and benefit from that knowledge. When it comes to meeting the energy needs of a future and hopefully better world, we aren't dealing only with the laws of nature—we are also dealing with human behavior.

We physicists should not only concern ourselves with finding ways to satisfy the difficult-to-meet needs of a future economy on the basis of current trends of human-population growth and energy consumption. We should also advocate for different ways of living that require far less resource consumption and promote greater equity between the richest and poorest nations.

Julia Steinberger is a trained physicist and currently an ecological economist whose outlook on such matters is one that the physics community should consider when discussing the transition to a carbon-free economy. She has argued that countries that have decent living standards can and should greatly reduce their consumption of energy. She and her colleagues have shown that the countries using the highest amounts of energy can accomplish such reductions while still meeting the needs of citizens.[1]

Wealthy countries should create space for developing nations to grow their economies while ensuring that the global economy operates within parameters that are consistent with ecological sustainability.

Reference

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Robert A. Austin
(austin97@purdue.edu)
Purdue University
West Lafayette, Indiana PT
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A new proxy for Earth's past energy imbalance

Oxygen-isotope measurements of ocean-bottom organisms are an excellent indicator of the atmosphere's radiation flux.

The amount of incoming solar energy that warms our planet today is greater than the energy radiated back to space. That radiation imbalance, predominantly attributable to anthropogenic fossil-fuel emissions, has heated Earth at an average rate of about 0.5 W/m^2 over the past 50 years.

To better understand present and future climate change, researchers study the geologic past—often during ice ages and other periods of extreme climate variations—using measurements from ice cores, sediment records, tree rings, and the like. (See, for example, the article by Toby Ault and Scott St. George, Physics Today, August 2018, page 44.)

Marine sediment records include the shells of micron-sized foraminifera, shown in figure 1. They're single-celled organisms, many of which live at or near the ocean bottom. To paleoclimate researchers, they're useful indicators of climate conditions. Foraminiferal δ^{18}O is the amount of the trace isotope oxygen-18 relative to the more abundant oxygen-16 in the organisms' shells. That geochemical signal primarily depends on the temperature of the ocean, which affects foraminifer biochemistry, and seawater δ^{18}O, which depends on the volume of Earth's ice sheets and glaciers.

Now Princeton University's Sarah Shackleton and colleagues have combed through global foraminiferal δ^{18}O records[1] and found a new use for those data. The ocean temperature and ice-volume signals that contribute to the total δ^{18}O change are distinct. But when the signals are combined, they record global energy changes.[2]

Energy in, energy out

Daniel Baggenstos, who went to graduate school with Shackleton, published a paper in 2019 with her and other colleagues. They used an ice core, sediment records, and coral measurements to estimate Earth's radiation imbalance from the Last Glacial Maximum, about 20 000 years ago, to the present day.[3]

When more energy comes to Earth than goes out, it has to go somewhere: into the oceans, ice sheets, the atmosphere, or land surfaces. Today, a whopping 90% of the excess radiative flux is absorbed by the ocean. But what Baggenstos and colleagues found about past energy imbalance, says Shackleton, is that "warming the ocean and melting the ice sheets are really the only changes

FIGURE 1. MARINE INVERTEBRATES, like the many micron-sized species of foraminifera that form the tens of millimeter-sized shells shown here, are useful indicators of changes in ocean temperature and ice volume. (Photo by the Natural History Museum, London/Alamy Stock Photo.)

that matter." Every other process affected by the total energy imbalance has a much smaller contribution.

That study got Shackleton thinking about whether the foraminiferal δ^{18}O record would show similar trends to the results in the 2019 paper. "In any kind of Paleoclimate 101 class," says Shackleton, "one of the first things that you'll see is the δ^{18}O records, and they really are kind of a template for understanding the ice ages. Because they record changes in ice volume and ocean temperature, in the past several decades there have been a lot of efforts to interpret them in terms of either one of these properties." (For more about one recent reconstruction, see PHYSICS TODAY, January 2022, page 14.)

Compared with the records that Baggenstos and colleagues used to construct 25 000 years of energy-imbalance history, foraminiferal archives have some advantages. For one, the plentiful number of the fossilized organisms in marine sediment cores make them a practically continuous record of change over time. And foraminiferal archives go back tens of millions of years, whereas ice-core records only extend back 800 000 years. (Efforts are underway to find even older ice in Antarctica; see PHYSICS TODAY, April 2023, page 18.)

Two for one

Compared with the heavy ^{18}O, the light ^{16}O more readily evaporates from the ocean. Polar ice sheets, therefore, are enriched in ^{16}O and return the isotope to the ocean when they melt. Because the foraminiferal δ^{18}O record reflects the oxygen-isotope composition of seawater, it's a good proxy for ice volume. The foraminiferal δ^{18}O record is also affected by a temperature-dependent process during shell formation that separates ^{16}O from ^{18}O at chemical equilibrium, which makes it a useful ocean paleothermometer.

Rather than interpret the foraminiferal δ^{18}O record as a proxy for ice volume or ocean temperature, Shackleton and her colleagues considered whether it could be representative of Earth's energy imbalance. Their crucial insight was that melting ice and rising ocean temperatures have nearly the exact same effect on foraminiferal δ^{18}O.

That is, when they modeled foraminiferal δ^{18}O as a function solely of ice-volume changes or ocean temperature, the energy changes associated with each variable were quite similar: 19 × 10^{24} J/ppt (parts per thousand) for ocean warming and 16 × 10^{24} J/ppt for ice-volume changes. "From what I understand," says Shackleton, "it's just a strange coincidence that they end up translating into similar total energies."

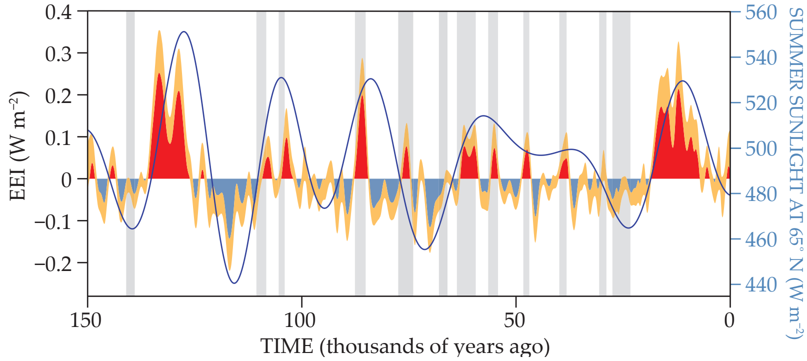

FIGURE 2. ISOTOPE MEASUREMENTS—made from the shells of some ocean-bottom-dwelling foraminifera similar to ones shown in figure 1—estimate Earth's energy imbalance (EEI, yellow line) over the past 150 000 years. Unlike most times with negative energy change (blue area), the periods of positive changes (red area) are associated with Heinrich events (gray shading), when icebergs broke off North America's Laurentide Ice Sheet into the ocean. The reconstructed energy imbalance largely follows the amount of sunlight Earth receives during the summer at 65° N (blue line). (Adapted from ref. 2.)

Thanks to that similarity, Shackleton and colleagues inferred the energy imbalance directly from foraminiferal δ^{18}O without needing to do the difficult task of deconstructing the isotope measurement into its constituent parts. The paleoclimate community already has independent records of ocean temperature and ice volume, but having a single record sensitive to both variables avoids some challenges, such as the need to carefully align different data to the same age model.

The researchers compared the energy imbalance calculated from foraminiferal δ^{18}O over the past 25 000 years with previous energy-imbalance predictions. Reassuringly, their results agree with an energy reconstruction based on ocean temperature from noble-gas measurements[3] and ice volume inferred from coral and sediment records.[4]

Figure 2 shows the new energy-imbalance calculation from the foraminiferal δ^{18}O data, and it extends back 150 000 years. The ups and downs in energy imbalance have a clear association with periods of abrupt climate change known as Heinrich events, when icebergs broke off into the ocean from the Laurentide sheet that once covered much of North America. "That was definitely very interesting, although not necessarily incredibly surprising, based on our understanding," says Shackleton. "But it was really nice to see that come out of the energy-imbalance reconstruction."

The new record also tracks strongly over time with another well-studied climate variable: the amount of sunlight Earth receives during the summer at 65° N, a bit south of the Arctic Circle. Previous research has linked variations in Earth's orbit to reductions of sunlight at that latitude and consequently the onset of global-scale ice ages. Increased sunlight there triggers deglaciation. (For more on orbitally driven ice ages, see the article by Mark Maslin, PHYSICS TODAY, May 2020, page 48, and PHYSICS TODAY, September 2016, page 13.)

"This record that we've all been looking at and interpreting," says Shackleton, "can be interpreted in a completely different way." With their new approach to measuring Earth's energy imbalance, she and her colleagues plan to better study millennial-scale perturbations of the climate system and whether they instigate a large restructuring of atmospheric and oceanic circulation patterns.

Alex Lopatka

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Electron scattering provides a long-awaited view of unstable nuclei

Nuclear reactions produce a plethora of short-lived artificial isotopes. Figuring out what they look like has been a challenge.

The cartoon picture of an atomic nucleus looks kind of like the inside of a gumball machine that dispenses only two flavors: protons and neutrons, evenly mixed in a compact, spherical cluster.

That's not generally what real nuclei look like. Neutron-rich lead-208, for example, has a thick skin of neutrons encasing its proton-endowed core (see Physics Today, July 2021, page 12). Some nuclei are flattened, and some are elongated. Some are even pear shaped.

The more unstable a nucleus, the stranger the structures it can adopt. Short-lived nuclei might form bubble structures with depleted central density, or they might have a valence nucleon or two that form a halo around a compact central core. (See the article by Filomena Nunes, Physics Today, May 2021, page 34.) Frustratingly, though, those exotic structures are hard to experimentally confirm, because the gold standard for probing nuclear structure—electron scattering—has been off limits to short-lived nuclei.

That could change soon. Kyo Tsukada and colleagues, working at RIKEN's Radioactive Isotope Beam Factory (RIBF) in Wako, Japan, have performed the first electron-scattering experiment on unstable nuclei produced on the fly in a nuclear reaction.[1] Their isotope of choice, cesium-137, has a half-life of 30 years. It's not so exotic that the researchers expected—or found—anything unusual about its structure. But the technique they used is applicable to shorter-lived nuclei, so more experiments are on the way.

Backscatter

Probing nuclei through particle scattering dates back to the discovery of the nucleus itself, in 1911, when Ernest

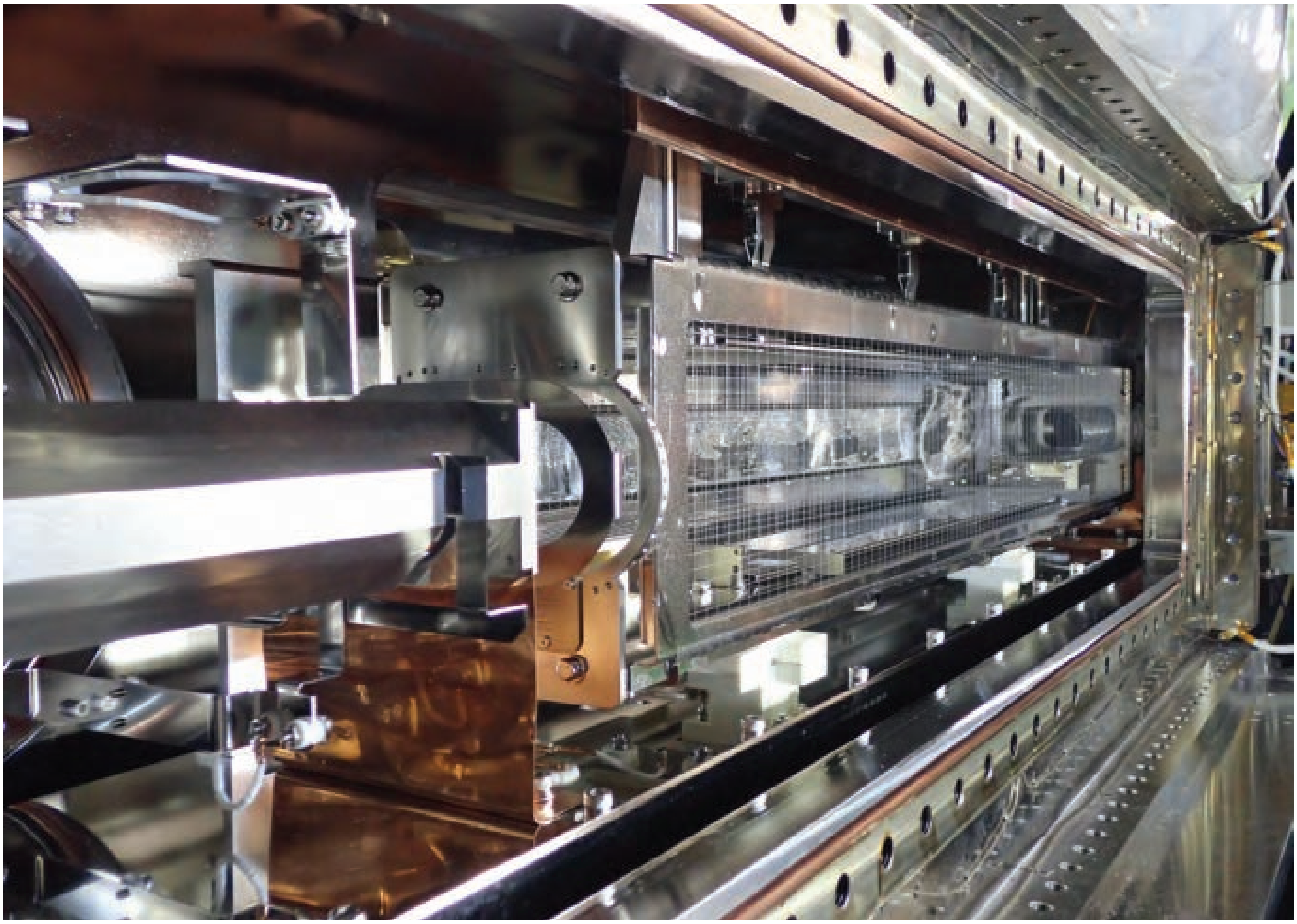

FIGURE 1. RADIOACTIVE IONS too short-lived to be made into a solid target can nevertheless be trapped in an electron beam. The beam itself traps the ions in two dimensions; the cage of thin wire electrodes creates an electric potential that traps them in the third. (Courtesy of Tetsuya Ohnishi.)

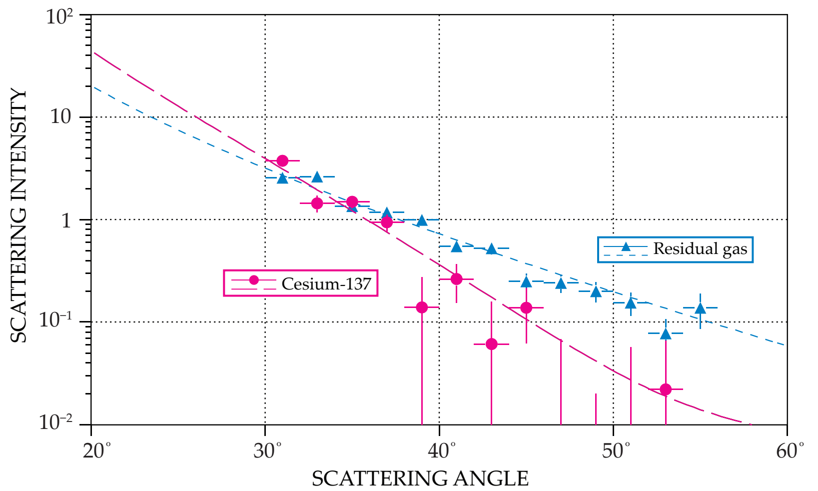

FIGURE 2. CESIUM-137 is the first unstable artificial nuclide to be studied by electron scattering. To obtain the ^{137}Cs data, shown in pink, researchers first had to measure and subtract out the background from residual gas, shown in blue. Theoretical calculations (dashed lines) agree reasonably well with the data for both the ^{137}Cs signal and the residual-gas background, although the ^{137}Cs error bars at high scattering angles are large. (Adapted from ref. 1.)

Rutherford and colleagues fired alpha particles at a thin gold foil. Most of the alpha particles passed straight through. But unexpectedly, a few were scattered to high angles, with some even bouncing straight back the way they came. The only way such a thing could happen, Rutherford reasoned, is if most of the atomic mass is concentrated in a seemingly impossibly tiny volume.

Alpha particles are nuclei themselves, so they're rather crude probes of nuclear structure. When an alpha particle strikes a larger nucleus, it jostles the arrangement of protons and neutrons. And because we now know that protons and neutrons are made up of quarks, the nucleon–nucleus scattering interaction is rather complicated to model.

Electrons, on the other hand, are light, structureless, fundamental particles. With enough energy, an electron can bore straight through a nucleus almost without disturbing it. As Robert Hofstadter discovered in the 1950s, electrons are a near-perfect probe of nuclear structure: From the distribution of electron-scattering angles, one can derive the distribution of charge in the nucleus. For his work, Hofstadter was awarded a share of the 1961 Nobel Prize in Physics (see PHYSICS TODAY, December 1961, page 68).

Hofstadter, like Rutherford, used solid foils and other stationary bulk samples as targets for his scattering experiments. And it's hard to imagine doing electron scattering any other way. For alpha-particle or proton scattering, there's the option of so-called inverse kinematics: shooting a beam of heavier nuclei into a stationary target of helium or hydrogen, rather than the other way around. But that approach isn't feasible for electron scattering.

At the RIBF and a growing number of other facilities around the world (see PHYSICS TODAY, June 2023, page 21), researchers are producing purified beams of rare and radioactive isotopes, and they're already using inverse kinematics to do proton-scattering experiments on short-lived unstable nuclei. Electron scattering, on the other hand, has been limited to stable isotopes and a few long-lived, naturally abundant radioisotopes, such as carbon-14.

From bug to feature

The RIKEN researchers' new achievement was decades in the making. Electron scattering from unstable nuclei was a primary goal for the RIBF ever since the facility was conceived in 1996. "At the time, nobody knew how to make it possible," says Masanori Wakasugi, an author on the new paper who's been involved in the project from the beginning.

At first, the only idea on the table was to create countercirculating beams of electrons and radioactive ions and smash them together. But the RIBF was to be a cyclotron facility, whereas electrons would need to be held in a synchrotron storage ring. Getting the incompatible beams to meet and collide was a technical challenge that ultimately proved too difficult and expensive to tackle.

In search of a better idea, Wakasugi and colleagues found inspiration in what had been a thorn in the side of electron-storage-ring operators: The negative charge of a circulating electron beam creates an electric potential that attracts and traps positively charged ions. "Usually the ions are due to residual gas in the ring, and they're disliked for ring operation," says Wakasugi. "But we noticed that if we can replace the residual gas ions with unstable nuclear ions, then electron scattering is possible."

Thus was born the idea of SCRIT—the self-confining radioactive-isotope ion target—which Wakasugi and colleagues laid out in a 2004 paper.[2] The electron beam itself traps ions in two dimensions, so all that's left is to add a set of electrodes (as shown in figure 1) to trap them in the third dimension and to funnel atoms from a low-energy beam into the SCRIT trap. The trap can be emptied and filled with fresh ions every few seconds, so it could eventually be possible to use SCRIT to study isotopes with half-lives as short as 10 seconds.

The past two decades have been spent building, refining, and testing the necessary instrumentation. The first tests of the SCRIT system used the stable isotopes cesium-133 and xenon-132: Researchers formed the ions into a beam, caught them in the SCRIT trap, and measured their electron-scattering distributions.[3] Satisfied that those parts of the experiment were working, they were ready to move on to artificial radioisotopes.

Electrons and beyond

The subject of the new experiment, ^{137}Cs, isn't found in natural cesium samples. But it's abundantly produced in the fission of uranium-235 and other fissionable isotopes. With its half-life of 30 years, it sticks around for a moderately long time, and it's one of the main radioactive contaminants in the vicinities of both the Chernobyl and Fukushima Daiichi nuclear power plants. If researchers really wanted to, they could make a bulk ^{137}Cs target for a conventional electron-scattering experiment. But because it's easy to extract with high purity from a beam of uranium fission products, it's the perfect isotope for a proof-of-concept SCRIT experiment.

To achieve controlled uranium fission, Tsukada and colleagues shoot their electron beam at a small disk of uranium carbide. When electrons strike the solid target, they rapidly decelerate and create a shower of bremsstrahlung gamma rays that break the uranium nuclei apart. The photofission produces a multitude of isotopes, including ^{137}Cs. Just a few seconds after forming, the ionized ^{137}Cs atoms are separated out and loaded into the SCRIT trap, where their electron scattering can be measured.

But it's not just ^{137}Cs ions in the SCRIT trap. Ions of residual gas—the inspiration for the SCRIT technique—are still present, and they outnumber the target ^{137}Cs atoms. To single out the ^{137}Cs signal, Tsukada and colleagues measured the electron-scattering signal with and without ^{137}Cs ions loaded into the trap. If the residual gas presence is the same in both cases, all they have to do is subtract.

The results are shown in figure 2. As expected, the residual-gas ions—mostly small, compact nuclei such as nitrogen and oxygen—scattered more electrons to high angles than the large, spread-out ^{137}Cs nuclei did. As a consequence, although the ^{137}Cs signal agrees with expectations, the error bars on the high-angle data points are large. To improve their measurement precision, the researchers are simultaneously working on better understanding the residual-gas background and upgrading their isotope separator to load more target atoms into the SCRIT trap.

As they continue to improve their apparatus, Tsukada and colleagues have their sights set on some specific unstable isotopes. In particular, they'd like to study tin-132, one of the 11 known doubly magic nuclei whose closed shells of both protons and neutrons grant it extra stability against decay. With 82 neutrons and just 50 protons, ^{132}Sn is so neutron rich that it's still unstable, with a half-life of 40 seconds, so not much has been directly measured about its shape and charge distribution. "That's the goal of the first stage of the SCRIT project," says Tsukada.

"The current facility is dedicated to elastic electron scattering," he continues, "but the SCRIT method can be used for other applications." SCRIT creates a fixed, stationary target of unstable nuclei—something that has never been possible before—which can be used not just for all kinds of scattering experiments but also for photoabsorption measurements, reactive nuclear collisions, and more. Especially intriguing to the RIKEN researchers is the prospect of studying collisions between two unstable isotopes: one in a beam and one in the SCRIT trap.

Johanna Miller

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Extreme weather makes monitoring snowpack increasingly relevant

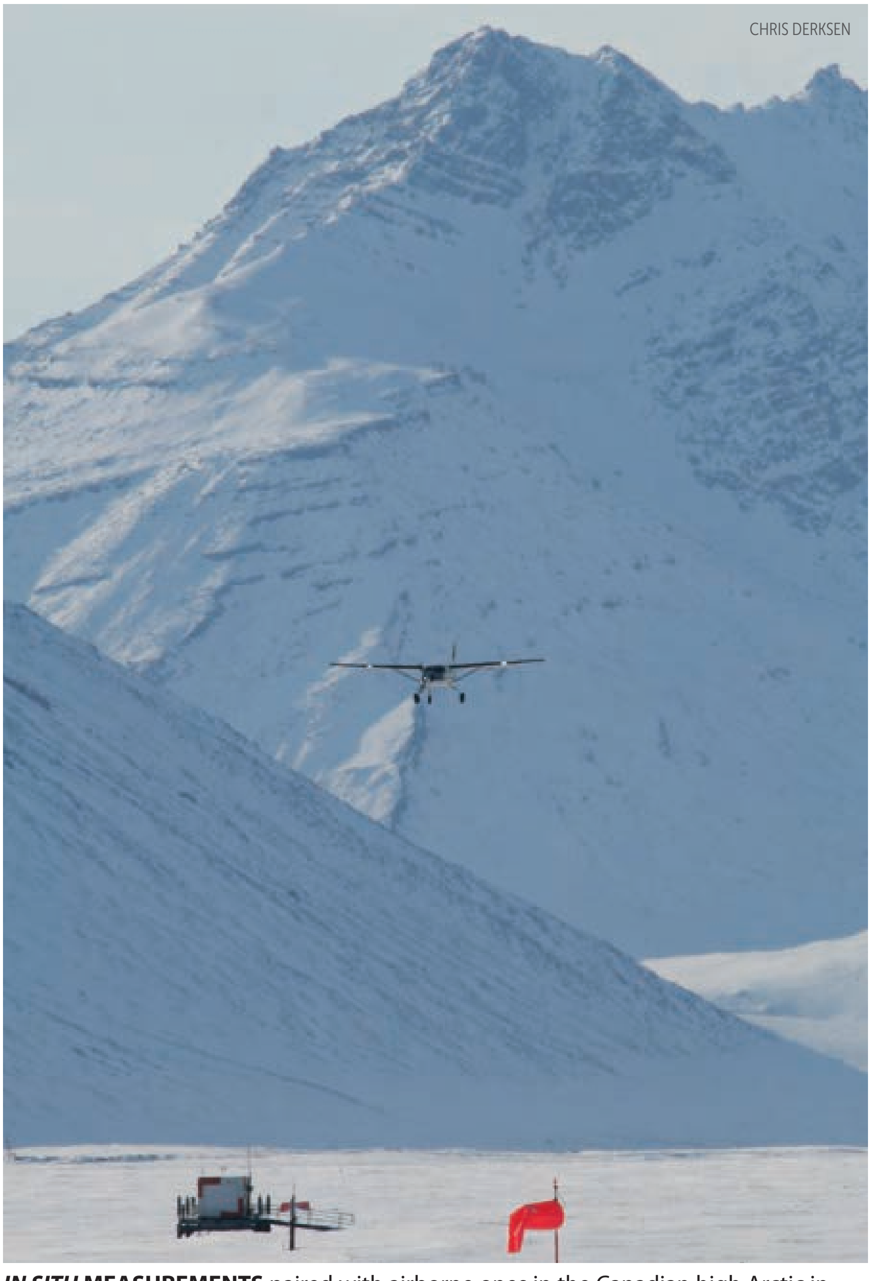
A dedicated satellite would provide global coverage to improve understanding of the hydrologic cycle and inform water-use and risk-management strategies.

What do salmon, hydroelectric power, and agriculture have in common? They all depend on snowmelt. So do floods and wildfires. "We are seeing more fires because the snow is melting earlier," says Ana Barros, an engineering professor at the University of Illinois Urbana-Champaign, recalling how swaths of the US were shrouded in smoke from the record fires in Canada this past summer. Early melt can make soil soggy at the wrong time, and less snowmelt can leave soil dry; both force farmers to change their planting strategies to successfully grow crops.

The chief challenge in understanding and predicting seasonal snowmelt is measuring the snowpack. Snow accumulation varies spatially and temporally. It gets deep in mountains and remains shallower on prairies. Snow is porous, and its density varies with air, ice, and liquid-water content. Substrate, vegetation, sun, dust, soot, wind, snow grain size, and other factors affect how snow settles and melts and how sensors respond to snow.

Snow is a gap in the current understanding of the hydrologic cycle, says Barros. "Scientists don't have the understanding to really be able to assess and improve computer models." Hans-Peter Marshall, a snow physicist at Idaho's Boise State University, says that "we have to move to remote sensing, and monitoring snow will take more than one solution."

In the past 10 years or so, airborne remote sensing of snow has taken off. And for a couple of decades, scientists have been angling for a satellite dedicated to measuring the amount of water contained in snow, called the snow–water equivalent (SWE). A satellite could obtain global coverage every few days and complement other measurements and modeling to provide guidance on water consumption and risk management and to glean insights into Earth's hydrologic cycle, which becomes increasingly important as weather patterns morph because of climate change.



CHRIS DERKSEN

***IN SITU* MEASUREMENTS** paired with airborne ones in the Canadian high Arctic in 2016 were part of a US–Canadian effort to test methods for measuring water content in snow. The campaign was carried out in places with varied snow and terrain and is intended to ultimately help in satellite design.

TURLOCK IRRIGATION DISTRICT

TIMELY, HIGH-RESOLUTION SNOWPACK DATA help water managers avoid floods like one from the Don Pedro Spillway on New Year's Day 1997. When water managers for the Turlock Irrigation District in California released about 1700 cubic meters of water, the road below was damaged.

A major goal is to monitor the total amount of water stored in snow in the mountains, Marshall says. Mountain snowmelt supplies water to one-sixth of the global population, he adds. "Water security and food security are key issues."

Three satellite proposals—one in Canada and two in the US—are under review; the prospects for going forward are expected to become clear in the next year or two.

Snow courses and pillows

Snow has been monitored in mountain ranges around the world for more than 100 years. The simplest and cheapest method is to measure snow depth with a ruler at various spots during the winter months. Measurements might be collected monthly, daily, or even multiple times a day. Sometimes snow is dug out and weighed every few centimeters to assemble a profile of density as a function of depth. For bulk water content, the snow core extracted from plunging an aluminum tube into the snow is weighed to get the SWE. Typically, permanent manual-measurement sites, or snow courses, are located along paths above the snow line.

In the 1990s, many previously manual-monitoring sites in Canada were automated. "Human observers would weigh the snow to get density," says Chris Derksen, a research scientist for the government agency Environment and Climate Change Canada. "We lost that when we went to automated measurements. Depth on its own is useful, but without density, we can't know how much water there is."

In the US beginning in the 1960s and continuing for a few decades, large sacks of antifreeze were introduced to weigh snow. Called snow pillows, the roughly 3 m × 3 m waterbed-like containers are outfitted with pressure transducers. As snow piles up, the transducers weigh it and transmit the data. Some 150 snow pillows dot the Sierra Nevada, and there are more than 800 in mountains across the US; they don't work well in plains because winds blow the snow around.

But snow courses and snow pillows provide only spot measurements, snapshots in time and space. Water managers need estimates of when—and how much—melted snow will hit reservoirs and streams. Governments, municipalities, irrigation districts, and utilities need forecasts of water availability and risk associated with too much or too little water. "Snowpack varies over the length of a football field," says Marshall, "so stations are not representative of a watershed. And as soon as the snowpack moves up in elevation, you are left with dead sensors."

Predicting the volume of water that will flow into streams from the time of peak snowpack—traditionally 1 April in the Sierra Nevada—works "pretty well if the year is representative and close to the average over the past 30 years," says Marshall. "But we are having more extremes." For example, California had lower-than-average snowfall in the winter of 2019–20, but then three years later, this past winter, it had the most snow on record. Unusual weather patterns—rain on snow, early melt, excessive snow—challenge the traditional statistical approach. Traditional methods, Marshall says, have "no hope of getting measurements everywhere and estimating how much water you have. We need to go from statistics-based models to physics-based models."

Marshall adds, "We understand the physics well, but we need better inputs." Those inputs include snowfall, rainfall, condensation, absorption by the soil, evaporation, and albedo—the amount of the Sun's energy a surface reflects. Topography and meteorological variables such as temperature and wind speed and direction are also taken into account. "Put everything into a complicated model," he says, "and you can keep track of the energy and mass of the inputs and outputs."

Remote sensing

Snow is bright, so its extent is easy to map from satellites, says Derksen. "Getting more hydrologically significant measurements is the hard part." Snow depth and SWE can be measured by using remote sensing of microwaves or gamma rays emitted from Earth and comparing natural radiation at a given location with and without snow. Low-resolution passive microwave measurements can be made from space, while passive gamma signals are smaller and need to be measured closer to Earth, such as from towers or planes. Passive monitoring works best when the soil is frozen and the snow is shallow. "Passive gamma is more accurate than passive microwaves," says John Pomeroy, a professor at the University of Saskatchewan and director of its Centre for Hydrology. "It's not affected by ice layers or thawed snow."

Thomas Painter's company, Airborne Snow Observatories, flies planes over watersheds in the Sierra Nevada. The flights use lidar to obtain snow depth by comparing times for a laser signal to reflect back with and without snow coverage, and they use multiwavelength spectroscopy to measure albedo. By measuring multiple wavelengths, says Painter, the snow's grain size and the amounts of liquid, dust, black carbon, and biological matter in the snow can be discerned. "Those things affect how fast the snow melts." To get the SWE, he combines flight measurements of depth with modeled snow density constrained by data from existing snow courses and snow pillows. "The snow density doesn't change much across the mountain landscape compared with the change in depth," he says. (To learn how Painter's career has taken him from professor to NASA scientist to entrepreneur, see physicstoday.org/painter.)

"Ten years ago, we would take 17 snow course measurements over about 1500 square miles," says Wes Monier, chief hydrologist for the Turlock Irrigation District, which serves about 8500 farmers in California. "The sophistication we had was 'my aunt's cabin has snow to the eaves.' " Now, about a million data points from Airborne Snow Observatories feed into models. Without the technology, he says, "we wouldn't be able to adapt to the weather going from extreme to extreme. The information gives you time to develop a plan to use the water."

Satellites could help provide more accurate and refined measurements for water management, says Painter. "We may be able to use their inferences of SWE in dry snow." And indications from satellites that the snowpack "is melting could be helpful for modeling." The proposed satellites would use radar. But the problem with radar, says Painter, "is that, for the same reasons a microwave oven works, almost all of the microwaves will be absorbed in wet snow, so you have no signal. It only works if the snow is dry or has low liquid content."

Satellite monitoring of snowpack, Painter says, would be most valuable for hydrologic science and cryosphere science on the global scale—to understand glaciers, sea-level rise, and more. And, he adds, "the great thing about satellites is that they can cross geopolitical boundaries."

Dedicated snow satellites

Derksen is the principal investigator for Canada's proposed *Terrestrial Snow Mass Mission*, the satellite considered by the snow community to be closest to getting the nod. It would use radar scattering from snow volume to obtain the snowpack mass. The method has been demonstrated with instruments on towers and aircraft, Derksen says, but has yet to be tried from space. The concept is similar to a satellite proposal that didn't make the cut at the European Space Agency about a decade ago.

An advantage of radar is that it can be used at night and in cloudy weather. The plan is to use two frequencies, 13.5 GHz and 17.5 GHz (wavelengths of approximately 22 mm and 17 mm, respectively). The longer wavelength penetrates more deeply than the shorter one, and they scatter differently. With two frequencies, Derksen says, the SWE estimates will be better. "And it's not a huge cost to add the second frequency." The satellite would cover the globe every five to seven days and collect data at 500 m resolution.

In the US, two proposals are under review for satellites that would measure SWE. One, led by the University of Illinois Urbana-Champaign with NASA's Goddard Space Flight Center as a partner, is similar to the Canadian proposal, but at frequencies of 9.6 GHz (31 mm) and 17.2 GHz (17 mm). It would provide global coverage with a five-day revisit cadence and 250 m resolution.

All microwave techniques face limitations when the snow is wet, says Illinois's Barros, principal investigator for the US radar-scattering proposal. "But a combination of measurements at microwave frequencies can be used to infer snow conditions, including for melting and refreezing," she says. "And if we know the peak dry SWE, we can model the melt season."

The other US proposal would take advantage of existing signals, or "signals of opportunity." It is led by UCLA, with NASA's Jet Propulsion Laboratory as a partner. The approach relies on military communications signals at 260 MHz (1.2 m) and 370 MHz (0.81 m), and it is limited to lower latitudes (below about 60°) where those signals are found.

The longer wavelengths allow for seeing through forest cover and deeper snow, and they are less affected by liquid water in the snow than are millimeter signals, says principal investigator Steven Margulis of UCLA. It saves on transmitters, which at microwave frequencies can be bulky and expensive. "We would launch a constellation of receivers," he says. "The receivers are the eyes looking for signals that are reflected off Earth's surface. Measuring the change in reflected signal from snow-covered surfaces allows for retrieval of SWE at spatial resolutions of hundreds of meters every six days."

In competition with each other, the teams for the two US proposals are for now keeping mum on details. They are 2 of 14 proposals submitted last summer to NASA that target seven observables identified in the 2017 decadal survey on Earth system science: greenhouse gases, ice elevation, ocean surface winds and currents, ozone and trace gases, snow depth and SWE, terrestrial ecosystem structure, and atmospheric winds. Next spring, four of the proposals are to be selected for further study, and in 2025 two will be chosen to fly. NASA has said that one of the two final winners will likely focus on greenhouse gases.

Despite the competition between the US proposals, Boise State's Marshall says that "the snow community will rally behind either if one is funded." Barros agrees: "Everybody is hungry for data."

In the meantime, scientists will focus on getting relevant data from other, multipurpose satellites. They include *NISAR*, a collaboration between NASA and the Indian Space Research Organisation, set to launch early next year; it will collect data from which snow mass can be calculated. The European Space Agency plans to launch a similar satellite, *ROSE-L*, in 2028, and its *Copernicus Imaging Microwave Radiometer*, planned for launch within the next decade, will provide passive microwave data. Scientists expect to be able to extract changes in SWE every few weeks from those satellites' data, Marshall says, "but it is likely to only work some of the time due to the longer repeat intervals designed for other applications." NASA's *Surface Biology and Geology* mission will quantify global albedo when it flies later this decade.

Noah Molotch, of the University of Colorado Boulder, studies how stream flow will change as the quantity of snow and the timing of snowmelt changes. He notes that "simply from an accounting standpoint, our estimates of water stored in snow globally are at best within 40%." Studying SWE with a space-based instrument would help, he says. Without one, "we are flying blindly into the future when it comes to snow–water resources on the global scale. One of the big questions is, How does snowpack change as climate changes?"

Toni Feder

The future has arrived for securing confidential data

Though quantum computers are still a decade or more away, NIST is finalizing new encryption standards now to replace current vulnerable protections.

Breaches to data security are almost an everyday occurrence. Yet much worse could lie ahead: Cryptologists agree that quantum computers will be able to crack current encryption systems that now protect e-commerce transactions, mobile-device conversations, personal identifiers such as social security numbers, national security and industrial secrets, and other confidential information. And much of that information that already exists on networks could be saved and decrypted whenever quantum-decryption capabilities do arrive.

There's no consensus on when quantum computers will render current encryption obsolete. In a 2022 survey by the Global Research Institute and evolutionQ, a Canadian quantum security consulting firm, 20 of 40 academic and industry quantum computing leaders said they considered it more than 5% likely to happen within 10 years, while 9 respondents indicated that the likelihood was 50% or greater. For 20 years from now, 14 said there would be a 70% chance, and all but 5 gave the same odds within 30 years.

And if such computers become available within the next couple decades, much of the sensitive information that is being shared over networks today may be vulnerable. "Imagine you have classified information you want to keep safe for 30 years," says Dustin Moody, a NIST computer-security mathematician. "It is safe for now, but if a quantum computer comes in 15 years, someone can break [into] it and they will have access to it 15 years before you wanted them to."

Many experts are all but certain that intelligence agencies in the US and other nations have been harvesting and storing massive amounts of data they can't currently decode, waiting for future decryption by quantum computers. In September 2022, China's National Computer Virus Emergency Response Center claimed that it had uncovered spyware from the US National Security Agency on the computer network of Northwestern Polytechnical University in Xi'an. The ministry accused the NSA of conducting a 10-year campaign to covertly gather information from China, Russia, and other nations on military secrets, scientific research, telecommunications, energy, and other topics.

For its part, the US and many of its allies have banned the use of telecom products from Huawei out of concerns that the Chinese company has built spyware backdoors into its cellphones, telecommunications, and internet network equipment. People outside of classified circles don't know what's actually happening, says John Schanck, a cryptography engineer at Mozilla, but "that's kind of the point for cryptographers in the risk assessment business: If someone can be doing something, you assume that they are doing it."

The debut of a quantum computer may well be kept under wraps, says Peter Schwabe, of the Max Planck Institute for Security and Privacy in Bochum, Germany. "Once this computer gets built, when will we know about it? Who will build it?" If a government acquires one, he asks, "are they going to say?"

Postquantum cryptography

In December 2022, President Biden signed into law a measure instructing federal agencies to hasten their adoption of postquantum cryptography (PQC). NIST is now on the verge of standardizing three algorithms that are aimed at protecting network data from quantum decryption and spoofing. A fourth is slated to be proposed next year in draft form.

Whereas the material that encryption algorithms protect is often secret, the process of developing the algorithms is fully open. That contrasts with the secret ciphers such as Germany's Enigma, which the Allies had to break during World War II. "The interesting thing about modern cryptography is you don't assume that anything is secret from your attacker," says Moody. "You assume they have the complete specifications for how your security system works and you still want to be secure if they know all of that."

NIST's postquantum effort dates to 2016, when it invited the world's cryptographic experts to submit PQC candidates. Teams from academia and industry responded with 69 proposals, which were evaluated internally and released to the outside community to analyze and crack if they could. Through three elimination rounds, NIST winnowed the proposals to seven finalists and eight alternate schemes.

In August NIST posted for public comment drafts of the three postquantum encryption algorithms it plans to issue next year as federal information processing standards, data security and computer systems criteria to which federal agencies must adhere; businesses and other organizations that interact with federal agencies must also be compliant. A fourth algorithm is due to receive its draft standard in 2024. Many other governments, including the European Union, are expected to follow the NIST standards rather than develop their own.

Evaluating a PQC algorithm using classical computers is tricky, says Moody. You have to try to estimate how a quantum computer would work. "We don't know how fast it will be or how expensive it will be. So we extrapolate the best we can and set the parameters high enough."

Two NIST hopefuls were broken in 2022 in the later stages of the process. An IBM team defeated Rainbow, which had made it to the penultimate elimination round, on a laptop in 53 hours. SIKE, which made it to the final round, employed a relatively new mathematical approach of maps between elliptical curves. It was taken down by a desktop in one hour.

Moody says NIST had already decided to hold SIKE back for further evaluation. The algorithm's failure showed the selection process worked as intended, that "the strongest ones survive." Schwabe, who contributed to three of the four draft standards, though not to SIKE, says the defeat was "very dramatic" and unexpected. But he adds that it doesn't necessarily rule out other schemes employing similar mathematics.

Public and private keys

Encryption can be either asymmetric or symmetric. In asymmetric encryption

NIST SELECTED three algorithms for postquantum cryptography. A fourth is expected next year. They are based on module lattices and hash functions, two families of math problems that could resist a quantum computer's assault.

QUANTUM COMPUTERS capable of decrypting messages protected using today's encryption algorithms are still likely a decade or more away. But experts warn that they could easily decode sensitive information that is being collected and stored right now.

systems, also known as public-key encryption systems, the string of numbers or letters that constitute the encryption key is published for anyone to use to encode their messages. Only the receiving party has access to the decryption key that allows the messages to be read. In symmetric encryption, the same key is used to encode and decode the message. Once the sender and receiver make contact using public encryption, they exchange a symmetric-encryption key that they use for subsequent messages.

By their nature, asymmetric systems are less secure than symmetric ones, says Schanck. "They are public-key systems, meaning that the server you connect to can publish the key and anyone can see it, and anyone can encrypt to it. That's not something you can do with perfect security."

All encryption algorithms are fundamentally mathematical problems. Today's widely used public-key encryption algorithms typically provide 128 bits of security. That means it would take a computer 2^{128} operations to break the encryption key using a brute-force attack. For comparison, it's estimated that there are 2^{166} atoms on Earth. National security data requires stronger, 256-bit encryption.

The RSA public-key algorithm is based on the difficulty of factoring large integers—NIST recommends more than 600 digits, and more starting in 2030—into their prime numbers. Defactoring through a brute-force attack is theoretically not impossible using today's high-performance computers, but a conservative estimate is that it would take a supercomputer 16 million years. Similar levels of security are embodied in the other currently used encryption approaches that use a different computationally difficult problem.

Yet experts agree that a three-decade-old algorithm developed by mathematician Peter Shor will enable cryptologists to break current asymmetric encryption systems in minutes if it is run on a sufficiently powerful quantum computer. Shor's is a simple quantum algorithm, they say, and decryption should be one of the easiest tasks for a quantum computer to perform.

For symmetric-key encryption, the 256-bit version of the Advanced Encryption Standard first approved by NIST in 2001 is already considered quantum resistant. Although quantum computers won't be able to break symmetric encryption, a slightly longer key may be required. "But we don't have to replace the whole crypto system," Moody says.

Hybrid encryption

NIST's PQC choice for general encryption purposes is Kyber, part of the Cryptographic Suite for Algebraic Lattices (CRYSTALS). Schanck, one of the many coauthors, is working to incorporate it into the Firefox web browser. He says network protocols, such as Transport Layer Security, that establish secure connections between browsers and web servers have already been adjusted to accommodate experimentation with Kyber. Many businesses, including IBM, Google, Amazon Web Services, and Cloudflare, have deployed a version of Kyber in their networks, and once NIST formalizes the standard, Transport Layer Security will likely be tweaked a bit further.

Two of the draft standards are for digital signatures, used for authenticating identities and denying fake web pages and malicious software updates. Like Kyber, Dilithium is part of CRYSTALS and uses a mathematical framework known as module lattices. SPHINCS+ implements a stateless hash-based signature scheme.

The standards-setting Internet Engineering Task Force recommends that a PQC scheme such as Kyber be combined with prequantum encryption to ensure that deploying the newly developed algorithm won't degrade security. The Chrome web browser is now packaging Kyber together with an existing prequantum algorithm.

"When the standards come out in 2024 they still have to be implemented and tested, and auditors will have to write guidelines for certification," says Andreas Hülsing, a cryptographer at Eindhoven University of Technology in the Netherlands who codeveloped SPHINCS+. "Getting them deployed in critical infrastructure sectors will easily take another three to four years."

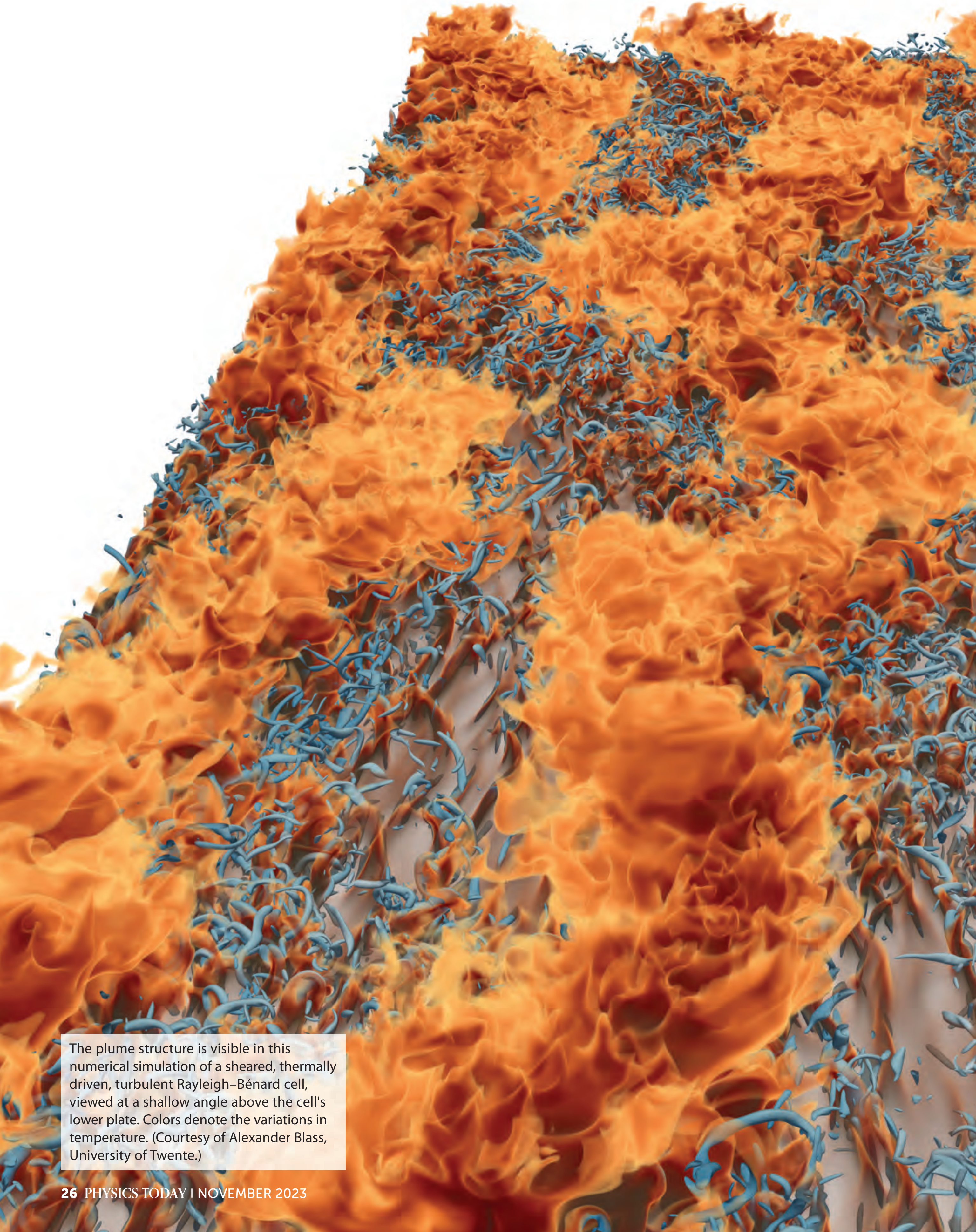
NIST is considering two other algorithms for standardization, Moody says. Both are for general-purpose encryption, and both are based on error-correcting codes that apply the underlying principle that errors constantly occur in transmission and storage of data and in mobile-communication networks. In the encryption schemes, errors are deliberately inserted before transmission and are later corrected during decoding.

Kyber runs faster on some platforms than the prequantum algorithms in wide use today, but the Transport Layer Security message containing the Kyber public-key algorithm is large—approximately a kilobyte, while schemes currently use double-digit bytes. Google and Cloudflare have demonstrated that web servers can easily handle the larger size, the companies say. But some web "middlebox" devices, such as firewalls, that haven't been updated will reject Kyber-encoded messages. For now, Chrome offers affected network administrators the ability to disable Kyber.

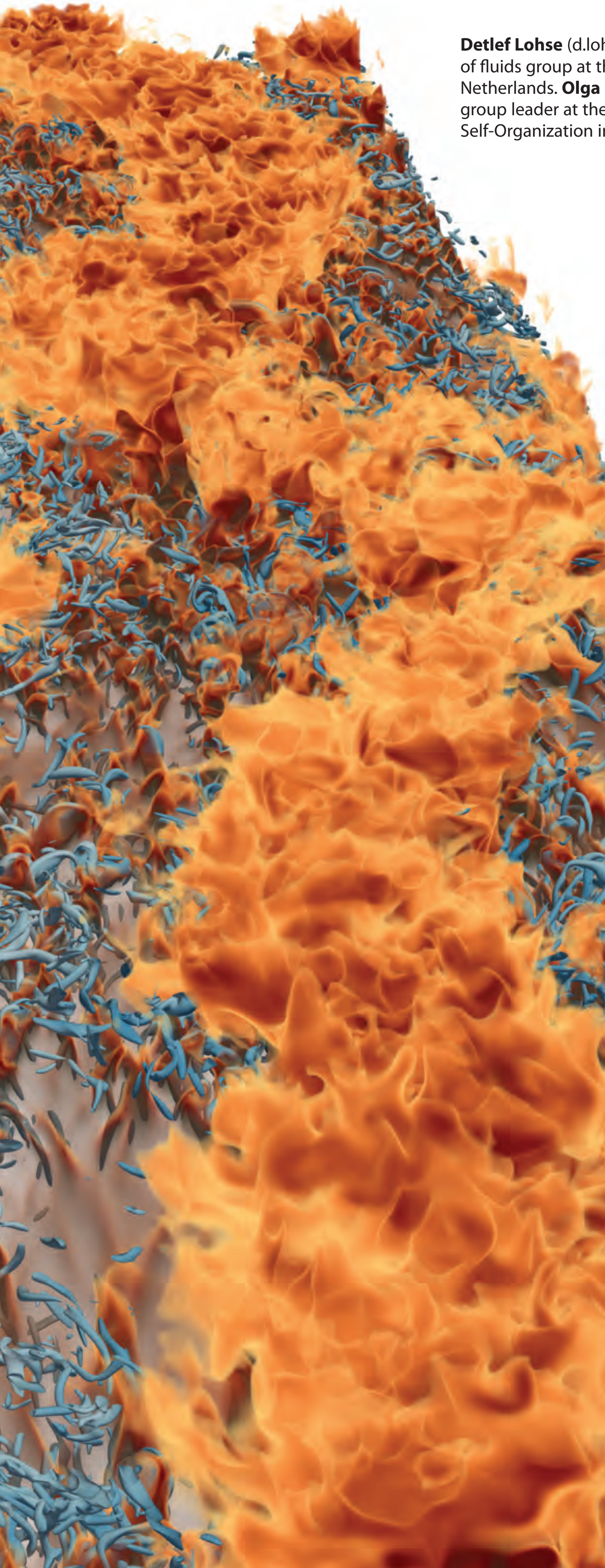
One question yet to be resolved is how PQC will affect the "internet of things," the networked microprocessor devices that control such things as automobile functions and the sensors and switches that govern many industrial and infrastructural processes, including electricity transmission, water treatment, and oil and gas pipeline operations. While laptops and cellphones can easily handle the larger postquantum encryption, many smaller internet-of-things devices can't, says Moody. "There's a lot of research going on in that direction."

"Some [internet-of-things] systems will need to be replaced, other systems will get software updates, and still others will be insecure until their end of life," says Schanck.

David Kramer PT



The plume structure is visible in this numerical simulation of a sheared, thermally driven, turbulent Rayleigh–Bénard cell, viewed at a shallow angle above the cell's lower plate. Colors denote the variations in temperature. (Courtesy of Alexander Blass, University of Twente.)



Detlef Lohse (d.lohse@utwente.nl) is the chair of the physics of fluids group at the University of Twente in Enschede, the Netherlands. **Olga Shishkina** (olga.shishkina@ds.mpg.de) is group leader at the Max Planck Institute for Dynamics and Self-Organization in Göttingen, Germany.

Ultimate turbulent thermal convection

Detlef Lohse and Olga Shishkina

Recent studies of a model system—a fluid in a box heated from below and cooled from above—provide insights into the physics of turbulent thermal convection. But upscaling the system to extremely strong turbulence remains difficult.

Thermally driven turbulent flow can be found throughout nature and technology. Such flow transports not only heat but also mass and momentum. Comprehending what determines that transport is key to understanding numerous geophysical and astrophysical flows and to being able to control the industrial and more general flows that people experience every day.

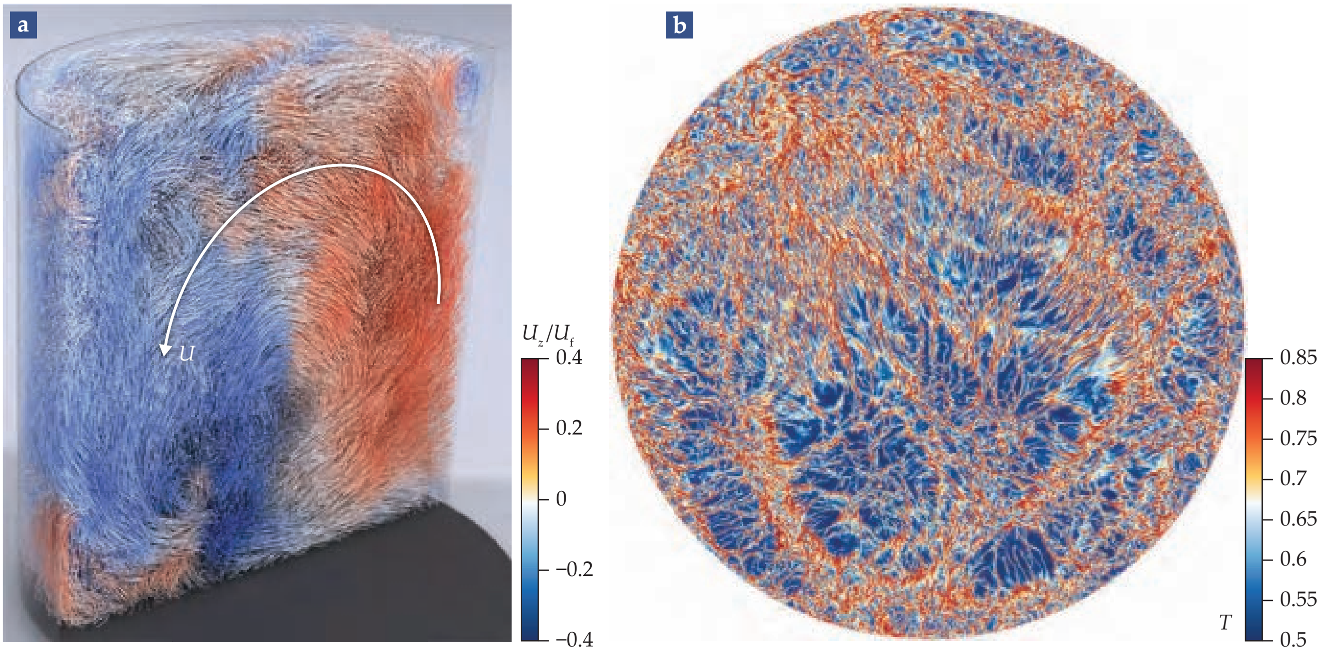


FIGURE 1. THREE-DIMENSIONAL VISUALIZATION of experimental turbulent structures **(a)** in half of a cylindrical Rayleigh–Bénard cell with diameter-to-height aspect ratio $\Gamma = ½$, Rayleigh number $Ra = 1.5 \times 10^9$, and Prandtl number $Pr \approx 0.7$ (see the main text for definitions). The particles with trails reveal small turbulent structures in the dominating large-scale convection, which has typical velocity U. The vertical component of the velocity, U_z, is plotted here, normalized by the so-called free-fall velocity $U_f \equiv \sqrt{\beta \Delta g L}$. (Adapted from P. Godbersen et al., *Phys. Rev. Fluids* **6**, 110509, 2021.) **(b)** This cross-sectional snapshot from a fully resolved direct numerical simulation of a cylindrical convection cell with $Ra = 10^{13}$, $Pr = 1$, and $\Gamma = ½$ shows the dimensionless temperature field T, which varies from 0 at the top of the cell to 1 at the bottom. It reveals the tiny detaching plume structure. (Courtesy of Richard Stevens, University of Twente; based on an advanced finite-difference code developed by Roberto Verzicco, Tor Vergata University of Rome.)

Geophysical flows include the transport of heat in the atmosphere and the ocean, which determines weather, climate, ocean circulation, and the melting of ice shelves. Astrophysical examples include the transport of heat in the core and in the outer layer of stars and planets. Industrial examples include the transport of heat in chemical reactors and in electrolysis and other contexts of energy conversion. At the human scale, people most directly experience heat transport in the buildings, rooms, and vehicles whose temperature they control.

In all those systems, the fundamental question is, How much heat, mass, or momentum is transferred by the system? Direct measurements are difficult to make, as the geometries are often complicated, heat may leak out of the system, the boundary conditions may not be well known or well controlled, and global measurements may not be possible, given the length scales of the systems. What's more, direct numerical simulations may be prohibitive if the exact experimental boundary conditions are unknown.

Given those difficulties, the aim should be to understand real systems by using simple model systems, from which one can extrapolate the transport properties to the relevant flows. But developing those models requires a deep understanding of the system. That is especially true when the system undergoes a transition from one state to another—from a laminar-like state to a turbulent one, for instance—as then the transport properties of the flow can dramatically change. It is thus key to identify possible transitions between different states in such systems.

The most famous and most frequently used model to study thermally driven flows is the Rayleigh–Bénard (RB) system. It consists of a flow in a closed box of height L, homogeneously heated from below through a hot bottom plate and cooled from above through a cold top plate. The flow is driven by the density differences between the lighter (usually hot) fluid, whose buoyancy makes it rise, and the heavier (usually cold) fluid, which sinks. Figure 1, which shows experimental and numerical snapshots of the flow field for strong thermal driving—to be quantified below—illustrates the complexity of the flow and the large-scale structure that evolves, which is known as the "wind of turbulence" (see the article by Leo Kadanoff, Physics Today, August 2001, page 34).

RB convection has always been a popular playground in which to develop new concepts, such as instabilities, nonlinear dynamics, and the emergence of spatiotemporal chaos and patterns.[1] For very weak driving, the system has few degrees of freedom—it can be described using few coupled ordinary differential equations—but with increasing driving force it gains more degrees of freedom and eventually becomes turbulent.[2,3] The RB paradigm applies to heat transfer as well as mass transfer if it is driven by density differences—for example, in a system with heavier salty water at the top and lighter fresh water at the bottom, as can be found in the ocean and in industrial applications.

Several reasons account for the paradigm's popularity. The underlying dynamical equations—the Navier–Stokes equation, the advection–diffusion equation, and the continuity

Rayleigh and Prandtl numbers

For a Rayleigh–Bénard (RB) cell of height L, with a temperature difference Δ between the hot plate on the bottom and the cold plate on the top, the Rayleigh number Ra is defined as $\beta g L^3 \Delta/(\nu\kappa)$, where β is the thermal expansion coefficient, g the gravitational acceleration, ν the kinematic viscosity, and κ the thermal diffusivity. The ratio ν/κ is the Prandtl number Pr.

In principle, there are three methods for achieving large Rayleigh numbers in an RB system: Maintain a large Δ, use a box with large L, and make sure ν and κ are both small. But each method has its own caveats and difficulties.

Here are some typical values for the Rayleigh and Prandtl numbers: Convective fluid motion sets in at $Ra \sim 2000$ for a large-enough aspect ratio of width to depth, independent of Pr. Under stronger forcing, the flow becomes turbulent, and much more complicated flow structures emerge, as shown in figure 1. For water, for which Pr typically ranges from 4 to 10, in a 20-cm-high container heated to 60 °C from below and cooled to 30 °C from above, Ra can reach up to 10^{10}. In industrial applications with $L = 20$ m, the same temperature difference implies that Ra is roughly 10^{16}.

In the atmosphere, where $Pr \approx 0.7$, values of Ra above 10^{21} are not uncommon. In the ocean, assuming a water depth of 5 km, Ra can exceed 10^{20}, whereas in the upper convective zone of the Sun or stars, it is on the order of 10^{25}. Liquid metals, like those in Earth's core, typically have $Pr \sim 0.01$. The magma in Earth's mantle has $Pr \sim 10^{20}$ because of the high viscosity, which typically leads to an Ra value of only 10^6 to 10^7.

equation—result from momentum, energy, and mass conservation, respectively. And the respective boundary conditions are well known, so the system is mathematically well defined. The RB system is closed, so that exact global balances between the forcing and the dissipation can be derived. It also has various symmetries, such as temporal and spatial translation symmetries, rotational symmetry, and, for small-enough temperature differences, top–bottom reflection symmetry; they make it attractive for theoretical approaches. And thanks to its simple geometry, the system is accessible to controlled experiments and to direct numerical simulations, provided the thermal driving is not too strong.

Dimensionless numbers

The most relevant question in turbulent RB convection is, How does the heat transport—that is, the time- and area-averaged vertical heat flux (in dimensionless form, the Nusselt number Nu, the ratio of convective to conductive heat transfer)—depend on the three dimensionless control parameters of the system? Those parameters are the Rayleigh number Ra (the nondimensionalized temperature difference Δ between the hot and cold plates—that is, the thermal driving strength), the Prandtl number Pr (the ratio of the momentum diffusivity to thermal diffusivity), and the aspect ratio Γ (the ratio of the container's width to its height).

The box above lists some typical values for Ra and Pr in nature and technology. Both Nu and the Reynolds number Re (the ratio of inertial forces to viscous forces) are dependent on Ra, Pr, and Γ. Those dependencies are traditionally sought in the form of scaling laws: $Nu \sim Ra^{\gamma} Pr^{\delta}$ and $Re \sim Ra^{\xi} Pr^{\eta}$. Researchers have tried to measure and understand those dependencies for at least the last 60 years.[2,3] And for the past 30 years, they have been helped by direct numerical simulations of the system.

Classical regime

In the regime of Rayleigh numbers up to $Ra \sim 10^{11}$—which has become feasible in many labs over the past three decades and is nowadays known as the classical regime of turbulent RB convection—researchers have reached broad agreement among various experiments and numerical simulations. Figure 2 shows $Nu(Ra, Pr)$ for Prandtl numbers varying over six decades, $10^{-3} \le Pr \le 10^3$, in cylindrical cells with $\frac{1}{2} \lesssim \Gamma \lesssim 1$. Researchers have a good understanding of the regime, thanks to a unifying theoretical approach to wall-bounded turbulence developed by Siegfried Grossmann and one of us (Lohse).[4] Called the GL theory, it builds on the ideas of Ludwig Prandtl, Heinrich Blasius, Andrey Kolmogorov, and Sergei Obukhov.

The unifying theory uses two exact equations, which are straightforwardly obtained by volume integration and the divergence theorem from the Navier–Stokes equations for the velocity field $\mathbf{u}(\mathbf{x}, t)$, driven by the buoyancy force from the temperature, and from the advection equation for the temperature field $\theta(\mathbf{x}, t)$; here $\mathbf{x}$ denotes spatial coordinates and t, time. Assuming that the material properties apart from density are temperature independent, the two equations for the time- and volume-averaged viscous and thermal dissipation rates are, respectively,

$$\varepsilon_u \equiv \nu \langle (\partial_i u_j(\mathbf{x},t))^2 \rangle_V = \frac{\nu^3}{L^4}(Nu - 1)\, Ra\, Pr^{-2}, \text{ and}$$

$$\varepsilon_\theta \equiv \kappa \langle (\partial_i \theta(\mathbf{x},t))^2 \rangle_V = \kappa \frac{\Delta^2}{L^2} Nu.$$

Those equations are remarkable insofar as they connect volume-averaged quantities (ε_u and ε_θ) with the vertical heat transport, Nu. The basic assumption of the GL theory is that the physics inside the turbulent core—the bulk of the flow—is fundamentally different from that in the boundary layers (BLs), as shown in figures 3a–3b. Accordingly, the time- and volume-averaged viscous and thermal dissipation rates are composed of two parts, namely

$$\varepsilon_u = \varepsilon_{u,\mathrm{BL}} + \varepsilon_{u,\mathrm{bulk}} \quad (1)$$

and

$$\varepsilon_\theta = \varepsilon_{\theta,\mathrm{BL}} + \varepsilon_{\theta,\mathrm{bulk.}} \quad (2)$$

Because of the differing physics in the bulk and in the boundary layers, their scaling behaviors differ as well. That, in turn, rules out the traditionally assumed pure scaling behavior $Nu \sim Ra^{\gamma} Pr^{\delta}$ and $Re \sim Ra^{\xi} Pr^{\eta}$ over the full range of Ra and Pr.

How do the four individual contributions in equations 1 and 2 scale? In the turbulent bulk, the viscous and thermal dissipation rates $\varepsilon_{u,\mathrm{bulk}}$ and $\varepsilon_{\theta,\mathrm{bulk}}$ follow the 1941 Kolmogorov–Obukhov scaling relations for turbulent flow (Kolmogorov turbulence). In terms of the turbulent wind velocity U and the temperature difference Δ between the plates, those relations

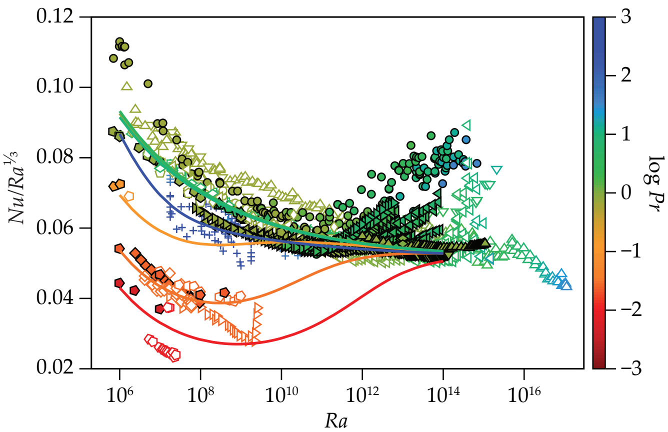


FIGURE 2. HEAT TRANSPORT, parameterized by the dimensionless Nusselt number *Nu* (the ratio of convective to conductive heat transfer), depends on the control parameters of the system—the Rayleigh number *Ra* and Prandtl number *Pr*. It is plotted here divided by $Ra^{1/3}$, so that differences can be better seen. Colors denote the Prandtl number dependence. The experimental and numerical data points, taken between 1997 and 2020, come from various groups, most of which are discussed and cited in this article. The solid lines were produced for various Prandtl numbers using the Grossmann–Lohse unified theory for Rayleigh–Bénard turbulence.[4]

imply that $\varepsilon_{u,\text{bulk}} \sim U^3/L$ and $\varepsilon_{\theta,\text{bulk}} \sim \Delta^2 U/L$. Those scaling relations cannot hold in the boundary layers near the walls, where viscosity and thermal diffusivity matter. There, as long as the driving is not too strong, the viscous and thermal dissipation rates $\varepsilon_{u,\text{BL}}$ and $\varepsilon_{\theta,\text{BL}}$ scale according to the Prandtl–Blasius theory for laminar-type boundary layers that develop along a solid horizontal plate when a fluid flow has relatively low velocity. (See the article by John D. Anderson Jr, Physics Today, December 2005, page 42.)

The splitting of wall-bounded turbulent flow into two regions in equations 1 and 2 can be understood by analogy to Prandtl's foundational insight from 1904 that the potential, or Bernoulli, flow around a plate cannot hold close to the plate itself but must be matched to boundary layers with quite different physics and scaling relations. Only with that insight could Prandtl have obtained the observed Reynolds-number dependence of the drag, as shown in figures 3d–3f. The GL theory follows the same spirit, but for wall-bounded turbulent flow, the outer flow is not of the Bernoulli type but of the Kolmogorov–Obukhov type.

The details of the GL theory are worked out in references 2 and 4. The theory describes the experimentally and numerically observed dependencies *Nu*(*Ra*, *Pr*) and *Re*(*Ra*, *Pr*) over six orders of magnitude in *Ra* and in *Pr* up to *Ra* of about 10^{11}. The theory has proven its predictive power for *Ra* and *Pr* parameter ranges for which measurements were carried out only later. The team of Ke-Qing Xia (Chinese University of Hong Kong) measured for large *Pr* values, and the teams of Sven Eckert (Helmholtz Center Dresden-Rossendorf), Peter Frick (Polytechnical University of Perm), and Jonathan Aurnou (UCLA) measured for small ones.

The key idea of the GL theory—namely, to start from exact global balance equations and to split the dissipation rates into boundary-layer and bulk contributions—is quite general. It has also been applied successfully to various other turbulent flows, such as internally heated turbulence, double-diffusive convection—in which the flow velocity is coupled to both the temperature and the salinity—horizontal convection, and magnetohydrodynamically driven turbulence.

Experiments at large *Ra*

For very large thermal driving beyond $Ra \sim 10^{11}$, the experimental results for *Nu*(*Ra*, *Pr*) seem to contradict each other, as shown in figure 2: For very similar *Pr*, the *Nu*(*Ra*) dependencies are quite different in different experiments. For those large *Ra*, direct numerical simulations become increasingly difficult to perform because of the many degrees of freedom in the system; extremely fine computational grids are required to run the simulations. For many applications, including those in geological and astrophysical contexts, however, the large-*Ra* limit is of particular interest. So how can one extrapolate insights from the lab scale and numerical simulations at smaller *Ra* and estimate the heat transport and the turbulence intensity on geo- and astrophysical scales? And how can one perform experiments for very large values of *Ra* in order to scale up the RB system?

To open the large-*Ra* regime to experimental studies, the University of Chicago's Albert Libchaber and colleagues used helium gas close to its critical point in an RB system, as it has extremely low kinematic viscosity and thermal conductivity. In 1989 he and his coworkers[5] achieved $Ra \sim 10^{14}$. Bernard Castaing, Philippe Roche, and coworkers in Grenoble, France, continued to pursue that line of research. In 1997, Castaing and his collaborators[6] found a transition around $Ra \sim 10^{11}$ toward a steeper effective scaling of roughly $Nu \sim Ra^{0.38}$, much larger than has been seen at lower *Ra*, where the effective scaling exponent never exceeds ⅓. They termed that new regime "ultimate."

In later work, Roche and his colleagues found the transition Rayleigh number to vary up to $Ra \sim 10^{13}$, depending mainly on the aspect ratio of the cell and the Prandtl number.[7] The transition was also evidenced by the buildup of fluctuations in the boundary layer at the same transition Rayleigh number, supporting the view that the transition is connected with a destabilization of the boundary layer—meaning that in the new regime, the flow in the bulk and in the boundary layers are both turbulent.

Russell Donnelly and coworkers at the University of Oregon followed Libchaber's path of using helium gas as the working fluid close to its critical point,[8] but they increased the height of the RB cell and achieved an even larger *Ra*, up to $\sim 10^{15}$. In those experiments, however, no transition to a regime with enhanced scaling dependence for *Nu* could be identified. Nor was there evidence for an enhanced scaling regime in team members' follow-up experiments, carried out by Joseph Niemela and Katepalli Sreenivasan[9] and by Ladislav Skrbek and coworkers.[10]

Guenter Ahlers and Eberhard Bodenschatz proposed another idea for how to achieve very large *Ra*—namely, to use pressurized sulfur hexafluoride as the working fluid. The advantage of using pressurized SF_6 in RB experiments is that over a very large *Ra* range the system keeps roughly the same *Pr*. Ahlers, Bodenschatz, and coworkers at the Max Planck Institute for Dynamics and Self-Organization in Göttingen, Germany, performed their experiments with SF_6 pressurized up to 19 bars, for which *Pr* remains roughly 0.7. In 2012 they observed a transition to an ultimate RB regime around $Ra \sim 10^{14}$

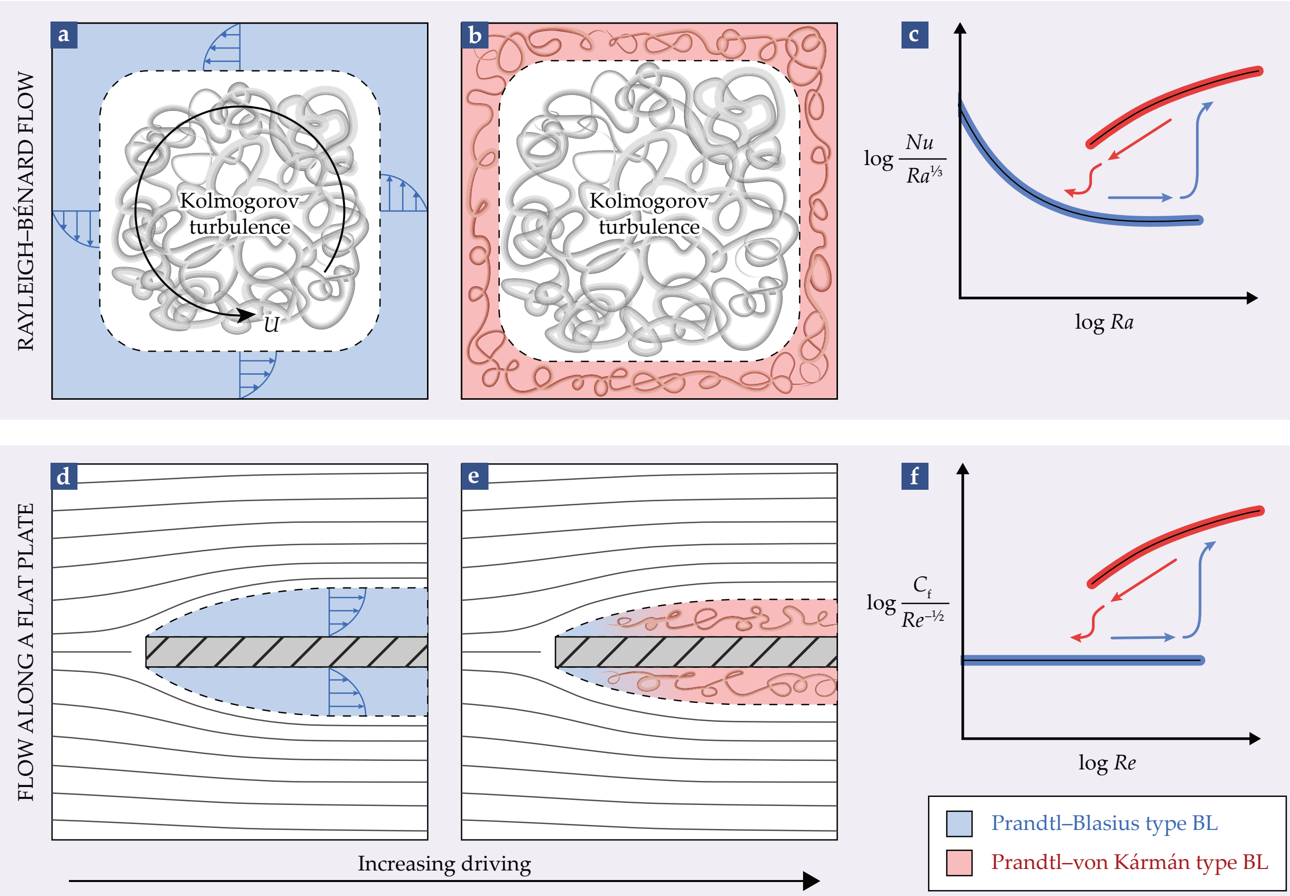


FIGURE 3. THE ANALOGY between Rayleigh–Bénard flow and parallel flow along a flat plate. **(a–c)** In turbulent Rayleigh–Bénard convection, the core part of the flow is always turbulent (Kolmogorov turbulence), whereas the flow velocity along the wall drops to zero, as illustrated by the decreasing magnitude of blue arrows on each side in panel a. With increasing thermal driving strength—in other words, increasing Rayleigh number *Ra*—the boundary layers (BLs) change from a laminar (blue) Prandtl–Blasius type BL, with velocity profiles sketched in blue, to a turbulent (red) Prandtl–von Kármán type BL. The different cases have distinct dependencies of the heat transport (expressed by the Nusselt number *Nu*) on *Ra*, as shown, respectively, by the blue and red lines in panel c. **(d–f)** Parallel flow along a flat plate undergoes an analogous transition between laminar and turbulent BLs, each with different dependencies of the skin-friction coefficient C_f on the Reynolds number *Re*, as sketched, respectively, with blue and red lines in panel f.

and with an aspect-ratio dependence consistent with the Grenoble results. The *Nu* dependence on *Ra* was steeper above the transition than below it and can be described with an effective scaling law $Nu \sim Ra^{0.38}$ (see reference 11 and later papers by the Göttingen group). The sharp transition was found not only for *Nu* but also for *Re* and consistently at the same *Ra*. That observation also supports the view of a fundamental flow transition in an RB cell.

The discrepancy in the large-*Ra* regime between a typical Grenoble data set (with a transition toward an enhanced scaling around $Ra \sim 10^{11}$), a typical Oregon data set (without a transition), and a typical Göttingen data set (with a transition around $Ra \sim 10^{14}$) can be seen in figure 2. What is the origin of those different findings in the large-*Ra* experiments, even for very similar control parameters? At the moment, that's an open question.

Ultimate turbulence regime

What do theories suggest about the existence of an ultimate regime? As early as 1962, Robert Kraichnan proposed an ultimate regime of RB convection[12] and assumed a fully turbulent boundary layer and a certain scaling relation between *Nu* and *Re* for that boundary layer. He obtained $Nu \sim Ra^{1/2}Pr^{1/2}$, with logarithmic corrections. Note that in the ultimate regime, in no case can *Nu* grow faster than $\sim Ra^{1/2}$. That upper bound, which is much larger than any experimental or numerical data for *Nu*, was rigorously proved[13] by Louis N. Howard in 1963, with $Nu - 1 \leq CRa^{1/2}$, in which *C* is the constant $\sqrt{3}/8$. Other researchers verified the upper bound for slightly smaller values of *C* later.[14]

The GL theory of thermal convection[4] also suggests an ultimate regime: For large-enough driving strength, the laminar Prandtl–Blasius boundary layers, shown in figure 3a, should become unstable and undergo a transition toward turbulent boundary layers, the so-called Prandtl–von Kármán boundary layers (figure 3b). The transition is a direct analogue of the laminar-to-turbulent transitions of the boundary layers around a plate, as shown in figures 3d–3e or within a pipe. Those transitions are subcritical—meaning that around the transition different states coexist—and have a so-called nonnormal and nonlinear character, where nonnormal refers to the eigenvectors of the linear operator being nonorthogonal. Such transitions have a double-threshold behavior: They can arise when the shear is sufficiently strong and disturbances (such as small wall roughnesses or thermal inhomogeneities in the plates) are large enough to trigger the onset.[15]

Typically, such an onset of shear instability in wall-parallel flow happens when the shear Reynolds number Re_s exceeds a value of about 420, as estimated by Walter Tollmien almost a century ago. The GL theory adopts Tollmien's value as a typical guideline for the onset of the shear instability (for $\Gamma \sim 1$), although, of course, in the case of RB flow in a box, the flow is not strictly parallel to the wall. For $Pr \approx 0.7$ and $\Gamma \sim 1$, the critical Rayleigh number for the onset of the ultimate regime in RB convection[4] can be estimated to be around 10^{14}. But given the double-threshold feature of the transition, it may also be earlier or later for different small disturbances. For larger Pr or smaller Γ, the critical Rayleigh number increases.

What dependence $Nu(Ra, Pr)$ should be expected in the ultimate regime? From an integration of the energy-dissipation rate in the turbulent boundary layer,[16] one obtains $Nu \sim Ra^{1/2}Pr^{1/2}/(\log(Ra))^2$, which in today's experimentally accessible regime implies an effective scaling of roughly $Nu \sim Ra^{0.38}$.

How then can one reconcile the various seemingly contradictory measurements of $Nu(Ra, Pr)$ for $Ra > 10^{11}$, evident in figure 2? The analogy to pipe flow or other shear flows has been helpful to researchers, and over the past few years, they have made some intriguing suggestions as to why the Rayleigh numbers of the observed transitions to the ultimate regime depend on details of the different experiments. The key idea, proposed by Roche in 2020,[7] is to realize the subcritical nature of the transition, which has the above-mentioned double-threshold behavior and is the typical feature of transitions in shear flows,[15] applies in this case because of the strong local shear at the boundaries.

The subcritical nature of the transition implies that multiple states can coexist and that the transition is hysteretic—it depends on the system's history—and that for strong-enough shear, even quite small disturbances can trigger the transition from laminar flow to turbulent flow (notice the analogy between figure 3c and figure 3f). That interpretation has the potential to reconcile the various observations and different values of the Rayleigh number at which the transition occurs.

Although the transition toward an ultimate turbulence regime for RB turbulence is under intense discussion, no one disputes its relevance for Taylor–Couette (TC) turbulence.[17] The TC system—two coaxial corotating or counterrotating cylinders with fluid between them—is sometimes called the twin of the RB configuration because of many similarities between the two systems.[18] The analogy between RB and TC also holds in the ultimate regime and has been observed in all of the experiments and numerical simulations of turbulent TC flow made at large-enough driving strength.

That large-enough driving strength is more easily accessible in TC flow than in RB flow reflects the fact that the mechanical driving in TC flow is much more effective than the thermal driving in RB flow. Similarly, one should also expect an ultimate regime in pipe flow, horizontal convection, and other systems. Were the existence of an ultimate regime doubted in any of those flows, then one would have to come up with a mechanism by which the laminar flow in the boundary layers would remain laminar at arbitrarily large driving strength and the transition to turbulence would be suppressed. Frankly, we do not see what such a mechanism could be.

How then can the controversy on the ultimate regime in RB flow be settled? Given that striving toward ever-larger experiments and numerical simulations is extremely difficult and costly, one possibly promising route is to further explore the analogy to the laminar-to-turbulent transition in flow around a plate, illustrated in figure 3, or in pipe flow. In both cases a detailed analysis of the lifetime of disturbances of different strength has led researchers to conclude that the transition can be interpreted as a directed percolation transition.[15] Such a transition is quite universal in physics, and it also applies, for example, to epidemiological models for the spreading of diseases. One can hope that analogous experiments, as in pipe flow, and corresponding numerical simulations—including those in which Prandtl numbers vary—will further elucidate the fascinating transition to the ultimate regime.

The issue is of utmost relevance: Researchers must understand how to extrapolate the heat flux from controlled lab-scale experiments to the scales relevant in geophysical contexts. Whether a transition to an ultimate regime occurs or not will change the heat flux by orders of magnitude. But climate models and models for heat circulation in the ocean—with their implications for melting glaciers, nutrition transport, and the prediction of tipping points—clearly require more precision and reliability.

The scientific insights conveyed in this article come from more than three decades of collaborations and interactions with colleagues, postdocs, and doctoral students. We thank all of them for their contributions and for the intellectual pleasure we *have enjoyed while working together. We thank Dennis van Gils for help with the figures.*

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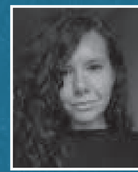
“Peaceful” nuclear explosives?

US GOVERNMENT

Hannah Pell is a science writer based in south-central Pennsylvania interested in the history of physics and the energy industry. She works in nuclear licensing and compliance.



Hannah Pell

Proponents of Project Plowshare argued that using nuclear explosives for peaceful means offered technical and economic advantages. But getting the biggest bang for the buck didn't outweigh the varied environmental and sociopolitical costs of their use.

On 10 December 1961, a crowd of several hundred people, including officials from the US Atomic Energy Commission (AEC), scientists, reporters, members of the public, and guests from 13 nations, gathered roughly 40 kilometers southeast of Carlsbad, New Mexico, and eagerly waited for the countdown. The nuclear testing moratorium initiated in November 1958 between the US and the Soviet Union had ended four months earlier (see the timeline in figure 1), and Project Gnome, the first nuclear explosive test detonated as part of the AEC's Project Plowshare, was finally about to occur after years of delay. Information acquired from Gnome was intended to support research on using nuclear explosives to produce recoverable energy, to mass produce radioisotopes for scientific and medical uses, and to demonstrate that such devices could be utilized for "peaceful" purposes—Plowshare's primary objective.

At noontime, the 3-kiloton-yield nuclear explosive buried 361 meters deep was detonated and formed an underground cavity chamber of 27 200 cubic meters. As reported in a 22 December 1961 *Time* article, one onlooker described the seismic activity as having "shook up your rattlesnakes" as the earth above the blast site rose almost two meters. Although Gnome was designed to be self-contained, the article reported that an "ominous-looking mushroom cloud" emerged from the shaft opening just minutes after the shot, venting radiation into the atmosphere. It damaged chemical samplers over ground zero and film in nearby cameras. The exit road from the site had to be temporarily closed, and cars in the area were washed down. A moment of nuclear promise evaporated into one of disappointment.

From the 1961 Gnome experiment through 1973, Project Plowshare detonated 35 nuclear explosives in 27 tests. It was organized under the AEC's division of military application in 1957—the same year that the world's first nuclear plant for commercial electricity generation began generating electric power and the International Atomic Energy Agency was established. Plowshare's purpose was to study the technical and economic feasibility of using "peaceful nuclear explosives" (PNEs) for civilian industrial applications. (For a contemporary look at Project Plowshare, see the article by David Lombard, Physics Today, October 1961, page 24.) The name was biblical in nature, chosen to emphasize its peaceful aims: "And they shall beat their swords into plowshares, and their spears into pruning hooks; nation shall not lift up sword against nation, neither shall they learn war any more" (Isaiah 2:4).

The development (and ultimate cancellation) of Plowshare occurred amid Cold War tensions and international negotiations for nuclear disarmament, a national environmental movement wary of "the unnatural creation of man's tampering with the atom" (reference 1, page 7), and heightened public opposition to new nuclear applications. There was also a need for greatly expanded domestic energy production driven by predicted near-term significant

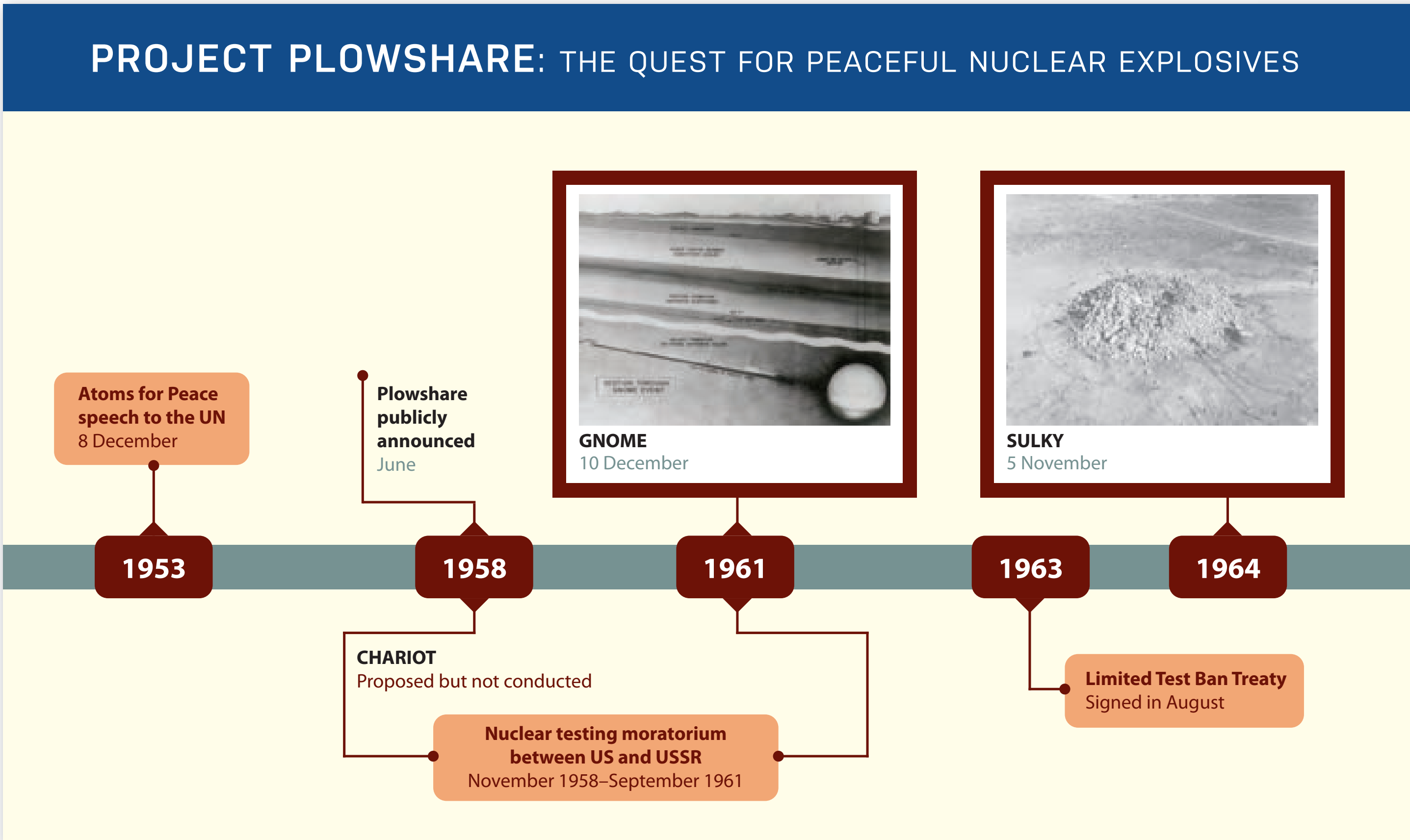


FIGURE 1. PROJECT PLOWSHARE took place among changing political treaties and shifting public opinion on nuclear technology. The timeline shows a small selection of Plowshare and other important events to put the tests into a wider context. (Images courtesy of the US Department of Energy.)

consumptive increases and national security interests, to which nuclear technologies could, in theory, provide economical solutions. The fundamental question of costs—whether to the budget, environment, or public confidence and safety—remained a central challenge to the AEC's efforts to demonstrate that PNEs were indeed worth their while.

Construction from destruction

“Occasional pages of history do record the faces of the ‘great destroyers,’ but the whole book of history reveals mankind's never-ending quest for peace and mankind's God-given capacity to build,” declared President Dwight D. Eisenhower during his Atoms for Peace speech to the United Nations General Assembly on 8 December 1953. “My country wants to be constructive, not destructive.” The following year Congress amended the Atomic Energy Act and codified such peaceful nuclear aims into law by requiring that “the development, use, and control of atomic energy shall be directed so as to promote world peace, improve the general welfare, increase the standard of living, and strengthen free competition in private enterprise.”

With the dawn of the “peaceful” atomic age, the AEC exercised its dual regulatory and promotional roles to oversee the development of civilian nuclear programs and to encourage and mediate partnerships between the federal government and private sector. AEC officials believed that the key to success of new nuclear endeavors lay in placing the burdens of technological risks and financial liabilities onto private companies through contractual agreements. In other words, it was to be a prime example of the military–industrial complex that Eisenhower would come to warn about in his farewell address. The AEC itself would remain responsible for all aspects of radiation safety. In prepared remarks for an American Institute of Chemical Engineers meeting in March 1954, AEC member Henry Smyth said, “Private industry already is carrying a major share of our enterprise under contract to the Government and is now becoming more and more active on its own initiative. This is as it should be” (reference 2, page 17).

Civilian access to nuclear technology opened the door for new applications. The 1956 Suez Canal crisis motivated Harold Brown, a physicist at the University of California Radiation Laboratory at Livermore (now Lawrence Livermore National Laboratory), to wonder about the possibility of using nuclear explosives to construct sea-level canals as a solution to the international trade disruption (see the map in figure 2). The success the following year of Project Rainier, the first underground nuclear shot, demonstrated that PNEs could produce underground cavities as predicted, which further catalyzed interest from oil, gas, and mining companies. (To read more about the promise of nuclear excavation with Plowshare, see the article by Gerald Johnson, Physics Today, November 1963, page 38.)

Project Plowshare's ambitions were frequently limited by measures put in place for other nuclear programs, regardless of intention. Plowshare was publicly announced in June 1958, only to be curtailed by the three-year nuclear weapons testing

1965

PALANQUIN
14 April

1967

GASBUGGY
10 December

KETCH
Proposed but not conducted
August

1969

RULISON
10 September

National Environmental Policy Act of 1969
Signed into law on 1 January 1970

1973

RIO BLANCO
17 May

1977

Plowshare terminated

moratorium that went into effect four months later. The moratorium broke down when the Soviet Union resumed nuclear testing on 31 August 1961 and the US promptly followed suit two weeks later.

Under Project Plowshare, six tests, including Gnome, would be conducted before the Limited Test Ban Treaty was adopted in August 1963. It prohibited nuclear explosions "in any other environment if such explosion causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted." To the extent Plowshare experiments could breach that provision, the treaty remained a risk to the program's prudence, although the Soviet Union was administering its own nuclear testing program for peaceful applications.

"The nuclear reactor has become a symbol of the constructive uses of atomic energy; the nuclear bomb, a symbol of destruction. What peaceful end could ever be served by a nuclear explosion?" wondered Brown and Gerald Johnson, also a physicist at the Radiation Lab.[3] The goal of Plowshare was to find out.

How atomic energy could change the world

In its early years, Plowshare was focused on large-scale geographical engineering projects, such as digging harbors, manipulating mountains, and altering watersheds. "We will change the earth's surface to suit us," wrote physicist Edward Teller in *The Legacy of Hiroshima* (page 84), his 1962 book with Allen Brown. Teller was an infamously outspoken advocate of Plowshare during his tenure at the Radiation Laboratory at Livermore. Earlier, in June 1959, while in Alaska promoting Project Chariot, he was quoted by an Anchorage newspaper as saying, "If your mountain is not in the right place, just drop us a card." Such dreams of earthmoving intersected with a galvanized national environmental movement, often marked by the 1962 publication of Rachel Carson's influential *Silent Spring*, which compared the invisible threats of radioactivity with the indiscriminate spread of pesticides and other poisons, an ecological crisis of our own making.[1]

"Unquestionably, the environment has suffered from the actions of man," stated Sam Smith, director of exploration for the El Paso Natural Gas Company, in 1970. "Some of this damage has been unavoidable, some the result of ignorance, and unfortunately, some has resulted from lack of responsibility. . . . However, we must consciously recognize that the expanding population and improved standard of living will require continued modification of our environment" (reference 4, page 21). That observation exemplifies Plowshare advocates' negotiations of PNEs' consequent ecological and biological hazards and to what extent such incurred environmental costs could be justified in their attempts to demonstrate the program's utility.

Project Chariot, an experiment designed to blast a new harbor in Cape Thompson, Alaska, was among the first of those ventures. It was planned as a series of five thermonuclear devices with a 2.4-megaton yield, but the design was later replaced with smaller fission explosives, cutting several million off its price tag. The blasts would create a harbor 823 meters long and 229 meters wide at a site only 300 kilometers from Siberia. Though the project site was repeatedly described as "a barren wasteland" that was "far away from any human habitation," an Inupiat community was located only 48 kilometers from the planned project site, but the AEC repeatedly failed to engage with its residents (reference 5, page 33). Aware of the 1954 catastrophe at Bikini Atoll,

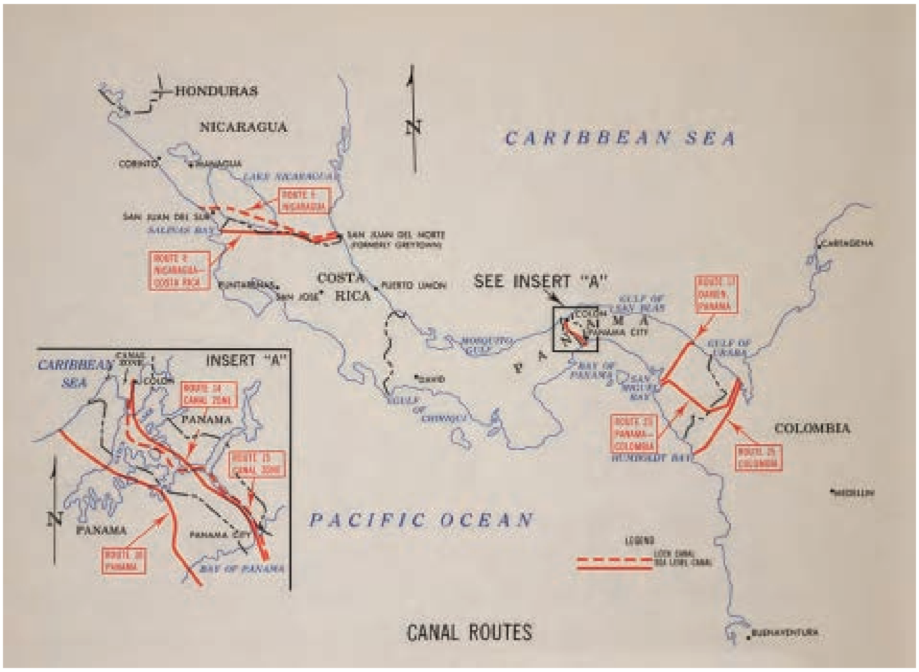


FIGURE 2. SEA CANAL ROUTES. One considered use for peaceful nuclear explosives was the building of canals. As part of the Atlantic–Pacific Interoceanic Canal Study, many routes across Central America were considered. (From ref. 7, page vi.)

the Point Hope residents organized against Chariot. Establishing a village council, they wrote letters expressing their concerns about the radiation hazards and questioning the AEC’s right to use the land for the experiment, especially because they relied on it for hunting caribou. “I’m pretty sure you don’t like to see your homeland blasted by some other people who don’t live in your place like we live in Point Hope,” Kitty Kinneeveauk told the AEC during a March 1960 meeting (reference 5, page 34).

Understanding how radioactivity could travel through and accumulate in an ecosystem was a crucial factor in weighing the biological cost of the proposed excavation. Biologists at the University of Alaska Fairbanks raised concerns that Chariot had no plans for ecological assessments. “It is scarcely too early in the Atomic Age to give considerable attention to the environment which supports man on this planet,”[5] said John Wolfe, an ecologist with the AEC’s division of biology and medicine (reference 5, page 35). The AEC established a Project Chariot environmental studies committee, chaired by Wolfe, to oversee the bioenvironmental program. The end result was a 1200-page publication of 42 environmental studies of the Cape Thompson region,[6] often considered the first environmental impact statement. Such statements have been required since passage of the National Environmental Policy Act of 1969. Importantly, ecological studies confirmed that radiation could be traced from the lichens to the caribou that eat them, to the Inupiat community who eat the caribou. Although Chariot was never formally canceled, it was among Plowshare’s numerous geographical engineering failures.

On 22 September 1964, Congress authorized $17.5 million for the Atlantic–Pacific Interoceanic Canal Study to evaluate construction methods, including the use of nuclear excavation techniques. The commission looked at numerous routes through Panama, Colombia, Costa Rica, and Nicaragua and later conducted field surveys in the countries. But it determined that the use of PNEs to create a “panatomic” canal was not technologically feasible. The unavoidable risk of radiological consequences in foreign territories also exacerbated existing political objections.

In pursuit of a sea-level canal, the US leveraged the PNE as an instrument of technological and engineering prowess for geopolitical gain. US proposals were met with demands by Panama for revisions to the Hay–Bunau-Varilla Treaty of 1903. By 1967 three new treaties were drafted, including one for granting the US rights to build and operate a sea-level canal in Panama, but they were never ratified. In the cover letter to its 1970 Interoceanic Canal Study final report, the commission concluded that “no current decision on United States canal policy should be made in the expectation that nuclear excavation technology will be available for canal construction.”[7]

The Limited Test Ban Treaty’s prohibition on the spread of fallout across international borders also presented issues for the nuclear excavation of a sea-level canal. The AEC interpreted the treaty’s language to mean that only a measurement of radioactivity higher than internationally accepted standards would constitute a violation, and, according to the commission, “there was confidence . . . that the radioactivity effects could be held to insignificant levels” (reference 7, page 34). Fallout patterns were predicted along the potential sea-level canal routes, and the study results suggested that up to 30 000 people could require evacuation. To a large degree, however, the maps were an illusion of control; other Plowshare tests—namely, Palanquin, which released airborne debris that was approximately 2500 m above the unexpected crater, had higher-than-predicted radiation levels, and nearly drifted across the US–Canadian border—cast considerable doubt that the spread of radioactivity subject to changing meteorological conditions could be accurately predicted.

The Plowshare efforts for nuclear-excavated canals were exemplary of the 1960s US practice of deploying state-sponsored technocratic projects to conquer nature “on a scale comparable to waging war.”[8] It became clear that the potential costs of PNEs demanded a fuller evaluation of the environment surrounding the test sites so that the impacts could, in theory, be calculated and mitigated with engineered controls.

Energy problems, nuclear solutions

In the 1950s, signs of an impending energy crisis were evident—a booming population, increasing consumption, and depleting natural resources—and the question was not only how nuclear energy could be part of the solution but how it could effectively compete in the energy market. In a 1954 congressional report on the AEC's proposal for a five-year reactor development program, the pressurized water reactor was ranked as the least promising of the proposed reactor designs for achieving economically competitive nuclear power: "It is clearly of conservative design and has a poor long-term prospect for producing low-cost atomic power" (reference 2, page 3). Nine years later, Teller wrote that "nuclear energy is not yet competitive. It has contributed to the national economy by providing additional incentive for lower cost of the conventional installations."[9]

Market incentives for a more efficient and economical means to increase natural-gas production drove industry participation in Plowshare, but the potential for long-term profits was uncertain. Gas production models suggested that PNEs would be advantageous over conventional extraction techniques—for example, using a hydrochloric-acid solution to dissolve calcium carbonate in a limestone reservoir—because their higher yield would increase the permeability of the surrounding medium and the radius of the chimney formation fracture system (as seen in figure 3), thereby increasing the rate of gas flow. A 1967 report suggested that PNEs used in low-permeability gas fields could increase recoverable natural-gas amounts by adding at least 18 years to the national supply at a fraction of the cost.[10] Project Gasbuggy, the first Plowshare experiment to produce natural gas, was undertaken by the AEC, the Radiation Laboratory at Livermore, the El Paso Natural Gas Company, and the US Bureau of Mines to confirm to what extent that was indeed the case.

Gasbuggy aimed to stimulate the Pictured Cliffs, a low-permeability formation in New Mexico's San Juan Basin where the El Paso Natural Gas Company owned oil and gas leases. The experiment was conservatively predicted to make 67% of the 149 million cubic meters per acre of natural gas recoverable, a sevenfold increase compared with conventional stimulation. It was unclear, however, to what extent the radioactive byproducts would contaminate the natural-gas supply, given that certain gaseous radioisotopes—krypton-85, xenon-133, and tritium—could not be filtered out. According to a 22 September 1967 article in the *New York Times*, before the Gasbuggy shot, a Radiation Laboratory representative at a public meeting told the attendees, from 14 countries, that "current estimates for gasbuggy itself indicate that with regard to tritium, the gas (released by the explosion) will not be suitable for unrestricted use unless diluted with uncontaminated gas." The AEC needed to determine whether use of the gas would result in radiation exposure above normal levels received by the public under the standards set by the Federal Radiation Council before the El Paso Natural Gas Company could sell it. But even if the AEC determined that the natural gas was acceptable to sell, would consumers be convinced of its safety?

After several delays, Gasbuggy was detonated on 10 December 1967. The 29-kiloton explosive created a chamber just over 46 meters in diameter and 101 meters high with approximately 57 000 cubic meters of space. Although the test was successful in that the radioactivity was completely contained in the underground cavity, samples of the natural gas revealed significant amounts of tritium and a dramatic decrease in the percentage of hydrocarbon. Post-shot surveillance by the US Public Health Service showed that the highest concentration of tritium in the environmental samples coincided with the highest daily release rates during initial flaring operations in November 1968, a standard part of the natural-gas extraction process. El Paso was never able to sell the gas produced.

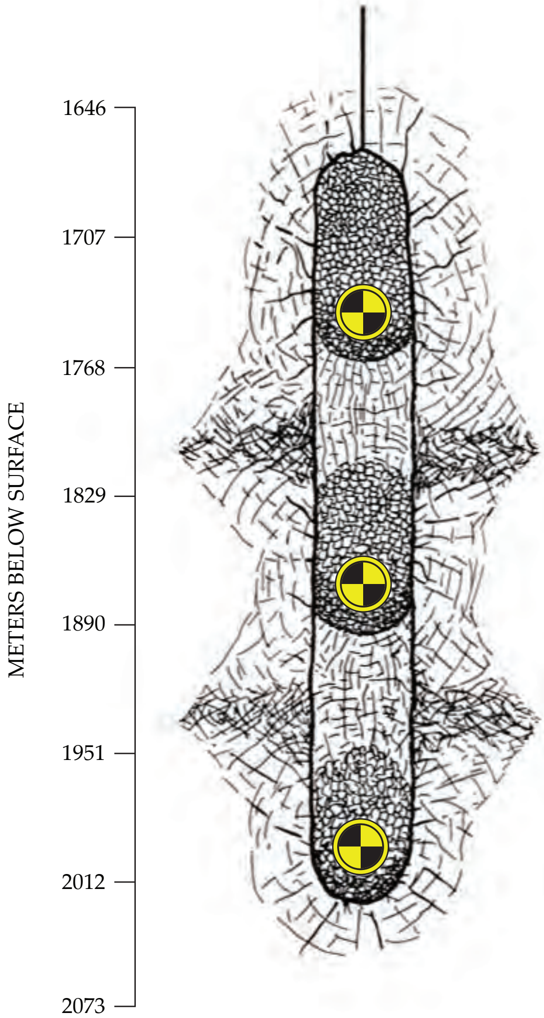


FIGURE 3. PROJECT RIO BLANCO aimed to use three detonation sites in vertical arrangement in order to optimize the yield. (Adapted from J. Toman, H. A. Tewes, *Project Rio Blanco: Phase 1 Technical Studies*, Lawrence Livermore Laboratory, University of California, 24 January 1972.)

Like Gasbuggy, Project Rulison—sponsored by the AEC, the Department of the Interior, and the Austral Oil Company with CER Geonuclear Corp—aimed to test PNEs' effectiveness for gas stimulation in the Rulison Field in Garfield County, Colorado. Under the contract, 90% of the $6.5 million cost would be covered by private industry. Austral Oil had the lease for the land, so no state approvals were required before the shot was detonated, but local environmental groups, including the Colorado Committee for Environmental Information, were vocally opposed to the blast. After several delays because of legal challenges from conservation organizations and unfavorable weather forecasts, the 40-kiloton explosive was detonated almost 2600 meters underground on 10 September 1969. Initial results were positive: The radioactivity was completely contained, and the well produced nearly 6 million cubic meters of gas in one month, equal to six years' worth of production for the region. But

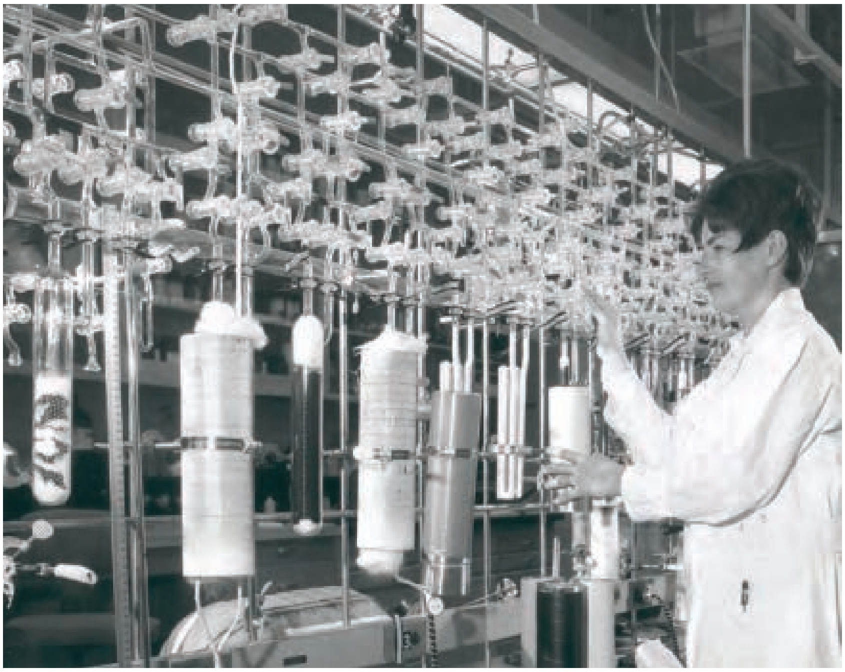


FIGURE 4. LAWRENCE RADIATION LABORATORY, around 1968. The branch at Livermore housed chromatographic gas columns with samples from Project Gasbuggy. JoAnn Rego was one of the scientists who worked in the radiochemistry laboratory. (Courtesy of the US Department of Energy.)

similar to Gasbuggy, the natural gas contained tritium, and the AEC would not permit Austral to sell it. The experiment ultimately cost Austral nearly double the original contract estimate, and the company did not recoup a single penny.

Rio Blanco, Plowshare’s third gas stimulation experiment, was similarly unsuccessful. Scientists began studying a site near Rifle, Colorado, in December 1970. The previous January, the National Environmental Policy Act had been signed into law and required government agencies to prepare an environmental impact statement for “major Federal actions significantly affecting the quality of the human environment” and to solicit public comment. Akin to Chariot, Rio Blanco received a barrage of public scrutiny. A US representative on the Joint Committee on Atomic Energy described it as “an unnecessary waste of the nation’s uranium.” A member of the Sierra Club, a US environmental organization, said, “We are the nation’s guinea pigs in an insane experiment for a few dollars for a few corporate enterprises which includes the AEC.”[11] The final Rio Blanco environmental assessment stated that the amount of tritium to be released during flaring was expected to be less than the amount released during Rulison. The predicted total maximum potential dose to local populations was less than 1% of annual background radiation, an “adverse environmental impact which cannot be avoided.” The report also said that “the development of this technology must be evaluated in terms of whether the benefits derived from the gas production outweigh the economic and environmental costs.”[12]

Rio Blanco was detonated on 17 May 1973, and the results were disappointing: The three vertically placed blasts created separate cavities, as seen in figure 3, rather than one, and no gas could be found in the top chimney. Discovery of cesium-137 immediately put a stop to the post-shot flaring, and the Nuclear Regulatory Commission, established in 1975, would not allow the sale of any gas produced because strontium-90, a dangerous byproduct of nuclear fission, was detected in 1974. The 85% of Rio Blanco’s $8.9 million cost covered by private industry resulted in zero financial gain.

After more than $80 million spent on Plowshare’s natural-gas stimulation efforts, the unique liabilities and risks presented by PNEs proved too costly for private industry’s comfort. “Analysis of the stimulation effects and the attendant costs leads to the conclusion that nuclear-explosive well fracturing at its present stage is not commercially attractive,” said an Energy Research and Dev-elopment Administration representative at a 1976 conference on the future of petroleum and gas production. “Public acceptance of the technology is equally important; it has never been favorable and is downright hostile at this time with no prospect for near-term improvement. The problems are exemplified by voluminous environmental statements.”[13]

Political costs

Three years of collaboration among the Columbia Gas Corp, the AEC, the Lawrence Radiation Laboratory at Livermore (see figure 4), and the US Bureau of Mines to identify a means of providing new natural-gas storage in Pennsylvania resulted in the Project Ketch feasibility study, finalized in July 1967. Ketch would require that a 24-kiloton nuclear device be detonated 1006 meters underground to create a chimney that could provide 13.2 million cubic meters of gas storage. Given that the Appalachian states made up 38.6% of the US’s total natural-gas storage at the time, the region became a priority for the prospect of nuclear-induced storage. Columbia Gas felt Pennsylvania would be particularly accepting of atomic testing, given it was home to the Shippingport Atomic Power Station and had a history of innovative energy production. In his 1 August 1967 letter of support for the project, Maurice Goddard of the Pennsylvania Department of Forests and Waters (now the Department of Environmental Protection) acknowledged Ketch as an opportunity: “If Pennsylvania is to economically supply this important energy fuel to the rapidly expanding industries and population of the Commonwealth throughout the remainder of this century, the amount of gas pipelined . . . will have to be doubled from the present rate of about 683 billion cubic feet annually.”[14]

The proposed Ketch site, located in Sproul State Forest in central Pennsylvania, was primarily chosen for its proximity to major sources of natural-gas production and significant market needs for increased gas storage capabilities—remote from civilization and yet close enough to existing pipelines to make it economical, as the AEC described it. Similar to Chariot, the AEC asserted the marginality of the central Pennsylvania region’s residents by depicting the site as a “hole in the map,” despite its location roughly 48 kilometers outside State College, home of the Pennsylvania State University, and even closer to the nearby towns of Renovo and Bellefonte. Although Columbia Gas repeatedly emphasized that the blast would help stimulate local economic development, it offered little details on the long-term benefits. At the time, Ketch was proposed as nothing more than an experiment in feasibility; there were no long-term commitments from the AEC or Columbia Gas for continued use and operation of the site. A headline in the 23 April 1968 edition of the *Renovo Daily Record* boasted: "If Successful, 'Ketch' will Employ 2 to 4 Men." An editorial in the *Centre Daily Times* on 13 May observed that "the same arguments of economic advantages are being used for Project Ketch that were used for strip mining 20 years ago. Now the long suffering taxpayer must raise the money to try to repair some of the damage so that his environment will be fit to live in."

Many local organizations issued public statements against the experiment. Eventually, the Clinton County Central Labor Union presented the county's commissioners with a 4600-signature petition. A citizens group called People Against Ketch was formed, and its members produced pamphlets and organized a caravan to visit the proposed project site. The AEC and Columbia Gas hosted numerous public meetings in an attempt to mitigate Ketch's ongoing public relations problem. At an April 1968 public forum held at Penn State, questions from the audience lasted for more than three and a half hours. One attendee observed that the others "clobbered" the panel. "Objections appear to be based on fear of the unknown—or partially understood," Ernest Weidhaas, a professor of engineering at Penn State, scribbled in a note to Nunzio Palladino, dean of the College of Engineering and chairman of the Pennsylvania Advisory Committee on Atomic Energy Development and Radiation Control subcommittee on Ketch.[14]

To the residents of Clinton and Centre Counties, Ketch just wasn't worth it. Within three months of the forum, Columbia Gas withdrew its lease application for the Ketch site.

The commercialized atom: At what cost?

Plowshare, fundamentally, was about selling the industrial economic benefits of the peaceful atom. Signs of an impending energy crisis drove market incentives. That created favorable conditions for companies to see the most financial reward from the then newly commercialized atom. But as with the introduction of any new technological application, there are real costs—monetary, environmental, and sociopolitical—initially unforeseen and incurred over time. Nevertheless, the AEC and Plowshare proponents hardly lost faith; they advocated with conviction that something constructive needed to come of a technology capable of such indiscriminate destruction.

Plowshare's defenders remained steadfast that PNEs were an agent of progress driving the future of commercial nuclear capabilities. PNEs were technically sound and economically advantageous, they argued, under the right theoretical conditions. Yet when such grand, visionary ideas were removed from the laboratories and imposed on various environments, initial conditions and assumptions broke down. Despite hundreds of millions of dollars spent on repeated failures to prove any of Plowshare's programmatic aims or reach its goal of becoming a "viable commercial enterprise" (reference 4, page 1), the project was not terminated until 1977.

As Plowshare faded, the idea of using nuclear technology for peace persisted through the construction of nearly 100 operating reactors in the US. Nevertheless, popular enthusiasm for nuclear power faded after the partial meltdown of the Unit 2 reactor at Three Mile Island in 1979. (See "Three Mile Island and lessons in crisis communication," Physics Today online, 5 May 2020.) A "nuclear renaissance" seemingly emerged in the 2000s, however, following passage of the 2005 Energy Policy Act, when the Nuclear Regulatory Commission received applications for combined—both construction and operation—licenses for 29 new reactors. Billions of federal loans were allocated to support new projects at the Virgil C. Summer Nuclear Station, which was ultimately canceled in 2017 due in part to astounding cost overruns, and for two units at the Alvin W. Vogtle Electric Generating Plant. The cost of the Vogtle Unit 3 project alone more than doubled over the course of its lifetime, from $14 billion to over $30 billion.

Such a nuclear resurgence continues through the development of small modular reactors, which have a capacity of less than 300 megawatts electric. Aided by the 2022 Inflation Reduction Act's tax incentives for advanced nuclear deployment, developers of the small reactors are hoping to capitalize on yet another round of the nuclear hype cycle,[15] and they are anticipating that such "deliberately small" designs[16] will not inevitably be subjected to the same economic challenges that are found throughout the history of nuclear technology. Examining Plowshare's varied costs shows that the commercial development of civilian nuclear technologies very much depends on the best price determined by the current political economy—and if private industry is willing to pay it.

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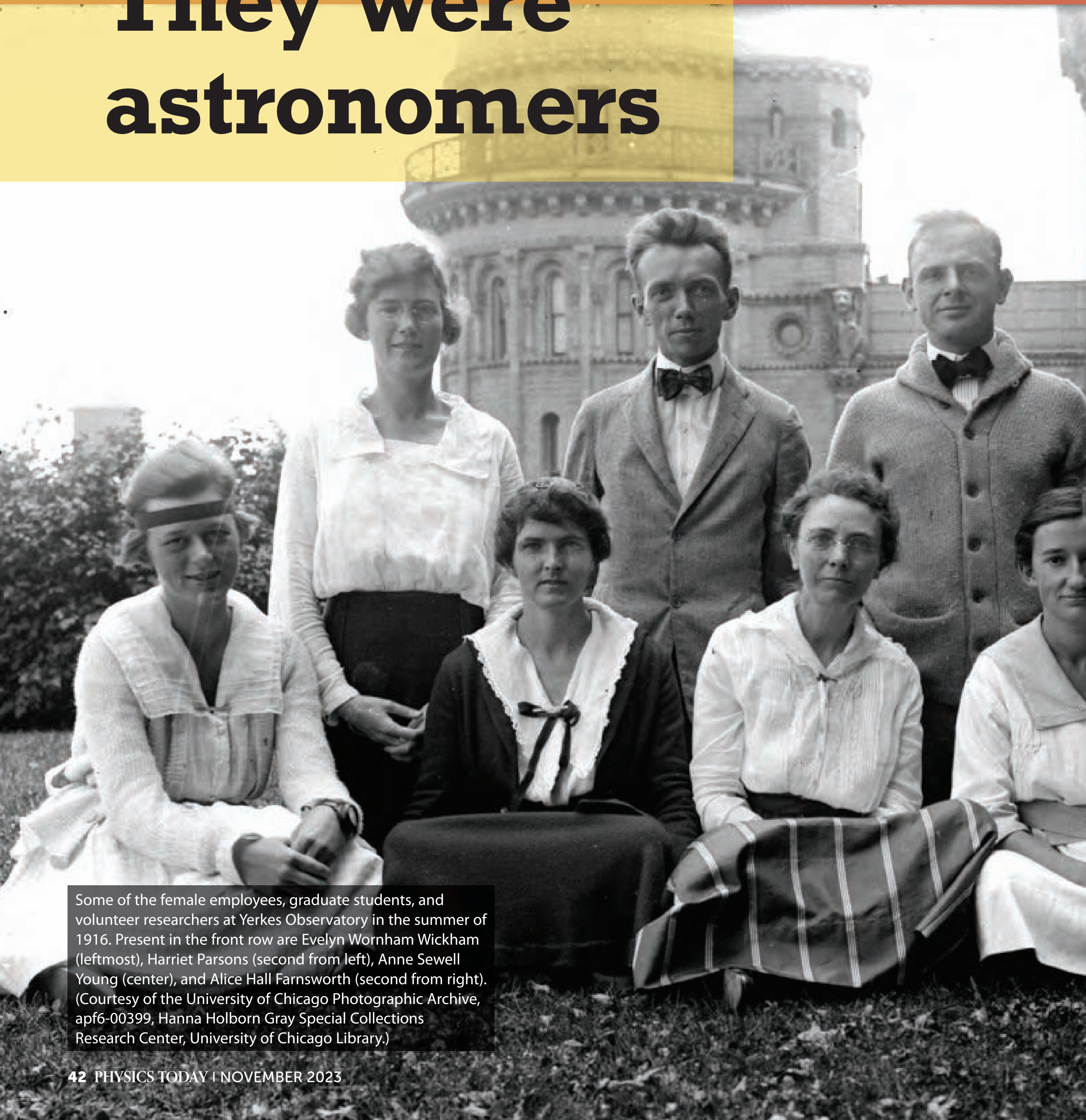
They were astronomers



Some of the female employees, graduate students, and volunteer researchers at Yerkes Observatory in the summer of 1916. Present in the front row are Evelyn Wornham Wickham (leftmost), Harriet Parsons (second from left), Anne Sewell Young (center), and Alice Hall Farnsworth (second from right). (Courtesy of the University of Chicago Photographic Archive, apf6-00399, Hanna Holborn Gray Special Collections Research Center, University of Chicago Library.)

Kristine Palmieri is a postdoctoral researcher at the rank of instructor with the Institute on the Formation of Knowledge at the University of Chicago. She is a cocurator of the exhibit *Capturing the Stars: The Untold History of Women at Yerkes Observatory*, which will be on display at the University of Chicago Library until 15 December 2023.

Kristine Palmieri

Unlike at most other observatories in the early 20th century, women working at Yerkes Observatory were able to earn graduate degrees. Here are some of their stories.

Despite never finishing high school, Mary Calvert was one of the most famous female astronomers in the US during the 1930s. Calvert's star rose in large part because of the death of her uncle E. E. Barnard in 1923: She took it on herself to complete his unfinished magnum opus, *A Photographic Atlas of Selected Regions of the Milky Way*, which was published in 1927. Having her name on the work's title page brought Calvert a new level of national prominence and earned her a promotion from (human) computer to assistant at the University of Chicago's Yerkes Observatory.

That familial connection identifies Calvert, like Caroline Herschel and Maria Mitchell, as a woman whose entry into science was facilitated by male relatives to whose work her labor contributed.[1] That was a common path into astronomy for women during the 19th century. But as the discipline professionalized in the latter half of that century, even women with familial connections, such as Antonia Maury and Anne Sewell Young, increasingly found it necessary to acquire educational credentials. And for women who had no relatives working in astronomy, those degrees opened a pathway into a field that was otherwise closed.

By 1900, women were attending college in such numbers that anxieties about the feminization of higher education abounded, but they received graduate degrees in much smaller numbers.[2] Part of the reason for that was cultural. Many female college graduates would go on to become schoolteachers, a career that did not require advanced scientific training. Another reason was structural. Well into the 20th century, women were expected to leave the workforce when they married.[3] Advanced training for women thus diverted resources from "outstanding young men" who would remain in the field for their entire lives and thus deserved promotion over and above any woman, no matter how talented. Or, at least, that was the argument deployed by physicist Robert Millikan when protesting the 1936 appointment of German physicist Hertha Sponer to a professorship at Duke University.[4]

In certain quarters, however, women made inroads. Psychology, anthropology, zoology, botany, and especially home economics, for example, came to be coded as more feminine than fields such as physics or astronomy, in part because of the relatively large numbers of women earning advanced degrees in those fields. But the relatively large number of female graduates in those disciplines did not lead to a proportional increase in the number of professional women with careers in those fields. After graduating, many of the women found themselves overcredentialed and underemployed.

Staff or students?

In astronomy, there was a strong demand for educated women, who were hired as human computers at facilities such as the Royal Greenwich Observatory in London; the Harvard College Observatory in Cambridge, Massachusetts; and Mount Wilson Observatory near Pasadena, California.[5] But their work was routine and required only a basic knowledge of mathematics, not advanced astronomical or astrophysical training. Those observatories hired women because they provided cheap and reliable labor. At Greenwich, for example, calculations had previously been carried out by boys.[6] And at Dudley Observatory in Albany, New York, women without college degrees were preferred precisely because they were cheaper.[7]

As a rule, the women were employees, not graduate students. For that reason, early women astronomers who made significant contributions to science, such as Annie Jump Cannon and Henrietta Swan Leavitt, are generally identified as exceptions who succeeded despite being confined because of their gender to scientifically ancillary, professionally marginal, and poorly remunerated positions as computers. Cecilia Payne-Gaposchkin, who worked at the Harvard College Observatory and in 1925 became the first woman to earn a PhD in astronomy from Radcliffe College, was an exception among exceptions.

At Yerkes Observatory, however, a different system emerged. Because it was attached to the University of Chicago, which was coed from its foundation in 1890, women astronomers at Yerkes always had the opportunity to obtain advanced degrees. Emily Dobbin became the first woman to earn an MS in astronomy from the university in 1903. Her thesis, "The orbit

WHILE EMPLOYED AT YERKES OBSERVATORY, Jessie May Short, Evelyn Wornham Wickham, and Dorothy Block (from left to right) all worked toward graduate degrees at the University of Chicago. (Image of Short courtesy of Special Collections and Archives, Eric V. Hauser Memorial Library, Reed College, Portland, Oregon; images of Wickham and Block courtesy of the University of Chicago Photographic Archive, apf6-04196 and apf6-04180, Hanna Holborn Gray Special Collections Research Center, University of Chicago Library.)

A YERKES OBSERVATORY staff photo from August 1919. Present in the third row are Evelyn Wornham Wickham (fifth from right) and John Paraskevopoulos (rightmost). Yerkes director Edwin Frost is sitting third from right in the second row. Present in the first row are Mary Calvert (leftmost), Harriet Parsons (second from left), and Alice Hall Farnsworth (second from right). (Courtesy of the University of Chicago Photographic Archive, apf6-00413, Hanna Holborn Gray Special Collections Research Center, University of Chicago Library.)

of the fifth satellite of Jupiter," was published in the *Astronomical Journal* the following year.[8]

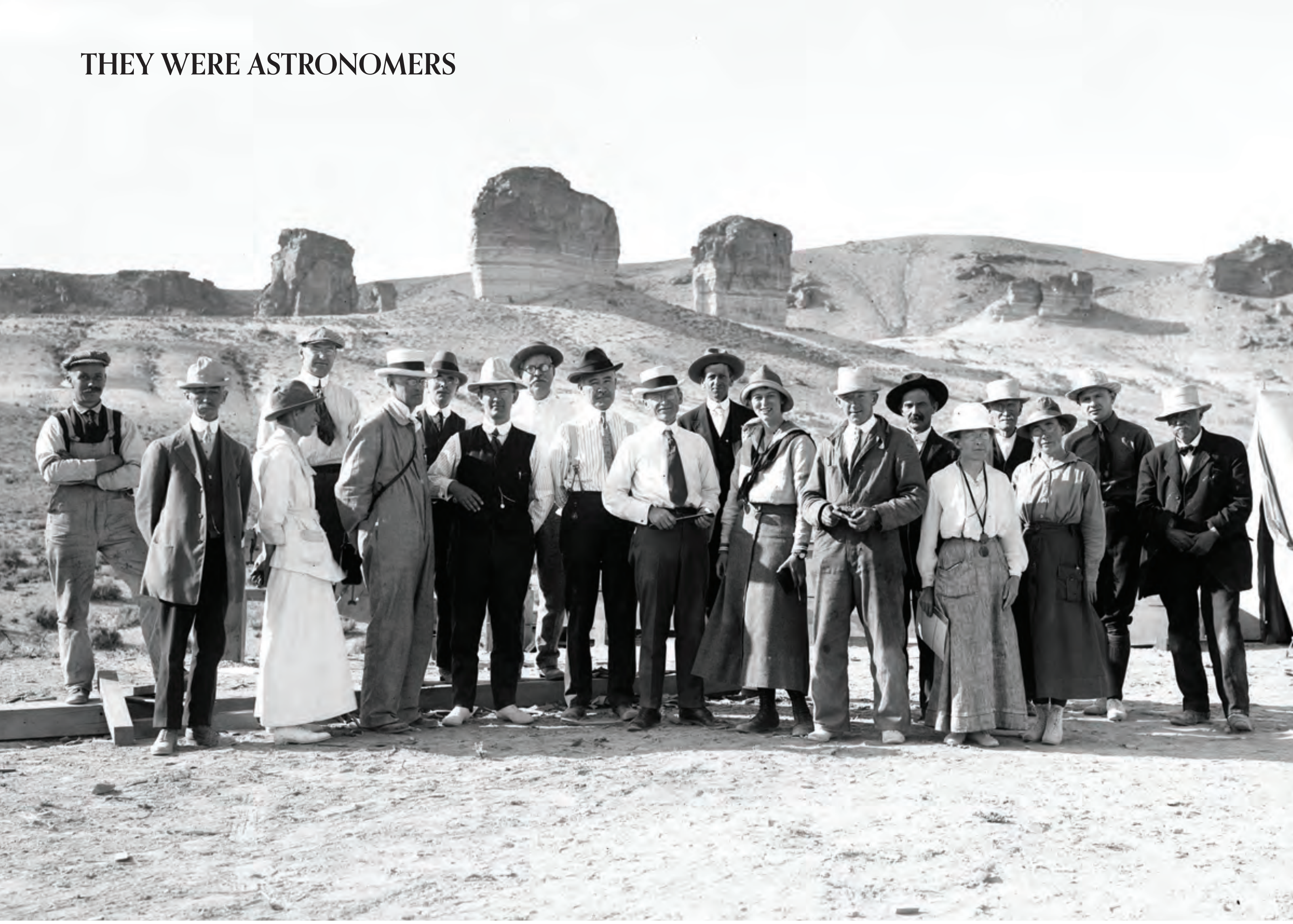
Yerkes was also unique because its location in the southern Wisconsin village of Williams Bay made it accessible. Not only was the municipality the last stop on a train line that connected the town with Chicago, but the observatory's proximity to the community also enabled women to find respectable accommodations nearby. That was unusual. Mount Wilson, for example, was not only difficult to get to but intentionally designed to exclude families and, by extension, all women. Moreover, women who worked as computers for Mount Wilson at its office in Pasadena were unable to pursue a degree. As Mount Wilson director George Ellery Hale explained in a 1919 letter to the future University of Chicago PhD candidate Dorothy Block, "No academic credit is given for work in the Observatory."[9] At Yerkes, however, a system was in place by the early 1910s in which someone working as a calculator had the opportunity to simultaneously earn credits toward an advanced degree. The first woman to take advantage of that opportunity was Jessie Short (1873–1947).

First but not forgotten

Born into a farming family in College Springs, Iowa, Short earned her BA from Beloit College in 1900 and started working as a schoolteacher in Minnesota after graduation. But Short wanted to do graduate work. In 1911 she began working on her master's degree in astronomy at Carleton College, where she eventually completed a thesis on the Algol star system. The essay "involved considerable original research," as her supervisor stated in his recommendation letter.[10]

On track to finish her degree, Short reached out to Edwin Frost, director of Yerkes, in September 1910 with a plan. "I should be glad to spend most of the Summer at Yerkes Observatory," she wrote, "if I could arrange to do enough assistance work to pay expenses while there, combining study and computing or assistant work of some kind." She hoped that such an arrangement would enable her to focus on her studies and that, after working at Yerkes for a couple of summers in that manner, she could then take a year's break from her teaching work to focus on completing a PhD. Frost responded that her plan would require more than one year's residence, even with several summers of study at Yerkes behind her. But the biggest obstacle to her plan, he explained, was the observatory staff's unfamiliarity with the "red tape and formality in connection with candidates for degrees from the University." In other words, no one had yet pursued a graduate degree in that way.

For the time being, Short stayed at Carleton. But even as she advanced to become the college's acting dean of women, she



YERKES STAFF pose for a group picture during the observatory's expedition to Green River, Wyoming, where they recorded the 8 June 1918 total solar eclipse. Present in the image are Mary Calvert (third from right), Evelyn Wornham Wickham (eighth from right), and Edwin Frost (fifth from left). (Courtesy of the University of Chicago Photographic Archive, apf6-00786, Hanna Holborn Gray Special Collections Research Center, University of Chicago Library.)

nurtured her dream of earning a PhD. She wrote to Frost again in 1914, and that time he told her to apply for a fellowship. In the intervening years, the staff at the observatory had figured out how to make graduate work at the observatory a reality.

But just because there was now a path forward did not mean that it was open to Short. Frost supported her application for a fellowship, but there were those on the faculty who questioned her suitability. One of those was E. H. Moore, the first head of the University of Chicago's mathematics department. As he wrote to Frost, "You write of Miss Short. Being already forty-one, does she give promise of doing anything noteworthy for the University? I should think that the policy would be to 'catch em young.'" Fortunately for Short, Frost's endorsement carried the day. Nevertheless, at $120, her fellowship was significantly smaller than those awarded to male classmates.

Short started work on her PhD in the summer of 1914, focusing her attentions on the distortions of the reflector field on plates taken using a 12-inch aperture on the 24-inch reflecting telescope. In her research, she discovered that the Gaertner measuring engine—a cutting-edge piece of technology used to rapidly measure glass plates—had a progressive error in its screw, which affected the machine's accuracy. That also led her to conduct research on the calibration of the screw. Both areas of research reveal the absence of a gendered division of labor at Yerkes: Edwin Hubble, Short's fellow graduate student, also conducted research on the distortions of the reflector field, and Oliver Lee, who left Yerkes for a position at the Dearborn Observatory at Northwestern University in 1928, also conducted research on the errors of the screw.[11]

But soon disaster struck. Short failed her qualifying exam in mathematics. It's unclear whether that was because she truly did not understand the material, as the all-male examining committee stated; they held her to an impossibly high standard; or they were simply unwilling to advance a woman to candidacy. Whatever their reasons, the committee declined to let her pass. Short left Yerkes shortly thereafter and, after a brief spell at Rollins College in Winter Park, Florida, landed a job at the Workmen's Compensation Service Bureau in New York City.

But she was nothing if not persistent. In 1923 Short wrote to Frost to ask about finishing her dissertation. It had taken a long time for her to revisit the matter, she wrote, because her job at the Service Bureau left her barely any time for research. The period during and after World War I had been particularly difficult in that regard, but even under normal circumstances, overseeing a staff of 90 left her little opportunity to revisit her dissertation. Even after leaving the bureau in 1920 to assume

Digitizing photographic glass plates

Since early 2019 the Capturing the Stars undergraduate research group led by University of Chicago astronomer Richard Kron has been measuring the brightness of stars on century-old photographic glass plates taken at Yerkes Observatory. Many of those plates, which are now held at the University of Chicago Library, were taken by women astronomers. Once a plate has been digitized, the next steps involve calibrating it over a large range of stellar brightnesses. That plate-specific calibration is challenging because of the nonlinear response of the photographic emulsion to illumination and the quirks of the digitizing equipment.

Two papers have been published on the methods developed so far. The first focuses on a plate taken in 1901 depicting a small field of view pointing out of the Milky Way;[15] the second analyzes a 1905 plate of a large field of view pointing into the Milky Way.[16] The plates each contain thousands to tens of thousands of stars, which are useful for time-domain studies over a longtime baseline. The Yerkes collection includes tens of thousands of spectrograms, many of which are of variable stars, and the student group is currently exploring the scientific potential of those taken in the late 1920s.[17]

an instructorship in the mathematics department at Reed College, she had been occupied with teaching.

Frost responded by informing her that research at the observatory had moved on. "I do not feel the investigation of the field of the reflector is yet exhausted," he wrote, but producing something new that was worthy of a PhD "would require more plates and some new refinements in measurement and reduction." In other words, Short would essentially have to start again. That she did not do. But although Short never earned a PhD at the University of Chicago, she nevertheless earned a place in James Cattell's *American Men of Science*.[12]

Work-study at Yerkes

Short played a crucial role in making it possible for both men and women to do graduate work at Yerkes while working as a computer. But that was only one of the paths that brought women to the observatory. Harriet Parsons (1892–1986), for example, obtained funding for graduate work from other sources, most notably from nonresident graduate fellowships financed by Vassar College alumnae. Women did not have to do graduate work, however, if they were employed as a computer. For example, there is no evidence that Eudora Magill (1855–1948), who was employed at Yerkes from 1912 to 1916, ever sought to earn an advanced degree. But she could have.

When Magill left Yerkes for a job at the University of Virginia's Leander McCormick Observatory, Frost wrote to colleagues to ask if they knew anyone who would be interested in the position. One of those he wrote to was the Vassar astronomer Caroline Furness (1869–1936), to whom he emphasized the uniqueness of the opportunity precisely because "one advantage of the computerships here over those at certain other places is that they permit enrolment as graduate students and credit for the time toward a higher degree."

Furness recommended her student Evelyn Wornham Wickham (1895–1988) for the position. But Wickham's was not the only application Frost received. Based on the strength of those applications, he decided to split the position in two. Each woman would be appointed as a computer but would spend only half her time computing and the other half doing graduate work. They would each earn $30 per month, as opposed to the $50 per month received by a full-time computer, but less time spent computing for the observatory would make it possible for the women to finish a master's degree in a single academic year.

The offer was financially meager, but Wickham did not want to pass on the opportunity. As she wrote to Frost, "Although I had hoped to be entirely self-supporting next year, I realize that this is a good opportunity for further study." But even with the pay cut, the Yerkes position was still Wickham's

A PHOTOGRAPHIC GLASS PLATE of the Pleiades star cluster taken by George van Biesbroeck at Yerkes Observatory on 3 January 1916. Harriet Parsons studied the region in her University of Chicago master's thesis submitted that same year. She described how she used photography to obtain visual magnitudes of stars and performed calibration calculations to determine both their relative and absolute magnitudes. (Courtesy of the Yerkes Glass Plate Collection, Hanna Holborn Gray Special Collections Research Center, University of Chicago Library.)

Yerkes Observatory today

In 2020, the nonprofit Yerkes Future Foundation (YFF) took ownership of Yerkes Observatory and its 50-acre campus from the University of Chicago. The YFF has dedicated the past three years to conscientiously restoring the landmark institution and grounds. Staff members now conduct astronomical research and educational outreach. They are also building a series of programs bridging science with the arts and culture through bold ideas and performances. In only its second year open to the public, YFF has established a space where astrophysicists collaborate with musicians, sculptors, landscape designers, writers, and artists to create contemporary, cross-pollinated works and programs.

Walt Chadick
Yerkes Observatory
Williams Bay, Wisconsin

first choice: While waiting for Frost to confirm the position, she passed up two other job offers.

Apologizing for the delay, Frost confirmed her appointment and reiterated the fact that on top of calculating, she would undertake the "regular work" of a graduate student at the University of Chicago. In other words, graduate work was graduate work; her course of study was identical to that of her male peers. When not computing, Wickham spent her time studying subjects such as spectroscopy, stellar photography, and photometry. Like that of her male peers, Wickham's work also included observing with the 40-inch refracting telescope.

That the kinds of work Wickham and her peers were doing at Yerkes far exceeded the scope of conventional women's work is further underscored by correspondence between Frost and Ida Manley, who contacted him for information about the employment and occupations of female college graduates shortly after Wickham had arrived at Yerkes. Manley had a particular interest in photography, and she was especially excited to learn that women at Yerkes were taking part in photographic research. As she wrote, "In California, up to this time (report from Mt. Lowe), though fourteen women are employed, none is engaged in [the] photographic phase of astronomy, so it is a gratifying discovery to find four at Chicago university, and their contributions will add not a little strength to our argument in favor of this field of college women's employment."

After Wickham finished her MS, she remained at Yerkes for two more years before landing a job as an electrical engineer at American Telephone & Telegraph Company. Frost himself flagged those financial motivations when he wrote in his reference letter, "We shall be sorry to lose her, but realize that it is to her interest to obtain a position that will give her a different experience and better pay than we are able to offer." Wickham married in 1925 but remained at the company until the birth of her first child in 1927.

Astronomical careers

Of the nine PhDs awarded for work done at Yerkes before 1923, three of them went to women. One of those was Alice Hall Farnsworth (1893–1960), who was born in Williamsburg, Massachusetts. She received her BA from Mount Holyoke in 1916 and earned her MS from the University of Chicago one year later. Writing in support of her application for a fellowship in 1920, Frost stated, "Miss Farnsworth has now been a student in this department for 13 quarters and is one of the most competent that we have ever had of either sex." Her work was not just good for a woman, it was good for an astronomer.

At Yerkes, Farnsworth worked predominantly with John Parkhurst on photometry. That work informed her PhD thesis, which compared the photometric fields from two of the observatory's telescopes. After earning her degree in 1920, Farnsworth returned to Mount Holyoke as an instructor in the department of astronomy. She often looked back on her time at Yerkes fondly. As she wrote to Frost shortly after leaving, "I am finding your Y.O.-itis a difficult disease to recover from and doubt if I [will] ever entirely get over the effects of it." But Farnsworth's graduation did not bring her relationship with Yerkes to an end. She returned regularly as a volunteer research assistant and, after Parkhurst's death in 1925, she spent a year completing several of his unfinished projects while officially employed by the University of Chicago as an instructor.

Because of her position at Mount Holyoke, where she became a full professor in 1937 and remained until her retirement in 1957, Farnsworth was arguably the most successful of the Yerkes women. Her legacy has not garnered more attention in large part because of the persistent belief that women who taught—even at universities—did not have the wherewithal to conduct original research.[13] But Farnsworth's correspondence with Frost, as well as a publication record stretching through the 1950s, challenges that narrative.

The legacies of other Yerkes women such as Short and Wickham have also been overlooked because conventional metrics for assigning credit for scientific work or recognizing scientific achievement prioritize publications, awards, and prestigious credentials. Block was also left out in the cold for similar reasons: Although she was adamant that she wanted to pursue graduate work, she never finished her PhD.

But unlike Short, Block made that decision herself. While working at Yerkes, Block met and married the Greek astronomer John Paraskevopoulos, who was doing postdoctoral work in the US. She went with Paraskevopoulos when he returned to Greece to become the head of the astronomy department of the National Observatory of Athens. For Block, marriage presented an opportunity. As one half of an astronomical couple, she did astronomical work in Athens; Arequipa, Peru (when Paraskevopoulos became director of the Harvard College Observatory's Southern Station); and Bloemfontein, South Africa.

Block does not appear to have any publications in her own name, but numerous communications and estimates from her—or from her and her husband—were reported in the Harvard College Observatory Bulletin.[14] But even though her publication record pales in comparison to that of Farnsworth, her labor was essential for the operations of the Southern Station. The words of Block's former professor Harold Jacoby when he recommended her for a position at Yerkes were prescient: "She has just the right personality, and her astron. work is done for love of it, for she could get more pay teaching." Block ultimately left Yerkes without a PhD to do more astronomy, not less.

Astronomy was something that female graduate students at Yerkes chose and loved. They studied at Yerkes because they wanted to; other careers were more lucrative and did not require an advanced degree. Their educational and scientific aspirations took precedence over financial or familial considerations, at least for a time. But even when marriage, motherhood, or examination committees brought their astronomical careers to an end, they never stopped being astronomers. The length of one's research career or the number of one's publications are not the only measures of a scientific life.

In 1928 a mother from the Chicago area wrote to Frost asking if her daughter, who wanted to study astronomy, could make a career of it. Frost replied, "Not a few fine young women have specialized in Astronomy and have later found positions as computers, assistants, or professors of Astronomy in Observatories, schools, and colleges. . . . No large remuneration is paid to any astronomers of any rank, but the ordinary salary of teachers may be expected of able students." The Great Depression would change things, but by the late 1920s, there was a path forward for women interested in astronomy. And of all the women at Yerkes who took that path, even if they were on it for only a short time, it can be said: They were astronomers.

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PT

SAURABH JHA/RUTGERS UNIVERSITY/NASA/STSCI/ESA

Einstein rings, such as the one pictured here taken by the *Hubble Space Telescope*, are a result of the gravitational lensing of a light source.

A relativistic dialog

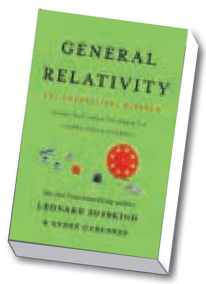
Physicists commonly have only cursory knowledge of general relativity (GR); for a long time, the subject simply wasn't needed for many careers in physics. That has been changing over the past two or so decades. Especially for those working in astrophysics or field theory, GR has become an essential piece of the foundation of what we do. There are now many good textbooks at a range of levels that introduce students to the field and take them as deeply into its details as they need or want to go.

Leonard Susskind and André Cabannes's *General Relativity: The Theoretical Minimum* is an intriguing addition to the landscape of GR resources. As the subtitle indicates, the book is part of the Theoretical Minimum series written by Susskind and collaborators, which grew out of coursework Susskind teaches at Stanford University in the institution's Continuing Studies program for adult learners. In the preface, Cabannes describes himself as an example of the book's audience: "individuals who studied physics . . . when they were students, then did other things in life, but kept an interest in sciences and would like to have some exposure to where physics stands today at a level above plain vulgarization." As someone who regularly teaches relativity, I dove into this text eager to see how a master presents it.

Most of *General Relativity* does not disappoint. The book is presented as a lecture by Susskind and is mostly written as though he were speaking, with occasional interjections and questions from Cabannes. Its discussion of general relativity's foundations is clear and deftly uses the principle of equivalence to describe the connection between gravity and geometry. It goes through the mathematics of curved spacetime in easy-to-follow language, laying out how to compute important quantities such as the motion of a body that freely falls in some spacetime. A student using this text should have no problems doing real GR calculations—in other words,

General Relativity
The Theoretical Minimum

Leonard Susskind and André Cabannes
Basic Books, 2023.
$32.00



General Relativity is indeed well above vulgarization.

A good portion of the book focuses on the Schwarzschild metric, which describes nonrotating black holes and is an excellent tool for explaining how bodies and light move under the influence of gravity. The authors' discussion shines in its use of simple, clear language and mathematics to map the global structure of spacetime and show which regions are in causal contact with others. It also brilliantly clarifies the nature of a black hole's event horizon and singularity, the latter of which appears to be in the center of the black hole but in reality is in the future of anything crossing the horizon. Their description of Penrose diagrams, and how infalling matter forms black holes, is particularly lucid and beautiful.

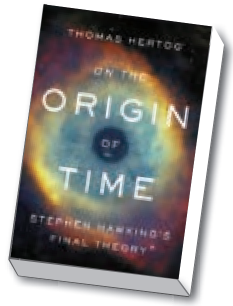
Although I quite liked the overall approach and the topics presented in *General Relativity*, I found myself frustrated by what felt like a lack of attention to small but important details. At times the authors introduce terms, such as geodesic and parallel transport, that they do not define until many pages later. A brief description, perhaps with a parenthetical note indicating that the term will soon be carefully defined, would help in such cases.

Certain other things Susskind and Cabannes examine are simply wrong. For example, their discussion of black holes includes a description of the photon sphere—namely, light rays whose trajectories are bent by gravity so strongly that they orbit the black hole. They call that configuration an Einstein ring. But an Einstein ring is in fact a weak-gravity phenomenon that has nothing to do with black holes: It is a ring-shaped image caused by the serendipitous alignment of a light source, a gravitational lens, and an observer. Another example is in the discussion of gravitational waves, in which they write, "I think we could detect, in theory, one black holes collision per year. It is a lot." But binary black hole collisions were first detected in September 2015, and the collaborative efforts of the Laser Interferometer Gravitational-Wave Observatory, the Virgo interferometer, and the Kamioka Gravitational-Wave Detector have now uncovered nearly 90 of them. That is a lot.

Although there are a moderate number of nits to pick, like those errors, they could easily be corrected in a future printing. Doing so would alleviate the unfortunately slapdash impression that they leave. Despite those flaws, Susskind and Cabannes's *General Relativity* is an excellent volume for readers who know physics but aren't familiar with GR and want a thorough introduction to the topic. I recommend it both to colleagues who want to learn the subject without sitting in on a whole course and to students who would like to learn the key concepts and techniques before studying the subject in detail. And I will happily incorporate many of the ways things are explained in this book into my own lectures.

Scott A. Hughes
Massachusetts Institute of Technology
Cambridge

A timely retrospective

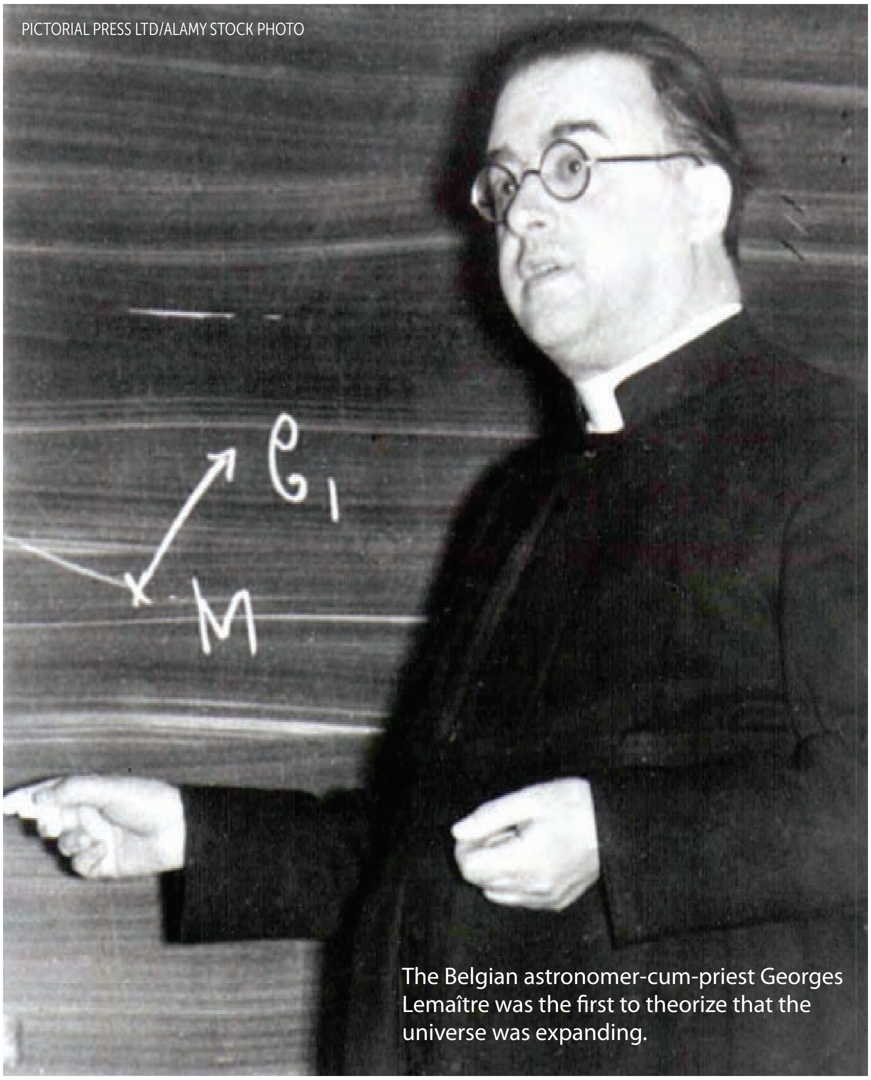


On the Origin of Time
Stephen Hawking's Final Theory
Thomas Hertog
Bantam Books, 2023. $28.99

In his new book, Thomas Hertog delves into quantum physics and cosmology while simultaneously giving readers an insider's view into the cosmological theory he developed in collaboration with Stephen Hawking. In *On the Origin of Time: Stephen Hawking's Final Theory*, he interlaces personal stories, historical anecdotes, and other elements to craft a compelling and thought-provoking story.

Hertog eagerly tackles complex physical and cosmological ideas, presenting them in an accessible yet intellectually substantial manner. For example, he employs an endearing analogy involving eggs, chickens, and farms: "How come we have unbroken low-entropy eggs available to make an omelet? Eggs come from chickens, which are low-entropy systems on farms that are themselves part of a low-entropy biosphere." Similarly, he presents an explanation of cosmic inflation, tailored to a wide readership, that highlights the importance of scalar fields by cleverly describing them as drivers of repulsive "antigravity."

Throughout the book, Hertog crafts beautiful sentences that captivate the reader's imagination. One sentence that particularly struck a chord with me describes the Feynman path integral formulation of



PICTORIAL PRESS LTD/ALAMY STOCK PHOTO

The Belgian astronomer-cum-priest Georges Lemaître was the first to theorize that the universe was expanding.

quantum mechanics: "In Feynman's view, the world is a bit like a medieval Flemish tapestry—a woven texture of crisscrossing paths that stitch a coherent picture of reality from the threads of a myriad of possibilities."

The illustrations featured in the book are appropriate and attractive. Some notable examples include Georges Lemaître's sketch of a hesitating universe born out of a primeval atom and John Wheeler's depiction of the quantum universe as a self-excited circuit, which add an extra layer of engagement. Hertog also interjects moments of levity into his scientific exploration by including whimsical elements, such as Wheeler's clever puns. Those lighthearted anecdotes provide a contrast to the weighty scientific discussions and add to the book's charm.

The question Hertog addresses—namely, what happened at the beginning of time—is deep and fascinating. If time originated with the Big Bang, contemplating what occurred before is meaningless. Even speculating about the cause of the Big Bang seems paradoxical because causality necessitates the existence of time. Among the many who have pondered those questions was Lemaître. Possibly because of Hertog's background—he is Belgian, as was Lemaître—he provides a comprehensive historical account of Lemaître's oft-underplayed contributions to the Big Bang theory and the philosophical questions it prompts. As Hertog describes, the Belgian physicist was in dialog with Arthur Eddington and Albert Einstein. But unlike Lemaître, who was deeply religious, Eddington and Einstein cautiously approached the concept of a universe with a starting point because it seemed to imply a supernatural intervention.

In the final chapters, Hertog reveals his theory of cosmology. Although traditional physics works by separating the laws of time evolution, boundary conditions, and observations, Hertog boldly advocates for a cosmology that integrates the three elements. Although I empathize with that perspective, I have some reservations about Hertog's tendency to overstate the significance of his own idea by likening it to the Copernican revolution. Moreover, it is important to acknowledge that Hertog's theory, which he credits to himself and Hawking, remains in the realm of speculative debate and contemplation. But even though the final verdict on their cosmology is yet to be issued, Hertog's description of both the theory and his collaboration with Hawking remains fascinating.

Hertog's ability to convey profound ideas, such as the enigmatic nature of time and our place in the universe, is on par with that of his mentor Hawking. I had the pleasure of reading most of *On the Origin of Time* by the shores of Lake Michigan near my home in Hyde Park, Chicago. As I gazed on the vast expanse of the lake, I contemplated the concept of deep time. The ice age that shaped the Great Lakes occurred just 12 000 to 17 000 years ago, which is a flicker compared to the immense stretches of time we physical scientists consider. But there is an undeniable joy in imagining the beginning of all things, especially the beginning of time itself.

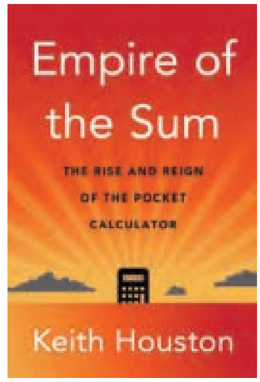
Savan Kharel
University of Chicago
Chicago, Illinois

Empire of the Sum

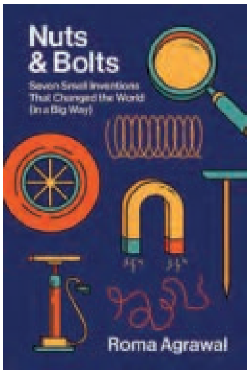
The Rise and Reign of the Pocket Calculator

Keith Houston

W. W. Norton, 2023. $32.50



Although the pocket calculator's heyday was brief compared with the technologies that superseded it, including the home computer and cell phone, it serves as evidence of the fast pace of technological change in the 1970s and 1980s. Author Keith Houston begins with a history of the various counting mechanisms humans have devised over the past millennia, such as the abacus and slide rule. He then dives into a discussion of some of the most important modern desktop and handheld calculating devices, including the Friden STW-10, which Katherine Johnson used to help John Glenn orbit Earth, and Texas Instruments' TI-81, which became a fixture in US high schools in the 1990s. —CC



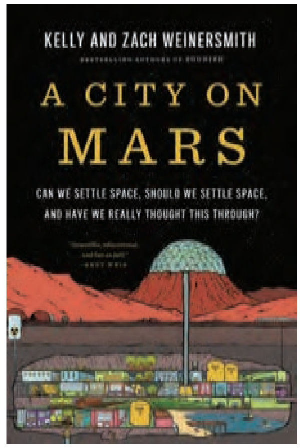
Nuts and Bolts

Seven Small Inventions That Changed the World (in a Big Way)

Roma Agrawal

W. W. Norton, 2023. $29.99

Named for the fundamental parts that make something work, *Nuts and Bolts* focuses on seven simple pieces of engineering—nails, wheels, springs, magnets, lenses, strings, and pumps—that have shaped the modern world. Structural engineer Roma Agrawal devotes a chapter to each, discussing its unique function, history, and uses in modern appliances, structures, and technologies. Throughout, she promotes the value of learning how to take things apart to see how they work. Once you've read this book, you'll never look at a can opener or a ballpoint pen the same way again. —CC



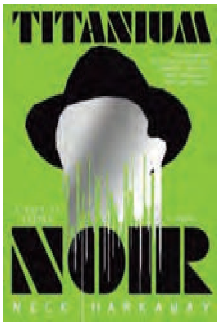
A City on Mars

Can We Settle Space, Should We Settle Space, and Have We Really Thought This Through?

Kelly Weinersmith and Zach Weinersmith

Penguin Press, 2023. $32.00

Given what we're hearing from governmental space agencies and billionaires like Elon Musk and Jeff Bezos, one might think that humanity will soon be colonizing the Moon and Mars. In *A City on Mars*, Kelly Weinersmith and Zach Weinersmith—a behavioral ecologist and cartoonist, respectively—throw a healthy bucket of cold water on such fantasies. The Weinersmiths, self-proclaimed "space geeks," started their project wanting to support space settlement, but they came to believe that many members of the field weren't being realistic. Chapters cover such topics as space physiology, space psychology, space law, space politics, and the sheer inhospitality of outer space and other celestial bodies. Deeply informed by current research, *A City on Mars* is a witty, accessible introduction to a topic more people should be familiar with. As they note, "Space is one more place where humans will be humans." —RD



Titanium Noir

Nick Harkaway

Knopf, 2023. $28.00

A futuristic take on the hard-boiled-detective novel, *Titanium Noir* centers on a consulting detective reminiscent of Sam Spade and Philip Marlowe. Cal Sounder has been called on to investigate an unusual murder: The victim, Roddy Tebbit, is a Titan—a genetically rejuvenated human—who is 91 years old and over seven feet tall. Titans are rare because the procedure is expensive, so Sounder's hunch that the murderer may also have been a Titan adds to the intrigue. Replete with the genre's requisite inner monologuing, playful banter, and femmes fatales, *Titanium Noir* follows Sounder as he is pulled into a tangled web of mad scientists and corporate intrigue. —CC PT

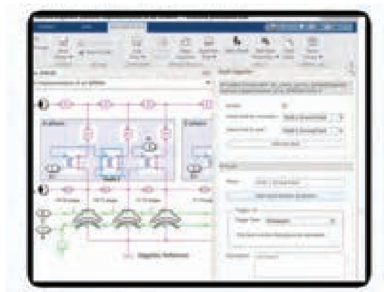
NEW PRODUCTS

Focus on software, data acquisition, and instrumentation

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

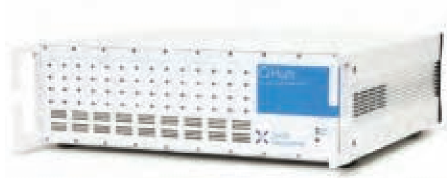
Andreas Mandelis

Mathematical programming software



Release 2023b (R2023b) of MathWorks MATLAB and Simulink software introduces two new products and major updates that simplify model-based design and streamline workflows. Simulink Fault Analyzer lets users carry out fault injection simulations without modifying engineering designs. They can time or trigger faults by specific system conditions and perform safety analyses, such as failure mode and effects analysis. When paired with the Requirements Toolbox, Simulink Fault Analyzer helps users create and document formal connections between faults, hazards, fault detection and mitigation logic, and other artifacts. R2023b also includes Polyspace Test, which enables users to develop, manage, and execute C and C++ code tests in embedded systems. With the Polyspace xUnit application programming interface or a graphical test-authoring editor, users can create stubs (simulations of methods or objects) and mocks (for verification of the behavior of code) to make component testing simpler and more efficient. R2023b also features updates to MATLAB and Simulink tools, including the Aerospace, Predictive Maintenance, Signal Integrity, and Wavelet Toolboxes. ***The MathWorks Inc**, 1 Apple Hill Dr, Natick, MA 01760-2098, www.mathworks.com*

Quantum computing control system



To help quantum computing researchers meet the challenge of scaling up quantum computers, Zurich Instruments has brought to market its QHub Quantum System Hub. The QHub orchestrates in real time all the high-speed electronic components required to control a quantum computer. According to the company, unlike many other commercial control solutions, its quantum computing control system is designed with a central feedback architecture that provides low and equal latency between all endpoints to optimally support error-correction technologies. The QHub synchronizes up to 448 microwave channels. Through a dedicated interface, it enables precise, reproducible timing synchronization across components and ensures that readout and gate operations on separate channels are aligned and stable in time. Users can program the instrument to optimize for rapid tune-ups and error correction; the processing can be adapted to the specific algorithm and computer architecture used. With its 56 ZSync ports, QHub connects systems suitable for quantum processors with up to 300 superconducting qubits. ***Zurich Instruments AG**, Technoparkstrasse 1, 8005 Zürich, Switzerland, www.zhinst.com*

High-accuracy mid-IR laser wavelength meter

Bristol Instruments has added the model 671A-MIR to its 671 series of laser wavelength meters. The 671A-MIR supports the characterization of free-space, mid-IR lasers operating in a broad spectral range. The most precise instrument in the 671 product family, it provides an accuracy of ±0.2 ppm in the 1.5–5 µm spectral range and an accuracy of ±1 ppm in the 5–12 µm spectral range. To achieve reliable accuracy for demanding applications, the 671 laser wavelength meters are continuously calibrated with a built-in helium–neon (HeNe) laser. This is an ideal reference source because its wavelength is well known and fixed by fundamental atomic structure. To achieve the highest accuracy, the model 671A uses a single-frequency HeNe laser that is stabilized using a balanced longitudinal mode technique. For less exacting experiments, the company offers the more economical model 671B with an accuracy of ±0.75 ppm. It uses a standard HeNe laser as the wavelength reference. ***Bristol Instruments Inc***, *770 Canning Pkwy, Victor, NY 14564, www.bristol-inst.com*

Micro-diaphragm gas pump

According to KNF, the optimized design of its NMP 820 micro-diaphragm gas pump significantly reduces noise and vibration, which is critical for certain applications. The compact NMP 820 delivers up to 2.1 L/min of free flow. It operates at pressures of up to 1.3 bar relative and generates a vacuum of down to 300 mbar absolute. Adding a second pump head increases free flow up to 3.6 L/min and allows for an ultimate vacuum of down to 100 mbar absolute. Applications for the NMP 820 include point-of-care diagnostics, emissions monitoring, and use in portable medical equipment and fuel-cell and inkjet systems. A standard mounting plate is included for flexible, easy installation, and a four-wired brushless motor option is available for pump control. ***KNF Neuberger Inc***, *2 Black Forest Rd, Trenton, NJ 08691-1810, https://knf.com*

Control platform for large-scale quantum computers

Quantum Machines designed its OPX1000 ultrahigh-speed quantum controller to address the demands of the largest quantum computers. The scalable, modular system features up to 64 output and 16 input channels. According to the company, with up to 10 field-programmable gate arrays, the OPX1000 offers the highest classical processing resources available in any dedicated quantum control solution. The system provides high-speed data sharing between the different front-end modules (FEMs) and between different OPX1000 devices, which allows multiple FEMs to run calculations together. The OPX1000 delivers high analog performance: It offers a bandwidth of 750 MHz and low 1/*f* noise, and it supports 2 gigasamples/s and both direct mode (1 V_{pp}) and amplified mode (5 V_{pp}) with a fast, clean step response. The OPX1000 employs Quantum Machines' proprietary Pulse Processing Unit, which optimizes the integration of quantum operations with ultrafast classical processing and allows for simple programing from 1 to 1000 qubits. ***Quantum Machines***, *HaMasger St 35, Tel Aviv-Yafo, 6721407, Israel, www.quantum-machines.co*

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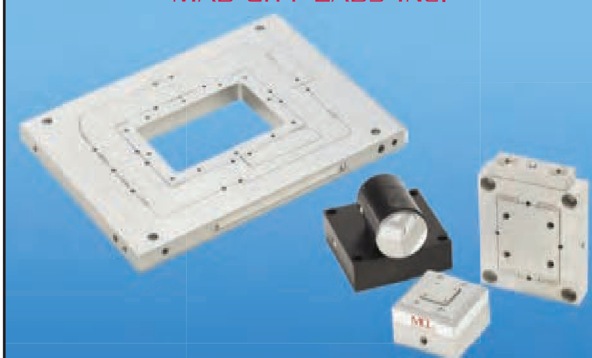
Richard Fitzgerald, Publisher

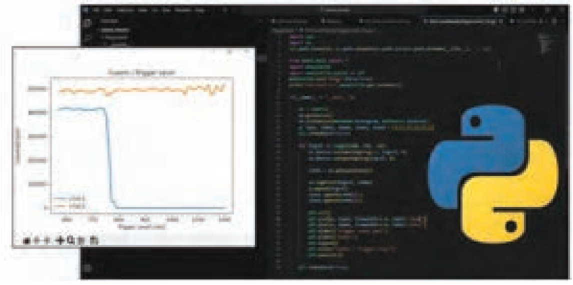
Pulse-tube cryocooler and helium compressor

Cryomech has unveiled its PT450 pulse-tube cryocooler and CP3000-series helium compressor. According to the company, the combination delivers a heat removal rate, or heat lift, of 5.0 W at 4.2 K, which will facilitate advances in ultralow-temperature applications, including the superconducting qubit modality in quantum technology. The demand for higher-powered dilution refrigerators to cool superconducting qubits has increased, and with it the need to balance the high heat lift and the ultralow vibration required to achieve fast cooldown. Cryomech says its pulse-tube cryocoolers meet those demands. The PT450 features a base temperature of less than 2.8 K, a cooldown time of 60 min to 4 K, and a long maintenance interval. And it's compact compared with many available 4 K cryocoolers. ***Cryomech Inc****, 6682 Moore Rd, Syracuse, NY 13211, www.cryomech.com*

Software for ultra-wideband RF amplifier

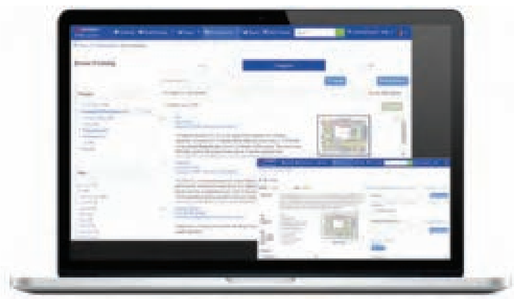
Rohde & Schwarz now offers new software for its BBA300 RF amplifiers. The BBA300-PK1 software option lets users accurately set the operating parameters of the amplifier and manage test sequences. It introduces two tools with which users can fine-tune test signals and react flexibly to various requirements. The first is the ability to shift the operating point between Class A and Class AB, which changes the amplifier's response. As a Class A amplifier, the BBA300 provides excellent linearity and harmonic performance. Shifting to Class AB allows pulsed signals to be reproduced accurately and more efficiently at high power. The BBA300-PK1 software also lets users set the amplifier between high power mode for maximum power with a well-matched RF path and VSWR (voltage standing wave ratio) mode for rated power with high tolerance to load mismatches. The VSWR mode is useful in electromagnetic compatibility applications because it maintains rated power up to a VSWR of 6:1. ***Rohde & Schwarz GmbH & Co KG****, Mühldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*





Python wrapper

PicoQuant has announced its Snappy application programming interface (snAPI). It is a Python wrapper that enables seamless communication and configuration with the company's time-correlated single-photon counting (TCSPC) and time-tagging electronics. By leveraging the power of Python, users can build their own algorithms, implement complex calculations, and develop tailored data-processing pipelines for analysis. Taking advantage of C++ for optimal speed and performance, snAPI bridges the gap between the high-speed capabilities of PicoQuant's TCSPC devices and the ease of use and flexibility of Python. The low-level control offered by C++ ensures smooth data processing and enables efficient handling of large photon counts and their real-time analysis. The wrapper provides the option to access unfolded data from the TCSPC devices or conveniently read from PTU (Performer Terrain Utilities) files. That allows researchers, developers, and scientists to explore their data more deeply and extract valuable insights. PicoQuant's snAPI is available free at GitHub. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*



Design and simulation software

The latest release of Keysight's suite of electronic design automation (EDA) software tools, PathWave Design 2024, includes new features to enhance design productivity. A Python application programming interface enables Keysight's EDA software tools and third-party partner tools to interoperate in automation workflows in RF/microwave and high-speed digital design. It supports more efficient design verification, reduces repetitive work, and helps cut down on human errors. With the former Cliosoft products now integrated into PathWave Design 2024, Keysight Design Data Management (formerly Cliosoft SOS) offers designers optimal file archiving, advanced revision control, disk storage optimization, and more. Keysight IP Management (formerly Cliosoft HUB) enables efficient IP management, IP reuse, and IP traceability. ***Keysight Technologies Inc***, *1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Virtual chart recorder and Web server

Omega's new-and-improved iServer 2 virtual chart recorder and Web server provides an intuitive way to collect and display live temperature, humidity, and barometric pressure readings using either a Web-based user interface (UI) or the Omega Link ecosystem. With expanded internal nonvolatile storage, up to 10 years of data can be stored and viewed locally at any time with no need for external SD cards. When the power adapter is plugged in, the preconfigured Omega Link smart probe and the unit begin to log data and display live readings. To manage stored data, view live data, and configure alerts through the Web-based UI, users can connect to the iServer 2 via a wireless network or USB. Configurable features include selective data extraction, measurement and device traceability, local alarms, and adaptive transmission rates. Standard and deluxe models provide configurable input/output ports that can be used for applications such as driving relays, triggering physical alarms, and sensing contacts like door switches. ***Omega Engineering Inc***, *800 Connecticut Ave, Ste 5N01, Norwalk, CT 06854, www.omega.com*

Compact dual-comb spectrometer

The IRis-C is the next-generation instrument in IRsweep's quantum cascade laser (QCL) frequency-comb spectrometer line. It uses the same dual-comb spectroscopy technology as IRsweep's IRis-F1, which offers microsecond time resolution, high spectral resolution, and high optical brightness in the mid-IR, but has been reduced in size and cost. Within a compact design, the prealigned reference-beam path ensures high signal quality, and the free-space sample beam ensures easy coupling to any application-specific interface. The high optical power of QCLs facilitates their use with strongly absorbing samples, such as aqueous solutions, and the internal coalignment of the two frequency combs ascertains good copropagation over distances of up to 2 m. The IRis-C is suitable for chemical and biochemical reaction kinetics, protein folding and similarity tests, catalysis studies, combustion diagnostics, and other challenging vibrational spectroscopy tasks. ***Sensirion AG c/o IRsweep***, *Laubisrütistrasse 44, 8712 Stäfa, Switzerland, https://irsweep.com* PT

James Burkett Hartle

James Burkett Hartle died on 17 May 2023 in Zurich, Switzerland. Known as the father of quantum cosmology, Jim made landmark contributions to the understanding of the origin of the universe.

Born in Baltimore, Maryland, on 20 August 1939, Jim obtained his BA in physics in 1960 at Princeton University, where he was mentored by John Wheeler. He earned his PhD in 1964 from Caltech, where he worked in particle physics under Murray Gell-Mann. He remained close friends with both Gell-Mann and Wheeler throughout their lives.

At Caltech Jim attended Richard Feynman's classes and assisted with lecture demonstrations, including the celebrated bowling-ball example illustrating energy conservation. He also helped with redacting *The Feynman Lectures on Physics*.

After receiving his PhD, Jim taught at Princeton before going to the University of California, Santa Barbara (UCSB), in 1966. Excited by pulsars, quasars, and the cosmic microwave background, Jim turned away from particle physics. In the late 1960s, he wrote a series of influential papers, one with Kip Thorne, on the dynamics of rotating neutron stars. Jim and Thorne organized regular gatherings between their research groups, which turned into the Pacific Coast Gravity Meetings that still run today.

In 1971 Jim went to Cambridge University and became immersed in the emerging fields of relativistic astrophysics and cosmology. There he met Stephen Hawking; on the same scientific wavelength, they developed a remarkable long-term collaboration. Their 1976 classic paper introduced the Hartle–Hawking quantum state for matter outside a black hole, which is fundamental to black hole thermodynamics.

In a landmark 1983 paper, Jim and Hawking employed their new approach to quantum gravity to rethink the universe on the largest scales. They put forward the Hartle–Hawking "no-boundary" wavefunction, showing for the first time how the conditions at the Big Bang could be determined by physical theory.

Except for a brief stint at the University of Chicago, Jim spent his career at UCSB, which he found congenial, supportive, and inspiring. Jim was a wise and caring mentor to young scientists, and he did much to forge a strong physics community. In 1979 Jim cofounded UCSB's Institute for Theoretical Physics (now the Kavli Institute for Theoretical Physics), where physicists worldwide convene to discover and debate the frontiers of physics.

The Hartle–Hawking wavefunction revolutionized quantum cosmology and raised tantalizing new questions. Jim began thinking more deeply about how to apply quantum mechanics to the universe as a whole. Throughout the 1990s he and Gell-Mann developed a quantum mechanics formulation, known as the consistent-histories formulation, that clarified the physical nature of Everettian "many worlds" branching and was sufficiently general to describe single closed systems.

While part of some extraordinary collaborations, Jim was also an independent thinker. His numerous single-authored papers, which he approached with enormous care and open-mindedness, are beautifully written and often touch on big, seemingly intractable questions.

In 2003 Jim published *Gravity: An Introduction to Einstein's General Relativity*, a gem based on a physics-first approach. With minimal new mathematics and numerous illustrations of observable relativistic effects and experiments, *Gravity* made Einstein's theory accessible to physics undergraduates.

Jim liked to wear hand-knitted woolen sweaters and always had a pen and paper—in case he'd get an idea. His suit was reserved for "special occasions," such as conference dinners, where he was legendary for witty dinner toasts. One of his favorites: "To gravity, the force that keeps our feet on the ground—and money in our pocket."

In 2005 Jim retired—to focus on physics. In 2006 he became an external professor at the Santa Fe Institute. That year also marks the start of my own collaboration and friendship with Jim. By then he saw the universe truly through a quantum lens. In contrast to most cosmologists, when Jim said "the universe," he meant the abstract quantum universe, awash in uncertainty, with all its possible histories existing in some sort of superposition.

We took up quantum cosmology again and became immersed in some of the field's heated debates. Jim, however, seemed unperturbed and calmly set out the beacons. Often we would be joined by Hawking, who by then had great difficulties communicating. Jim would position himself in front of Hawking and probe Hawking's mind by firing yes–no questions. In that way we fleshed out the predictions of the no-boundary wavefunction. Studying the role of the observer in a quantum universe, we were led to introduce a top-down approach to quantum cosmology in which quantum observations retroactively determine the outcome of the Big Bang.

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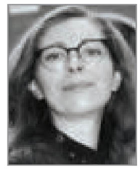
James Burkett Hartle

Few physicists ventured as deeply into their field's fundamentals as Jim did. In 2021 he published several philosophical reflections in *The Quantum Universe: Essays on Quantum Mechanics, Quantum Cosmology, and Physics in General*, a rich source of inspiration for how to think about the subject.

Despite his having Alzheimer's disease, physics remained Jim's passion and the driving force in his life until the very end. Yet his intellectual curiosity stretched far beyond physics. He was a polymath and an eclectic reader whose wide-ranging interests included Middle Eastern and Mayan archaeology, American colonial history, Russian literature, and eccentric 19th-century female religious figures. But above all, Jim was an exceptionally generous, wise, humble, and gentle man.

Thomas Hertog
KU Leuven
Leuven, Belgium

Kate Allen is a recent postdoctoral fellow in the department of psychological and brain sciences at the Johns Hopkins University Batlab in Baltimore, Maryland.



Bats thrive in cluttered spaces

Kate Allen

The winged mammals produce high-frequency sounds and listen to their echoes from surrounding objects to track down insects to eat. Counterintuitively, the interference from the echoes of clutter nearby can help.

Remember Where's Waldo? Finding one character amid a visually cluttered page might be a fun game, but what if it was one you needed to play every night to survive? Like young readers searching for a man in a red-striped shirt in a sea of barber poles and candy canes, bats must identify small targets in large, busy environments. But unlike a casual Waldo seeker, bats must search while they actively avoid colliding with obstacles.

Just as visual clutter impairs the ability to find important information or objects, auditory clutter can interfere with the detection or identification of nearby sounds. Although reflective surfaces give sound life and richness and affect one's sense of space, people are rarely aware of their echoes or reverberation. Bats must distinguish the echoes from insects they are interested in from the echoes produced by trees, branches, buildings, and other bats in the colony. This quick study sheds some light on how bats navigate and hunt in the dark.

Hearing, interrupted

Bats echolocate targets in their environment by emitting repeated calls with brief pauses to listen for returning echoes. The delay from call to return determines the distance to a target, while intensity and spectral features determine its size and shape. But in cluttered environments, important sounds may become indistinguishable. When off-target clutter and target sounds reach a listener's ears within a short time period they interfere with each other, a phenomenon known as auditory masking. More intense sounds mask less intense sounds even when the sounds don't arrive at the same time. That effect is referred to as forward masking when the higher-intensity sound arrives slightly earlier and backward masking when it arrives slightly later.

FIGURE 1. A BROWN BAT relaxes on a perch. (Courtesy of SMBishop, CC BY-SA 3.0.)

Objects that are too close to the animal may be masked by a loud outgoing call, whereas foreground objects may be masked by the echoes of background objects. What's more, clutter, such as the wall of a barn, is often large and reflective, whereas insects are small and absorbent. Large differences in returning sound pressure levels from obstacles and targets further exaggerate the masking problem.

Another challenge faced by bats is the interference between overlapping echoes from closely spaced objects. Big brown bats echolocate with sweeps of sound 1–10 milliseconds long. The echoes returning from distinct objects, such as an insect and the leaf it's sitting on, can overlap and produce an interference zone several centimeters wide.

The interfering echoes produce spectral peaks in which discrete frequency bands are out of phase with each other. Those overlapping frequencies from two or more echoes cancel each other out and create a single sound with distinct gaps in frequency. The result is a single, composite echo that may not resemble what the bat recognizes as "leaf" or "dinner." How bats translate the spectral profiles of composite echoes is central to understanding how bats perceive target shape.

Despite the challenges, the extraordinary animals remain highly successful in capturing prey in diverse environments and conditions. Bats have a few tricks to localize and track targets: They can shorten the duration of their call to minimize its overlaps with the echo, reduce call intensity to narrow their sonar angle and thus reduce echoes from clutter, and fly in trajectories that maximize the separation between targets and clutter. Such tricks indicate that bats are sensitive to the effects of reverberation and clutter, but not how those processes are encoded in the brain. The Batlab at Johns Hopkins is trying to understand the neural adaptations that allow brown bats, like the one shown in figure 1, to successfully find Waldo.

Signal in the noise

Contrary to interfering with auditory processing, clutter can potentially provide useful information. In a recent experiment,

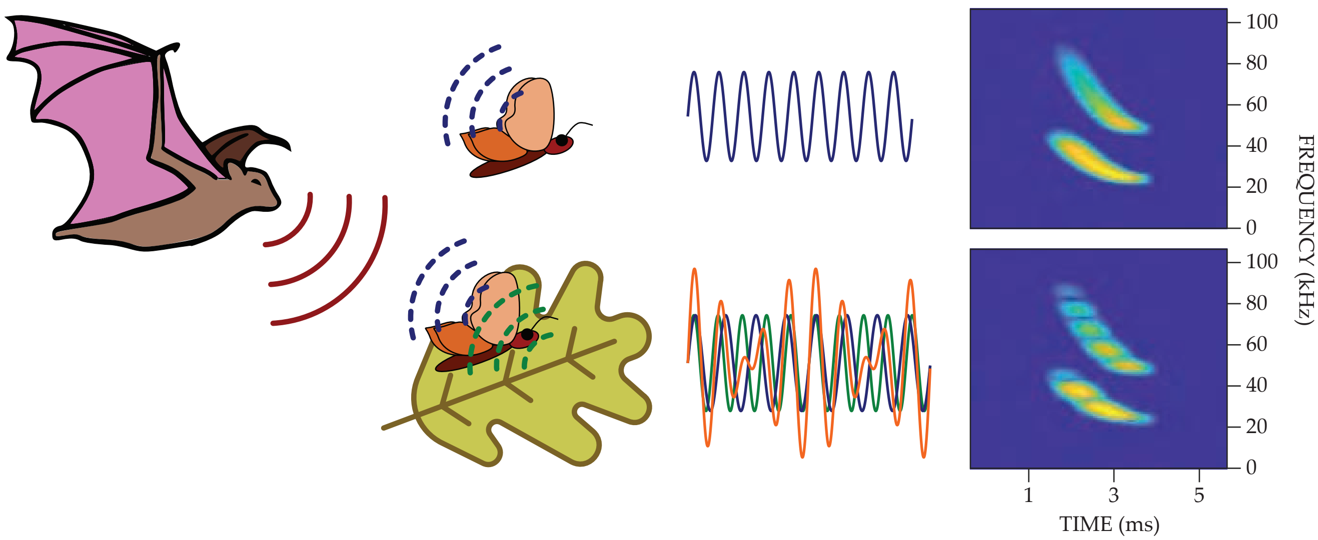


FIGURE 2. ECHOES IN CLUTTER are spectrally distinct from echoes in isolation. Bats use the frequency and temporal profiles of returning echoes (blue sine wave) to understand target size, shape, texture, and distance. In cluttered conditions, however, the two returning echoes (blue and green sines from moth and leaf, respectively) interfere with one another to produce a single composite echo (orange). That echo has distinctive notches in its spectrum that change the profile of the target echo. The notches may provide the bat with additional information about the target's size and its distance from the clutter.

the Batlab found that clutter can alter how targets are represented by the bat's brain. We created synthetic echolocation sounds by playing bat calls at objects and recording their echoes. We placed objects 10–20 cm in front of artificial houseplants—our in-lab simulacrum of natural clutter. The spacing simulated a clutter interference zone of varying overlap, and we also tested a no-clutter condition.

We then played those echoes to bats while recording the animals' neural responses in a brain region called the inferior colliculus. The area is a key part of the auditory pathway, where sound selectivity properties, such as frequency tuning, begin to emerge. We looked at responses of inferior-colliculus neurons and applied a classification algorithm to determine if they contained enough information to accurately discriminate which objects evoked a given neural response.

When we took a closer look at the responses to sounds recorded in and out of clutter, we found something unexpected: Sounds of objects with clutter 20 cm behind them are actually more easily discriminated by our classifier than sounds recorded in the no-clutter condition. That suggests that the bat brain gathers more information about targets near clutter, as shown in figure 2, than targets without any clutter. But objects placed too close to the clutter—within 10 cm—impair the brain's ability to distinguish object echoes. The discrimination of small objects benefits more from clutter than the discrimination of large objects. But those observations raised more questions than they answered and left us with more hypotheses to test.

One hypothesis for the effect is stochastic resonance. Adding low-level noise to a weak signal can increase the detectability of that signal by creating resonant frequencies that boost the signal above the detection threshold of a sensor. In that instance, the resonance provided by the slight, but not complete, overlap of clutter and target echoes may increase the amount of information available to the bat's brain about the target.

If that's the case, bats would benefit just as much from the addition of a white-noise broadcast from a speaker as they would from physical clutter present while they look for targets.

The counterhypothesis to stochastic resonance is that clutter may serve as an acoustic mirror. As the sound waves reflecting from clutter return to the bat, they interact with the target a second time. The interaction may allow those second echo returns to carry an additional spectral "silhouette" of the target. It gives the bat more information about the size and shape of the target in front of the reflective surface. My colleagues and I are currently running behavioral experiments to test these hypotheses. We wonder whether bats are as accurate in distinguishing between targets in clutter as the neural data suggest, and how well different surfaces reflect sound back to a bat's ears.

The benefits of clutter extend to human listeners as well. Reverberation longer than 50 milliseconds impairs how well speech sounds can be discriminated. Adding more sound-absorbing clutter to a space, such as an auditorium full of people, can reduce reverberation times and improve the ability to understand words in a talk. But if there's too little reverberation and the room becomes dry and unnatural sounding, listeners at the back may struggle to hear the speech at all. Indeed, sound waves in a dead room won't propagate well without artificial enhancement.

The role of acousticians is one of finding that right balance of clutter in perceptual spaces. All told, it seems that people shouldn't be in a rush to completely embrace minimalism when it comes to their ears.

I appreciate Clarice Diebold's help preparing figure 2.

Additional resources

► K. M. Allen et al., "Effect of background clutter on neural discrimination in the bat auditory midbrain," *J. Neurophysiol.* **126**, 1772 (2021).
► B. Møhl, A. Surlykke, "Detection of sonar signals in the presence of pulses of masking noise by the echolocating bat, Eptesicus fuscus," *J. Comp. Physiol. A* **165**, 119 (1989).
► C. F. Moss et al., "Active listening for spatial orientation in a complex auditory scene," *PLoS Biol.* **4**, e79 (2006).
► H.-U. Schnitzler, E. K. V. Kalko, "Echolocation by insect-eating bats," *BioScience* **51**, 557 (2001).

Frictional flow patterns

A high-viscosity fluid moving into a low-viscosity one is typically stable enough that no patterns form. But complex flow behavior can arise if a high-viscosity fluid interacts with dry granular materials. The fluid dynamics and the friction of the granular materials sometimes combine to create intricate flow patterns. Dawang Zhang and Bjørnar Sandnes of the UK's Swansea University and their colleagues found one such pattern during their fluid-flow experiments with a Hele-Shaw cell, which consists of two parallel glass plates separated by a thin gap.

The researchers injected a white, high-viscosity fluid of water and glycerol from a central inlet into the cell's 0.9 mm gap, already partially filled with tiny hydrophobic glass beads. (The cell radius is about 14 cm, and the gray outer region is filled with air.) At low injection rates without viscous effects, a single finger-like structure formed, which eventually reached the cell's edge. At higher injection rates, rising viscous pressure forced the fluid to flow radially outward, and the additional fingers that formed pushed the granular material aside to create the spoke pattern seen in this image. (D. Zhang et al., *Nat. Commun.* **14**, 3044, 2023; image courtesy of Dawang Zhang and Bjørnar Sandnes.) —AL

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