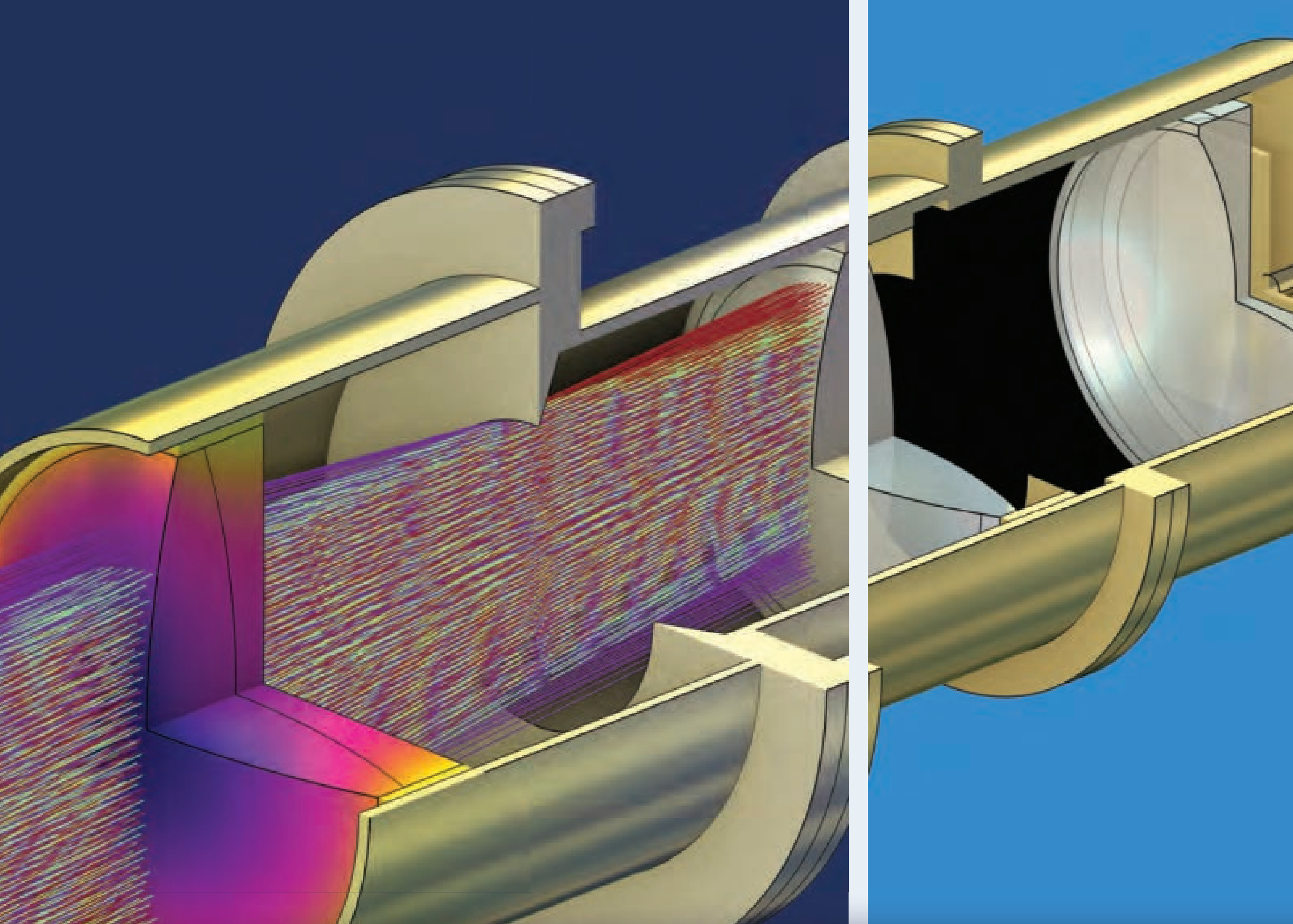

PHYSICS TODAY

January 2023 • volume 76, number 1

A publication of the American Institute of Physics

ARCTIC
WILDFIRES

Universe in a quantum gas

Enceladus's watery eruptions

Ethics in physics

Hong Kong University of Science and Technology: Innovating Today, Imagining Tomorrow

The Hong Kong University of Science and Technology (HKUST) is a dynamic, young research university with a diverse international student body and faculty who relentlessly pursue excellence in teaching and research. Situated on a hillside overlooking scenic Clear Water Bay at the eastern edge of Hong Kong and the southeastern coast of China, HKUST has rapidly established itself as a leading institution on the academic world map. Since the university's founding in 1991, the physics department has grown from 9 to 37 faculty members and now has 190 research graduate students. The department's research areas have also expanded to include condensed-matter physics; atomic, molecular, and optical systems and quantum optics; particle physics and cosmology; quantum information; scientific computation; soft-matter and biological physics; and metamaterials.

The physics department promotes the pursuit of cutting-edge research by cultivating a collaborative, supportive, and cohesive environment. For example, the Center for Fundamental Physics focuses on theoretical and experimental research about the origin, fate, and fundamental building blocks of the universe, and it has participated in several global endeavors, including the ATLAS collaboration at CERN. The emphasis of the Center for Metamaterials Research is on the design, fabrication, and characterization of different metamaterials to explore novel wave phenomena and to manipulate light and sound in ways not possible before. The newly established Center for Quantum Technologies brings together a team working across several core areas with focuses on quantum materials and devices, quantum control, and software.

The physics department's research efforts are supported by critical infrastructure, specialized equipment, high-performance computer clusters, and services provided by the university's Central Research Facilities. For example, the Materials Characterization and Preparation Facility offers advanced characterization tools, sample and materials preparation apparatus, and a helium liquefier. The Nanosystem Fabrication Facility has state-of-the-art equipment for developing innovative micro/nano devices and systems.

The department's goals for future growth are to enhance existing core strengths and build up world-class capabilities in rapidly developing areas aligned with university initiatives, such as big data and renewable energy and new energy materials. To achieve these goals, the department will strive to continuously attract outstanding new faculty members at all ranks, and it plans to fill 10 new faculty positions in the next few years. To learn about opportunities as soon as they are posted, interested candidates may visit jobs.physicstoday.org and create an alert for "HKUST."


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FEATURES

ON THE COVER: Although usually permanently frozen, carbon-rich peatlands across this 3-km-wide stretch of Arctic tundra burned on 18 June 2020. The true-color image is overlaid by an IR filter that shows the fire hot spots. Arctic fires were exceptionally widespread during the 2019, 2020, and 2021 fire seasons compared with those of the past 20–40 years. See **page 17** to learn more about the complex set of interactions that affect high-latitude wildfires. (Satellite photo created by Adrià Descals; imagery acquired by the European Space Agency.)

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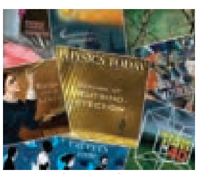

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Best of 2022

Explore Physics Today's most viewed pieces from last year, including several available only online. Topics include helium shortages, the quantum measurement problem, the 10th anniversary of the discovery of the Higgs boson, and strategies to advance equity, diversity, and inclusion.

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The year in books

Physics Today's books editor, Ryan Dahn, looks back at 2022 and compiles a list of recommended books for fans of physics and its history. Selections include an entertaining introduction to quantum thermodynamics and a biography of the late materials scientist Mildred Dresselhaus.

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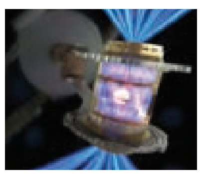

LLNL

Ignition attained

A fusion reaction at the National Ignition Facility yielded more energy than the laser energy required to spark it, Department of Energy officials announced last month. Physics Today's David Kramer details the long-awaited result and considers the implications for weapons research and energy applications.

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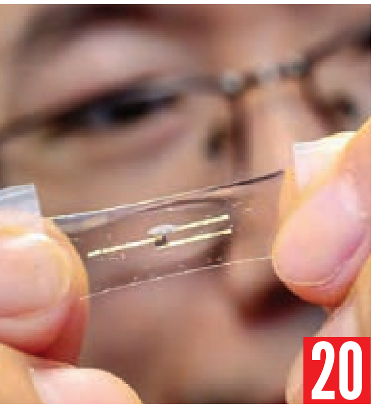
DEPARTMENTS



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Commentary

How to talk about climate change with politicians

Scientific training is largely silent about how to engage effectively with politicians. Fortunately, practices familiar to professional scientists are powerful in the policy arena, and what they need beyond their specialized training is within grasp.

Policy choices, like decisions of any kind, have the greatest chance to benefit people when they are informed by the best available knowledge and understanding. Evidence and information are never the only—or even the most important—factors in policy choices because values, interests, and personal preferences heavily influence what constitutes the most desirable option. But evidence is central to understanding options, their trade-offs, and their political implications.

Assessing and communicating information is what scientists are trained to do, and that expertise can be an enormously beneficial contribution to the policy process, which often resembles courtroom advocacy: People present only the evidence that supports their side and leave counterarguments to others. Scientists know the importance of controlling for biases, poking holes in their own views when they can, and incorporating all evidence, whether supportive or contradictory of a particular conclusion, into assessments of knowledge. Those practices are foundational to evidence-informed deliberation, and when shared broadly they can help improve and democratize decision making.

But scientists also need to engage policymakers with humility. Politicians are highly skilled, and most are much more high-minded than either the policy process or public narratives give them credit for. If that seems surprising, then it's especially important to spend time understanding politics and the policy process and what it takes for politicians to succeed. Few scientists would succeed as politicians without practice, training, and experience.

Politicians are experts in communicating; engaging with the public; knowing the views and interests of their constituents, supporters, colleagues, and rivals; and understanding the political opportunities and constraints that they face. If they aren't skilled in those areas, they won't win their elections, which is the primary prerequisite of their jobs. Some politicians may have areas of policy expertise, but that is the exception. Politicians have responsibility for many issues—they are generalists—but policy decisions are highly complex and require detailed understanding. Staffers, colleagues, and other policy professionals can focus more narrowly and provide that detailed policy expertise.


ARCHITECT OF THE CAPITOL

To engage effectively requires having a healthy respect for your audience members and being clear about your goals with yourself and with them. It's terrific when scientists help provide the best available understanding to inform decision making. It's also fine to ask for help, to promote your interests, or to champion what you care about. Being a scientist doesn't require relinquishing one's values or one's membership in the broader public. But care is needed to distinguish between the role of providing scientific understanding, for which scientists have specialized training, and that of being a member of public society, for which one's personal values and beliefs become directly involved even when informed by science. Failure to be clear on that distinction can damage science and weaken democratic principles by allowing one's professional standing to unduly support one's personal views.

Whatever scientists' goals are, they will be most effective in achieving them if they can align them with a policymaker's needs and objectives. Why does the science matter from the politician's perspective? How might the objectives help meet the needs of the policymaker? Effectiveness with engagement almost certainly depends on understanding and navigating the political landscape the decision maker faces. How will your policy solution impact the politician's constituents, and perhaps more importantly, how do the people perceive your issue and the stance you'd like a politician to take?

Climate change is a terrific illustration because it is an intensely researched scientific topic and a contentious public issue. It brings together scientific understanding, policy, and politics, and it is both politically challenging and crucial to everyone's future.

So what are the scientific conclusions at the foundation of evidence-informed policy deliberations on climate change?

► **Climate change is extraordinarily dangerous to humanity and all life.** That is because climate, and its stability within a relatively narrow range, is a requirement for life as we know it. The global change in climate people are causing is larger and faster than any humanity is known to have endured since beginning the societal transition from hunting and gathering to agriculture.[1] The physical characteristics of the planet, biological systems and the resources they provide, and social institutions that humans have created all depend heavily on climate, are central to human well-being, and are sensitive to climate change.

► **Solutions are available and highly promising—a serious reason for optimism.** Greenhouse gas emissions are an economically harmful market failure—a classic example of an economic externality. Those who emit pollution to the atmosphere shift the costs of climate damage onto everyone, including future generations. Making emitters pay for all the costs of their use of the atmosphere would help correct that failure and thereby improve economic well-being. Regulatory approaches can speed the adoption of best practices and better technologies, or promote fairness and the public interest. As a result, reducing greenhouse gas emissions can increase climate security, national security, the well-being of people and biological systems, and economic vitality. Existing and emerging technologies, such as rooftop solar panels, electric vehicles, and electric heat pumps, can reduce greenhouse gas emissions, improve air quality in homes and cities, and often provide superior products or services. Building resilience against climate impacts makes communities stronger and better able to deal with both existing vulnerabilities and emerging threats.

Comprehensively addressing the dangers of climate change will require two things: reducing, and ultimately eliminating, climate pollution as soon as possible and building the capacity to avoid—when possible—and otherwise overcome the consequences of climate change.

► **Broad scientific conclusions, like those described briefly here, result from decades of intensive research and examination.** The scientific evidence has been assessed comprehensively and repeatedly by independent experts convened by highly respected scientific institutions. Accuracy is central to credibility for scientific institutions, including the US National Academies of Sciences, Engineering, and Medicine; the American Meteorological Society (for which I work); and the American Association for the Advancement of Science, all of which have assessed climate science. I am not aware of any contradictory assessments from a credible scientific institution. People who target public audiences with messages that contradict broad scientific conclusions are not credible.

People are changing climate, and it poses serious dangers to humanity. A wide range of response options are well understood and would be broadly beneficial, if implemented. Scientists who are up to speed with the evidence have the opportunity to help inform societal deliberations on climate change. That contribution will be crucial for the advancement of evidence-informed policy responses. If scientists, recognizing that societal decisions go beyond science, provide information so that it enables broad public participation in decision making, even among those whose values and preferences differ, then they will simultaneously advance science and strengthen the broader society that they serve.

Therein lies an even greater opportunity for scientists and humanity. If scientists can engage effectively with the broader society to address the climate problem, they may contribute to a template for the wide range of challenges and opportunities facing humanity at this point in the 21st century.

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LETTERS

Antiquark asymmetry

It was interesting to read the item by Johanna Miller (PHYSICS TODAY, May 2021, page 14) on the asymmetry between up and down antiquarks in the proton. It does indeed provide fascinating insight into the quark structure of the proton and especially the role of chiral symmetry, which requires that the proton be surrounded by a pion cloud.

But I feel that it is necessary to add a little to the incomplete discussion of the history of that asymmetry discovery. Using the cloudy bag model, which successfully incorporates chiral symmetry into the MIT bag model, I predicted the asymmetry[1] in 1983, almost a decade before the violation of the Gottfried sum rule was experimentally confirmed.[2]

The mechanism is the dominance of the π^+–neutron configuration when the proton emits a pion. The pion contribution to deep inelastic scattering was first mentioned by J. D. Sullivan and Richard Feynman and is often referred to as the Sullivan process. In 1983, however, almost no one in the high-energy-physics community took the idea of a contribution from the pion cloud seriously, as deep inelastic scattering was such a short-distance phenomenon; the constraints of chiral symmetry there were not understood. Certainly no one else, including Sullivan, had discussed the process as a source of flavor asymmetry.

In a November 2021 letter (page 11), Edward Shuryak describes an alternative explanation of the effect and suggests that lattice quantum chromodynamics can be used with the Δ baryon to test the mechanism. The idea of using lattice quantum chromodynamics calculations of the Δ^+ to test the role of chiral symmetry in generating such an asymmetry was published several years ago.[3] In particular, one can expect a significant enhancement of the asymmetry as the pion mass approaches the Δ–nucleon mass difference from above.

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ITER's net loss

In July 2020 Physics Today published a letter from Wallace Manheimer (page 10) written in response to the article "The challenge and promise of studying burning plasmas" by Richard Hawryluk and Hartmut Zohm (December 2019, page 34). Manheimer criticizes the international fusion experiment known as ITER and the prospects for commercial fusion. I would like to point out an error in Manheimer's calculation, which, as it turns out, further supports his criticism.

Manheimer asks what the results of ITER would mean for power production. He applies a conservative thermal-to-electric power conversion factor of one-third to the projected 500 MW thermal output of ITER, and from that he concludes that ITER would generate a gross output of approximately 170 MW of electricity (MWe). He then says that the 50 MW heating input would require 150 MW of electrical power, leaving "virtually nothing for the power grid." Manheimer's calculation would mean a net electrical output of about 20 MWe.

Manheimer, however, doesn't account for the net plant power drain—known as the balance of plant—which is at least 150 MWe. That value includes such power drains as liquid-helium refrigerators, water pumps, and vacuum pumps. When one includes the injected heating power and the plant power drains, a reactor designed like ITER would result in a net loss of 80 MWe, at best.

ITER was never designed to provide net electricity or net thermal power across the entire reactor. Instead, it was designed only to generate net thermal power across the plasma. But in its public communications, the ITER organization until only recently did a poor job of communicating that distinction. That led to, as it did with Manheimer, the common misunderstanding about the expected power balance for ITER. That misconception does not account for at least half of the expected input power.

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Correction

December 2022, page 23—The image caption should read, "Stargazing events such as this one from 27 August at Moʻokini Heiau, a National Historic Landmark on the island of Hawaii, are among the activities that the Thirty Meter Telescope outreach team is collaborating on with Native Hawaiians in efforts to build positive long-term relationships." The credit should read "ʻOhana Kilo Hōkū/Keith Uehara." PT

The early universe in a quantum gas

With a Bose–Einstein condensate in a magnetic field, researchers see hints of particle production and cosmic sound waves—and they can run the experiment more than once.

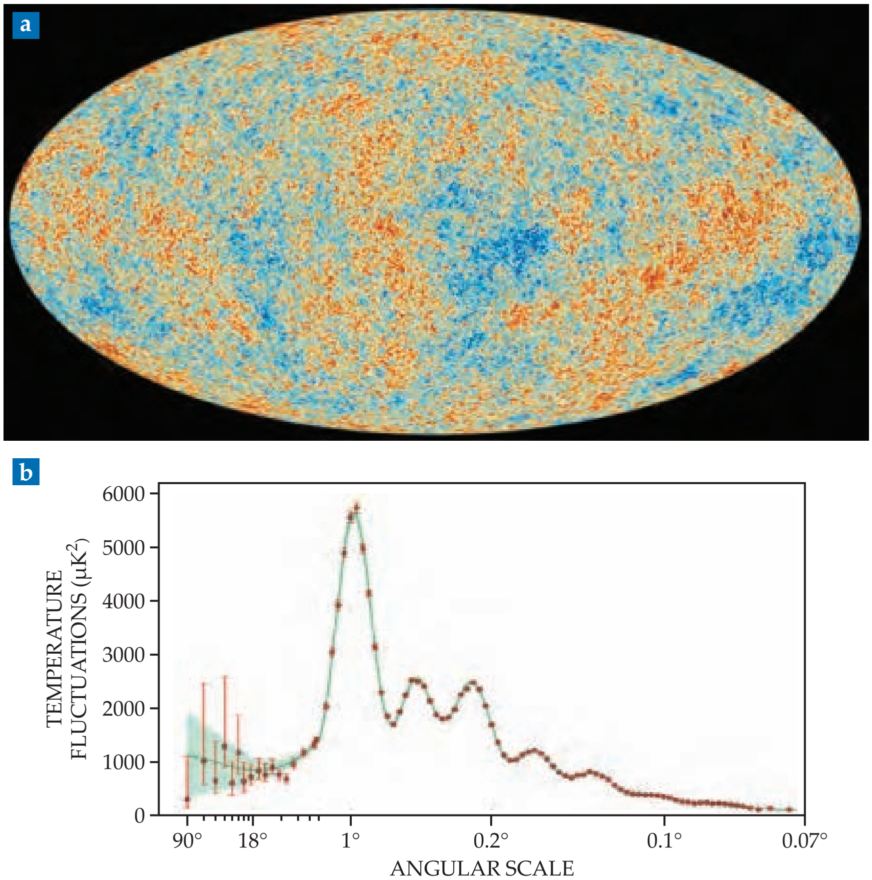

FIGURE 1. THE COSMIC microwave background **(a)**, as observed by the *Planck* spacecraft, looks almost the same in every direction. Its minuscule temperature fluctuations, shown in red and blue here, are evidence of cosmic sound waves that propagated through the early universe. **(b)** When broken down by angular size on the sky, the fluctuation data (red) generally agree well with the predictions of cosmological theory (green). At large angular scales, however, the comparison is hindered by irreducible cosmic variance—that is, the limited amount of data that can be extracted from one universe. (Both panels courtesy of the European Space Agency and the Planck Collaboration.)

To look back in time, astronomers and cosmologists need only look to the skies: When they view an object a million light-years away, they're seeing it as it existed a million years ago. That approach, however, hits a wall at the cosmic microwave background (CMB), which dates to 380 000 years after the Big Bang. Before that, the universe was filled with dense plasma, which was electromagnetically opaque.

Theorists have proposed that the very early universe experienced a so-called inflationary epoch, in which it doubled in size some 100 times in less than 10^{-30} of a second before the expansion abruptly slowed. (The universe is still expanding, and the expansion is accelerating, but nowhere near as speedily as it was then.) Confirming or refuting inflation theory, however, is challenging, because the only universe we can observe is the one we live in. Cosmologists can't run experiments to compare what did happen with all the other things that might have happened.

But it may be possible to mimic at least some of the physics of the early universe in another system that does lend itself to experiments. Heidelberg University's Markus Oberthaler, his PhD student Celia Viermann, and their colleagues are doing just that with their experiments on a pancake-shaped Bose–Einstein condensate (BEC) of potassium atoms.[1] Their goal is to study how quantum fields may have behaved in a rapidly expanding spacetime—and what imprints inflation may have left on the observable universe for eons to come. And they do it all without changing the physical size of their BEC.

Microwave fluctuations

Even though the CMB didn't originate until hundreds of thousands of years after the inflationary epoch, it offers some of the most suggestive evidence that inflation happened at all. Figure 1a shows the CMB temperature mapped over the whole sky, with the hottest spots shown in red and the coldest ones in blue. But those temperature fluctuations are tiny—on the order of parts per hundred thousand. Evidently, 380 000 years after the Big Bang, the whole observable universe had almost exactly the same temperature.

How can that be? CMB photons arriving at Earth from opposite directions originated at opposite edges of the observable universe. When would those points ever have had time to exchange information with each other, let alone come to thermal equilibrium? Inflation offers a compelling answer: Just before the inflationary epoch, the theory posits, the whole of the observable universe was less than the size of a proton. It could have quickly equilibrated, then expanded so fast that its most distant points were pulled out of causal contact. That's not the only possible answer (see the article by Robert Brandenberger, Physics Today, March 2008, page 44). But it's an elegant explanation of what's observed.

A closer look at the CMB strengthens inflation's predictive success. The temperature fluctuations in figure 1a are organized into a hierarchy of size scales, as plotted in figure 1b, with a primary peak around 1° in angular size and a series of smaller peaks at smaller scales. As anticipated in 1965 by the Soviet physicist Andrei Sakharov, those peaks are the signatures of acoustic waves that coursed through the universe during the plasma epoch, between the end of inflation and the production of the CMB (see the article by Daniel Eisenstein and Charles Bennett, PHYSICS TODAY, April 2008, page 44). The green line is the best fit to a cosmological model that incorporates inflation, with a handful of adjustable parameters.

For angular sizes of a few degrees and smaller, the model is an excellent fit to the data. But the agreement is shakier at larger scales. At the leftmost end of the plot, most of the red data points are on the low side of the green curve. But it's hard to tell how much of the discrepancy is real and how much is a statistical anomaly, because the uncertainties are so large—a consequence of the fact that we have only one universe to study and only one sky to look at. Only a few 90° patches can fit on the sky, so any analysis of them is fundamentally limited in precision. In principle, more data could be gathered by observing the CMB from a different vantage point, perhaps a billion light-years away. But practically, that's not going to happen any time soon.

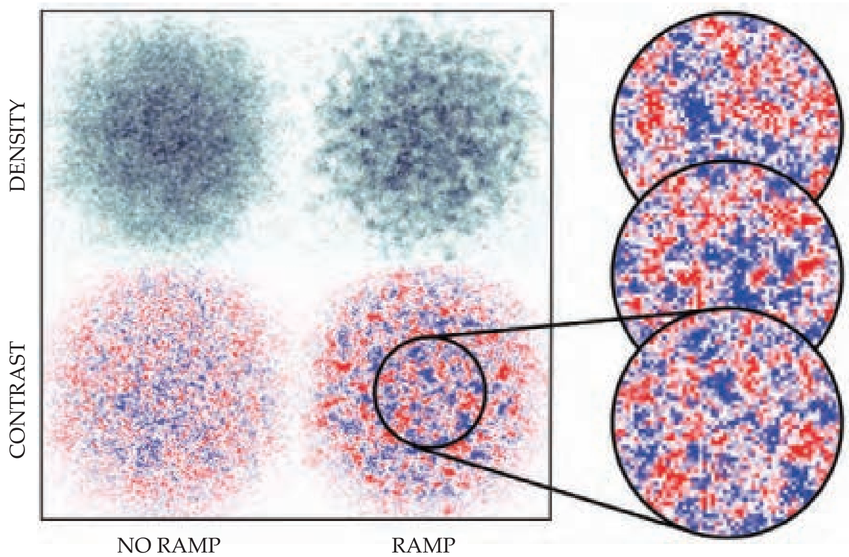

FIGURE 2. BY RAMPING a magnetic field in the vicinity of a so-called Feshbach resonance, researchers trick a Bose–Einstein condensate into behaving like the expanding early universe—even though the condensate's physical size remains the same. Under the ramped field, the condensate picks up density fluctuations; in the early universe, such quantum field fluctuations became particle–antiparticle pairs. The cutouts at right show how additional data can be gathered by repeating the experiment. (Adapted from ref. 1.)

Experimental simulations

By simulating inflationary-epoch physics in an experiment, Oberthaler and colleagues could help bypass such statistical limitations. Notably, they're not trying to exactly reproduce the inflationary universe in all its complexity. Instead, they're building an experimental platform for studying a quantum field in an expanding spacetime—a simplified model of the early universe, but one that's still difficult to solve theoretically.

Researchers have taken a similar approach in using quantum gases to simulate other mysterious systems, such as high-temperature superconductors. (See PHYSICS TODAY, August 2017, page 17.) Those experiments, and most other cold-atom quantum simulators, use atoms confined to a discrete lattice of optical traps. Oberthaler and colleagues, in contrast, are looking at a continuous BEC, which simulates a continuous quantum field.

Reducing the whole universe to a single field isn't as gross a simplification as one might think. According to inflation theory, the universe didn't begin the inflationary epoch with all the matter and energy that exists today packed into a space smaller than a proton. Rather, the inflationary-epoch universe was largely empty, apart from a field, called the inflaton, whose quantum fluctuations eventually gave rise to all the complexity we see today.

The inflaton would have been a scalar field, meaning that its quanta were spin-zero bosons. (In the standard model of particle physics, the only fundamental spin-zero boson is the Higgs particle; it's possible, but not certain, that the inflaton and Higgs fields were one and the same.) Because of its bosonic character, it's reasonably well simulated by a BEC.

But how can one study a BEC in expanding spacetime? One way, pursued recently by Gretchen Campbell and colleagues at the Joint Quantum Institute and the University of Maryland, College Park, is to physically expand the BEC.[2] Another way is to tinker with the interatomic interactions to make the BEC behave as if it's expanding, even though it's not. That's the approach that Oberthaler and colleagues used.

As a thought experiment, imagine that your body and all the objects around you were suddenly halved in size. Your arms could reach only half as far as before, and it would take twice as long to walk anywhere. It would seem as though space itself were twice as big.

To manipulate their BEC atoms' reach, the Heidelberg researchers applied a magnetic field in the vicinity of what's known as a Feshbach resonance. At the resonance exactly, 561 G for potassium atoms, the atoms' reach diverges, and they behave as if they're infinitesimally close together. Away from the resonance, their reach shrinks, and the effective space grows. In practice, if the field is tuned too close to the resonance, the atoms interact so strongly that they knock one another out of the condensate. To be on the safe side, the researchers ramped the field from 557 G to 540 G, which is enough to inflate the BEC universe by about a factor of three.

Postinflation oscillations

A simple prediction of quantum field theory is that in an expanding universe, a scalar field picks up quantum fluctuations that produce particle–antiparticle pairs, whereas in a static universe, it doesn't. In an expanding BEC, the particles produced would be phonons; the same physics is expected to describe how

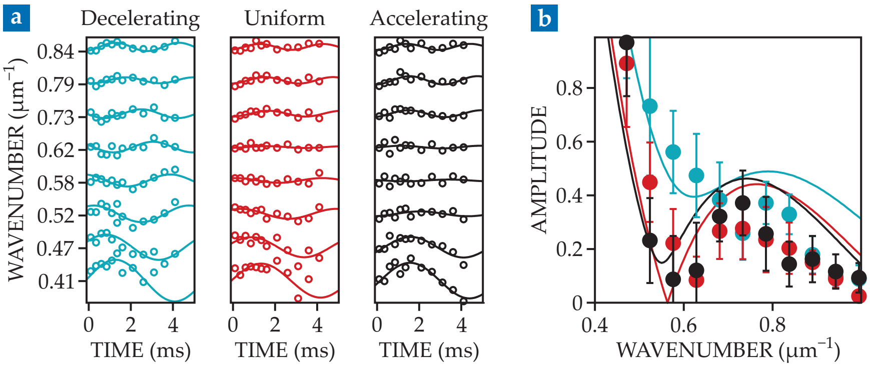

FIGURE 3. ACOUSTIC WAVES carry an imprint of a simulated universe's expansion history that's observable even after the expansion is over. **(a)** In the wake of three different expansion profiles—decelerating, uniform speed, and accelerating—the waves around a wavenumber of 0.6 μm^{-1} have different amplitudes. **(b)** The observations (data points in the same colors as panel a) agree well with theory (solid lines). (Adapted from ref. 1.)

real particles emerged from quantum fluctuations in the early universe.

The predicted particle production is borne out by the results shown in figure 2. When the researchers didn't ramp the magnetic field, the BEC density remained relatively smooth. But when they did ramp the field, they saw the gas develop regions of underdensity (blue) and overdensity (red). The cutouts on the right are from three repetitions of the experiment, from which they can study the statistics of particle production.

The qualitative dynamics of a Feshbach-resonance expanding universe were observed a decade ago by the University of Chicago's Cheng Chin and colleagues.[3] Those researchers looked at the effects of a step change in the magnetic field—an instantaneous, unmeasurably fast expansion. In contrast, Oberthaler and colleagues, in collaboration with the theorist Stefan Floerchinger, wanted to take the investigation a step deeper: What is the effect of inflation's functional form? Would different inflation profiles leave differing imprints on the simulated universe that could be observable long after the inflationary epoch was over?

To find out, they experimentally tested three different expansion histories: one that decelerated, one with uniform speed, and one that accelerated. (None of the three mimicked the exponential expansion of cosmic inflation; even the accelerating-expansion experiment followed a power law.) In all three cases, after the expansion was finished, the researchers saw the BEC fill with acoustic waves, similar to the ones that permeated the real universe during the plasma epoch and led to the temperature fluctuations in the CMB.

But whereas the CMB gives only a one-time snapshot of the cosmos, Oberthaler and colleagues can track the BEC waves in real time and break them down by wavenumber, as shown in figure 3a. The three histories yield broadly similar oscillations, but the uniform and accelerating expansions produce a lull in the oscillations, around a wavenumber of 0.6 μm^{-1}, that the decelerating expansion lacks. As figure 3b shows, the observation is roughly consistent with theory.

Now that the researchers have confirmed that their BEC can reproduce what theory predicts, they hope to be able to use it to investigate questions that theory, until now, has left open. For example, what, if anything, happened before inflation? If the inflationary epoch left an observable mark on the universe today, is it possible that a preinflationary epoch did also? That's an extremely ambitious question, but with an experiment that can probe the physics of an expanding universe in detail—including quantum fluctuations, correlations, entanglement, and thermalization—the researchers hope to make some headway.

Johanna Miller

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Climate change is redefining Arctic wildfires

The summers of 2019–21 have seen temperatures high enough to melt snow unseasonably early and alter polar atmospheric circulation.

As temperatures around the world rise, the threat of wildfires is becoming increasingly more frequent. For a heavily populated place like California, wildfires are particularly hazardous: Blazes in 2018 and 2020 killed dozens of people while burning hundreds of thousands of acres and causing billions of dollars in damages. Those risks are only getting worse (see "Fire season in the western US is intensifying," Physics Today online, 21 June 2021).

Even though wildfires in low-population areas may be less of an immediate danger to people, when they do happen they release vast amounts of carbon dioxide into the atmosphere. That is especially worrisome for the Arctic, which has a large amount of carbon stored in permafrost. Moreover, the region is subject to a positive ice–albedo feedback loop: Rising temperatures melt snow and ice and the liquid water reflects less sunlight than snow, so the area warms further. The mechanism is one contributor to Arctic amplification—temperatures in northern latitudes are warming at least twice as fast as the global average (see the article by Martin Jeffries, James Overland, and Don Perovich, Physics Today, October 2013, page 35).

Historically, the area burned by fires has been less in the Arctic than that at lower latitudes.[1] Early data on the 2019–21 fire seasons, however, have suggested that summer blazes in the Siberian Arctic—one of which is shown in figure 1—were widespread. That's particularly true in eastern Siberia, where high-pressure systems often develop in the summer. They generate several conditions that are more favorable for fire activity: stable high temperatures, precipitation deficits, and more lightning ignitions because of atmospheric convection.

To better connect how warmer-than-average temperatures lead to exceptional fire activity, two teams analyzed satellite-derived maps of burned areas in the Siberian Arctic.[2,3] Both found that compared with the past 20–40 years, several recent fire seasons were exceptional in the total area burned. The studies suggest that snow will continue to melt earlier each season, and a changing Arctic atmospheric circulation will accelerate fire activity.

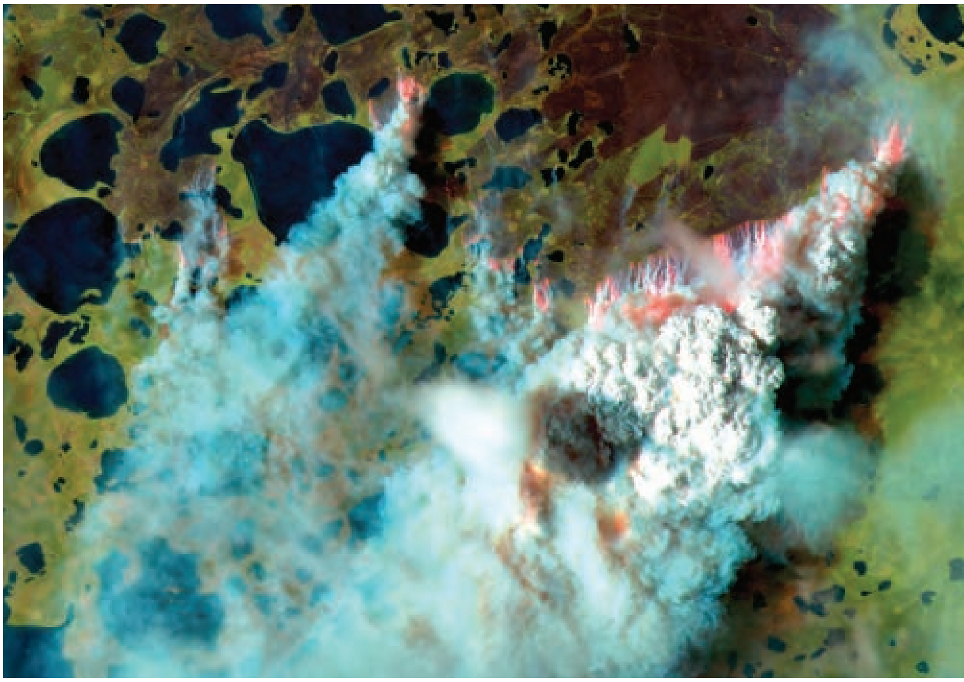

FIGURE 1. A PYROCUMULUS CLOUD formed from a wildfire that burned this 30-kilometer-wide area on 6 August 2020, during one of the most intense Siberian Arctic fire seasons of the past 40 years. (Satellite photo created by Adrià Descals; imagery acquired by the European Space Agency.)

Fire factors

The burn maps analyzed in both papers were made possible only by the decades of satellite data that were carefully collected during multiple missions led and funded by NASA, NOAA, and the European Space Agency. Adrià Descals, of the Centre for Ecological Research and Forestry Applications in Spain, and his colleagues found that of the 9.2 million hectares of burned area in the Siberian Arctic over 1982–2020, shown in figure 2, some 44% of that total burned in 2019 and 2020 alone. (The total area of the Siberian Arctic is some 286 million hectares.)

Other high-latitude regions in North America and western Europe experienced wildfires during those years too, but the blazes across the Siberian Arctic were noteworthy because of how widespread they were. Descals and his colleagues suspected that worsening fire-risk factors are to blame: climate factors, such as air temperature and atmospheric drought; vegetation conditions, such as the length of the growing season; and the number of ignition events over an area.

To analyze how the observed burned area was correlated with each of seven fire factors, Descals and his colleagues used regression models. He says, "We found a quite clear exponential relation between the annual burned area and several factors of fire. I expected a noisier relationship." The results showed that a 1 °C rise in temperature was correlated with an expansion of the burned area by 150–250%. But just because atmospheric drought or another climate variable covaries with a fire factor doesn't mean that it caused or exacerbated the blaze. The fire itself could, for example, make the local region drier.

To unpack any potential cause and effect between the environmental variables and the wildfires, Descals and his colleagues developed a structural equation

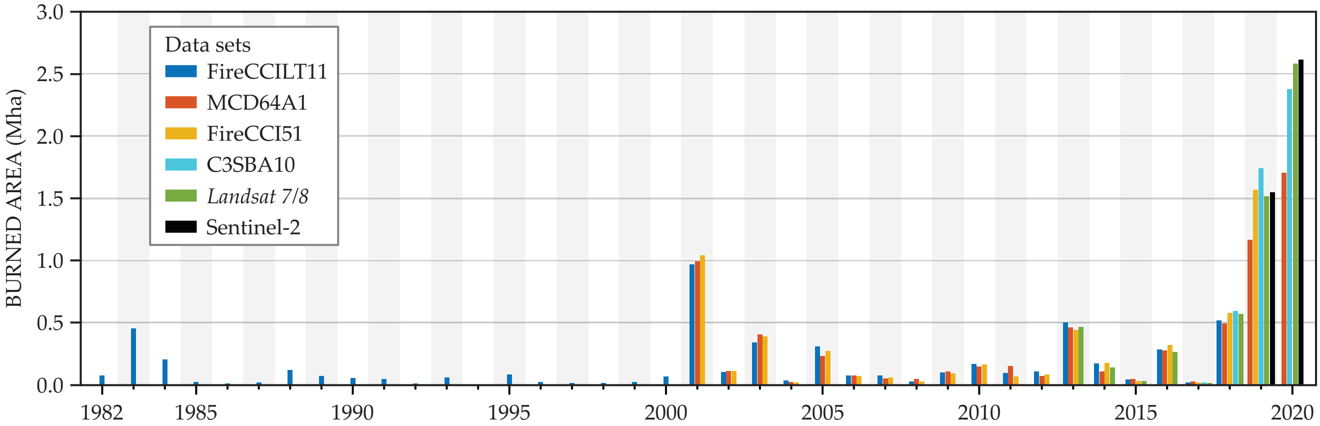

FIGURE 2. WIDESPREAD WILDFIRES burned millions of hectares of forest in the Siberian Arctic in 2019 and 2020, based on six data sets made with satellite measurements. The unusual fire activity persisted into 2021 and may continue in the future because of a complex interplay of earlier snowmelt and varying atmospheric conditions brought about by rising temperatures. (Adapted from ref. 2.)

model. It starts by hypothesizing that changes in an environmental variable could cause an accompanying change to a fire factor. Quantitative relationships in the literature show, for example, that a higher surface temperature over a longer period of time would stand to lengthen the growing season, and a lower total precipitation in the region would heighten the water stress on plants. To test whether those causal relationships could produce the observed wildfire conditions, a statistical goodness-of-fit test assesses how similar the model estimates are to remote and field measurements.

Most of the variables in the structural equation model had some effect on the incidence and extent of wildfires. But the large Arctic water deficit—that is, the difference between the available water and the maximum amount of water that plants could potentially use—was the biggest contributing factor to the total burned area. In addition, Descals and colleagues found that the years with the largest burned areas all had average summer air temperatures exceeding 10 °C, which is more than 2 °C higher than the Siberian Arctic's historical 40-year average. Those high summer temperatures are projected to become the new normal by 2040, according to climate models with an intermediate emissions scenario.

Atmospheric anomaly

The factors that affect wildfires are varied, complex, and tied to more than just surface temperature. Rebecca Scholten of Free University of Amsterdam, who led another research team, says, "It's not enough to just look at how much the average temperature is going to rise. If we want to understand how future fire activity looks in Siberia, we have to take into account the complexity of the system."

To obtain a more complete picture of wildfires in the Siberian Arctic, Scholten and her team analyzed the timing of snowmelt in the spring by reviewing maps made with data from the MODIS instrument aboard NASA's *Terra* and *Aqua* satellites. They saw that snow melted an average of four to eight days earlier in 2020, relative to the data set's average over 2001–21.

In addition to the burn maps, Scholten and her colleagues studied atmospheric-circulation data over the past 40 years. Over that time period, the data showed an increase in the frequency of a high-altitude wind pattern over the Arctic coastline. Scholten and her team suspect that the pattern may be anchoring high-pressure systems over northeastern Siberia and thus may partially be responsible for the drier conditions there.

The years 2019, 2020, and 2021 all had that wind pattern and earlier snowmelt timing. When both were added to a fire-activity analysis, the probability of wildfire activity in a summer week increased to 44%, compared with just 2% for conditions with snowmelt occurring later in the season than usual. The peculiar atmospheric circulation also increases convection and consequently generates more thunderstorms with lightning strikes that can spark wildfires.

To make Arctic wildfire predictions under changing future scenarios requires Earth system models that compute the complex interactions between the atmosphere, land, oceans, cryosphere, and biosphere. So far, however, those models lack enough detail to make robust wildfire predictions. One nagging unknown is whether wildfires are diminishing the Arctic boreal forests' ability to act as a carbon sink. Eastern Siberia contains a large share of continuous permafrost. If rising temperatures and wildfires thaw the carbon-rich permafrost, the region would emit more carbon dioxide to the atmosphere than previously estimated.[4]

More observations, particularly ground-based measurements, of carbon emissions should help researchers better understand the interplay among all the variables and how that translates to changes in the incidence and extent of wildfires. Scholten began collecting field data on the carbon emissions from wildfires in Siberia in 2019. But the global shutdown in 2020 forced by the coronavirus pandemic and, more recently, the 2022 Russian war against Ukraine have prevented her and her team from collecting all the Siberian wildfire observations they wanted. "It's a big loss for the climate science community to not be able to get these data," says Scholten. "And I think this paper really shows that it's a very important region where a lot of things are changing very rapidly."

Alex Lopatka

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PT

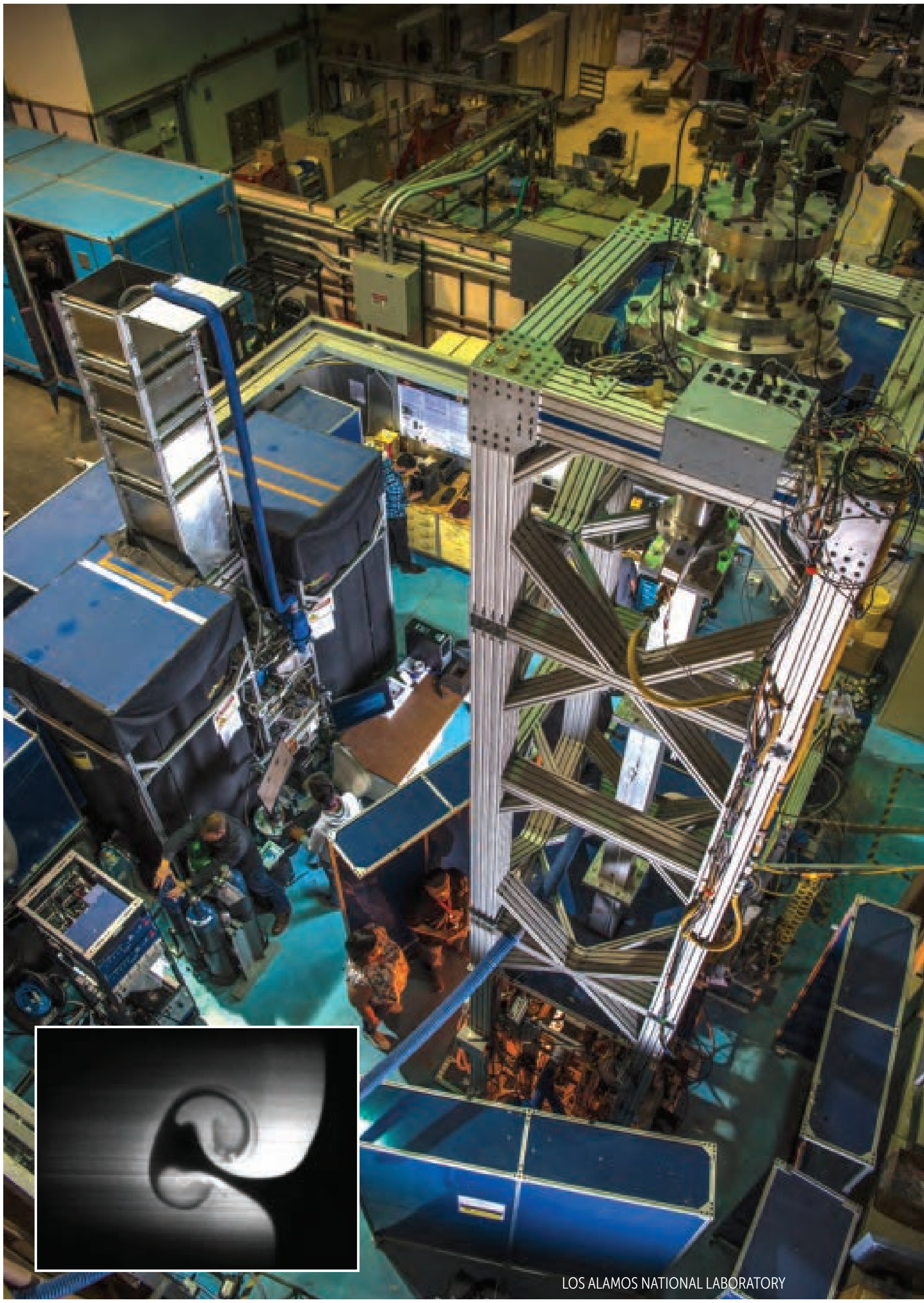
Scientists take steps in the lab toward climate sustainability

They are working to lower greenhouse gas emissions without compromising research.

Reducing air travel, improving energy efficiency in infrastructure, and installing solar panels are among the obvious actions that individual researchers and their institutions can implement to reduce their carbon footprint. But they can take many other small and large steps, too, from reducing use of single-use plastics and other consumables and turning off unused instruments to exploiting waste heat and siting computing facilities where they are powered by renewable energy. On a systemic level, measures can encourage behaviors to reduce carbon emissions; for example, valuing in-person invited job talks and remote ones equally could lead to less air travel by scientists.

So far, the steps that scientists are taking to reduce their carbon footprint are largely grassroots, notes Hannah Johnson, a technician in the imaging group at the Princess Máxima Center for Pediatric Oncology in Utrecht and a member of Green Labs Netherlands, a volunteer organization that promotes sustainable science practices. The same goes for the time and effort that they are putting in for the cause. One of the challenges, she says, is to get top-down support from institutions, funding agencies, and other national and international scientific bodies.

At some point, governments are likely to make laws that support climate sustainability, says Astrid Eichhorn, a professor at the University of Southern Denmark whose research is in quantum gravity and who is active on the European Federation of Academies of Sciences and Humanities' committee for climate sustainability. "We are in a situation to be proactive and change in ways that do not compromise the quality of our research or our collaborations," she says. "We should take that opportunity now and not wait for external regulations."



LOS ALAMOS NATIONAL LABORATORY

A VERTICAL SHOCK TUBE at Los Alamos National Laboratory is used for studies of turbulence. Sulfur hexafluoride is injected at the top of the 5.3-meter tube and allowed to mix with air. The waste is ejected into the environment through the blue hose at the tube tower's lower left; in fiscal year 2021, such emissions made up some 16% of the lab's total greenhouse gas emissions. The inset shows a snapshot of the mixing after a shock has crossed the gas interface; the darker gas is SF_6 and the lighter one is air. The intensities yield density values.

If humanity manages to limit emissions worldwide to 300 gigatons of carbon dioxide equivalent (CO_2e), then there is an 83% chance of not exceeding the 1.5 °C temperature rise above preindustrial levels set in the 2015 Paris Agreement, according to a 2021 Intergovernmental Panel on Climate Change special report. That emissions cap translates to a budget of 1.2 tons of CO_2e per person per year through 2050. Estimates for the average emissions by researchers across scientific fields are much higher and range widely in part because of differing and incomplete accounting approaches, says Eichhorn. She cites values from 7 to 18 tons a year for scientists in Europe.

To be sure, the greenhouse gas contributions of the scientific community are small in the grand scheme of global emissions. Still, the community has a "moral responsibility," says Thomas Roser, an emeritus senior scientist at Brookhaven National Laboratory (BNL) and author of a white paper on sustainability for future accelerators written for the recent Snowmass exercise. (See Physics Today, October 2022, page 22.) That's especially true for a "luxury field" like high-energy physics, he says, "which doesn't have a societal benefit other than knowledge and some spinoffs." Science and academia can serve as examples for the rest of society, he says, "and the development of energy-efficient technologies could be an important bonus."

PLASTIC CONSUMABLES PILE UP as waste in many wet labs. An exhibition last winter at the Lakenhal Museum in Leiden, the Netherlands, aimed to motivate scientists and the public to find ways to make science more sustainable.

"Carbon-neutral for everything"

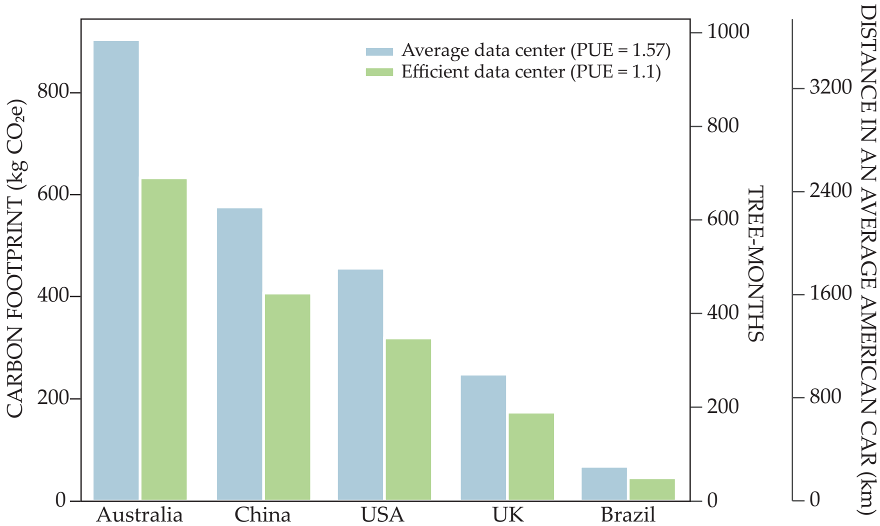
Scientific facilities often include renewable energy as part of their sustainability plans. "I'm leery about that," says Roser. "If a scientific facility switches to renewable energy, it takes that energy source away from other parts of society." The focus should be carbon-neutral for everything, he says, but until that happens, "scientific facilities should strive for energy efficiency and energy recovery."

As an example of increasing energy efficiency in experimental particle physics, Roser suggests using permanent magnets rather than power-hungry electromagnets where feasible. Advances have made it possible to make precise permanent magnets, he says, pointing to the Cornell University facility CBETA, the Cornell–BNL ERL (Energy Recovery Linear) Test Accelerator. Multiple permanent magnets are glued together and fine-tuned with wire shims to create a field accurate to 10^{-4} in strength and direction. Permanent magnets are a "big opportunity for synchrotron light sources," with their static storage rings and fixed fields, says Roser. They have also been patented for use in cancer radiation therapy. Another sustainable aspect of CBETA is energy recovery, whereby the energy the electrons collect while accelerated is removed when they are decelerated and then reused. CBETA "substantially reduces energy consumption and still maintains performance," says Roser. "Nobody wants to compromise performance."

Across the sciences and beyond, computation is a growing area of energy consumption and carbon emissions. Scientists tend to think that computing is free because the financial cost is low and a lot of supercomputer time is available, says Loïc Lannelongue, a postdoc in computational biology at the University of Cambridge. "Very rarely does someone decide not to run a calculation because it's too expensive."

In 2020 Lannelongue took what he thought would be a two-week detour from his PhD studies to create a calculator of carbon footprints. That detour has become an ongoing side project, as he refines the calculator (see https://green-algorithms.org) for broad use and writes papers and gives talks on the topic. "If people realize there is a carbon cost, they will be more mindful," he says. "I no longer do a computation just because I can."

Other carbon-footprint-reducing measures that individuals can take, Lannelongue says, include optimizing code and updating software. In one case, a particular calculation done with the latest version of a genomic analysis software package created only a quarter of the carbon emissions of the first commercial version, he says. "The team behind the tool is making it more efficient. As a side effect, it's better in terms of carbon emissions. It doesn't have to be a trade-off. It can be win-win."



GREENHOUSE GAS EMISSIONS from computing vary widely by location, depending on the energy source, and also on cooling and other design features. For a test calculation quantifying radiation damage to DNA, the blue bars show the values for an average data center for a given country and the green bars are for energy-efficient data centers in the same country. The power usage effectiveness (PUE) is a measure of the energy efficiency of the data center. At near right, the time it would take a tree to sequester the emitted carbon dioxide is shown. At far right is the distance that a car in the US would drive on average to emit the same amount of CO_2 as the computation. (Courtesy of Loïc Lannelongue; data and details at https://www.carbonfootprint.com/international_electricity_factors.html and https://doi.org/10.1002/advs.202100707.)

At the institutional level, the carbon emissions of computing can be reduced by modifying cooling designs and locating computing centers where renewable energy is available. For example, CERN has upgraded the efficiency of an existing data center by cooling corridors of computers rather than the whole room, among other measures. "The upgrades brought the PUE down from 1.7 to 1.5," says Bob Jones, deputy head of the lab's information technology department. (The PUE, or power usage effectiveness, is the ratio of the total energy used by the facility to the energy delivered to its computing equipment.) A new data center due to open at CERN later this year will have a PUE of 1.1, he adds. CERN plans to recuperate the heat generated by the new center; similarly, some of the hot water currently generated from cooling the Large Hadron Collider (LHC) is diverted for use in a neighboring town.

Fluorinated gases

Because CERN is powered mostly by nuclear energy from France, its enormous energy consumption is not the main contributor to its greenhouse gas emissions. Instead, roughly 80% comes from fluorinated gases used for particle detection and detector cooling in the LHC experiments and for electrical insulation in power supplies, according to the lab's 2021 environmental report. Fluorinated gases have a warming potential that is thousands of times greater than that of CO_2.

Some 20 detector systems in the LHC experiments use various gas mixtures as the active medium to detect particles generated in collisions. The gases, which include hydrofluorocarbons and perfluorocarbons, as well as CO_2, neon, argon, and oxygen, are chosen to "fulfill the requirements of the particular experiment—the time resolution, efficiency, rate capability, and so on," says Beatrice Mandelli, a particle physicist who is on the team that oversees CERN's gas detector systems. Harm to the environment occurs through leakage.

One type of gaseous detector contains mostly tetrafluoroethane with small amounts of isobutane and sulfur hexafluoride (SF_6). The mixture allows for primary ionization and an avalanche, and suppresses the development of sparks, Mandelli explains. Carbon tetrafluoride, which is used in a different type of gaseous detector, provides high time resolution and mitigates detector aging. Tetrafluoroethane is common in refrigeration, in automobile air conditioners, and more. Industry has found replacements, says Mandelli, but they are not suitable for particle detectors.

"Our needs are very specific," Mandelli says. The geometry and electronics are customized, and the detectors have to be able to run for many years. When the detectors were designed decades ago, she adds, "there was not awareness of the emissions of greenhouse gases."

CERN has decreased emissions by closing detector systems so gas mixtures can recirculate, recuperating fluorinated gases, and fixing leaks when the accelerator is off. Pointing to ongoing research on eco-friendly alternatives, Mandelli says that future detectors will not use greenhouse gases. Aside from polluting the environment, they are likely to become harder to obtain, she notes, because of industry shifting away from fluorinated gases and the Kyoto Protocol having called for their phaseout.

Researchers at Los Alamos National Laboratory (LANL) in New Mexico likewise are stymied in finding replacements for fluorinated gases. In fiscal year 2021, fluorinated gases were responsible for 20% of the lab's greenhouse gas emissions; LANL did not say how much those total emissions amounted to.

John Charonko leads a group at LANL that studies mixing of heavy and light gases. In one setup (see the photo on page 20), SF_6 is pushed down a 5.3-meter vertical tube to mix with air, and the researchers take pictures of the mixing. The group uses SF_6 because it's heavy, nontoxic, and cheap. The experiments are analogous to part of the inertial confinement fusion process studied at the National Ignition Facility, Charonko says. (See "National Ignition Facility surpasses long-awaited fusion milestone," Physics Today online, 13 December 2022.) They also are relevant for understanding astrophysical processes, such as the evolution of white dwarfs and supernova explosions.

Per an executive order signed by President Biden in December 2021, LANL is working to achieve a carbon-pollution-free electricity supply by 2035 and net-zero emissions by 2050. LANL plans a 50-acre photovoltaic farm and is considering a nuclear microreactor for on-site power generation. For now, the lab is focusing on renovating buildings to be more energy efficient and procuring carbon-free power. Transportation is also in their sights: Ideas being floated to encourage employees to cut emissions include providing electric bikes for campus transportation, offering parking only to carpoolers, and switching the lab's vehicles to electric cars, says Shannon Blair, who is on the lab's sustainability team. "Our government fleet is 1500 vehicles. It's 2% of our total emissions. That's tiny, but it's visible."

At Johnson's workplace in Utrecht, the ultralow-temperature freezers consume the equivalent energy of 60 average Dutch households. "We are facing a huge energy crisis in Europe, so the sustainability community is using that to get attention and to get institutions on board," she says. Increasing a freezer's temperature to –70 °C from the typical –80 °C uses about 30% less energy. "Through an ongoing in-house challenge, some groups have combined the contents of freezers and turned some off altogether."

Efficiency in cost and carbon

A few years ago, the Gemini Observatory telescopes got solar panels and energy-efficient equipment, including transformers, cooling systems, LED lights, and motion sensors. Solar panels provide 20% of the energy needed at Gemini South on Cerro Pachón in Chile, 12% at Gemini North on Mauna Kea in Hawaii, and 20% at the observatory's Hawaii offices. The upgrades were intended to lower operating costs, but they also reduced the facilities' carbon footprint, says Inger Jorgensen, associate director of operations at NOIRLab, NSF's National Optical–Infrared Astronomy Research Laboratory, which comprises several telescopes and other facilities. "By next year they will have paid for themselves," she adds.

In its 2021 request to NSF for a five-year renewal grant, NOIRLab proposed to reduce staff travel by half compared with pre-COVID-19 levels and to use the consequently freed-up $4.7 million on additional energy-efficient equipment. NSF agreed, and the changes, Jorgensen says, will reduce NOIRLab CO_2e emissions by 30%, from the estimated 8700 tons of CO_2e in 2019 to a target of 6200 tons by late 2027. That reduction "is equivalent to what 500 average US houses emit in a year," she says. "Every little piece makes a difference. And it shows it can be done."

Funding agencies have agency

Eichhorn and others want funding agencies to step in and use their leverage to nudge researchers and institutions to reduce their greenhouse gas emissions. A first step would be for the agencies to require applicants to estimate the carbon footprint of their proposed work. Eichhorn notes that while a growing number of universities and research institutions globally are doing so, the lack of standardization makes it difficult to compare them. "The day funding bodies say you have to estimate your carbon footprint, everyone will do it," says Lannelongue. "I haven't seen compulsory estimates yet, but things are moving in that direction."

Funding agencies could also reward proposals that include ways to reduce emissions. One incentive, suggests Johnson, could be to recognize institutions that behave sustainably—along the lines of the UK's Athena SWAN (Scientific Women's Academic Network) program, which recognizes good practices in advancing gender equality in higher education.

Limiting scientists to listing only one invited in-person talk on grant applications would be an incentive to travel less, says Eichhorn. And conducting all grant or job interviews virtually would likewise reduce travel. Institutions and funding agencies could ease the requirement of taking the cheapest form of transportation to meetings and instead include the carbon budget in such decisions.

Remote conferences reduce emissions by up to 98%, Eichhorn notes. Even selecting a conference location based on where attendees will travel from can reduce a conference's carbon footprint by 20%, she notes. (See PHYSICS TODAY, September 2019, page 29.)

Says Eichhorn, "Reducing emissions in the science community will require creativity and culture change."

Toni Feder

A computing hardware approach aspires to emulate the brain

Neuromorphic computing promises energy savings, a deeper understanding of the human brain, and smarter sensors.

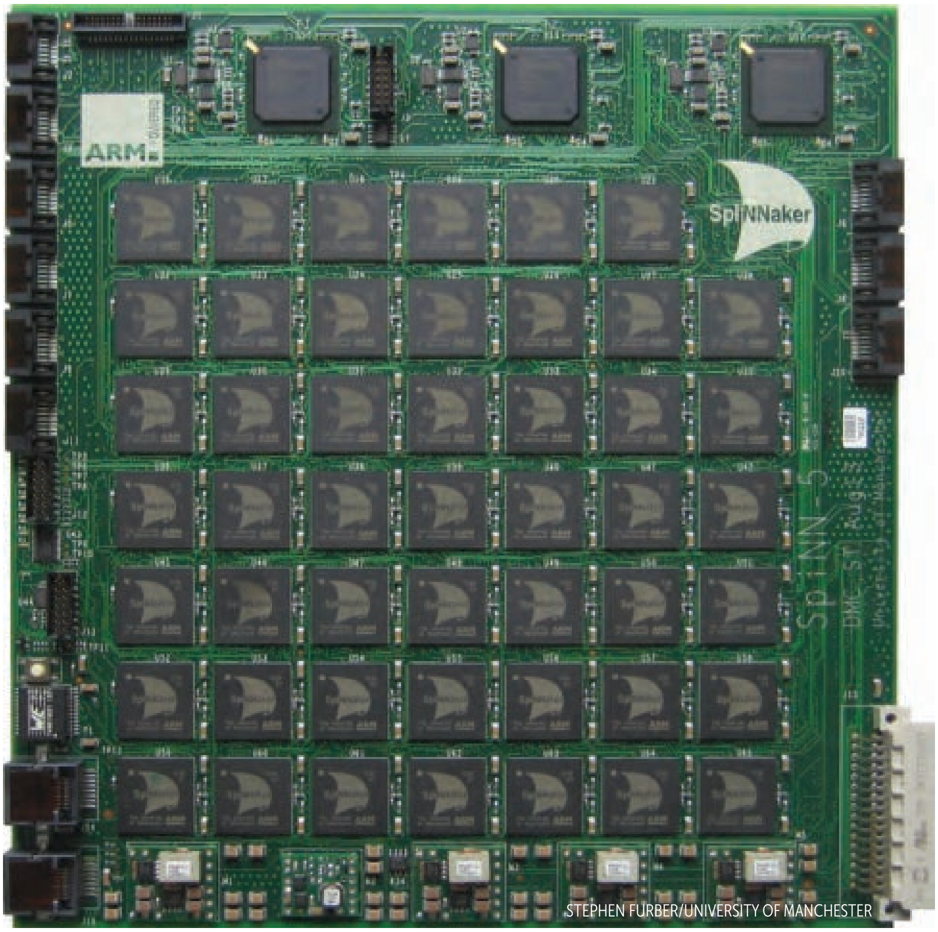
Imagine getting the performance of today's supercomputers but drawing just a few hundred watts instead of megawatts. Or computer hardware that can run models of neurons, synapses, and high-level functions of the human brain. Or a flexible patch that could be worn on the skin that could detect serious health disorders before symptoms develop. Those are a few applications that could be enabled by neuromorphic computing.

Today's high-performance computers have a von Neumann architecture, in which the central processing or graphics processing units (CPUs and GPUs) are separate from memory units, with the data and instructions kept in memory. That separation creates a bottleneck that slows throughput. Accessing data from main memory also consumes a considerable amount of energy.

In so-called neuromorphic systems, units known as neurons and synapses operate as both processors and memory. Just like neurons in the brain, artificial neurons only perform work when there is an input, or spike, to process. Neuromorphic systems are most often associated with machine learning and neural networks, but they can perform a variety of other computing applications.

Just a handful of large-scale neuromorphic computers are in operation today. The Spiking Neural Network Architecture (SpiNNaker) system located at the University of Manchester in the UK has been operating since 2011 and now has 450 registered users, says Stephen Furber, the Manchester computer engineer who led the computer's construction. The UK-government-funded 1-million-core platform was optimized to simulate neural networks.

A next-generation machine, dubbed



STEPHEN FURBER/UNIVERSITY OF MANCHESTER

CIRCUIT BOARDS containing 48 SpiNNaker neuromorphic chips are at the heart of a 1-million-core computer built at the University of Manchester for the Human Brain Project. The Technical University of Dresden, in collaboration with Manchester, is developing a 10-million-core machine built around the more powerful SpiNNaker2 chip.

SpiNNaker2, is under construction in Dresden, Germany. It's being supported by the state of Saxony and by the Human Brain Project, the European Union's decade-long flagship program, whose goal is advancing neuroscience, computing, and medicine. That program was initiated in 2013 and will end in March. (See Physics Today, December 2013, page 20.) Based on a more powerful SpiNNaker2 chip, the eponymous computer will consist of 10 million processers, each of which has 10 times the processing and storage capacity of the SpiNNaker chip, Furber says.

Targeted applications for SpiNNaker2 include remote learning, robotics interaction, autonomous driving, and real-time predictive maintenance for industry, says Christian Mayr, an electrical engineering professor at the Technical University of Dresden. Mayr coleads SpiNNaker2 with Furber. SpiNNcloud Systems, a spin-off company Mayr cofounded to commercialize neuromorphic technology, is in discussions to supply a neuromorphic system to a "large smart city" customer that he declined to identify.

Germany is host to another large-scale neuromorphic platform, BrainScaleS (brain-inspired multiscale computation in neuromorphic hybrid systems) at Heidelberg University. That project also began as a component of the Human Brain Project.

Working with Intel, Sandia National Laboratories plans to complete assembly this spring of a neuromorphic computer consisting of 1 billion neurons. The human brain is estimated to contain 80 billion neurons. "There's a lot of reason to expect that we'll be able to achieve more biological-like capabilities as we get to that scale," says James Bradley Aimone, a Sandia computational neurological scientist.

Sandia has built a 128-million-neuron neuromorphic system, based on Intel's Loihi chip. Each Loihi chip houses 131 000 neurons. The billion-neuron machine will be based on Intel's Loihi 2 chips, which contain 1 million neurons each. (Loihi is named for an active underwater volcano in Hawaii.) The new machine is expected to draw less energy than a high-end workstation typically used for applications such as three-dimensional graphics, engineering design, and data science visualization, says Craig Vineyard, a Sandia researcher.

For Sandia, a nuclear weapons lab that hosts some of the world's largest high-performance computer (HPC) assets, energy savings and Moore's-law limitations are the main attractions of the neuromorphic approach. Conventional supercomputers are power hungry, and the potential to further scale their computational capacity is expected to be held in check by that growing appetite and the inability to further increase processor density, says Vineyard. The world's first exascale HPC, for example, is expected to draw 40 MW, enough power to supply 30 000 homes and businesses, when it begins full operation at Oak Ridge National Laboratory this year. Exascale is at least 10^{18} floating-point operations per second (FLOPS). "Things like neuromorphic offer a viable path forward, because we can't just keep building larger and larger systems," Vineyard says.

Energy-use comparisons between neuromorphic and classic supercomputing will vary depending on the application. But in some cases, a billion-neuron Loihi system should perform a petascale-equivalent calculation in the same amount of time for as little as 200 W. (Petascale is at least 10^{15} FLOPS.) That's a job for which the most power-efficient supercomputers require 20 kW, says Sandia's Aimone.

Some of today's very large deep-learning neural networks require hours just to train. Deep learning is a subfield of artificial intelligence (AI) that uses brain-inspired algorithms to help computers develop intelligence without explicit programming. The Generative Pretrained Transformer 3 (GPT-3) language model, for example, can generate text that is difficult to distinguish from that of a human. Training it is estimated to require more than 1 GWh. Equal or greater amounts of energy are consumed when deep-learning models are put to use. The human brain, with its vastly greater computing capacity, operates on 20–30 W, says Mayr.

Unparalleled parallelism

Apart from energy savings, proponents of neuromorphic computing say it can offer equal or faster performance over classical HPCs for some applications. The number of processors in even the most powerful HPC machines pales in comparison with hundreds of millions of simulated neurons, though each neuron is far less computationally powerful than a GPU or CPU. Neuromorphic's unrivaled level of parallelism is well suited for calculating certain kinds of algorithms, such as Monte Carlo random-walk simulations, says Aimone. Those algorithms are used in modeling molecular dynamics in drug discovery, stock-market predictions, weather forecasts, and a host of other applications.

"Is it possible to spread out this exploration of where a stock price may go over the large population of neurons? It turns out that you can," Aimone says. Sandia demonstrated that a neuromorphic simulation of how radiation diffuses through materials performed on a Loihi system was nearly as fast as one accomplished on a CPU or GPU platform and at far lower energy cost.

"From the algorithm side, we've recognized that neuromorphic systems provide computational advantages, but that only becomes apparent at large scale," says Aimone. That's partly due to the overhead associated with setting up the machine to solve a new problem, adds Vineyard. "It's not a magic solution, so research is identifying where those advantages are."

Neuromorphic computers won't pose a threat to HPCs, says Rick Stevens, associate director for computing, environmental, and life sciences at Argonne National Laboratory. "There are a handful of examples that have been demonstrated where you can do interesting problems. But it's nowhere near a general-purpose platform that can replace a conventional supercomputer." Neuromorphic hardware is particularly well suited to simulate computational neuroscience problems, he says, "because that's the computational model it's directly implementing."

But for the hundreds of applications that general-purpose supercomputers can perform, the alternative hardware has yet to show it offers advantages or even works well, Stevens says. And there are companies building specialized accelerators for deep learning that can implement abstractions of neurons without making any claims about being neuromorphic.

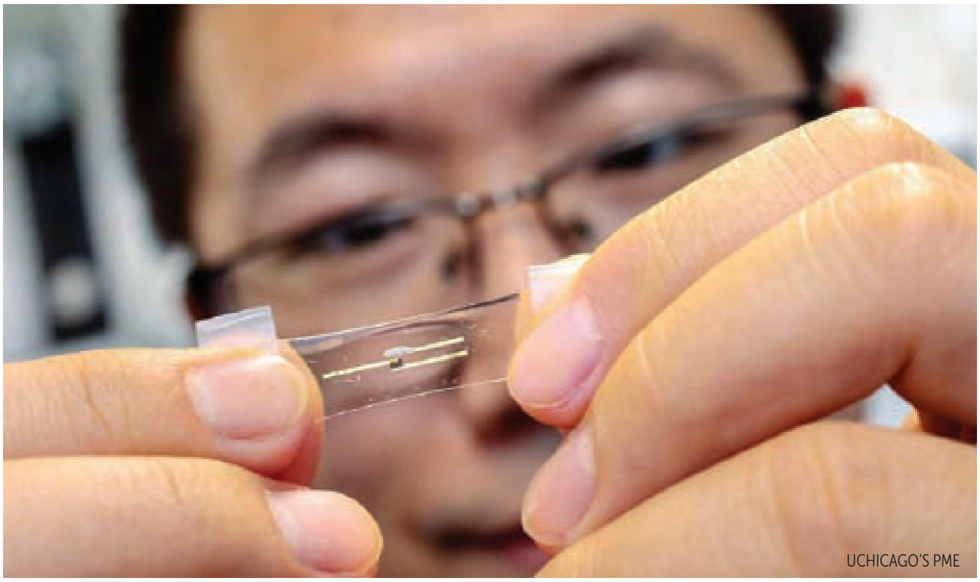
Comparing neuromorphic computing power with that of HPCs is not straightforward. "They are different animals," says Furber. Each of SpiNNaker's processors, for instance, is capable of delivering 200 million instructions per second, so the million-core machine can deliver 200 trillion instructions per second. HPCs are measured in FLOPS, but the Manchester machine has no floating-point hardware, he says.

"[Neuromorphic] is kind of similar to quantum in that it's a technology waiting to prove itself at scale," Stevens says. "Loihi is a great research project, but it's not at the point where commercial groups are going to deploy large-scale versions to replace existing computing."

At the opposite extreme from supercomputers, neuromorphic computers may benefit so-called edge-computing applications where energy conservation is a must. They include satellites, remote sensing stations, weather buoys, and visual monitors for intrusion detection. Instead of sending data on a regular clock cycle, spiking neuromorphic smart sensors would transmit only when something is detected or when a threshold value is crossed. "It should be smart about what it collects, what it transmits, and wake up if something is going on," says Aimone. "That requires computation." Adds

WALDEN KIRSCH/INTEL CORP

INTEL'S LOIHI second-generation neuromorphic chip was unveiled in September 2021. With up to 1 million neurons per chip, it supports new classes of neuro-inspired algorithms and has 15 times the storage density, faster processing speed, and improved energy efficiency compared with the predecessor Loihi chip. Sandia National Laboratories is building a 1-billion-neuron neuromorphic computer based on Loihi 2 architecture.



A SKIN-LIKE SENSOR developed by Argonne National Laboratory and the University of Chicago features stretchable neuromorphic electronics. The technology could lead to precision medical sensors that would attach to the skin and perform health monitoring and diagnosis. Holding the device is the project's principal investigator, Sihong Wang.

Stevens, "You're trying to go from a sensor input to some digital compact classification or representation of what that sensor is doing."

In November, Argonne and the University of Chicago's Pritzker School of Molecular Engineering announced the development of a skin-like wearable patch featuring flexible and stretchable neuromorphic circuitry. If developed further, such wearable electronics hold promise for detecting possible emerging health problems, such as heart disease, cancer, or multiple sclerosis, according to a lab press release. Devices might also perform a personalized analysis of tracked health data while minimizing the need for their wireless transmission.

In one test, the research team built an AI device and trained it to distinguish healthy electrocardiogram signals from four different signals indicating health problems. After training, the device was more than 95% effective at correctly identifying the electrocardiogram signals.

A tall order

In Europe, a major motivation for neuromorphic R&D has been to improve understanding of how the brain works, and that's no small task. "First and foremost the goal is fundamental research to see if we can learn from biology a different way of computing, and if this alternative way of computing can help in neuroscience as a research platform," says Johannes Schemmel, a Heidelberg University researcher who heads BrainScaleS.

"We have a very massive neural network in the brain, but it's on the scale of 99% idle," says John Paul Strachan, who leads the neuromorphic compute nodes subinstitute at the Peter Grünberg Institute at the Jülich Research Center in Germany.

SpiNNaker and Loihi systems are fully digital. But BrainScaleS is a hybrid: It has analog signals for emulating individual neurons and digital ones for communications among neurons. "We've developed electronic circuits from transistors that behave similar to neuron synapses in the biological brain," says Schemmel. "They are all continuous analog quantities."

At higher levels, however, "we use digital communication between the neurons, because in principle there is no real analog communication possible," Schemmel says.

The brain is highly sparse: When a neuron fires in response to a stimulus, its signal is transmitted only to the thousands of other neurons it connects to, not to the billions of others in the brain. Sparsity is critical to brain function. "If all our neurons were firing and communicating, we'd heat up and die," says Strachan. But working with sparse data isn't an ideal fit for HPCs. "If the hardware has been designed to optimize for dense computations, it will be idle or doing a bunch of multiply-by-zero operations," he says. That means that simulating one second of just a tiny portion of the brain on an HPC today requires minutes of processing time.

The brain has various mechanisms to keep processing to the absolute minimum required, says Mayr, "but AI networks do a lot of irrelevant stuff. Take a video task, where every new frame of a video only contains maybe 2–3% new information, and even that can be compressed. All the rest is rubbish; you don't need it. But with a conventional AI HPC chip-based approach, you have to compute all of it."

"One of the biggest research tasks in computational neuroscience is to merge the function of the brain with what works in AI. This is the holy grail," says Schemmel. Ideally, AI training would use localized learning rules that work at the level of neurons and synapses. Such rules could also permit robots to learn without needing to be uplinked to computers.

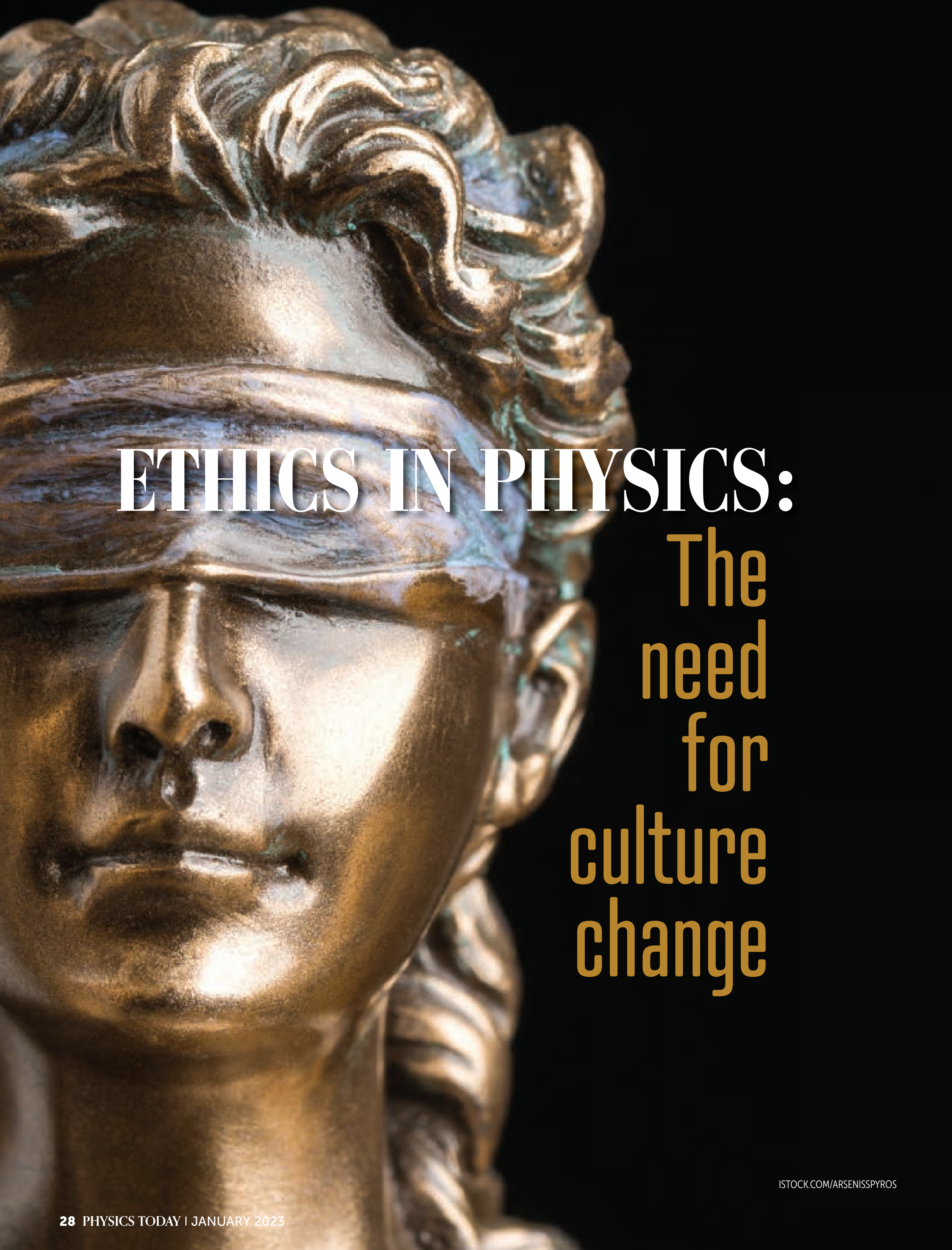
Limited funding is a restraint on the mostly academic field. Hardware is expensive to build, and it's not surprising that Intel has the most advanced neuromorphic chips, says Schemmel. Algorithms are needed, and their development lags the state of hardware. "We now have large-scale platforms that can support spiking networks at bigger scales than most people can work out what's useful to do with them," says Furber.

Interchangeability is another issue. "We haven't come up yet with a neat software framework that the neuromorphic guys can all subscribe to," says Mayr. "We need to standardize a lot more."

Yet perhaps the greatest limitation on R&D is a paucity of trained scientists, particularly computational neuroscientists. "Students have to have knowledge on a lot of different levels. You need longer to train; you can't compartmentalize problems like you can do in software engineering nowadays," says Schemmel.

David Kramer

ETHICS IN PHYSICS: The need for culture change



ISTOCK.COM/ARSENISSPYROS

Frances Houle is a senior scientist at Lawrence Berkeley National Laboratory. **Kate Kirby** is CEO emerita of the American Physical Society. **Michael Marder** is a professor of physics at the University of Texas at Austin.



Frances A. Houle, Kate P. Kirby, and Michael P. Marder

A new American Physical Society survey shows that although ethics education is more prevalent than it was nearly two decades ago, unethical research practices and harassment are still significant problems in the physics community.

In 2002 two highly publicized events shattered the common complacent view that the quantitative nature of physics research and strong peer-review practices would shelter the discipline from ethics violations. The first, at Lawrence Berkeley National Laboratory, was the retraction of Victor Ninov's claimed discovery of two new elements[1] (atomic numbers 116 and 118). The other, at Lucent Bell Labs, was mounting suspicions about Jan Hendrik Schön's data showing extraordinary properties of many novel materials, including high-temperature superconductors and thin films for device applications. (See Physics Today, November 2002, page 15.) Investigations at both institutions uncovered flagrant data fabrication. Those events showed that ethical practice in physics could not be taken for granted and added to a growing awareness that ethical practice in scientific research was not a given.

The American Physical Society's Panel on Public Affairs (POPA), which in 2002 had the primary responsibility for ethical matters, commissioned a task force charged with understanding how physicists are taught about ethics and with making recommendations for further actions APS could take to address ethical concerns. The task force—on which two of this article's authors (Kirby and Houle) served—surveyed physicists at diverse career stages in 2003. The most informative survey was of what were then called junior members, which roughly corresponds to today's APS Early Career members. Those physicists had acquired their PhDs three years or less before the survey and could speak to their experiences as students, postdocs, and newly independent researchers. They were asked how they learned about ethical practices and what their experiences were with ethics issues in their research training. That survey found a distressing rate of unethical research practices and a lack of formal ethics training, as described in an article from two of us (Kirby and Houle) on page 42 of the November 2004 issue of Physics Today.

In 2020 a follow-up survey was sent out to two APS member cohorts, early-career scientists and graduate students, to investigate whether ethics awareness and practice had changed since the original survey. The data show that although ethics education improved over the 17 years—addressing what a 2003 respondent called "the silence that exists now"—serious challenges remain. The push to do flashy science and publish numerous papers creates pressure to cut ethical corners. Early-career physicists and graduate students also continue to report mistreatment and abuse. Drawing from the responses, the APS Ethics Committee has formulated recommendations for consideration by the APS leadership, which are given at the end of this article.

Box 1. Research misconduct

The Office of Science and Technology Policy defines "research misconduct" as "fabrication, falsification, or plagiarism in proposing, performing, or reviewing research, or in reporting research results."[7]

▶ Fabrication is making up data or results and recording or reporting them.

▶ Falsification is manipulating research materials, equipment, or processes or changing or omitting data or results such that the research is not accurately represented in the research record.

▶ Plagiarism is the appropriation of another person's ideas, processes, results, or words without giving appropriate credit.

The office's research misconduct policy also sets the legal threshold for charges of misconduct. To be considered research misconduct, actions must represent a "significant departure from accepted practices," be "committed intentionally, or knowingly, or recklessly," and be "proven by a preponderance of evidence."[7]

Original survey and its aftermath

In the 2003 surveys, unethical practices were narrowly defined according to the still-current Federal Policy on Research Misconduct, explained in box 1. The definition includes fabrication of data, falsification of research processes or misrepresentation of the research record, and plagiarism, often shortened to fabrication, falsification, and plagiarism (FFP). The FFP definition establishes a minimum standard for acceptable behavior and does not imply that all other behaviors are acceptable. For example, it does not encompass criminal behavior, conflicts of commitment, violations of grant-management policies, or other unacceptable behaviors not unique to research, such as discrimination and harassment.

The original APS survey focused on FFP and the best practices for preventing that behavior, such as maintaining an accurate research record and properly citing the literature. Nearly 50% of APS junior members responded—most within hours of receiving the web-based survey. That remarkable response rate suggested the topic hit a nerve with the group. The responses revealed that ethics were not routinely taught in any part of the educational environment, including laboratory and lecture courses and research groups. Moreover, open-ended responses revealed a shocking level of abuse of students and postdocs, including harassment, threats, and expectations of overwork.

As a result of those findings, APS issued a statement on respectful treatment of subordinates and launched a Task Force on Ethics Education to create a set of case studies specific to physics as a resource for active education about research ethics. (The library of case studies is now linked to the Ethics Program webpage of APS's website.) The Task Force on Ethics Education also recommended establishing a standing committee on ethics in APS, but that recommendation was not adopted at the time. The then editor-in-chief of *Physical Review*, Martin Blume, brought together an international consortium of scientific journal editors that led to the formation of the Committee on Publication Ethics. It has put in place many standards and processes for journals to ensure the integrity of the research record. Those standards impact how papers are submitted for publication, how journals evaluate the integrity of those manuscripts, and how concerns about specific papers are managed.

After 2003, ethics-focused activities in APS went into a quiet period, aside from the work of the Task Force on Ethics Education. Other organizations, however, continued to work on ethics education. As part of the America COMPETES Act in 2007, NSF was and still is required to ensure that any institution applying for research funds provides appropriate training in responsible and ethical conduct of research for students and postdocs. American Geophysical Union (AGU) members raised issues about how people were treated in the field and pointed to the impacts of harassment on the scientific enterprise. In response, AGU created a code of conduct for its meetings and issued the comprehensive 2017 document *AGU Scientific Integrity and Professional Ethics*, which expanded scientific misconduct beyond FFP to include mistreating people. That same year, the National Academies of Sciences, Engineering, and Medicine issued the report *Fostering Integrity in Research* to address

Box 2. Ethics surveys

The 2003 American Physical Society survey was the first to examine ethics in practice in physics and among the first to examine ethics in any of the physical sciences. Since then important surveys of physics and other disciplines have been published and revealed nuances in how the scientific enterprise works. The frequency of misconduct is somewhat lower in the physical sciences than in biological, medical, and social sciences, but the patterns and types of misconduct are similar. Those patterns help pinpoint where significant improvements in ethics education and practice are needed in all sciences.

Reports examined ethics in medical physics,[8] sexual harassment experienced by female undergraduate physics majors and how that negatively affects their persistence in STEM (science, technology, engineering, and mathematics) fields,[9] the scope of National Institutes of Health–funded scientists' misconduct beyond fabrication, falsification, and plagiarism,[10] and research practices across disciplines in the Netherlands.[11] The Dutch survey, for example, showed that half the respondents admitted to questionable research practices and that about 4% said they had fabricated or falsified data in the preceding three years. The findings in those publications are consistent with those of the American Physical Society surveys in 2020 and 2003.

concerns that a lack of focus on ethics, including research misconduct and detrimental research practices, places the systems that fund and train young scientists at risk.

In 2017 one of us (Kirby) was serving as CEO of APS and another of us (Houle) became the chair of POPA, which is responsible for the oversight of ethics and for APS's policy statements. We realized that it was an opportune time for POPA to undertake a significant refresh of the APS ethics statement. We saw that scientific misconduct occurred across all disciplines, not only physics, in part because of the high-pressure and competitive research climate. (For an overview of ethics surveys across fields, see box 2.) Additionally, people who are considered outsiders, such as underrepresented individuals, or powerless, such as students, were often subject to abuse. POPA saw that the existing APS ethics policies needed to be updated and that a new approach was needed to communicate ethics expectations beyond a series of short, disconnected statements.

After considerable work by a group of POPA members and external experts, completed when another one of us (Marder) was POPA chair, APS adopted a unified comprehensive set of Guidelines on Ethics, part of which is shown in box 3. The lengthy document covers many aspects of ethics, including core topics addressed in earlier statements, such as FFP, conflicts of interest and commitment, treatment of subordinates, and authorship. It also adds elements, such as the Code of Conduct for APS Meetings, guidance on the appropriate use of research funds, and sections that raise harassment and bias to the level of ethical violations. At the same time, POPA recommended and the APS Council approved the establishment of a committee on ethics.

The Ethics Committee (EC) started its work in 2019. Among many initial activities, the EC proposed processes to ensure that ethical conduct is considered when nominating physicists for awards and elected positions in APS and to revoke honors or appointments of individuals who had been found by institutional investigations to have committed violations called out in the APS Guidelines on Ethics. The EC also recognized the importance of measuring physicists' awareness of ethics to compare with the 2003 findings. With oversight from the EC, APS worked closely with the American Institute of Physics's Statistical Research Center to craft, conduct, and analyze the 2020 survey. (The American Institute of Physics is the publisher of Physics Today.)

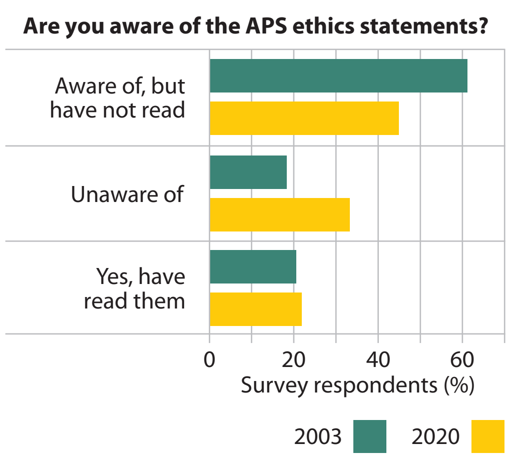
Box 3. APS Guidelines on Ethics

The American Physical Society Guidelines on Ethics rest on the principles given in its preamble (https://www.aps.org/policy/statements/19_1.cfm): "As citizens of the global community of science, physicists share responsibility for its welfare. The success of the scientific enterprise rests upon two ethical pillars. The first of them is the obligation to tell the truth, which includes avoiding fabrication, falsification, and plagiarism. The second is the obligation to treat people well, which prohibits abuse of power, encourages fair and respectful relationships with colleagues, subordinates, and students, and eschews bias, whether implicit or explicit. Professional integrity in the conception, conduct, and communication of physics activities reflects not only on the reputations of individual physicists and their organizations, but also on the image and credibility of the physics profession in the eyes of scientific colleagues, government, and the public. Physicists must adopt high standards of ethical behavior, and transmit improving practices with enthusiasm to future generations."

Then and now

We (Houle, Kirby, and Marder) and the other members of the EC wanted to know how the physics ethical landscape had evolved since the 2003 survey. The 2020 survey thus repeated many of the same questions word for word from the 2003 survey. The 2003 survey went to all APS junior members, and 748 responded. The 2020 survey had a roughly 30% response rate and received 1390 responses from APS members within five years of their PhD, the most similar current APS membership cohort. In 2003 and 2020, the EC received thousands of responses to open-ended questions. As part of the analysis of the 2020 survey, James Heath of Austin Community College in Texas grouped those responses into categories, and we (the authors) selected representative quotes.

As shown in figure 1, around the same percentage of early-career APS members had read the previous APS ethics statements in the 2003 survey as had read the current guidelines in



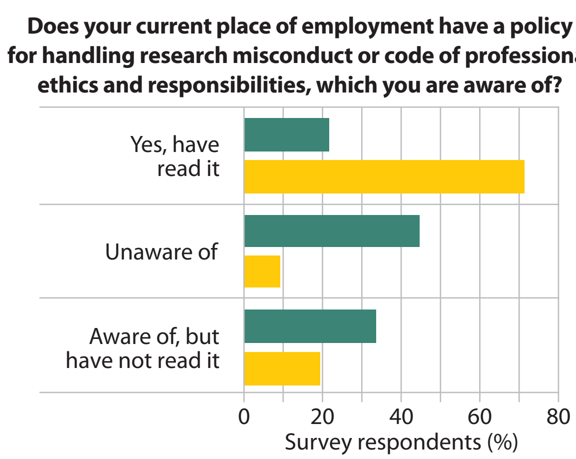


FIGURE 1. SURVEY RESPONSES from early-career American Physical Society members in 2003 and 2020 show how their awareness of ethics statements and guidelines has changed.

the 2020 survey. But in 2020 far more of those surveyed knew about the policies for misconduct at their institutions. In 2003 only 22% had read their institutional policies for misconduct, whereas in 2020 the percentage rose to 71%.

In 2003, 61% of early-career APS members said they had never had formal ethics training, but by 2020 that percentage dropped below 5%. In both surveys, group meetings with research supervisors were the most common training setting; see figure 2. The 2020 respondents were somewhat less likely to have discussed ethics informally and somewhat more likely to have discussed the issues in coursework.

In the earlier survey, 7.7% of the early-career APS members said they had at some point felt pressure to violate professional ethical standards. In 2020, that percentage significantly increased to 12.5%. In open-ended responses, the 2020 early-career members described the factors that led them to consider ethical violations: pressure from supervisors, pressure to publish, pressure to acquire funding, pressure to get a high citation count, and pressure to obtain significant results even if data must be manipulated. Here are some representative anonymous responses:

> *"[There is a] declining quality of publications due to senseless publication pressure. In my opinion, the number of publications should be in no way an indicator for the scientific standing of e.g. an applicant. What is better: One revolutionary, mind-blowing paper, o[r] a large number of meaningless papers? Often only the number of publications is important."*

> *"Supervisors and funders demand results and don't appreciate that ethical and thorough research takes time."*

> *"My advisor was unethical and pressured me to do unethical things. I resisted and was punished by him for it."*

By contrast the percentage who observed or had personal knowledge of ethical violations showed a significant drop from 39% in 2003 to 26% in 2020. Enthusiasm for that progress must be tempered, however, when specific violations are examined in more detail.

The respondents could select from an identical list of ethical violations in 2003 and 2020. Although a smaller percentage of 2020 respondents reported seeing any violations at all, those who reported violations reported more of them. The net result is that many violation categories show no significant change between 2003 and 2020.

The two most serious ethics violations that affect the research record are plagiarism and data falsification. The incidence of plagiarism remained about the same as in 2003, as shown in figure 3. Data falsification, on the other hand, increased from 3.9% of respondents reporting witnessing it in the earlier survey to 7.3% in 2020. The result is consistent with the increased pressure to commit ethical violations that early-career members reported. For example, some respondents said:

> *"I felt as if I wouldn't survive in the environment that I was in if I didn't 'go with the flow.'"*

> *"We wouldn't fake data, but we would sometimes omit data for impact reasons or shove it deep in the supplementary. For example, one measurement or two measurements that show good agreement with our hypothesis would go into the main manuscript, and any subsequent ones that were noisier or 'weird' would go to supplementary or be left out."*

There was a modest although significant decrease in the incidence of some more minor infractions: putting nonauthors on

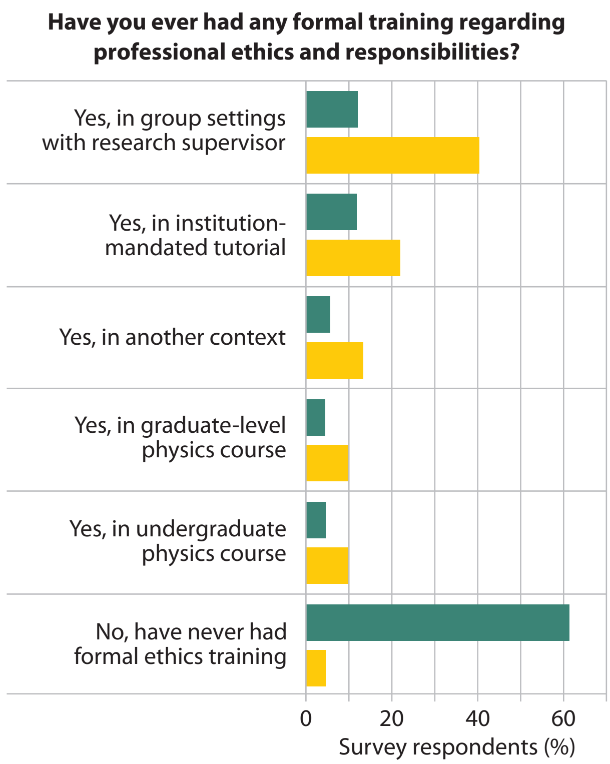


FIGURE 2. ETHICS TRAINING has become more common in 2020 than it was in 2003, according to the responses from early-career American Physical Society members.

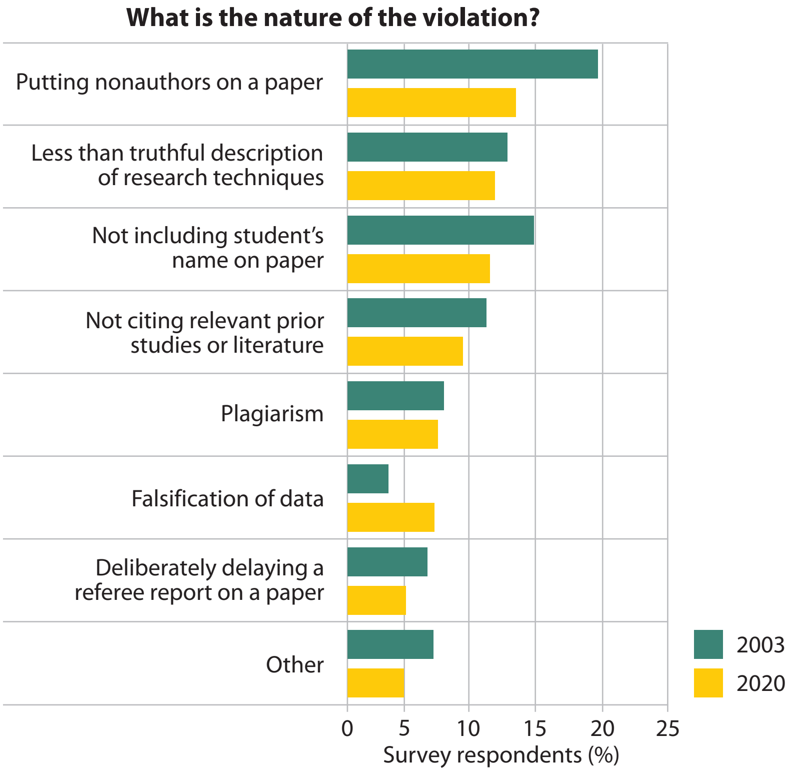


FIGURE 3. ETHICAL VIOLATIONS across a range of categories were observed by different percentages of early-career American Physical Society members in 2003 and 2020. Notably, although many categories show no significant changes, the rates of data falsification nearly doubled in 2020 compared with 2003.

a paper, omitting a student's name from a paper, and failing to cite relevant literature.

The 2020 survey included information from 2829 graduate students, a group not included in the 2003 survey. The most noteworthy differences between graduate students and early-career members are that graduate students were significantly less likely to report having seen ethical violations—19% versus 26%—and significantly less likely to report pressure to violate ethical standards—9% versus 13%. That difference may be because the early-career members have been in the field longer and have greater awareness. Alternatively, it may be because those who continue in a research career feel pressure to succeed more acutely and are thus more likely to speak up. Another possibility is that the graduate students may not feel confident or empowered enough to protest even in an anonymous survey. One respondent said:

> *"For us coming from humble backgrounds standing up against injustice is incredibly hard for the fear of losing our educational degrees. It would be extremely nice if APS monitor[ed] physics departments in the Universities to keep an eye out for unjustified unethical behavior towards minority/women."*

Harassment

The new survey also included questions on harassment that had not been posed in 2003. To those questions overall, there were 3577 responses from graduate students and early-career APS members, of whom 795 identified as women, 2348 identified as men, 37 identified as neither women nor men, and 397 preferred not to identify gender.

The differences between the experiences of men and women are striking, as shown in figure 4. Women are five times as likely as men are to feel that they were treated differently, ignored, or put down because of their group affiliation and to have heard comments of a sexual nature or tone. Around 15% of the female respondents reported being touched without permission compared with 2% of male respondents. The written comments even included multiple reports of rape by coworkers. Respondents with gender identities other than male or female gave responses between those of men and women.

People who have been treated badly may be more likely to respond to surveys. But the 70 early-career women who reported physical harassment constitute 8.3% of all female early-career APS members. That prevalence is unacceptable even if none of the nonrespondents have been harassed.

A question about whether the respondent had reported inappropriate behavior and whether they were satisfied with the institutional response elicited more than 900 open-ended responses. The majority (740) said they did not report the harassment. For example, one respondent wrote:

> *"As it happened to me, I chose not to mention it. I was also about to graduate and didn't want anything to delay that."*

Of the 190 respondents who said they reported the behavior, only 61 said they were satisfied with the institutional response, while 93 said they were unsatisfied. The others didn't declare one way or the other. More than half (97) of the respondents said they feared retaliation. One respondent said:

> *"I and several others reported the sexual harassment. I was extremely unhappy with the institutional response. The institution moved very slowly and made the person who was harassed repeat her story many times over to many different people reopening the wound constantly."*

Interpersonal interactions

The early-career physicists of 2003 are today's midcareer scientists. Although today's early-career scientists are more aware of responsible research conduct and ethical practices in general, the experiences of physicists at all career levels have not changed significantly. The physics community still needs to deal with serious ethical issues.

One of the last questions on the survey asked what the respondents thought were the most serious professional ethics issues that should be addressed by APS. Of the total 1199 responses, interpersonal ethics issues—such as discrimination, harassment, and abuse of power—were listed twice as often (60% of responses) as professional practice issues (30%). One respondent wrote:

> *"I have not witnessed unethical practices in data collection/reporting. I have witnessed unethical personal interactions."*

Among those professional ethics topics, 17% of respondents deemed data manipulation the most serious, but the pressure to publish, the review process, and citation and authorship each garnered 4–5% of responses. Here are some representative responses about the potential role of APS in addressing such ethical issues:

> *"The APS has the greatest authority to speak on issues of scientific ethics."*

> *"I think APS is in a strong position to set the tone for professional conduct in the physics community at large."*

> *"I think there is not only a concerning lack of diversity in physics, but a culture that reinforces the homogeneity through biased comments and attitudes. Addressing these is the most important ethics issue I think APS should deal with."*

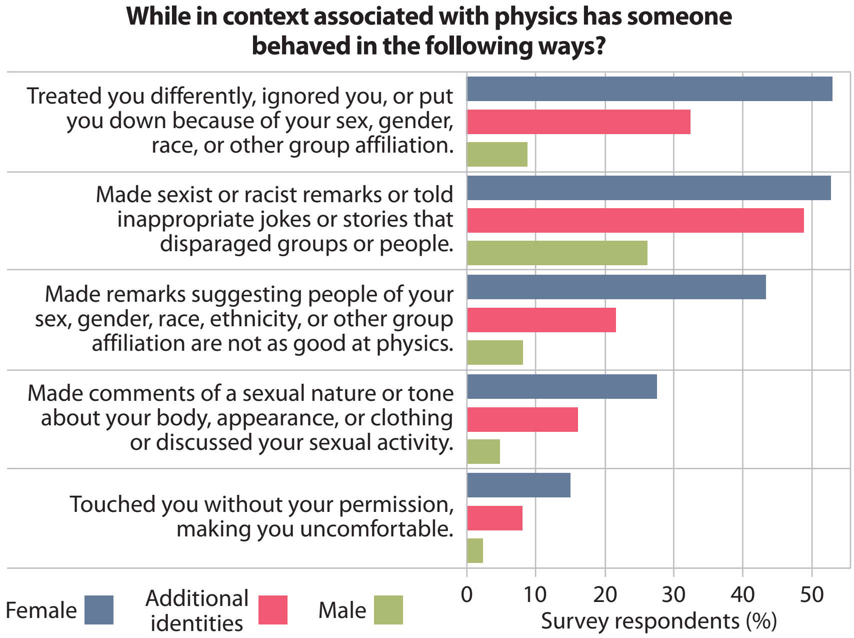


FIGURE 4. HARASSMENT is a common experience, particularly for women, as reported by graduate students and early-career American Physical Society members in 2020. The 397 respondents who left the question about their gender blank are not included.

Discrimination, harassment, and abuse of power often stem from and flourish in the unequal power dynamics in academia, which can become toxic when advisers, principal investigators, or other authority figures are themselves under pressure to publish. As one respondent said:

> *"The advisor has complete control over the student's future, so preventing that inherently unequal power dynamic from becoming a major problem is absolutely paramount."*

Respondents noted that toxic dynamics give rise to increased stress, mental health problems, and unsustainable work–life balance for students and postdocs. Numerous studies have found that individuals who are part of one or several underrepresented groups—such as women and people of color—experience more toxic behavior than, for example, white men.[2] One survey respondent said:

> *"Everyone I know who is not a cisgendered heterosexual white man [and] who has left the field has left because of how they were treated, not because they didn't want to be a physicist."*

As in the 2003 survey, many 2020 early-career scientists said that the pressure to publish research results quickly and in high-impact journals leads to a decline in the quality of papers, careless or shoddy handling of data, and other ethical concerns. Many respondents made accusations of blatant data falsification and manipulation:

> *"Distorted data and interpretations are widespread. These are not obvious violation[s] of professional ethics but can cause harm and waste to other researchers [that] trust the publications. Grad students, and researchers in general, should receive a formal course in data collecting and reporting practice."*

> *"However, instances of data-falsification, plagiarism, unnecessary inclusions of authors on papers, etc. are either directly due to or at least encouraged and exacerbated by the highly competitive environment of science/academia."*

The responses show that early-career scientists have a strong desire for APS to address interpersonal interactions as well as the ethics involved in professional practice. Doing so is a significant challenge for the organization and will involve establishing and helping to enforce new behavioral norms in the physics community.

Recommendations

With the concerns of students and early-career physicists in mind, the APS Ethics Committee formulated a number of recommendations currently under consideration by APS leadership.

1. Develop educational materials

Although ethics education has improved at the university level over the past two decades—driven in part by NSF requirements for responsible and ethical conduct of research and Title IX compliance—the survey results cast doubt on its effect. That minimal influence may be because of the nature of most formal institutional ethics training: largely web based, without detailed discussions of situations, and lacking opportunities for questions. APS should develop new materials that are relevant to physics and effective.

2. Foster more respectful behavior

Changing the physics culture to embrace respectful treatment of others as a core value could help reduce instances of harassment, discrimination, and toxic power dynamics.[3] Much work remains to reduce the pressures that have fueled and enabled such behavior. A new initiative, the APS Inclusion, Diversity, and Equity Alliance, helps physics departments and laboratories to share and implement strategies for improving diversity, equity, and inclusion and thus decrease instances of harassment and discrimination. The goal is a more respectful, welcoming, and inclusive community. The Effective Practices for Physics Programs guide, which was created in a collaboration between APS and the American Association of Physics Teachers, also provides practices and strategies to improve physics-department culture in many areas, including ethics.[4]

3. Identify new ways to assess researchers

The San Francisco Declaration on Research Assessment[5] and the Leiden Manifesto[6] are important initiatives in the social science and biology communities that promote moving beyond simplistic metrics, such as journal impact factors or *h*-indexes, to evaluate the quality of scientific work. APS should consider following suit and establishing a task force to develop ideas for assessing physics research quality that can guide hiring and tenure or promotion review at research institutions.

4. Highlight accountability

To demonstrate that the APS Guidelines on Ethics are taken seriously, APS should find ways to highlight when its policy for revocation of honors has been implemented and an honor has been revoked. APS should also promote structural best practices that reduce the absolute power that an individual research adviser has over the careers of graduate students and postdocs. For example, rather than relying solely on the opinion of the adviser, a departmental committee could meet once a year or more to assess a student's progress, identify problems and roadblocks, and help ensure timely completion of the PhD.

5. Expand the concerned community

In an increasingly interdisciplinary scientific world, changing the physics culture and advancing ethical best practices can only be accomplished by working with other scientific and engineering societies. APS leadership should reach out to other science-based organizations and explore mutual interests, activities, and potential opportunities.

The authors are grateful to the many people involved in this project, especially Jeanette Russo for her work on the survey, James Heath, the members of the Ethics Committee from 2019 to today, and the APS leadership for their comments and support. We thank the respondents to the surveys for their time and thoughtful comments, which are tremendously helpful to APS and the physics profession.

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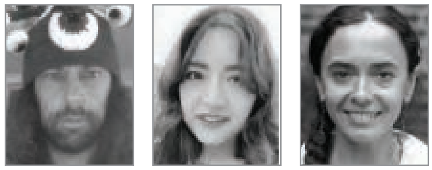

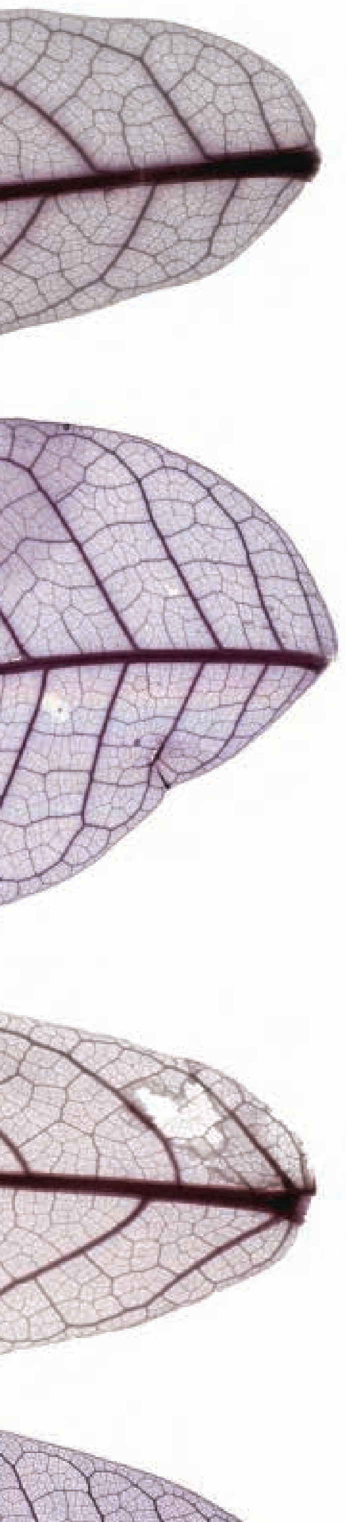

THE TOPOLOGY OF DATA

Mason A. Porter, Michelle Feng, and Eleni Katifori

Topological data analysis, which allows systematic investigations of the "shape" of data, has yielded fascinating insights into many physical systems.

A wealth of complex data is increasingly available in almost every aspect of the physical and social world. Such copious data offer the potential to help unlock new ways of understanding and manipulating our surroundings. The demographic characteristics of human populations convey information about heterogeneous regions of a city or a country, and our online activities encode data about who we are and what we do. Networked systems—in people, cities, animals, plants, computers, and more—are also rich in data, which are present both in their structure and in their dynamics. The flows of nutrients in vascular structures, the complicated dynamics of fluids, and the forces in granular materials all provide huge amounts of complex data. Parsing—and hopefully eventually understanding—such data requires a diverse set of tools.

One family of tools, called topological data analysis (TDA), employs ideas from the mathematical field of algebraic topology.[1] Algebraic topology gives a framework to rigorously and quantitatively describe the global structure of a space. By building on and adapting this framework, researchers in physics and many other disciplines are increasingly using TDA to examine how the "shape" of data changes when one views a system at different scales.[2] TDA has led to fascinating insights in biophysics, granular materials, fluid dynamics, and many other areas. It has been used to study phase transitions,[3] temperature fluctuations in the cosmic microwave background,[4] chaotic behavior in nonlinear dynamical systems,[5] and much more.[6]

In this article, we present a few examples of TDA in condensed-matter and soft-matter physics. We hope that this small selection of TDA research in physics will help illustrate the flavor of insights that one can obtain by applying a topological lens to data.

A few ideas from topology

Topology is a branch of mathematics that concerns the shapes of objects.[1] It provides a framework that describes the properties of an object that stay the same if we stretch it, shrink it, or bend it without any tearing or gluing. Consider a circular rubber band. Because we can stretch the rubber band into an oval, the circle and the oval are topologically equivalent. However, the rubber band is not topologically equivalent to a segment of a string: The circular rubber band has a hole in the middle, but the string does not.

An important aspect of topology is the characterization of the connectedness of objects by counting their numbers of pieces and numbers of holes. Researchers use that information to group objects into different types. For example, a doughnut has the same number of holes and the same number of pieces as a coffee cup with one handle (see figure 1), but it is different from a filled sphere, which has the same number of pieces but does not have any holes.

Algebraic topology gives a framework to rigorously and quantitatively describe the global structure of a space. Methods for characterizing the global structure of a topological space and objects within it rely on information about the entire space. If we look at a neighborhood of any point on a sphere, we obtain a surface with the same properties as a plane. By zooming in extremely closely, we no longer notice the sphere's curvature. To a human standing on a very large sphere, such as a planet, the surface appears to be flat. We recover the fact that the sphere has curvature by considering all of its neighborhoods, but we still don't pick up whether there's a void inside the sphere. To fully characterize the structure of a sphere, we need to consider the entire sphere at once.

To consider an entire object at once, we use the algebraic-topology concept of homology, which allows us to distinguish between objects based on their numbers and types of "holes." To make this distinction, we need the notion of a topological space X. Such a space consists of a set of points, along with neighborhoods of each point, that satisfy certain axioms that relate them.[1] Intuitively, we consider neighborhoods of a certain size around each point and define what it means for the points to be "close" to each other based on whether their neighborhoods overlap. We do not require a numerical value to quantify that closeness; we just need to know when neighborhoods overlap. This gives crucial flexibility for using topological tools in applications.[2]

To develop an understanding of homology, it helps to be more precise. The homology of a topological space X is a set of topological invariants that are represented by homology groups $H_k(X)$, which describe k-dimensional holes in X. The rank of $H_k(X)$ is called the Betti number; it is analogous to the dimension of a vector space and counts the number of k-dimensional holes. A feature in H_0 is zero-dimensional and can be visualized as a point; the rank of H_0 is the number of distinct connected components in X. Similarly, a feature in H_1 is one-dimensional and can be visualized as a cycle (that is, a loop). A feature in H_2 is two-dimensional and can be visualized as a cavity. Researchers also examine H_k for larger values of k, but it is harder to visualize the associated features.

Returning to our filled sphere and our coffee cup, the sphere consists of one connected component and zero 1D holes—that is, no cycles—so $\text{rank}(H_0) = 1$ and $\text{rank}(H_1) = 0$; its zeroth Betti number is 1 and its first Betti number is 0. By contrast, a coffee cup has $\text{rank}(H_0) = 1$ and, because of its 1D hole, it has $\text{rank}(H_1) = 1$. We can also use homology to distinguish between a filled sphere and a spherical shell. The former does not have a cavity, so $\text{rank}(H_2) = 0$, but the latter does, so $\text{rank}(H_2) = 1$.

The shape of data

To identify "holes" in a data set and thereby describe its topological "shape," we need to assign a topological structure to the data and compute topological invariants. Homology groups are good invariants because there are efficient algorithms to compute them.

The most widely used tool in TDA is persistent homology (PH). In PH, one examines homologies across the scales of a data set.[2,7] Traditionally, one interprets topological features, such as cycles or cavities, that exist for a large range of scales—that is, persistent features—as genuine features of a data set and topological features that exist for only a small range of scales as noise.

FIGURE 1. TOPOLOGY is a branch of mathematics that concerns the shapes of objects. The aim of topology is to describe the properties of an object that stay the same if it is stretched, shrunk, or bent without any tearing or gluing. A classic joke is that a topologist cannot tell the difference between a coffee cup and a doughnut because they both are a single object with a single hole; that is, they are topologically equivalent. (Courtesy of Henry Segerman and Keenan Crane; used with permission.)

To introduce the main idea of PH, let's start with a collection of dots (see figure 2). Such an object, called a point cloud, is commonly studied in TDA.[2] Point clouds have an inherent 0D structure, and they thus have few interesting topological properties when viewed as a finite collection of points. We now place a ball of some radius ε around each point. The scaling parameter ε, which is sometimes called a filtration parameter, allows us to encode geometric information. The balls fill in areas between points that are close to each other. Essentially, we are squinting at a point cloud so that it blurs and takes some shape. The harder we squint—that is, as we increase the value of ε—the more the boundaries of the shape blur and expand. Points that start out as distinct begin to overlap with each other as ε increases, so the notion of what it means to be "close" changes.

Figure 2 demonstrates this idea with the Pokémon known as Jigglypuff. Jigglypuff starts out as a collection of dots—that is, a point cloud (figure 2a). As we increase the radius ε of the dots, progressively more of them overlap (figure 2b), and it becomes easier to identify Jigglypuff. As we continue increasing the radius of the dots, Jigglypuff has progressively fewer components (that is, $\text{rank}(H_0)$ decreases) and develops some 1D holes (that is, $\text{rank}(H_1)$ increases). As ε becomes larger, some holes also disappear (figure 2c), and it becomes harder to identify Jigglypuff. Eventually, when ε becomes sufficiently large, all of the holes disappear (figure 2d). We can see different features of Jigglypuff at different values of ε. A topological feature is "born" at the value of ε at which it first appears and "dies" at the value of ε at which it disappears.

The images in figure 2 demonstrate how the topological features that one obtains from a point cloud change as one views them at different scales. To examine the features systematically, one constructs a computationally convenient mathematical object from such images.[7] One such object is a filtered sim-

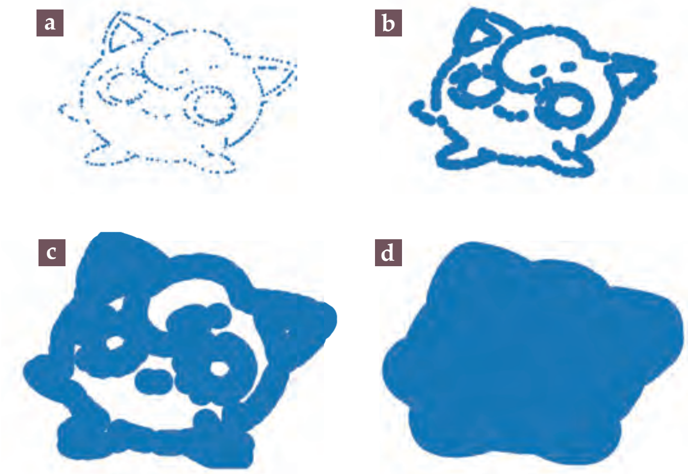

FIGURE 2. THICKENING THE DOTS of a point cloud and observing the changes in topological structure allows one to study the persistent homology (PH) of a data set. This figure depicts the Pokémon known as Jigglypuff, which we draw using dots of various sizes. As the dots thicken, both the number of connected components (that is, the 0D features) and the number of loops (that is, 1D holes, which are also called cycles) change. **(a)** When the dots are small, they do not overlap, so there are many components and no cycles. **(b)** As the dot size increases, some of the dots start to overlap, so there are fewer components; some cycles are also "born." At first, Jigglypuff becomes easier to discern, but **(c)** it then becomes harder to recognize until **(d)** eventually all of the cycles have "died" and it is one giant blob. By recording the dot sizes at which each component and each cycle is born and dies, we can track topological features in Jigglypuff. This collection of features and dot sizes is the PH of this thickening of Jigglypuff. (Adapted with permission from ref. 9.)

plicial complex, which is a sequence of simplicial complexes that are nested inside each other. A simplicial complex is a space that is built from a union of points, edges, triangles, tetrahedra, and higher-dimensional polytopes. (A polytope is a geometric object with flat faces and edges; it is a generalization of polygons and polyhedra to any number of dimensions.) The word "filtered" describes how simplicial complexes nest inside each other as one varies some parameter, such as the radius of the dots in figure 2.

Simplicial complexes are topological spaces that one can use to approximate other topological spaces in a way that captures their topological properties. For example, a tetrahedron can approximate a sphere. There are many choices for how to construct a filtered simplicial complex. For instance, in figure 2, the simplicial complex is based on distance (the dot size). For a given application, it is desirable to choose a construction that satisfies the intuition that genuine features are also persistent features.

The extension of homology to PH allows us to quantify holes in data in a meaningful way. We are interested in persistent holes (and other persistent features), such as Jigglypuff's eyes in figure 2, that exist for a large range of values of an adjustable parameter. When studying physical systems, it is desirable for the parameter to correspond to something physical. Such homological ideas have been used to analyze data sets in many applications.[2,7] The computation of PH has been especially prominent in neuroscience,[8] and it has also been used in areas such as granular physics, fluid dynamics, nonlinear dynamics, cosmology, string theory, and computer vision.

Introductions to PH and to TDA more generally are available for a variety of audiences. See reference 9 for an introduction to TDA and PH for teenagers and preteens, reference 2 for a recent review of TDA for a general physics audience, and reference 1 for a classic textbook on the mathematics of TDA. Reference 7 overviews PH and gives an introduction to the installation, use, and benchmarking of several software packages for it.

Amorphous and granular matter

TDA has yielded many insights into granular and amorphous matter. Notions of connectivity and gaps are natural in such systems,[10] and they relate to important physical ideas, such as which parts of a system will fail first and which physical quantities to measure to forecast the onset of failure. They are also relevant for obtaining insights into packing, jamming, and characterizing the different states of a system.

Lou Kondic and colleagues used PH to track how simulations of 2D granular force networks—sets of interparticle contacts that carry loads that are larger than the mean load of a system—evolve as a system crosses a jamming point.[11] They used the interparticle force as a filtration parameter. To compute H_0, they determined the distinct components of mutually contacting particles that experience forces above that force. They associated the jamming transition with a sudden large

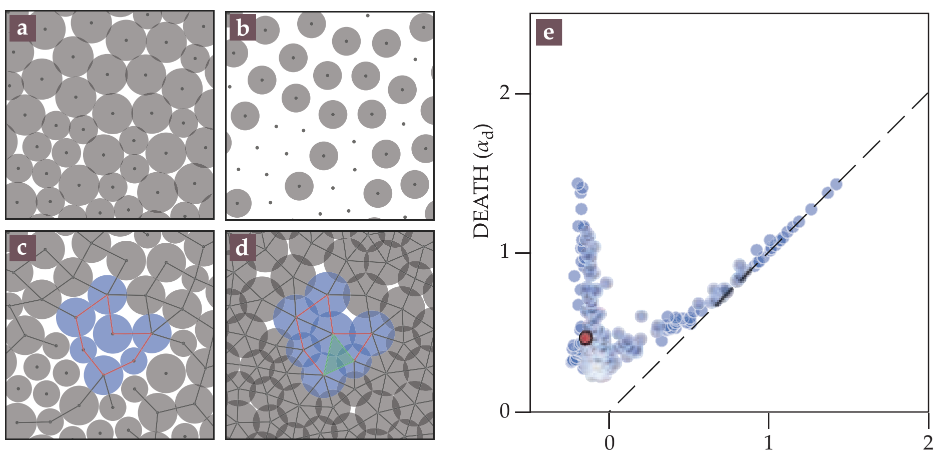

FIGURE 3. PERSISTENT HOMOLOGY of a packing of particles of two different sizes. **(a)** We place a node at the center of each particle. **(b)** Like the dots of the point cloud in figure 2, we center a disk on each of the nodes. The disk sizes are heterogeneous, but their radii depend on a single parameter α, which we discuss in the text. For the most negative value of α, the smallest disks are points. **(c)** For some larger value of α, the cycle (that is, a 1D hole) in red is born. **(d)** For some still-larger value of α, the cycle dies. **(e)** A persistence diagram tracks the birth (α_b) and death (α_d) coordinates of topological features, which are 1D holes in this example. (Adapted with permission from ref. 12. Licensed under a Creative Commons Attribution [CC BY] license.)

increase in the number of components, and hence in rank(H_0), above a threshold force that approximately equals the mean interparticle force in the system. Computing H_0 and H_1 also allows one to quantitatively describe the effects of bidispersity and polydispersity (the presence of particles of three or more sizes) and friction on the structure of granular force networks. In other studies, TDA was used to examine changes in the structure of polydisperse granular materials with packing fraction, the effect of compression on the relative prevalence of branching and compact regions in granular force networks, and more.[10]

In a recent study, Jason Rocks and colleagues used PH to systematically explore "softness" in amorphous packings of particles.[12] Notions of softness capture the propensity of particles to rearrange structurally. A good measure of softness should allow one to forecast structural rearrangements of particles. Using the approach that we illustrate in figure 3, Rocks and colleagues examined the topological structures of configurations at the onset of particle rearrangements in bidisperse particle packings and obtained interpretable, topologically informed descriptions of packing structure that are experimentally measurable.

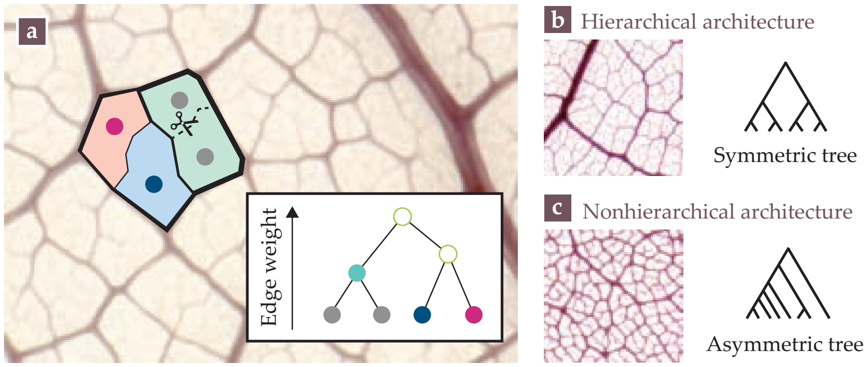

FIGURE 4. HIERARCHICAL DECOMPOSITION of the vein network of a dicot leaf. **(a)** A small portion of a leaf's vein network. Each vein segment is an edge of the network, and two or more segments intersect at nodes. Removing the thinnest edge causes two cycles—that is, 1D holes—to merge and form a single cycle that surrounds the light green region. The inset shows the tree graph that is associated with the merging. The colors of some of the nodes in the tree indicate their corresponding cycles in the leaf. The sequential removal of edges can yield trees with different structures. **(b)** A hierarchical, nested structure that is represented in idealized form by a symmetric tree. **(c)** A nonhierarchical structure that is represented by an asymmetric tree (which we depict in an idealized form). (Adapted in part from ref. 15.)

Consider the 2D packing of circular particles in figure 3a. We construct a distance-based simplicial complex that is known as an alpha complex. At the center of each particle i, we place a disk of radius $r_i(\alpha) = (R_i^2 + \alpha)^{1/2}$, where R_i is the radius of particle i and α is the filtration parameter. In essence, α is an interaction radius. When $\alpha > 0$, the disks are larger than their corresponding particles; when $\alpha < 0$, the disks are smaller than their associated particles. For the smallest value of α, we obtain figure 3b. At that minimum interaction radius, we have a point cloud.

The simplicial complex that corresponds to figure 3b consists of a set of nodes; these are the particle centers. There are no edges, triangles, or higher-dimensional polytopes that connect interacting particles. As we increase α, some of the disks overlap, and we add the associated polytopes to the alpha complex. Analogously to what we saw for Jigglypuff in figure 2, 1D holes are born (see figure 3c) and then eventually die (see figure 3d) as α increases.

A persistence diagram (PD) summarizes the births and deaths of topological features as a function of a filtration parameter. The PD in figure 3e conveys the births and deaths of 1D holes for progressively larger values of α. The horizontal axis of a PD indicates the filtration parameter values α_b at which features are born, and the vertical axis indicates the values α_d at which they die. Features that live longer—that is, that are more persistent—lie farther above the diagonal line.

Rocks and colleagues used PDs to quantify the topological structure of jammed packings and to connect that structure with dynamics.[12] Cycles—that is, 1D holes—play an important role in their topologically informed descriptions of packing structure. The birth value α_b measures the length of the longest edge in a cycle, and the death value α_d indicates the scale of the cycle in a packing. The researchers examined PDs for a range of system configurations. The birth and death values of cycles helped them examine the presence and absence of gaps between particles, which in turn allowed them to quantify local rearrangements of particles. The longest edge of a cycle with $\alpha_b < 0$ corresponds to a contact between particles, so such a cycle consists only of contacts. By contrast, the longest edge of a cycle with $\alpha_b > 0$ corresponds to a gap between particles; such a cycle may also include some contacts. The more gaps—and, hence, fewer contacts—that a particle has with its nearest neighbors, the more it participates in local rearrangements.

TDA can also help illuminate phase transitions, such as those between amorphous solids and other states. In amorphous solids—which include glasses, plastics, and gels—the atoms and molecules are not organized as a lattice. In a recent study of particle configurations in amorphous solids, Yasuaki Hiraoka and colleagues computed PH in random networks and random packings that they generated from molecular-dynamics simulations of various systems, including silica glass and copper–zirconium metallic glass.[13] They examined hierarchical structures in the systems by using PDs to characterize 1D and 2D homological features. They found that such topological features can clearly distinguish amorphous-solid states from liquid and crystalline states.

Vascular networks

From the unicellular and multinucleate slime mold *Physarum polycephalum* to the xylems of leaves and the circulatory systems of animals, vascular networks permeate every large-scale organism. The structure of a vascular network affects numerous crucial phenomena, such as the flow of water and other liquids, the distribution of nutrients in organisms, and the pressure distributions that drive nutrient flow. TDA is a valuable approach to study the properties of vascular networks and relate them to network function. For example, the computation of PH offers a potential tool for the early detection of subtle changes in microvasculature that can signify the onset of disease.

Vascular networks have hierarchical features (see figure 4) and are often dominated by cycles, which help determine system organization. Vein-width histograms and other prevalent

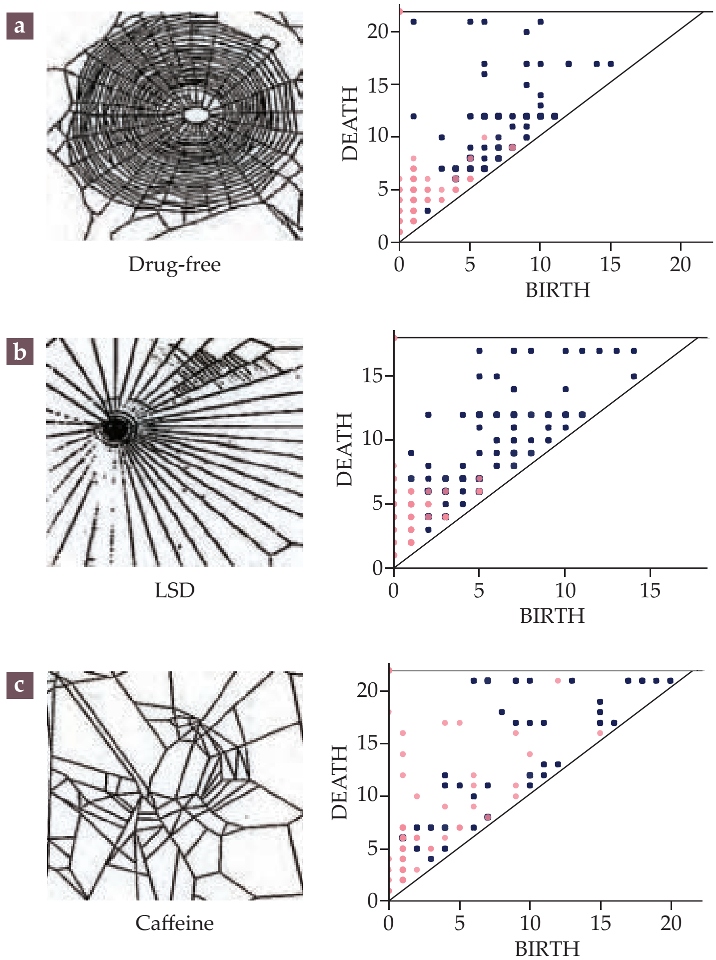

FIGURE 5. SPIDERWEBS and their associated persistence diagrams (PDs). The webs were produced by **(a)** a drug-free spider, **(b)** a spider under the influence of LSD, and **(c)** a spider under the influence of caffeine. In the PDs, pink disks indicate 0D features (that is, connected components) and blue squares indicate 1D features (that is, cycles). The spider that is under the influence of caffeine appears to have produced a particularly abnormal web. (Adapted with permission from ref. 18. The drug-free and caffeine spiderweb images are from D. A. Noever, R. J. Cronise, R. A. Relwani, *NASA Tech Briefs* **19**(4), 82, 1995; the LSD spiderweb image is from P. N. Witt, *Behav. Sci.* **16**, 98, 1971.)

tools to quantify the structure of vascular networks do not capture the hierarchical nature of their connectivity. Topological approaches, however, are able to uncover intricacies in the networks' hierarchical organization.

One starts by assigning a weight to each vascular segment, which is an edge between two junctions (that is, nodes) in a vascular network. Typical choices for edge weights are the segments' radii or conductances. As sketched in figure 4a, one can use edge weight as a filtration parameter by sequentially removing edges, starting from the one with the smallest weight—that is, the least significant vascular segment—and then removing the others in order by weight until finally removing the edge with the largest weight. The key in the analysis is the order in which one removes the edges; the actual values of the edge weights are not important.

At each stage of the above hierarchical decomposition, one calculates quantities such as the aspect ratios of cycles and tracks how they evolve. One can thereby quantify how the cycles in a vascular network are related to each other.[14] Vascular networks range from highly nested, fractal-like structures (see figure 4b) to seemingly random structures that are not particularly hierarchical (see figure 4c).[15] The traits that one can examine using such a topological approach complement traits that carry information about edge widths, edge lengths, and network geometry. Studying topological and geometric features enables the algorithmic identification of leaf species from leaf fragments.[15,16] Such an approach to leaf identification is analogous to identifying people from their fingerprints.

The conductances of the edges in a network of flows, such as a vascular network, do not fully determine network function on their own. One also needs to know the boundary conditions of the flows and the sources that drive the flows. In the vascular system of an animal, for example, it is important to consider the location of the heart and how much blood it can pump. If one knows the boundary conditions and conductances of the edges in a network, one can calculate the pressure that drives the flow through each edge and the pressure drop along each edge. The pressure drops carry information about both network structure and network function, and they provide sufficient data to examine PH in a flow network.[17]

Start, for instance, with an empty network and add edges one at a time in the order of the pressure differences along them. The pressure difference is thus a filtration parameter. Adjusting it yields a sequence of subnetworks of the original vascular network, and computing PH tracks topological changes across the sequence of subnetworks. For example, one knows which edge additions are birth edges that lead to the formation of new network components and which are death edges that merge existing components. A PD that records the births and deaths of components allows one to determine regions of the original vascular network that have relatively low pressure differences.

Think of a vascular network as a mountainous landscape in which the height of each edge is the pressure difference along that edge. If we start with an empty network, birth edges correspond to valleys (local minima) in the landscape and death edges correspond to the lowest mountain passes between neighboring valleys. If we instead start with a complete vascular network and remove edges one at a time, rather than adding them, then birth edges correspond to mountain peaks (local maxima) and death edges correspond to the highest mountain passes between neighboring peaks.

Rocks and colleagues used such a PH approach to study vascular networks that are tuned to deliver specific amounts of flow through particular edges or are tuned to have particular pressure drops along some predetermined edges.[17] They found well-delineated sectors of relatively uniform pressure that are not apparent from the underlying network structure. The pressure drops at the boundaries between those sectors revealed the pressures to which the networks were tuned.

Harnessing spatial features

Many of the examples that we have discussed are spatial in nature. A confounding factor in the use of PH to study spatial systems is that although it is able to capture information across different scales, traditional distance-based PH constructions can have trouble with applications in which differences in distance scales are less important than other features. For example, in human geographical data, traditional PH constructions often detect differences in population densities, like those between urban and rural areas. They can thereby miss important signals, such as voting patterns, that are not based on density.

Two of us (Feng and Porter) used PH to study spatial network models, street networks in cities, snowflakes, and spiderwebs.[18] We found it particularly amusing to examine the topological structure of webs that were built by spiders under the influence of psychotropic substances (see figure 5). The 2D images of spiderwebs provided initial surfaces for the construction of a filtered simplicial complex based on image geometry. The simplicial complex took advantage of the physical structure of spiderwebs and is also suitable for other images, maps, and so on. The topological structures of the spiderwebs—and, hence, the resulting PDs—differed considerably for spiders that were exposed to different drugs. The spiders that were given caffeine or chloral hydrate, a sedative used in sleeping pills, produced particularly abnormal webs.

Outlook

Topological ideas have yielded many insights into the "shape" of data in diverse applications. However, many challenges remain. A key one is the incorporation of system features, such as spatial embeddedness and known physical properties, into the construction of simplicial complexes and thus into how one applies a topological lens. Topological approaches such as PH are enabling important advances in the study of physical phenomena, and they promise to yield further insights into condensed-matter systems, biophysical systems, and many other areas.

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NAZIS, ÉMIGRÉS, AND ABSTRACT MATHEMATICS

Ryan Dahn

Today, Jordan algebras are a sprawling mathematical subfield, but the strange story of their discovery amid Adolf Hitler's seizure of power is not widely known.

Commemoration is a foundational practice of modern science. Researchers are expected to cite the fundamental work of others in their papers. Phenomena, formulas, effects, and discoveries get named after individuals. Think of Planck's constant, Newton's laws, the Schrödinger wave equation, and the Pauli exclusion principle. When we invoke them, we implicitly commemorate those individuals, whose ideas collectively form what one might call the textbook canon of physics.

One physicist who rarely makes it into that canon is the German theorist Pascual Jordan (1902–80). In 1926, at age 24, Jordan published a paper with Werner Heisenberg and Max Born that outlines the fundamentals of quantum theory.[1] He subsequently authored or coauthored dozens of foundational publications in quantum mechanics and quantum field theory.

But Jordan was also probably the most prominent physicist of his generation to join the Nazi Party. His affiliation with the regime was not merely opportunistic. As early as 1930, three years before Adolf Hitler took power, Jordan was expressing extreme antidemocratic viewpoints in far-right journals under the pseudonym Ernst Domeier. Despite collaborating with many Jewish colleagues, Jordan joined the party in May 1933. He then proceeded to shed his pseudonym and began authoring a series of articles that were laden with Nazi ideology. Aimed at party leaders, the texts argued that supporting modern physics would be the key to winning future wars.[2]

The fact that Jordan is rarely remembered today may seem like the rare example when an odious figure is successfully ousted from the canon. Indeed, many sources claim that Jordan's dubious political activities cost him a chance at the Nobel Prize. But that's not the whole story. Jordan probably was never awarded even a share of a Nobel Prize not so much because of his Nazi ties but because of his severe stutter, which prevented him from building the international reputation necessary to garner nominations, and of the Nobel committee's well-known tendency to award the prize to a lone genius—in the case of quantum mechanics, Heisenberg.

Moreover, Jordan's name did find its way into the canon of pure mathematics, where an entire class of algebras are named after him. And the story behind the birth of that subfield illustrates the value of interrogating the scientific canon. The very moment Jordan was proclaiming his allegiance to the Nazi regime in spring 1933, he was collaborating with his Hungarian Jewish friends John von Neumann and Eugene Wigner on a landmark paper on Jordan algebras.[3]

Like many scientists, Pascual Jordan often doodled while he worked. This artistic collage was assembled from drawings found in ref. 10. (Collage by Donna Padian; images courtesy of the Jordan family.)

Having lived in Germany for years, von Neumann and Wigner fled to the US as the paper was being drafted, but they still collaborated with Jordan after he joined the Nazi Party. Indeed, the seemingly paradoxical history of Jordan's algebra is a quintessential example of how historians have been contending with the thorny question of commemoration well before "cancel culture" entered the zeitgeist.

FIGURE 1. PASCUAL JORDAN, John von Neumann, and Eugene Wigner (from left). The picture of Jordan was taken in the 1930s; the images of von Neumann and Wigner date from after World War II. (Jordan image courtesy of the Voit Collection, Göttingen State and University Library; von Neumann and Wigner images courtesy of the US Department of Energy.)

Nonassociative speculations

The story begins in December 1932, in the dying days of the first German democracy—the Weimar Republic. That month, Jordan, who at the time was the professor of theoretical physics at the University of Rostock, published a short article in a field seemingly distant from his own: the subdiscipline of pure mathematics known as abstract algebra. An algebra generalizes the rules of arithmetic, and its most basic form follows what is known as the associative principle: When you multiply three or more quantities together, it does not matter how you group them when performing the operation. In other words, $(ab)c = a(bc) = abc$.

In his 1932 paper, Jordan described a type of nonassociative algebras, or algebras in which $(ab)c$ is not necessarily equal to $a(bc)$. The new algebras nevertheless retain a weaker form of the associative principle—namely, the power rule of exponents, in which $a^m \cdot a^n = a^{m+n}$.

Why would a physicist delve into abstract mathematics? As Jordan detailed in a second article submitted in December 1932, he hoped to use the new algebra in physics. After all, a form of noncommutative algebra—namely, matrix multiplication—had laid the path for the quantum mechanics revolution in the 1920s. Jordan hoped that nonassociative algebra might analogously serve as a tool to describe quantum electrodynamics. A third paper by Jordan describing how his new algebra could provide a method for generalizing the mathematical formalism of quantum mechanics[4] appeared in March 1933.

Eager to pursue the idea further yet recognizing the limits of his own mathematical talents, Jordan wrote to Wigner, a mathematical physicist who he believed was up for the task. In his letter, which likely dates from December 1932, Jordan asked Wigner if they could meet to discuss his new ideas, and he inquired about the whereabouts of their mutual friend, the brilliant polymath von Neumann (see figure 1).[5]

Wigner invited Jordan to meet him in Berlin, but the two never met in person because Jordan's finances were too "miserable" to afford the trip. Instead, collaboration began via mail. Unfortunately, almost all of Jordan's personal and professional papers dating from before 1945 are lost, so only one side of the correspondence remains—Jordan's letters to Wigner and von Neumann—and even that seems to be incomplete. Nevertheless, by late April 1933, Jordan sent a detailed letter to Wigner on his algebraic ruminations; he enclosed reprints of the three articles he had published on the subject and again implored Wigner and von Neumann to meet with him about his "nonassociative speculations."

An unlikely collaboration

At the time, the situation in Germany was rapidly changing. On 30 January 1933, Hitler was named German chancellor, and by late March, he and his Nazi Party had made Germany a one-party state in all but name. Beginning in April, Nazi authorities started purging Jewish and left-leaning scholars from German universities. It was the start of a decade-long intellectual exodus from Europe that would fundamentally transform the landscape of physics, mathematics, and many other academic disciplines.[6]

Routine correspondence between colleagues quickly took on another role under Nazism: Informal personal networks formerly used to exchange ideas, drafts, and offprints of upcoming articles became vehicles to inquire after and help displaced refugee scholars fleeing persecution. Jordan's letter to Wigner from late April falls into that category. Although most of it deals with their collaborative work, three terse paragraphs at its end are about several colleagues:

> Here in [Rostock] the mineralogical assistant Dr. [Günter] Nagelschmidt has been suspended; otherwise no mathematicians, physicists, or chemists have been affected. Do you know how it stands with [physicist Walter] Gordon and the mathematician [Max] Zorn in Hamburg? I have no idea.
>
> It is really very sad that we have so little prospect of seeing each other within the foreseeable future; there are so many things I would like to talk with you about. But I am fighting a desperate struggle against my financial deficit's tendency to increase monotonically.
>
> Many warm greetings, not only to you, but also to J. [von Neumann], [Leo] Szillard [sic], and all other mutual friends!

Nagelschmidt, Gordon, and Szilard were Jewish scholars working in Germany, and all three emigrated because of Nazi antisemitic laws. Zorn, too, was forced to flee because he had been an active member of the Communist Party of Germany in the Weimar era. The fact that Jordan inquired about Zorn and Gordon and expressed well-wishes to von Neumann and Szilard—another Hungarian Jewish physicist—makes it clear that he disapproved of at least some aspects of the Nazi purge. His warm tone also reflects the high esteem in which he held his Jewish and left-leaning colleagues. It does not seem a stretch to think that one of the "things" Jordan wished to discuss with Wigner was the dismissal policy.

One wonders why Jordan did not inquire about Wigner or von Neumann's own positions. The two were teaching part-time at universities in Berlin and were also hit by the Nazi purge because of their Jewish heritage. Wigner quickly made plans to emigrate and was officially dismissed on 6 September 1933. Von Neumann was already planning to move to the US before Hitler took power because he had been offered a position at the newly founded Institute for Advanced Study in Princeton, New Jersey, but he accelerated his departure after the Nazi takeover.[7]

It is possible that Jordan expressed concern in another letter that is now lost, or that Wigner informed him matter-of-factly in a lost letter. It is also possible that in spring 1933, with privacy of the mail no longer assured in Germany, Jordan did not want to overtly sympathize with a Jewish colleague who was about to lose his job. After all, it would look bad for an aspiring Nazi to sympathize with a Jewish academic.

The quantum Nazi

The friendly private correspondence with Wigner stands in stark contrast to Jordan's public acclaim for the Nazi takeover. On the rare occasions that he spoke about his actions under Hitler after the war, Jordan insisted that he only joined the party because he thought that doing so would enable him to protect science from Nazi incursions. That excuse is belied by several articles he wrote in 1933 under his Domeier pseudonym—many published in the far-right magazine *Blut und Boden* (Blood and soil; see figure 2)—which make clear that Jordan was euphoric when Hitler toppled German democracy. One of the articles focused on the necessity for Germany to attain economic self-sufficiency so that it could survive a blockade during a future war. Only then could Germany be reborn through a "profound *spiritual renewal* [emphasis in original]."[8]

No one in the scientific community, including Wigner and von Neumann, was aware of Jordan's pseudonym or any of his far-right writings. Yet shortly after Jordan sent the letter to Wigner in late April inquiring about the fate of a few Jewish colleagues, Jordan shed the Domeier pen name and published an endorsement of the Nazi "revolution" under his own name. In that piece, published in the University of Rostock's student magazine on 9 May 1933, he called for the university to be reorganized around the military needs of the "new National Socialist state," urged the student body to assume a "militant character," and insisted that "our life's goal lies . . . in the cratered field of no man's land."[9]

Eight days before that article appeared, on 1 May 1933, Jordan had joined the Nazi Party (see figure 3). The article indirectly establishes the terms of Jordan's Nazism. Even if, as hinted by his letter to Wigner, he privately disagreed with some Nazi antisemitic policies and would have preferred that so-called good Jews like Wigner and von Neumann be allowed to remain undisturbed in Germany, the regime's antisemitism was never a deal breaker for Jordan. Even as colleagues whom Jordan cherished, like Wigner and von Neumann, were dismissed and forced into exile, he vociferously proclaimed his allegiance to the regime. Jordan would maintain those terms

FIGURE 2. *BLUT UND BODEN*'S COVER for the November 1931 issue, which featured an article by Jordan authored under his Ernst Domeier pseudonym. *Nebelung* is a "Germanic" name for the month of November that roughly translates to "fogginess." Many proto-Nazi publications like *Blut und Boden* (Blood and soil) emphasized the alleged authenticity of their Germanness by using such Germanic month names, which, they claimed, long predated the standard Roman month names. But that was largely untrue: Names like *Nebelung* were largely 19th-century inventions. (Courtesy of the Siebenbürgen Institute, Gundelsheim, Germany.)

with Nazism—even as persecution of the Jews metastasized into genocide—until Hitler's demise in 1945.

A three-man paper

Amazingly, neither the purge of Jewish academics from German universities nor Jordan's decision to join the Nazi Party had much impact on his feverish exchange of letters with Wigner. As spring turned to summer, one of them (likely Wigner) finally managed to get hold of von Neumann. The three were making rapid progress, and by late July 1933, Jordan made a proposal to von Neumann that the trio publish a three-man paper together, assuming—in a between-the-lines reference to the political situation in Germany—that they could clarify all major remaining problems before Wigner and von Neumann's departure for the US that fall.

Work continued apace. In August 1933 Jordan sent a partial manuscript of the paper, titled "Über eine Verallgemeinerung des quantenmechanischen Formalismus" (On a generalization of quantum mechanical formalism) to Wigner and von Neumann.[10] That draft manuscript is largely unremarkable at first glance; much of it was translated into English and became part 1 of the eventual published paper. But below the surface are traces of the political turmoil in Germany. The byline at the top of the manuscript, for example, subtly references Wigner's and von Neumann's emigration from Germany by listing them as being "currently in Budapest": The two had stopped in the Hungarian capital before heading to the US.

A bit of historical detective work on the manuscript reveals something even rarer: a tangible trace of Jordan's double identity as Domeier. Jordan had a lifelong habit of reusing paper, and the entire manuscript was drafted on the back of old writings. Much of those scraps consist of discarded calculations. But on the back of page 7 of the manuscript, which discusses a mathematical proof that was largely eliminated in the published article, is the second page of a political essay by Jordan that attacks attempts to reconcile religion with socialism.

The essay is cut off at the bottom where Jordan had cut and pasted text, but by looking through the top layer of paper where he glued the pages together, it is possible to discern "E. Do.," an abbreviation for Ernst Domeier (see figure 4). It is unclear if that Domeier essay was ever published. The first page hasn't survived, so the essay's title is unknown, and its content doesn't correspond with any known published texts under the Domeier pen name. But there are almost certainly more Domeier articles yet to be uncovered: *Blut und Boden* was only one of many far-right journals in which Jordan published under his pseudonym, and those publications are hard to find today. In any event, that manuscript page embodies Jordan's two faces: He drafted a paper coauthored with two Jewish émigrés on the back of one of his proto-Nazi polemics.

A US journal

Despite his German nationalism, Jordan was "very pleased" when Wigner and von Neumann suggested submitting the paper to a US journal that promised to publish quickly, the Princeton-based *Annals of Mathematics*. (Perhaps Jordan also realized that the two likely had little interest in publishing in a German journal after the Nazi takeover.) And Jordan gave his two now-émigré colleagues carte blanche to do whatever was necessary for publication in the *Annals*.

As it turned out, soon after arriving in Princeton in fall 1933, von Neumann and Wigner realized that the higher-dimensional nonassociative algebras Jordan had discovered were not, in fact, suitable for further generalization of quantum mechanical formalism. So it was that despite its title, "On an algebraic generalization of the quantum mechanical formalism," the published paper was purely mathematical in content. Jordan was disappointed, but he remained in awe of his colleagues, as he noted in a letter to von Neumann from fall 1933: "I . . . would like to express how much I am delighted and relieved that you completely settled and resolved the matter in such a fantastically short time. Alone, it would have taken me years—if ever—to come up with it."[11]

And in Princeton, the story of Jordan's algebras took another turn. As Wigner and von Neumann were preparing the manuscript for publication, the classification of a specific case of what Jordan had termed "*r*-number algebras" gave them trouble. They turned to a young visiting fellow at the Institute for Advanced Study, A. Adrian Albert, an American Jewish mathematician, who solved the problem with assistance from von Neumann. Albert quickly wrote up an article on the topic, and it was published directly following the three-man paper in the January 1934 issue of the *Annals of Mathematics*.[12]

For Albert, that was the start of a lifelong interest in *r*-number algebras, which he dubbed "Jordan algebras" in the 1940s. A key figure in the internationally renowned University of Chicago mathematics department, Albert published many articles and advised several doctoral theses on Jordan algebras.[13] He and his school sparked interest in the subfield throughout the US mathematical community. It is probably due to his influence that Jordan, Wigner, and von Neumann's paper has been cited more than 1000 times. Jordan algebras have proven irresistible to mathematicians because they connect abstract algebra with other, seemingly disparate branches of mathematics, such as differential and projective geometry.

Jordan and the international community

Was the three-man collaboration an outlier? After all, it occurred in 1933, just as the Nazis were taking power and before Hitler consolidated control over German society. Surprisingly, it turns out to be one of many examples of how Jordan maintained contacts with the international scientific community before the outbreak of World War II. He coauthored another English-language article with von Neumann that was published in *Annals of Mathematics* in 1935, for example, and also coauthored an article the following year with Ralph Kronig, a physicist based in the Netherlands.[14]

Jordan continued corresponding with von Neumann into the late 1930s—the two even met in person in Cologne, Germany, in 1936 during one of von Neumann's trips to Europe—and he continued exchanging letters with Born, Kronig, and many

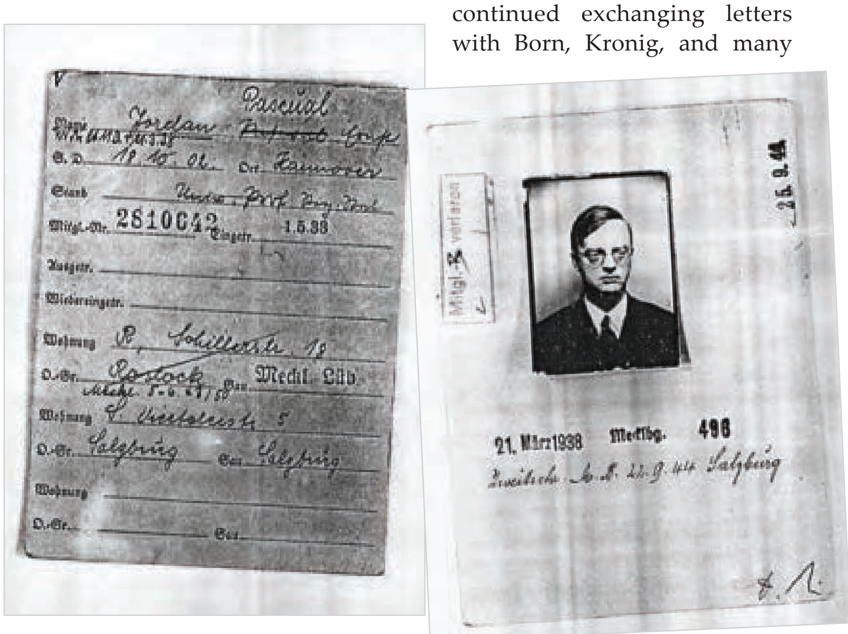

FIGURE 3. JORDAN'S NAZI PARTY membership card, which lists his member number, 2810642, and the date he joined the party, 1 May 1933. That was the same date that a ban on new party members came into effect, which was intended to halt the onslaught of Germans who sought membership after the Nazis seized power in early 1933 and whom party leadership feared were opportunists. (Courtesy of the US National Archives and Records Administration.)

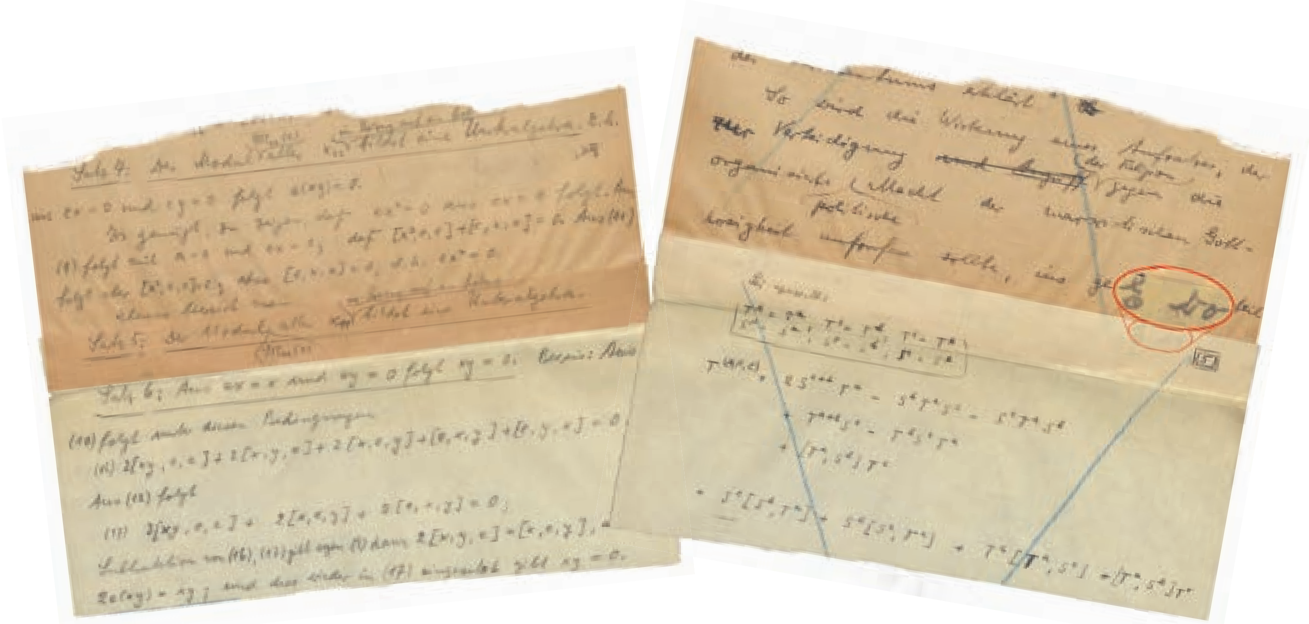

FIGURE 4. FRONT AND BACK sides from page 7 of Jordan's original handwritten manuscript of the three-man paper. The front side of the page contains part of the mathematical article, and the back side is a discarded draft of a political essay by Jordan. On the reverse side, "E. Do." (circled in red), for Ernst Domeier, can be made out where the pages were glued together. (Courtesy of the Jordan family and the Department of Manuscripts and Early Printed Books, Berlin State Library.)

other foreign colleagues until the start of World War II. And even as war began raging in Europe, Jordan corresponded with Max Delbrück, a German biophysicist in the then-neutral US, as late as November 1940. The surviving evidence suggests that Jordan remained accepted in the international scientific community despite staying in Germany and joining the Nazi Party.

How much did they know?

It is likely that many scientists outside Germany were unaware that Jordan had joined the Nazi Party. After all, there was no centralized database of known party members, and information traveled slowly in the 1930s. Although Jordan published a panoply of articles under Hitler that attempted to convince the regime that modern physics could help win future wars, they were largely printed in publications that did not circulate widely outside Germany, and many international colleagues were likely unaware of them. Jordan did mention politics in several popular-science books from the Nazi era that were more likely to be read abroad, but that content may have been viewed as the type of pandering necessary to get a book published in Hitler's Germany.

Of course, colleagues did occasionally stumble across Jordan's pro-Nazi writings. One instance occurred in 1933, when several Jewish colleagues, including Born, James Franck, and Niels Bohr, came across Jordan's paean to the Nazi state in the University of Rostock's student magazine. When they confronted him about such articles, Jordan sent cryptic explanations in return, which often used the vocabulary of physics to draw analogies with the political situation in Germany. His response to Bohr in 1934 is typical:

> I attempted . . . to deliver a contribution to the proof of the general theorem that the value of physics is a quantity that in magnitude and sign is invariant with respect to very general transformations of the external coordinate system. To this end it should be shown that the sign of this quantity can also be proven as positive with a system of axioms that stands in a relationship of complementary exclusion to those axioms from which one would otherwise [be accustomed to] derive this sign.[15]

In essence, Jordan was telling Bohr that he was attempting to prove that physics could be of value to the Nazi dictatorship, in the hope that they would support it financially. On another occasion, he analogized his actions to those taken by Soviet physicists, who, as he saw it, similarly aimed to convince Joseph Stalin's regime to support their scientific endeavors.[16]

And despite what many claimed after the war, those explanations were accepted by many international colleagues at the time. Bohr responded to Jordan's 1934 letter with a similarly cryptic note, but he remained in contact with him and even invited Jordan to a conference in Copenhagen in 1936. Franck, a German Jew who emigrated in 1933, had been one of Jordan's teachers at the University of Göttingen and readily accepted Jordan's explanation for his actions. He told other émigrés like Born who were offended by Jordan's magazine article not to take such publications "seriously."[17]

If physics analogies did not work, Jordan justified his actions by pointing to the city where he taught from 1929 to 1944: ultraconservative Rostock, which was already rabidly pro-Nazi in the Weimar era. Physicist Otto Stern, another German Jewish émigré, ran into Jordan at a party hosted by Bohr in Copenhagen sometime before World War II—probably in 1936, during the conference Bohr had invited Jordan to attend. Stern, who had previously held Jordan's position at the University of Rostock (shown in figure 5) in the 1920s, took Jordan aside during the event and asked him to explain his actions. Jordan responded: "Listen, you were in Rostock, right. You know what it's like there. I couldn't live there at all if I didn't do this [join the Nazi Party]."[18]

Stern was far from repelled by Jordan's explanation: Long after the war, he told an interviewer that he agreed "completely" with Jordan's assessment of Rostock and that one "couldn't hold it against him" for staying in Germany and publishing pro-Nazi texts.[18] Until the start of the war, even many scientists abroad who were aware of Jordan's Nazi ties accepted his justifications.

FIGURE 5. A COLOR POSTCARD from 1898 depicts the University of Rostock's main building, which is still used today. Jordan was the professor of theoretical physics at the university from 1929–44. (Courtesy of Brück und Sohn Kunstverlag Meißen, CC0 1.0.)

"Cancel culture" in science

What does it mean when we commemorate a scientist whose behavior would today be considered questionable? Historians have been wrestling with that question for decades, and Jordan is only one of many figures whose actions appear dubious from our vantage point. Isaac Newton was an eager investor in the South Sea Company, which traded in enslaved Africans (see the article by Andrew Odlyzko, PHYSICS TODAY, July 2020, page 30); Erwin Schrödinger would likely today be considered a sexual predator who took advantage of girls; and on a more prosaic level, Wolfgang Pauli was—to put it mildly—a jerk to his colleagues. Even the humanist paragon Albert Einstein expressed opinions in private diaries that today are considered racist.

By interrogating the textbook canon of physics and thereby making the discipline "more human" (see the article by Matt Stanley, PHYSICS TODAY, July 2016, page 38), we see that the questions raised, for example, by the Russian invasion of Ukraine—should scientists collaborate with colleagues that remain in Russia?—are not new. Wigner and von Neumann had to deal with something similar when they collaborated with Jordan back in 1933.

And like many scientists today who may not be aware of the political views of their Russian colleagues (see PHYSICS TODAY, June 2022, page 22), Wigner and von Neumann were likely in the dark about Jordan's political leanings. They probably didn't know he had joined the Nazi Party and were certainly unaware of the Domeier articles, which weren't unearthed until the 1990s. All they knew for certain was that Jordan planned to stay in Hitler's Germany. But in that regard, Jordan was one of many: Almost all German academics whose careers weren't directly threatened by the Nazis stayed in their homeland.

Although it was obvious that Hitler's regime would be repressive toward Jews and political opponents, antisemitism and authoritarianism were commonplace in 1930s Europe. The regime's murderous intentions would not become widely apparent until the *Kristallnacht* pogrom in November 1938, when synagogues were burned across Germany and Austria and when, for the first time, Jews were systematically rounded up and sent to concentration camps.

Most people are human, not heroes. It's easy to judge Wigner and von Neumann for maintaining ties with scholars like Jordan, but they didn't know the Nazi regime had genocidal intentions or that it would start the bloodiest war in history. How do we handle scientists who try to keep their careers afloat even as their society careens into dictatorship and madness? As historians can tell you, there's no easy answer. But that's precisely why it's so important to inject humanity into the textbook canon: The history of physics is a messy business.

I would like to thank Michael Barany for insightful comments that helped shape this article.

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Joanne Simpson (foreground) in the 1950s examining images of clouds she took during flights over the Pacific Ocean.

A stormy life in atmospheric science

First Woman
Joanne Simpson and the Tropical Atmosphere

James Rodger Fleming
Oxford U. Press, 2020.
$36.95

When Joanne Simpson (1923–2010) was awarded the Carl-Gustaf Rossby Research Medal in 1983, she was the first woman to win the award. The American Meteorological Society praised her outstanding studies of tropical convective clouds and her decades-long research on hot towers and hurricanes, which had transformed scientists' understanding of the global circulation of heat. But her mother was unimpressed. "Everyone wonders why, if you are so good," she sniped, "that you have not yet been elected to the National Academy." That tension animates James Rodger Fleming's gripping biography, *First Woman: Joanne Simpson and the Tropical Atmosphere*. Simpson's research took her to the top of meteorology, but it couldn't make her mother love her.

"You have to be lovable to be loved," her mother told Simpson as a child. That desire to be loved propelled Simpson through a painful life. She experienced sexual harassment at work and abusive relationships at home during her first two marriages before finding domestic peace in an enduring marriage to the hurricane expert Robert "Bob" Simpson. (She changed her name with each marriage, so Fleming refers to her as Joanne throughout the book.) She struggled with depression and migraines and was once fired midsemester when her department chair found out she was a woman. Through it all, she pursued meteorology with a fierce intensity. "Her work became a retreat from and recompense for all her personal problems," Fleming writes.

And what significant work it was! During World War II, Simpson learned meteorology and then taught it to aviation cadets at the University of Chicago. Pursuing a PhD, she persevered despite being discouraged by most of the faculty until she took Herbert Riehl's course on tropical meteorology. With Riehl as her graduate adviser, she developed a mathematical theory of entrainment in cumulus clouds and became the first woman to earn a doctorate in meteorology from a US university.

Simpson's research took off, literally, at the Woods Hole Oceanographic Institution during the 1950s. Supported by the Office of Naval Research and later the National Hurricane Research Project, she began to fly on heavily instrumented aircraft through tropical clouds. The observations led her and Riehl to develop the concept of "hot towers," or giant complexes of cumulonimbus clouds that provide the energy to power hurricanes and drive the tropical atmosphere.

Simpson's studies of cloud dynamics and hurricanes led to her involvement with weather control experiments during the 1960s. Resigning from a full professorship at UCLA that she had held for only three years, Simpson went to work for the bureaucracy that would soon become NOAA. She and Bob eventually became leaders in Project Stormfury, a substantial effort by the US Weather Bureau (now the National Weather Service) and the US Navy to understand hurricanes and attempt to control them with cloud seeding. While that put them at the center of hurricane research, their desire to understand the storms meshed uncomfortably with the navy's aspiration to control them for military advantage.

A much happier research environment came when Simpson became head of the Severe Storms Branch at NASA's Goddard Space Flight Center in 1979. There she improved cloud models and mentored young researchers. Her signature achievement was serving as project scientist for the *Tropical Rainfall Measuring Mission*, a satellite that provided crucial data to understand climate change.

Because *First Woman* is primarily based on Simpson's remarkable collection of personal papers, which are held at Harvard University's Radcliffe Institute for Advanced Study, she is the author of many of the words in the book. Fleming quotes at length from her personal journals, which contain intimate details about her scientific work and marital issues. He argues that Simpson chose not to place any restrictions on those diaries because of "her desire to be understood beyond her professional résumé."

Fleming also uses two oral history interviews: one conducted by Simpson's scientific colleague Margaret LeMone in 1989 and the other done by Kristine Harper, a historian of science, in 2000. The latter contains descriptions of what would now be recognized as extensive sexual harassment. For example, Simpson recalled that Riehl "tried to make a pass whenever he could, but I managed to resist just enough to keep him interested. And oh, we got to be really good friends and colleagues."

Fleming uses biography to illuminate the broader history of tropical meteorology. Simpson's career stretched from World War II into the 2000s, and her story sheds light on a field that Fleming argues has been neglected by historians in comparison to polar and temperate-latitude meteorology.

One inevitable cost to writing a concise book tightly focused on Simpson is that Fleming doesn't compare her with peers, such as the radar meteorologist Pauline Morrow Austin and the atmospheric physicist Florence van Straten, who also had successful research careers. But neither woman was as celebrated as Simpson nor had her life as well documented. The continuing work of understanding women's contributions to atmospheric science will certainly build on Fleming's scholarship.

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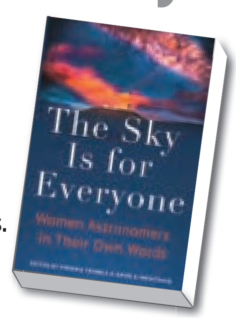
ANNE PYNE COWLEY (left) and **JOCELYN BELL BURNELL** (right) pictured at American Astronomical Society meetings in 1972 and 1987, respectively.

A survey of women in astronomy

The Sky Is for Everyone
Women Astronomers in Their Own Words
Virginia Trimble and David A. Weintraub, eds.
Princeton U. Press, 2022. $29.95



"Women hold up half the sky and some day it will be so in astronomy!" So opens *The Sky Is for Everyone: Women Astronomers in Their Own Words*, a new book coedited by Virginia Trimble and David Weintraub. It's an odd sentence with which to open a book about women in astronomy, in large part because it is adapted from a quotation by

Mao Zedong. (Were there really no appropriate quotations available from female astronomers or others who were not responsible for the Cultural Revolution?) Nevertheless, in that opening quotation, Trimble and Weintraub set out the agenda for their book: to demonstrate the significant contributions women have made, and continue to make, in astronomy and to further the inclusion and appreciation of women in the profession.

For most readers, like myself, Trimble and Weintraub are probably preaching to the choir. Sadly, those who remain unconvinced as to the merits of women in astronomy are unlikely to pick up a book like *The Sky Is for Everyone* with an open mind. Fortunately, however, that group is in the minority in comparison with those who will find its contents interesting, informative, and motivating.

The book begins with a historical digression that surveys women in astronomy with an emphasis on individuals from the US and Europe (primarily the UK). It leads into a who's who of early PhDs and other biographical sketches. Although that chapter does not add anything new to the historical literature, it is a useful survey of the history of women in astronomy, especially during the 19th and 20th centuries. The editors emphasize how many early women astronomers depended on a male mentor, husband, or family member to gain access to the profession and its networks. Although that is certainly not as true as it once was, it is still the case that female astronomers can be constrained by the infrastructures within which they work and that a supportive network can make or break a career, as the book's subsequent chapters illustrate.

The majority of *The Sky Is for Everyone* is a compilation of 37 autobiographical chapters by prominent female astronomers at a range of career stages. The chapters are ordered chronologically by the year in which the individual's PhD was awarded. The earliest ones primarily showcase accounts of white women from the US and UK, such as Anne Pyne Cowley and Jocelyn Bell Burnell, who received their PhDs in the 1960s. But as the book progresses, it features a more diverse subset of authors, including Gabriela González, Dara Norman, and Shazrene Mohamed.

Each author tells her story in her own way. Some authors go into great depth about their childhoods; others, about complicated career journeys. The degree to which each author focuses on her social and cultural surroundings also varies considerably, although all of them detail what they are most passionate about: the science. In some respects the book is a communal love letter to astronomy and the broader sciences that have inspired those women to look to the stars.

Unfortunately, as could be predicted given the identities of the authors, the course of that love has often not run smoothly. Multiple authors chronicle their experiences of personal and institutional sexism, and some describe stories of racism and xenophobia as well. Because the chapters are chronologically ordered, institutional barriers gradually but definitively drop away as the book progresses, although instances of harassment, microaggressions, and toxic academic culture remain present today. The biographies feature plenty of infuriating moments and plenty of moments that will make the reader sigh but also plenty of triumphs.

The Sky Is for Everyone is a valuable read for astronomers and those interested in the status of women in science, but also for department heads and policymakers who should take note of how institutional barriers can be broken down and accommodations made to improve the astronomy community. It may also prove inspiring and useful to early-career scientists: Although the book focuses primarily on highly successful astronomers at elite universities, it illustrates a multiplicity of possible career paths.

Finally, historians of astronomy will enjoy the book not only because it sheds light on the recent history of women in the field but also because it simultaneously serves as a history of 20th-century astronomy, with a focus on the growth of observatories, the increasing size of scientific collaborations, and the increased emphasis placed by national and international scientific societies on public outreach and institutional equity.

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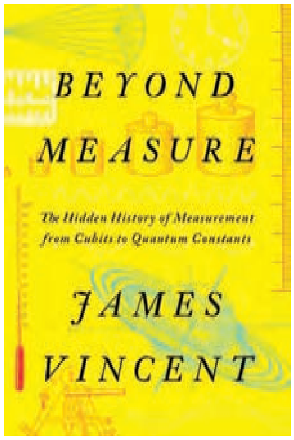
NEW BOOKS & MEDIA

Beyond Measure

The Hidden History of Measurement from Cubits to Quantum Constants

James Vincent
W. W. Norton, 2022. $32.50



Although modern science claims to be universal, measurement is intrinsically human. After all, units of measurement didn't exist before humans created them. In *Beyond Measure*, James Vincent, a technology reporter, probes that dichotomy by investigating the history of measurement and standardization from antiquity to the present day. It's no coincidence that most traditional units are based on the human body: For centuries, all we had to measure against was ourselves. Although he doesn't shy away from discussing the grimmer sides of standardization, such as its role in eugenics, Vincent does delve into some lighter topics. Did you know, for example, that there's an international standard for brewing tea? —RD

The Notebooks of Leonardo da Vinci

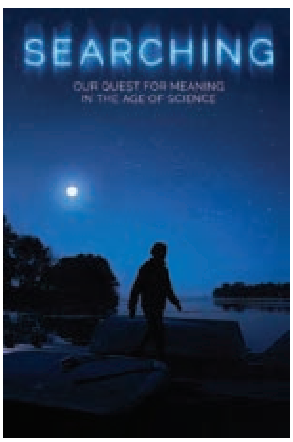
Mary Zimmerman
1993; revival 2022

Originally adapted by Mary Zimmerman in 1993, *The Notebooks of Leonardo da Vinci* has now been revived as a touring production. Zimmerman's play, based on the 15th-century manuscripts of Leonardo, does not have a traditional beginning, middle, and end. Rather, like the notebooks themselves, it consists of snapshots from different times of Leonardo's life on such topics as anatomy, love, turbulence, art, and philosophy. The cast members do a superb job mixing acting, choreography, and singing. So many subjects are thrown in front of the audience that theatergoers will be reaching for a biography of Leonardo afterward to read about the few ideas they may have missed. The production will appear at San Diego's Old Globe Theater from 21 January to 26 February. —PKG

Searching

Our Quest for Meaning in the Age of Science

Alan Lightman, host
PBS, 2023

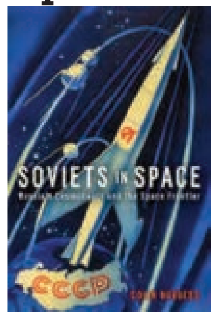


In this new three-part documentary series, the physicist and writer Alan Lightman investigates an age-old question: Can science ever explain the mysteries of human consciousness and thought? In other words, are we just atoms and elements? The series was inspired by a mystical experience Lightman once had on a boat in Maine, during which he felt as if he were "falling into infinity" and merging with the universe. Although some of the material Lightman covers, such as an explanation about DNA and RNA, is well-worn ground, his engaging narration and inquisitive, affable nature make the series an enjoyable watch nonetheless. —RD

Soviets in Space

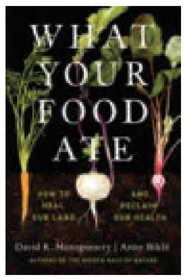
Russia's Cosmonauts and the Space Frontier

Colin Burgess
Reaktion Books, 2022. $35.00



Although the Soviet Union was the first nation to launch a satellite, an animal, and a human into space, not much was known about those early missions until the recent declassification of primary-source documents. Now Colin Burgess, a historian who specializes in spaceflight and military history, presents an account of the Soviet space program from the end of World War II to its present-day incarnation, Roscosmos. Amply illustrated with more than 80 black-and-white photographs, *Soviets in Space* provides an informed and interesting look into the trials and triumphs of the US's Cold War rival. —CC

What Your Food Ate



How to Heal Our Land and Reclaim Our Health

David R. Montgomery and Anne Biklé
W. W. Norton, 2022. $30.00

Although most Americans have plenty to eat, many continue to suffer from poor nutrition. One reason—write David Montgomery, a geologist, and his wife, Anne Biklé, a biologist—is modern agricultural methods, which emphasize quantity over quality. Mechanized plowing and chemical fertilizers reap high crop yields yet deteriorate the soil and reduce the amounts of beneficial compounds in fruits and vegetables; confining livestock and shifting their grazing from grasslands to feedlots maximizes meat production yet diminishes its nutrient content. In their new book, *What Your Food Ate*, the authors promote the value of regenerative farming methods, such as no-till planting, crop rotation, and reintegration of livestock grazing, to improve the health of the soil and, by extension, ourselves. —CC PT

NEW PRODUCTS

Focus on lasers, imaging, microscopy, and nanoscience

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

AFM and SEM imaging microscopy platform

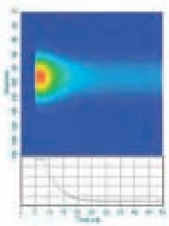
The FusionScope correlative microscope from Quantum Design integrates atomic force microscopy (AFM) with scanning electron microscopy (SEM) imaging. It features a novel shared coordinate system that automatically aligns AFM and SEM operations for measurements and sample positioning. The FusionScope software lets researchers interactively overlay AFM imaging data onto SEM images in real time and create 2D and 3D visualizations with nanoscale resolution. With that integrated shared mapping, they can easily identify areas of interest, measure samples, and combine imaging data. The FusionScope offers the ability to scan and image across differing magnification scales. Smooth image transitions between millimeter, micron, and subnanometer scales let users see new correspondences in data from specific sample areas. ***Quantum Design Inc****, 10307 Pacific Center Ct, San Diego, CA 92121, www.qdusa.com*

Fast high-definition IR camera

A new addition to Telops's FAST line of IR cameras, the M200HD, combines high-speed measurements with high image resolution. Capable of reaching 3 megapixels and an acquisition rate of 180 Hz, the FAST M200HD is suitable for applications such as experimental mechanics, nondestructive testing, and image signature processing. It has a spectral range of 1.5–5.4 μm and an optional range of 3.0–5.0 μm. The FAST cameras provide radiometrically calibrated measurements for all operating conditions; to ensure optimal imaging, they automatically adjust exposure time. A convenient four-position filter wheel makes it easier to change measurement scenarios; a certified IP67 sealed enclosure makes the cameras suitable for field measurements. ***Telops****, 100-2600 Ave St-Jean-Baptiste, Quebec City, QC G2E 6J5, Canada, www.telops.com*

Wavelength selector

The novel Flexible Wavelength Selector Poly (FWS-Poly) family of products from Spectrolight can perform both excitation and emission wavelength selection and can convert a basic light microscope into a cost-effective fluorescence microscope with minimal modifications. A commercial fluorescence microscope uses a tungsten or mercury lamp or an LED as a light source; in the case of a confocal microscope, lasers in the visible range are usually included. The FWS-Poly products widen the pool of the available fluorophores and impart flexibility in adjusting bandwidth as well as wavelength. For example, if the FWS-Poly, having a spectral range of 385 ~ 1015 nm, or the FWS-Poly-SWIR, used for shortwave IR and having a spectral range of 1015 ~ 1650 nm, is connected, any wavelength can be selected and used as excitation light. FWS-Poly products have a minimum bandwidth of 3 nm and can be widened to a maximum of 15 nm. The conversion is automatic, and the software provided can quickly adjust wavelength and bandwidth in real time. ***Spectrolight Inc****, 19800 MacArthur Blvd, Ste 300, Irvine, CA 92612, www.spectrolightinc.com*



Solid-state streak camera

Optronis has unveiled what it says is the world's first commercially available solid-state streak camera. Designed to enable detailed scientific investigations in the field of ultrafast processes, the semiconductor-based S3C-1 may open up new application possibilities in fields of significant growth such as plasma research, detonics, microfluidics, and the analysis of fast micrometer-level movements in MEMS. Compared with vacuum-tube-based streak cameras, the S3C-1 is more compact, more robust, and less costly. Also, measurements are now possible where no suitable trigger signal was previously available. A time window of 100 ns to 10 ms can be selected for acquisition, and the time resolution is close to 1 ns. The camera can perform continuous recording. With its compact size of 12 cm × 12 cm × 10 cm and light weight of 2 kg, the S3C-1 is suitable for studying fast physical phenomena in areas not feasible for tube-based cameras. ***Optronis GmbH****, Ludwigstraße 2, 77694 Kehl, Germany, https://optronis.com*

Beam sampler for high-power lasers

The BA32-1KW beam sampler from Gentec-EO provides camera-based beam profiling for kilowatt-level lasers. The water-cooled beam splitter inside the sampler is suitable for in-line beam profiling in various high-power applications, including R&D, industrial materials processing, and military uses. It uniformly attenuates all beam shapes, including Gaussian, flattop, and doughnut, and measures laser beam profiles with power levels from milliwatts to 1 kW and at power densities of up to 10 MW/cm^2. The device attenuates extremely high-power-density beams with an attenuation ratio of 1:1900, thereby enabling the use of very sensitive laser beam profilers to measure beam shape, focal spot, and beam waist. A power meter at the second residual beam window can monitor the laser's power simultaneously with the beam profiling. ***Gentec Electro-Optics Inc****, 445 Ave St-Jean-Baptiste, Ste 160, Quebec City, QC G2E 5N7, Canada, www.gentec-eo.com*

Compact UV-imaging cameras

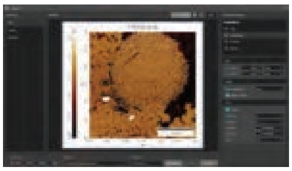
Allied Vision's Alvium camera series now includes models that incorporate the novel 8.1-megapixel Sony Pregius S IMX487 CMOS sensor. The backside-illuminated, global-shutter sensor is especially designed for the waveband between 200 nm and 400 nm. It is therefore suitable for scientific and industrial imaging applications in the near- and mid-UV range that require high-quality UV images with low noise at high resolution and frame rates. With a 2.74 μm pixel size, the cameras can detect tiny details at high UV sensitivity. According to the company, the Alvium UV cameras are the smallest industrial-grade UV-imaging devices on the market. They can be used to build extremely compact OEM systems for embedded and machine-vision applications such as UV microscopy and battery and forensic inspection. ***Allied Vision****, Taschenweg 2a, 07646 Stadtroda, Germany, www.alliedvision.com*

Scientific CMOS camera

The pco.edge 4.2 bi XU camera from PCO, an Excelitas company, is based on a back-illuminated scientific CMOS sensor with a very specific coating that allows for applications in the visible-light range down to extreme-UV and soft-x-ray radiation. It is adapted for ultrahigh-vacuum operation down to 1×10^{-7} mbar and offers high quantum efficiency in the energy range from 30 eV to 1000 eV. The image sensor features 2048×2048 pixels and a pixel size of 6.5 μm × 6.5 μm. It delivers full-frame acquisitions at 40 Hz with a dynamic range of 88 dB at a median noise level of 1.9 e$^-$. The compact pco.edge 4.2 bi XU camera offers various software-integration options. ***PCO-Tech Inc****, 1000 N West St, Ste 1200, Wilmington, DE 19801, www.pco-tech.com*

Single-photon fluorescence microscope

PicoQuant developed its Luminosa confocal microscope to make single-molecule and quantitative time-resolved fluorescence microscopy accessible to a broad range of researchers in molecular biophysics and structural biology. According to the company, with one-click auto-alignment and context-based intuitive workflows, Luminosa is easier to use than previous systems, and it's just as sensitive. For example, the system automatically recognizes individual molecules and determines correction factors for single-molecule Förster resonance energy transfer (smFRET). It offers advanced flexibility: All optomechanical components are accessible, data are stored in open formats, and the workflow and the graphical user interface can be customized. Methodologies include fluorescence lifetime imaging microscopy (FLIM), rapidFLIM^{HiRes} for fast processes, FLIM-FRET, single-molecule FRET through burst and time-trace analysis, fluorescence correlation spectroscopy, and anisotropy and differential interference contrast imaging. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*



Nanoscale-AFM data-analysis software

Park Systems designed its atomic force microscope (AFM) data-analysis platform, Park SmartAnalysis, to simplify nanoscale measurements. The software interface offers novice users automated analysis functions for fast, accurate data processing; users who do not want to rely on standard solutions can assume complete control of functions and parameter settings. To reduce time and effort in processing AFM data, SmartAnalysis supports capabilities such as the EZ Flatten machine-learning-based function. Flattening is required to level the slope of a sample surface and reveal the correct surface topography. If done incorrectly, minor experimental misalignments and external noise sources can affect the final image quality and distort the data. EZ Flatten automatically distinguishes the topography features from the substrate and applies an appropriate flattening algorithm. The operator simply loads the raw data and executes the function; users can select among six recommended output images. ***Park Systems Inc***, *3040 Olcott St, Santa Clara, CA 95054, https://parksystems.com*

AFM for nanoscience research

Oxford Instruments Asylum Research has launched its Cypher L atomic force microscope (AFM). The Cypher L is suitable for nanoscience research in such fields as polymer science, 2D materials, quantum technology, and energy storage. According to the company, the Cypher L is cost-effective, provides higher resolution than other AFMs in its price range, and approaches the ultrahigh performance of its Cypher S and Cypher ES family members. Operating on the new Asylum Research Ergo software platform, the Cypher L provides a simplified user experience through a streamlined workflow and intuitive image acquisition. AutoPilot algorithms automatically optimize scan parameters for high-quality images. Operating modes included are acoustic tapping with phase, contact with lateral force, and amplitude modulated Kelvin probe force microscopy (KPFM). Conductive atomic force microscopy, tapping mode in liquid droplet, and frequency modulated KPFM are optional. The Cypher L can be upgraded to the Cypher S, ES, or VRS1250 models as requirements evolve. ***Oxford Instruments Asylum Research***, *7416 Hollister Ave, Santa Barbara, CA 93117, https://afm.oxinst.com* PT

OBITUARIES

Maarten Schmidt

Maarten Schmidt, the Francis L. Moseley Professor of Astronomy Emeritus at Caltech, died on 17 September 2022 in Fresno, California. His contributions on comets, quasars, and other topics profoundly shaped our view of the cosmos.

Maarten was born on 28 December 1929 in Groningen, the Netherlands. Enduring five years under Nazi occupation and in blackouts, he became interested in the heavens during evening walks with his father and visits to his uncle, who was an amateur astronomer. At age 12 Maarten constructed his first telescope.

Despite the disruption of his early education by World War II, Maarten entered the University of Groningen at age 16. Upon receiving his bachelor's degree in astronomy in 1949, he entered the graduate program at Leiden University. His initial work on comets with Jan Oort, his PhD adviser, occurred at the time of the creation of the model that became known as the Oort cloud. Maarten's 1956 PhD thesis involved the new technique of radio astronomy; using observations at 21 cm of more than 800 hydrogen clouds, he constructed the first map of the spiral structure in the inner part of our galaxy.

His graduate career was unusually eventful. In 1950–51 he spent roughly 16 months in Kenya, where he participated in the Leiden Observatory's program to measure the precise positions of stars. During the dike-system collapse in the Netherlands in 1953, Maarten joined a team that rescued nearly a thousand people.

Following graduation, Maarten accepted a Carnegie fellowship at the Mount Wilson Observatory, where he used the telescopes to investigate star clusters and was able to hone his observational skills. After a brief return to the Netherlands, he joined the faculty at Caltech in 1959. That same year he also published a relationship, now known as the Kennicutt–Schmidt law, between the star-formation rate and surface gas density in galaxies.

At the time, an unusual class of radio sources—later named quasars—were discovered; they appeared to be stars, but their spectra were unlike any known object, and some displayed spectacular brightness variations on time scales of days to weeks. Intrigued by that puzzle, Maarten obtained a spectrum of the brightest quasar in December 1962 with the Hale Telescope. He realized that several of the features matched the Balmer series of hydrogen, only increased in wavelength by a factor of 1.16.

MATTHEW KUHN

Maarten Schmidt

After examining the possibilities of a gravitational redshift and a Doppler shift, Maarten concluded in his 1963 *Nature* paper that the redshift was produced by the expansion of the universe; quasars were beacons located at distances of billions of light-years with luminosities hundreds of times that of our entire galaxy. The brightness fluctuations demanded that the radiation be produced in a region whose scale was that of our solar system. It is now the consensus that quasars are supermassive black holes accreting approximately one solar mass each year.

In 1965 Maarten announced the identification of a quasar with a redshift in excess of two, which increased the volume of the observed universe by roughly an order of magnitude and provided the first glimpse of Lyman-alpha emission in the distant universe. The lack of strong absorption in the rest-frame UV measurements revealed that hydrogen in the intergalactic medium must be highly ionized. The discovery of that distant object was celebrated by a *Time* magazine cover in March 1966 containing a series of images of Maarten reverberating through the cosmos.

Maarten proceeded to lead a series of surveys to examine quasar evolution, and they demonstrated that the number density of quasars rose rapidly with increasing redshift. Starting in 1982 he and James Gunn employed a new detector, the CCD, to search for quasars at redshifts larger than four. Their program produced record-setting redshifts and showed that hydrogen in the intergalactic medium became less ionized as one moved to earlier epochs and that the quasar number density peaked at a redshift of approximately two to three.

In the 1990s Maarten's interests turned to high-energy astrophysics. With members of the *Rosat* satellite team, he performed a deep field survey, using the Hale and Keck telescopes to determine the distances and luminosities of faint x-ray sources. He also used an innovative analysis technique to create a uniform catalog of gamma-ray bursts from *Compton Gamma-Ray Observatory* archival data and determine the luminosity function of the bursts.

Maarten was quite active in service to the profession and held positions as chair of the division of physics, mathematics, and astronomy at Caltech; director of the Hale Observatories; and president of the American Astronomical Society. He received many awards for his scientific contributions, including the 1991 James Craig Watson Medal of the National Academy of Sciences and the Kavli Prize in Astrophysics in 2008. He had a wide variety of interests, and his sparkling sense of humor was particularly valued during cloudy nights at the telescopes. He was an excellent and thoughtful mentor of young scientists and a fierce dominos competitor.

Donald P. Schneider
Pennsylvania State University
University Park

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about a colleague's death, visit
https://contact.physicstoday.org
and send us a remembrance to post.
Select submissions and, space permitting, a list of recent postings will appear in print.

Karl von Meyenn

Karl von Meyenn died at his home in Neuburg an der Donau, Germany, on 18 June 2022. He was a central contributor to the history of physics through his long-term efforts to edit and publish the letters and writings of key physicists of the early to mid 20th century. Letters were then a primary means of collaboration among physicists. Through his work, Karl opened up valuable insights regarding the development of physics and the physicists who developed it.

Karl was born in Potsdam, Germany, on 7 November 1937. After World War II, he and his parents moved to Chile. There Karl studied physics at the Southern University of Chile in Valdivia and at the Pontifical Catholic University of Chile in Santiago, where in 1965 he was the university's first recipient of a diploma in physics.

The following year Karl returned to Germany to pursue his doctorate at the University of Freiburg. He completed it under the direction of Siegfried Flügge in 1971 with a dissertation on the order–disorder transition in sodium nitrite. He and his wife, Felicitas, then moved to Chile, where Karl taught at the Pontifical Catholic University of Chile. In September 1973, just days before the country's military coup, they returned to Germany. Karl had joined the University of Freiburg as a senior assistant in theoretical physics with Helmut Reik.

In 1975 Karl turned his attention to the history of science. In collaboration with Victor Weisskopf, Armin Hermann, who was head of the program for history of science and technology at the University of Stuttgart, invited Karl to undertake a long-term project to edit and publish the complete scientific correspondence of the brilliant and influential physicist Wolfgang Pauli. The multivolume project, titled *Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u.a.; Scientific Correspondence with Bohr, Einstein, Heisenberg a.o.*, was published by Springer (1979–2005) and funded by the German Research Foundation and later by CERN, ETH Zürich, and the Swiss National Science Foundation.

Karl took on the editorial task with his characteristic enthusiasm and intellectual rigor, as witnessed by one of us (Cassidy), then a postdoctoral fellow in Stuttgart. From the late 1970s until his untimely death in 1986, Roman Sexl, a University of Vienna theoretical physicist and historian of physics, became both a mentor and a friend to Karl and profoundly influenced Karl's development as a historian and his status as editor of the Pauli letters.

By the time he left Stuttgart in 1985 to become a German exchange professor of history of science at the Autonomous University of Barcelona in Spain, Karl had completed the first two volumes of the Pauli correspondence, comprising more than 1400 pages. He had also written an essay for the book *Atomvorstellungen im 19. Jahrhundert* (Conceptions of the atom in the 19th century) and, with Sexl and Klaus Stolzenburg, an edition of Niels Bohr's writings on the Copenhagen interpretation of quantum mechanics. While in Barcelona, Karl published several works in Spanish and a collection with Charles Enz of Pauli's writings titled *Das Gewissen der Physik* (The conscience of physics). Karl's Barcelona colleagues remember him for greatly strengthening the university's emerging doctoral program in history of science and for his knowledge and his extensive library, which he generously shared.

At the invitation of Hans-Peter Dürr, Karl moved in 1991 to the Max Planck Institute for Physics in Munich. Aside from a six-month sojourn as a guest editor of the Einstein Papers Project in Boston, Karl continued work on the Pauli correspondence. He also published numerous journal articles and a two-volume study of the lives and works of the great physical scientists from Aristotle to Murray Gell-Mann. Upon reaching retirement age, he moved in 2000 to his last destination, the Institute for Theoretical Physics at Ulm University, which was directed by Frank Steiner, a good friend and colleague. There Karl completed the last volumes of the Pauli correspondence, published in 2005. Six years later he published a two-volume edition of Erwin Schrödinger's letters on wave mechanics and the cat paradox in quantum mechanics.

Karl's massive volumes of the Pauli letters project amounted to roughly 7400 pages with more than 3200 edited and annotated letters, along with commentaries on their historical context. "His edition of the Pauli correspondence is fundamental for all historians of modern physics," writes the historian John Heilbron in an email to one of us (Hoffmann). "Truly a monumental achievement." From 1919 to his death in 1958, Pauli covered in his correspondence nearly the entire sweep of fundamental physics in his lifetime—from the early development of quantum mechanics and its interpretation through its applications and adaptations to nuclear physics, beta decay, and high-energy and particle physics, as well as such other topics as renormalization and parity violation. In addition to the science and personalities of their authors, the letters reflect the impact of Nazism and Fascism, World War II, and the Cold War. All lent a vital human dimension to the volumes of insightful scientific correspondence.

MEYENN FAMILY ARCHIVE

Karl von Meyenn

Karl was an avid reader of not only history and science but also classical literature. He spoke fondly of his younger days in Chile when he rode horses across the plains and worked as a gaucho on a cattle ranch. We sadly miss Karl's infectious enthusiasm, his tireless devotion to his work, and his friendliness and hospitality.

David C. Cassidy
Bay Shore, New York
Dieter Hoffmann
Max Planck Institute for the History of Science
Berlin, Germany PT

QUICK STUDY

Michael Manga is a professor and the department chair of Earth and planetary science at the University of California, Berkeley, and **Max Rudolph** is an associate professor of Earth and planetary sciences at the University of California, Davis.

Enceladus erupts

Michael Manga and Maxwell Rudolph

In the frozen reaches of the outer solar system, one Saturnian moon hosts rich geological activity, sustained by liquid water.

One of the most exciting discoveries in planetary science of the past few decades is the eruption of water from Enceladus, a small ice-covered moon of Saturn. Ice particles and vapor are ejected. Some of the ice falls back to the surface as snow, making Enceladus one of the most reflective objects in our solar system. Smaller ice particles not only feed the E ring of Saturn, but with the vapor, they also provide a window into the structure and dynamics of Enceladus's interior, including its rocky core, a potentially habitable liquid-water ocean, and the fissures through which the water erupts.

The sources of the eruptions are a set of fissures near the south pole of Enceladus. Properties of the erupted materials have been characterized by a host of instruments on the *Cassini* spacecraft, which explored Saturn and its moons between 2004 and 2017. (See the article by John Spencer, Physics Today, November 2011, page 38.) *Cassini*'s instruments included UV, visible, and IR spectrometers; mass spectrometers; and a particle analyzer. Collectively, their measurements revealed that the gas is mostly water vapor with a few percent of other volatiles. The total mass flux varies in time, with an average of tens of kilograms of ice particles per second and a gas flux an order of magnitude greater. Here, we discuss some of the physics of how the eruptions happen.

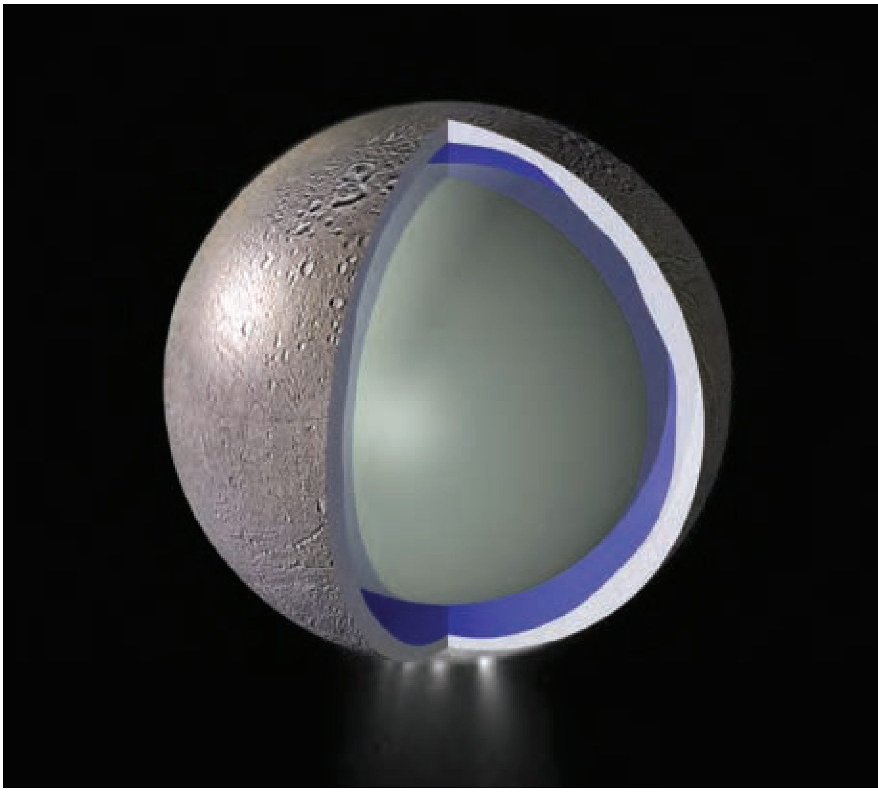

FIGURE 1. ENCELADUS in cross section. In addition to the craters that scar its icy surface, Enceladus contains smooth plains and cracks, ridges, and fissures. The moon's interior is composed of an ice shell (white), whose thickness is roughly 20 km on average but thins at the south pole, as modeled from gravity measurements. Below that shell is an ocean (blue) that covers a rocky interior (gray). (Courtesy of Doug Hemingway.)

Shell game

Although researchers initially debated whether the eruptions come from a body of liquid water or from the decomposition of gas-bearing ices in the ice shell, the presence of salts in the ice grains and silica nanoparticles indicates a source from an ocean in contact with a rocky core. The presence of a global ocean under Enceladus's ice shell is confirmed by gravity and shape measurements and the amplitude of the ice shell's tidal oscillations. The eruptions thus appear to be sourced from an internal ocean, shown in figure 1, with water traversing the ice shell through fissures near the south pole.

The presence of active water eruptions on a small (250 km radius) body in the cold outer solar system raises several questions: How is it warm enough to sustain a liquid ocean? What makes the cracks that enable eruptions? Why doesn't water freeze in the cracks? Why are the fissures only at the south pole? Those questions remain open research topics. Even so, we favor some intuitive explanations.

Enceladus orbits Saturn twice during each orbit of Dione, another of the planet's satellites. The orbital resonance forces Enceladus into an elliptical orbit, which in turn causes cyclic tidal deformation. Dissipated heat from that deformation keeps the interior warm enough to maintain an ocean. The same tidal dissipation inside water-filled cracks can help keep the water from freezing.

The presence of the ocean itself may cause those cracks to form in the first place because of feedback between Enceladus's

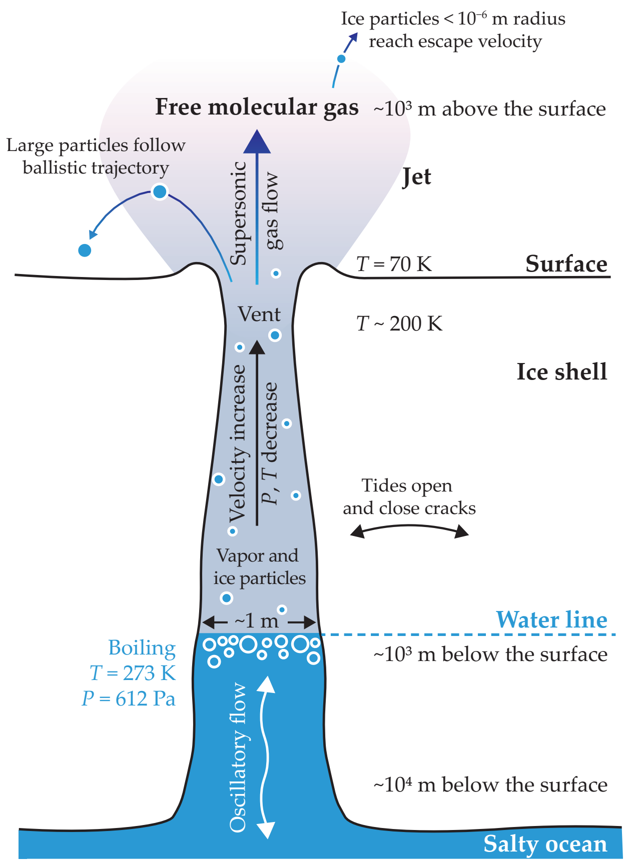

FIGURE 2. SHELL DYNAMICS. This schematic (not to scale) illustrates some of the main processes that occur inside the ice shell and its fissures. The eruptions are assumed to originate from water in an ocean under the shell, although any liquid-water source, such as a melt reservoir in the icy crust, should produce similar dynamics. As Enceladus's tidal forces open and close a crack in the fissure, water flows into (and recedes from) the fissure. The velocities of ascending vapor and ice particles increase in the vent as pressures and temperatures drop. Above the vent, they reach supersonic speed.

orbit and the tidal dissipation of heat. When the dissipation decreases, the ice shell thickens. The increase in the volume of liquid water as it freezes onto the ice shell's base compresses the ocean and stretches the overlying shell. If the stresses from the stretching become large enough, a crack can form.

Gravity on Enceladus is weak, and pressures remain sufficiently low throughout the ice shell that cracks could penetrate the entire shell. They form at the south pole where the ice shell is thinnest and the combination of heating from tidal deformation in the ice shell and the ocean circulation is highest.

Eruption mechanics

The processes governing the eruption of water vary with depth and altitude (see figure 2). In the fissures, water rises about 90% of the distance from the base of the ice shell to the surface because of the density difference between liquid water and solid water. The water line sits at water's triple point, where its liquid, solid, and vapor phases coexist. Immediately above the water line, decompression boiling produces a flow of vapor and entrained liquid droplets. The droplets freeze, possibly forming the salty ice particles sampled by the *Cassini* spacecraft.

As a first approximation, the flow of gas and ice in the fissures can be treated as being close to adiabatic—meaning that energy is only transferred to the surroundings as work—if two conditions are met. First, the flow must be sufficiently rapid that the exchange of heat with the fissure walls can be neglected. Second, erupted particles and gas must remain in thermodynamic equilibrium, and the vapor, liquid, and solids all move at the same velocity.

As the flow ascends, it decompresses and cools. Water vapor condenses on ice particles and nucleates new particles, creating a mixture of particles and gas. The velocity of the flow at the vent is likely limited by the sound speed of the two-phase mixture because the pressure gradient becomes infinite as velocity approaches the speed of sound.

The back pressure exerted by the mixture moving through the fissure and vent limits the rate of vaporization and the total mass flux from the eruptions. Above the surface of Enceladus, the erupting mixture forms a jet as it expands into space at velocities that become supersonic. With continued expansion, the mean free path of gas molecules grows too large for further condensation. As the plume becomes increasingly dilute, it turns optically thin and no longer expands with constant entropy as heat radiates to space.

In the fissure and just above the vent, the smallest ice particles can be accelerated by the expanding gas to reach escape velocities; larger particles reach lower speeds, follow ballistic trajectories, and fall back to the surface of Enceladus.

Physicists are less certain about what happens in the moon's interior, including whether liquid water can be generated in the ice shell and, hence, whether the eruptions need to originate from the ocean. Knowing the compositions of the ocean and erupted gases and particles is especially important to assess the habitability of the interior ocean and interpret possible biosignatures. Open questions also remain about the geometry of the eruptions and fissures, the longevity of the eruptions, how they are modulated by tides, and why they are at the south pole.

The proposed *Enceladus Orbilander* mission, which would collect fresh plume material from orbit and send a lander to gather samples from the surface, is one of two large missions prioritized in the 2023–32 Planetary Science and Astrobiology Decadal Survey. A new generation of instrumentation will be better able to probe the geochemical and physical processes that sustain the eruptions, assess the habitability of the ocean, and search for evidence of past or current life in the erupted materials.

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Additional resources

► C. C. Porco et al., "*Cassini* observes the active south pole of Enceladus," *Science* **311**, 1393 (2006).
► P. M. Schenk et al., eds., *Enceladus and the Icy Moons of Saturn*, U. Arizona Press (2018).
► M. Nakajima, A. P. Ingersoll, "Controlled boiling on Enceladus. 1. Model of the vapor-driven jets," *Icarus* **272**, 309 (2016).
► E. S. Kite, A. M. Rubin, "Sustained eruptions on Enceladus explained by turbulent dissipation in tiger stripes," *Proc. Natl. Acad. Sci. USA* **113**, 3972 (2016).
► D. J. Hemingway, M. L. Rudolph, M. Manga, "Cascading parallel fractures on Enceladus," *Nat. Astron.* **4**, 234 (2020). PT

Zinc snowflakes

The metal gallium is liquid at room temperature, which gives the chemical element all sorts of unique properties (see the article by Michael Dickey, Physics Today, April 2021, page 30). Shuhada Idrus-Saidi and Jianbo Tang, of the University of New South Wales in Australia, and their colleagues recently used gallium as a metallic solvent in their synthesis of crystalline structures made of zinc, shown in this tinted photo. Because of gallium's 30 °C melting point, it remained liquid when a gallium–zinc alloy was heated and subsequently cooled, which yielded solid zinc crystals. Like snowflakes formed from ice crystals, the zinc snowflakes have a highly ordered, hexagonal-like structure. Yet each one also has unique branching and needle-like components.

Zinc crystals can't be sieved and filtered from liquid gallium in the same way that particles are separated from an aqueous solution or an organic solvent. To isolate the zinc snowflakes, the researchers tuned the electrical properties of the gallium to break its surface tension. Then the gallium was carefully vacuum filtrated from the delicate snowflakes. The researchers are hopeful that their methods can offer a new manufacturing pathway for growing complex metallic nanostructures. (S. A. Idrus-Saidi et al., *Science* **378**, 1118, 2022; image courtesy of Jianbo Tang.) —AL

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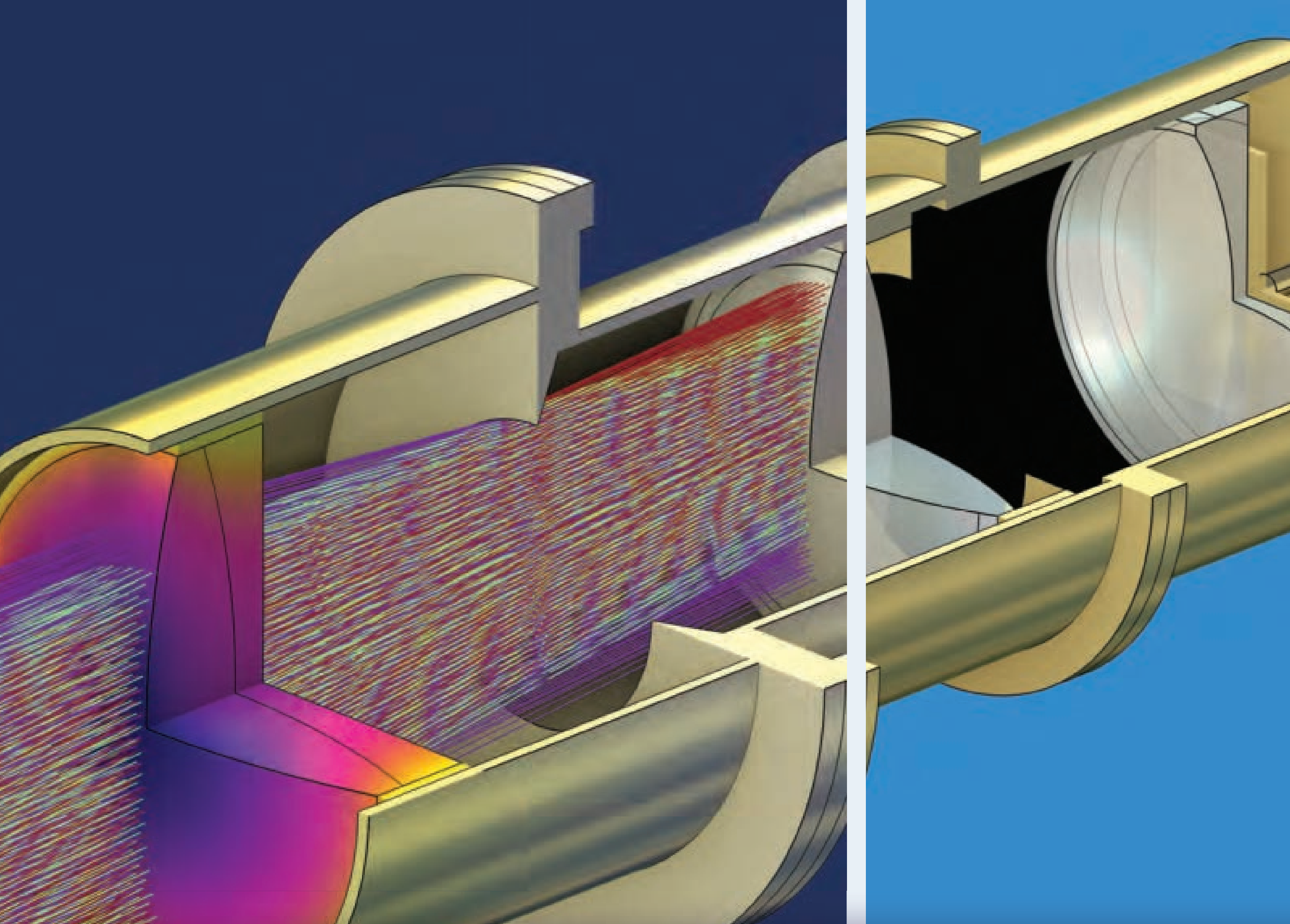

Semantic segmentation for wildlife conservation.