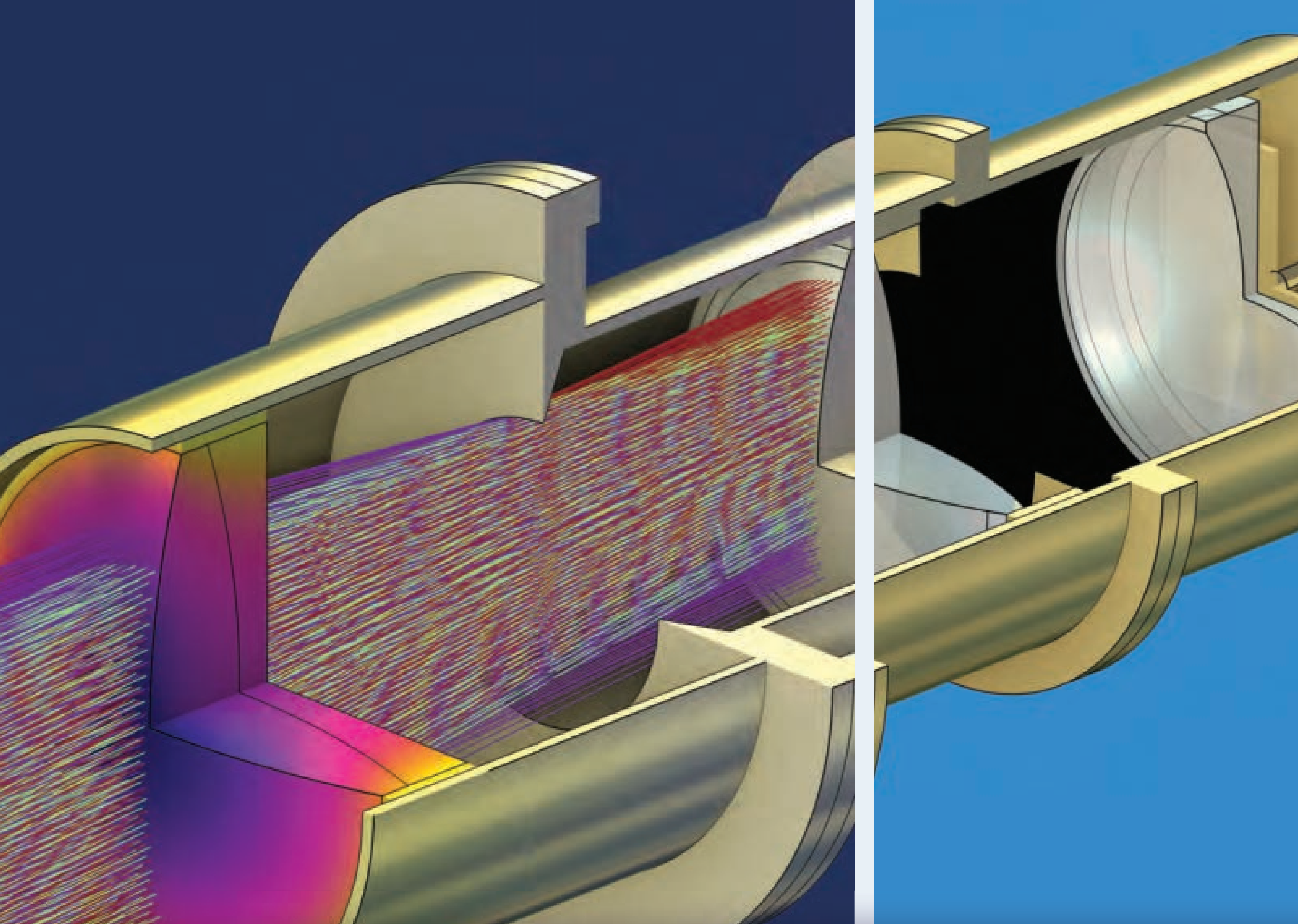

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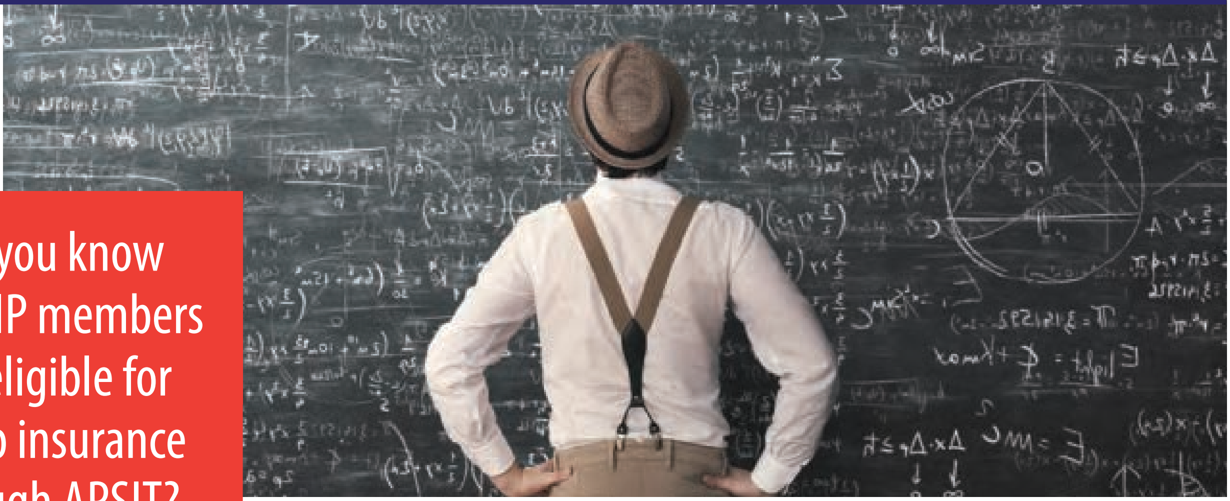

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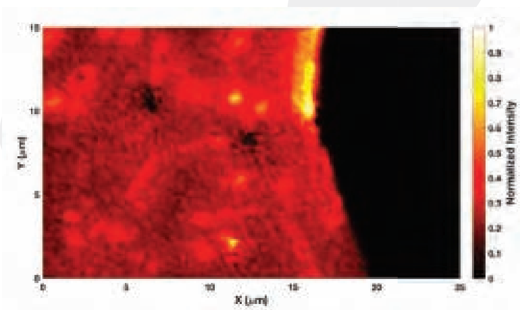

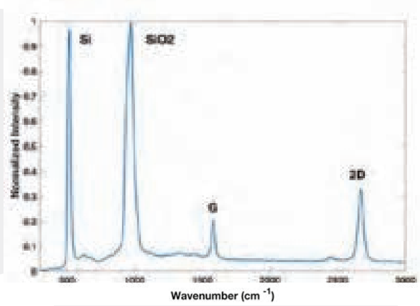

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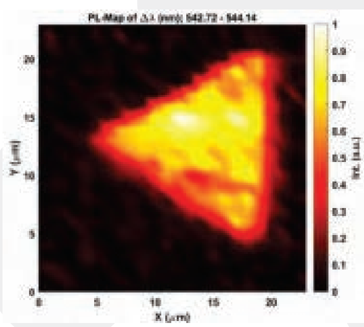

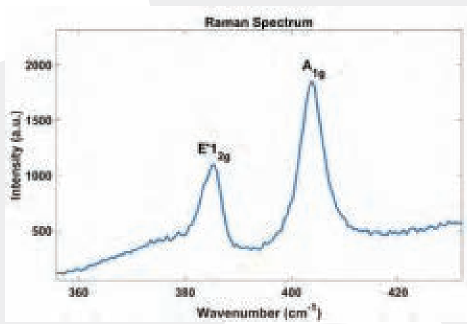

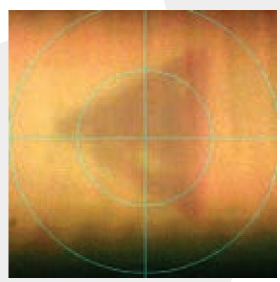

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PHYSICS TODAY

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Careers issue

ON THE COVER: Our fourth annual careers issue focuses on the public sector. On **page 32**, Christine Middleton describes an opportunity at NSF for researchers to lend their expertise and help guide scientific research. Two other features illustrate the variety of paths and opportunities to be found across the sector. On **page 40**, Tess Jaffe recounts her journey through positions in Europe and the US. And on **page 50**, Carl Williams discusses his path to and within NIST. (Image by Donna Padian.)

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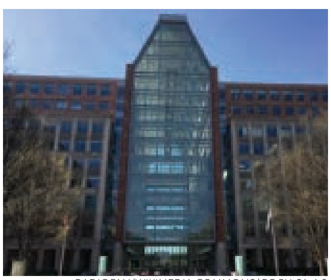

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Keep exploring government careers

The careers issue continues online with new articles published throughout October. Delve further into government jobs for physical scientists with an infographic about entering the government workforce, an interview with a physicist at the US Patent and Trademark Office (northern Virginia headquarters pictured), a profile of a grassroots group that prepares scientists and students for careers in science policy, and more. Check out all our careers coverage by visiting the link below or scanning the QR code.

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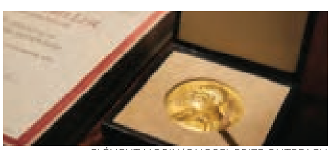

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It's Nobel season, and Physics Today is providing complete coverage of the 4 October physics prize. Read a comprehensive report on the newest laureates and their work, and check out the magazine's archives to see how PT originally covered the prizewinning research.

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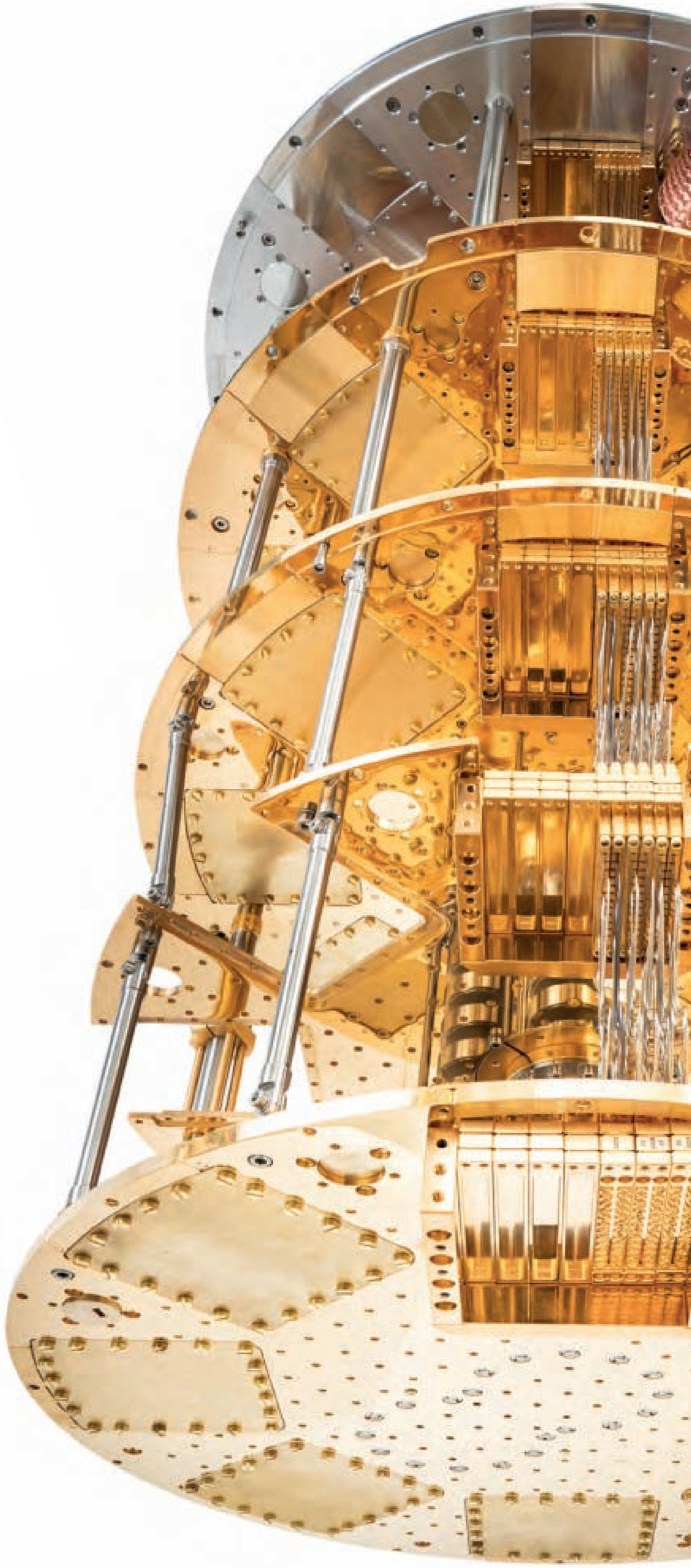
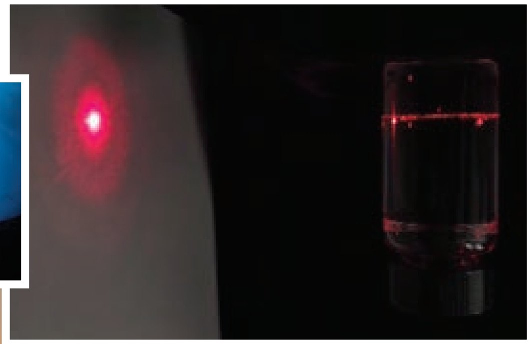


BLUE FORS

Commentary

Thinking of moving from academia into industry? Here are some things to consider



DAVID RAHMLOW, the author of this commentary, works at a company that focuses on using light-scattering tools to determine characteristics of nanoparticles and macromolecules. The intensity and angular distribution of scattered light depends on particle size and molar mass. The diffraction pattern of transparent particles, such as those made of polystyrene latex, is a consequence of Lorenz–Mie theory, and orange sunsets and underwater scenes owe much of their drama to Rayleigh scattering. (Underwater image courtesy of Steve Trainoff.)

I've been working in industry for about 10 years. I've always enjoyed building things, especially scientific apparatus. But putting my skills to use in industry, rather than academia, was not always a foregone conclusion.

I am currently an R&D staff scientist at Wyatt Technology Corp—a family-owned company based out of California that consists of 160 people worldwide—which is primarily focused on the use of light scattering to measure particle size. As a PhD candidate, however, I studied experimental atomic, molecular, and optical physics, and after grad school, I wasn't quite ready to leave the academic world.

After all, it has many comforts that private industry, particularly small businesses, can't easily replicate. Weekly departmental seminars can give those in academia a deep connection to the broader physics community. While local professional society meetings can offer people in industry opportunities to explore and network, they are narrow in scope compared with what universities can offer. One of the most significant challenges I've experienced since starting an industry career is the lack of access to scientific journals. Although open access is gaining ground, it is still uncommon, especially for older papers.[1] And when you work in industry, not only is it harder to get information, but intellectual property strategies may limit what information you can give.

If you're unsure about leaving academia, like I was, then you can always stay a bit longer before making the switch to industry. Spending a couple of years doing a postdoc isn't necessary for a job in industry, but it can be a valuable experience. In my case, a postdoc was my first time mentoring others: My responsibility was to work with half a dozen students—in contrast to graduate school, where it was to pursue research for my dissertation. Many postdoc opportunities are available. Statistics from the American Institute of Physics (the publisher of Physics Today) show that they are the choice of about half of physics graduates after completing their PhDs. Only about a fifth go directly to a potentially permanent job in the private sector.[2]

The problem with getting postdocs is that they often need to be followed by other postdocs before one can become a university faculty member. During my postdoc tenure, I realized that I wasn't willing to move around to other positions in the coming years in the way that the academic world might have required of me. It was time to find somewhere to settle down. And for me, that meant looking for a job in industry.

In my case, finding Wyatt was serendipitous. I wasn't planning to attend the American Physical Society March Meeting in 2012, but since it was nearby, on a whim I uploaded my resumé to the job fair. Less than half an hour later, I received an email inviting me to interview with Philip Wyatt—the company founder—who happened to be attending. We launched into a pop quiz after introductions. "Why is the sky blue?" "How does a laser work?" "Where does helium come from?" (I'm told the most unique answer he's heard for the last one was "Kansas.")

Job seekers may find that it is hard to come across opportunities at smaller companies because of the sheer number—and relative obscurity—of them. General-purpose job search engines, such as Indeed and Monster, can be overwhelming in their lack of specificity. Resources such as the American Physical Society jobs board and Optica's WORKinOPTICS website are focused on physics-related jobs, but only a subset of industry employers regularly use them.

So what might you do in industry? It's possible, but rare, that you may stay in the same field in which you did your doctoral research. Your field may have bountiful commercial applications, and you may find a company that sells specialized apparatus for them. But if you can't, don't despair. Chances are that the skills you learned when completing a PhD can still be put to good use.

In my case, I've found that the skills from experimental atomic, molecular, and optical physics are well suited to product development. An experimental physicist is a jack-of-all-trades, and understanding how all aspects of a system interact is critical when developing a product. Projects start with an analysis of the fundamental operating principles, but implementation depends on an intuition for the art of mechanical engineering, optics, and electronics. That insight is necessary when working with the engineers that will help bring the project to fruition. Experience in the machine shop and electronics lab has helped me to write more accurate specifications and better assess the elegance of a proposed solution.

If you choose to make the switch from academia to industry, consider what you value in a career. Are you looking for work–life balance? Is it important to see the impact of your work? Do you enjoy tackling every sort of problem, or do you see yourself as a specialist? Company size and culture has an impact on each of those. Last year's careers issue (Physics Today, October 2021) explored a few of the options in private industry. Fittingly for physics, it covered businesses of the smallest and largest scales—from entrepreneurship (see the article by Christine Middleton, page 42) to the Ford Motor Company (see the article by Mike Tamor, page 32). But I'd like to add that there's still plenty of room in between. Small and midsize businesses may not have the name recognition of Alphabet or Apple, but they make up the bulk of the economy and can be rewarding places for physicists to work.

The informal term "small business" is not well defined. For the US Small Business Administration, the definition depends on the field.[3] Personally, I like the idea of "Dunbar's number," approximately 150, which is a proposed limit on the number of stable relationships one can maintain. A business with that many employees is still small enough to have much of the nimbleness of an entrepreneurial startup but is not so small that added responsibilities take a toll on work–life balance. Such a business can be large enough to have resources, but it is small enough that its employees are more than "shiny cogs" in the machine, and they can see the impact that their contributions make.

If you're interested in continuing to put your physics skills to use, consider the opportunities that industry has to offer. There's more out there than you may think.

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1. H. Piwowar et al., *PeerJ* **6**, e4375 (2018).
2. AIP Statistical Research Center, *Initial Employment—Physics Bachelors and PhDs: Classes of 2019 and 2020* (March 2022).
3. US Small Business Administration, "Table of size standards" (14 July 2022).

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LETTERS

Fusion power's future

In the review of *The Star Builders: Nuclear Fusion and the Race to Power the Planet* (Physics Today, October 2021, page 64), reference is made to the old joke that controlled fusion power is 30 years away and always will be. I would like to update that observation, and perhaps make it more rigorous, by noting the history of controlled fusion research dating from the 1950s. In my 60 years of association with plasma physics and both magnetic- and inertial-confinement fusion, I've heard countless briefings and promises: When the research programs were 10 years old, the reactor was 10 years away. After 20 years, it was 20 years away; 30 years on, it was 30 years away; and so on. Now a commercially viable reactor could be more than 50 years away. It appears to be a self-similar problem, where the only time scale is the elapsed time.

Such behavior is not restricted to controlled fusion. The same joke, including

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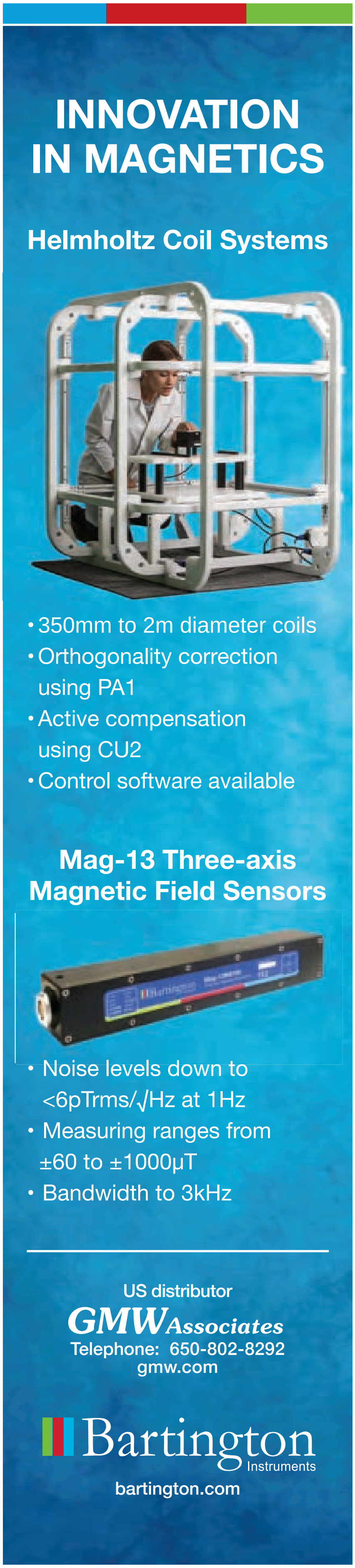

the 30-year time frame, used to be said of electric rocket propulsion, and there are now hundreds of spacecraft that use electric propulsion. Perhaps the problem is related to the so-called S curve for technology development. Until a technology rises above the early, exploratory stage, predictions about it becoming mature enough for practical use can be driven more by optimism and enthusiasm than by the available hard facts.

The recent surge in fusion startups[1] might be encouraging (to some), but it's reminiscent of the early days of aeronautics, when some folks began attempting heavier-than-air flight—and airplanes with heavy piston engines won out over the early aeronautical success of hot-air balloons. The accumulation of ideas and experience directed toward real systems may eventually make a difference for fusion power on its S curve. Electric rocket propulsion was helped by frequent, short-turnaround iterations, thereby providing a time scale for progress apart from the elapsed time. Unfortunately for fusion, the cost and size of useful technical demonstrations may preclude such iterations. Startup fusion concepts that substantially reduce cost and size offer optimism for faster progress.

Reference

1. D. L. Jassby, *Physics and Society*, October 2021, p. 5.

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More on being a physicist in industry

Mike Tamor's article, "Lessons from 35 years in industry" (Physics Today, October 2021, page 32), describes many of the challenges faced by a physicist trained in an academic institution and working in an industrial environment, including challenges involving management responsibilities. As someone who has worked in industry for many years—at places including General Dynamics and Mission Research—I would like to emphasize another factor that many academic scientists don't appreciate.

As Tamor points out, "Physicists are trained to revere new knowledge." In school, we are taught to push limits, explore the unknown, improve accuracy, explain the mysterious, and so on. That is the goal of fundamental research, which we are taught to respect above applied research. Fundamental research is relatively rare in industry—jobs for PhD physicists in industry across STEM (science, technology, engineering, and mathematics) and non-STEM fields are more likely to involve applied research, which can entail using a scientific approach to provide engineers with tools to solve practical problems.

The engineering world involves many trade-offs between considerations such as performance, cost, weight, and aesthetics, and they frequently compete with each other. The results can flow down to the research effort and influence required goals, such as performance and precision. Research scientists need to understand those goals, and they need to pursue the approaches that can reach the goals without expending undue effort that exceeds them. The leader of the research effort must have a clear understanding of the factors that are really important in the eventual application and how good is good enough—that is, when the design accomplishes its objective with an adequate margin and at a reasonable cost in resources.

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San Diego, California

Correction

July 2022, page 49—The Cowan–Reines experiment used large tanks of water with dissolved cadmium sandwiched between tanks of liquid scintillator. PT

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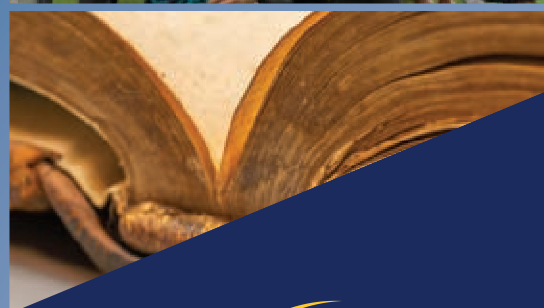

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Turbines and motors made of DNA

The medium of life's genetic code is also a versatile structural material for building nanoscale machines.

From the cogs and wheels of well-oiled machines to the spinning flagella of single-celled swimmers, rotation is one of the most versatile forms of mechanical motion at almost any size scale. The rotating wheels of cars and conveyor belts drive linear motion. At the subcellular scale, rotation powers not just mechanical processes but chemical ones. ATP synthase, the enzyme that assembles molecules of adenosine triphosphate to fuel cellular processes, is based on a spinning central protein cylinder.

Researchers have long sought to mimic the molecular machinery of life to build their own miniature molecule assemblers and more, but they've been challenged by the small-scale physics. A submicron spinning rotor in water lacks the inertia to keep turning in one direction. Instead, it's pulled to a stop by viscous drag and batted around by the Brownian storm of random molecular movements. On top of the difficulty of just building the tiny machines, researchers need to engineer the physical mechanism of their operation, and it's not clear what the best one would be.

There have been some successes. Bernard Feringa, honored with a share of the 2016 Nobel Prize in Chemistry, designed the first one-way synthetic molecular rotor, powered by alternating pulses of heat and light. (See Physics Today, December 2016, page 18.) David Leigh and colleagues at the University of Manchester have synthesized several rotors that, like biomolecules, are fueled chemically.[1] But so far, even state-of-the-art rotors have been impractically slow, taking minutes or hours to complete a single rotation.

Now two overlapping groups, both including Hendrik Dietz of the Technical University of Munich and his graduate student Anna-Katharina Pumm, have sped things up. They've designed two different rotors, both made with DNA origami, that rotate several times a second: not quite as fast as their biological counterparts, but in the same ballpark. Although superficially similar—both rotor blades are bundles of DNA some 500 nm long—they operate in completely different ways. One, described in *Nature Physics*, works like a turbine that's pushed by the flow of the surrounding fluid.[2] The other, described in *Nature*, spins autonomously like a wireless electric motor, powered by an AC electric field applied to the whole system.[3]

FIGURE 1. ION FLOW through a nanopore drives the rotary motion of a 500-nm-long bundle of DNA, much like a miniature turbine, windmill, or water wheel. The ion flow is initiated either by a salt gradient—placing salt water on one side of the membrane and fresh water on the other side—or an electric potential difference. (Courtesy of Cees Dekker Lab/Scixel.)

Breaking symmetry

Biology uses proteins to create the intricate shapes and structures of its molecular machines. Although researchers are starting to decode the links between protein sequence, structure, and function (see Physics Today, October 2021, page 14), they still have a long way to go before they can reliably design protein-based machines to order.

The advent of DNA origami is a testament to scientific creativity. In nature, DNA is an information-carrying material, not a structural one. But because of the ease of programming specific interactions—single strands of DNA stick easily to their complementary sequences, and almost not at all to any others—researchers have repurposed it to build things. (See Physics Today, April 2012, page 20, and the Quick Study by Oleg Gang, Physics Today, March 2021, page 58.)

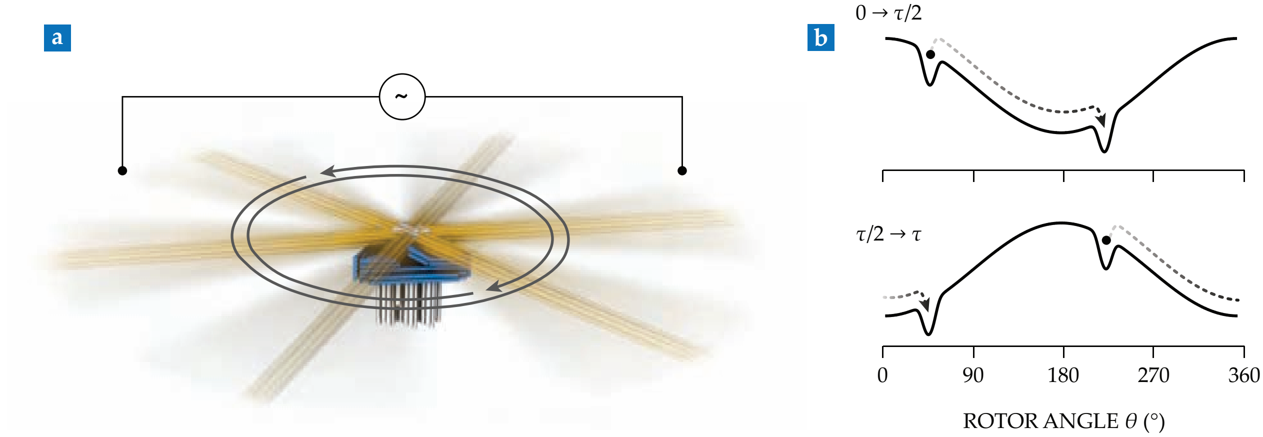

FIGURE 2. A WIRELESS ELECTRIC Brownian-ratchet motor **(a)** is made of three DNA-origami components: the rotor blade (yellow), dock (blue), and pedestal (white). An alternating applied electric field drives the blade's rotation in one direction or the other, depending on the motor's orientation. **(b)** Over the AC field's oscillation period τ, the energy landscape flip-flops between the two sine-wave configurations. The two small dips are created by the blade–dock interaction. The blade hops from one to the other, almost always in the same direction. (Adapted from ref. 3.)

Dietz, an expert in designing and characterizing sophisticated DNA nano-objects, got a grant in 2016 to work on DNA-origami motors. He started exploring different mechanisms of operation, including using an ion current through a nanopore to push a DNA rotor around in a circle like the blade of a windmill.

Cees Dekker, a biophysicist at Delft University of Technology in the Netherlands, had the same idea, and the *Nature Physics* paper is the result of his collaboration with Dietz, which included Dekker's postdoc Xin Shi. Together, they synthesized the rotor illustrated in figure 1: a long bundle of six DNA strands with a small protrusion that allows it to dock to a nanopore in a silicon nitride membrane. When an ion current (induced by either a salt gradient or an electrochemical potential) flows through the pore, the rotor starts to spin.

Curiously, the curvature that breaks chiral symmetry and enables one-way rotation is not inherent to the blade's structure. At equilibrium, a DNA bundle is a straight rod; it becomes curved only in the presence of ion flow. And there is no way to control or predict which way the symmetry is broken. Some rotors turn clockwise, some turn counterclockwise, and a few even spontaneously switch directions in the middle of an experiment.

Uncontrolled symmetry breaking wasn't the researchers' first idea for a rotor design. They tried for years to design a controllably curved blade. "But it never rotated," says Dietz. "So step by step, we stripped away all the complexity until all that was left was the achiral rod. And then that one rotated!"

To understand why, they turned to Ramin Golestanian, a theoretical physicist at the Max Planck Institute for Dynamics and Self-Organization, and his student Jonas Isensee. "The electric field, the hydrodynamic friction, the elasticity of the bundle, and the flow field around the pore all conspire to break the symmetry," Golestanian explains. "It's a gift from the nonlinearities in the underlying physics, much the same as the Higgs mechanism in elementary-particle physics." (See PHYSICS TODAY, September 2012, page 14.)

With the success of their symmetry-breaking rotor, they returned to the quest to build a rotor with deliberately designed chirality. And in the months since they submitted their *Nature Physics* paper, they succeeded.[4] The new rotor is still a straight rod, but the protrusion has three helical turbine blades wrapped around it. The chirality of the helix reliably controls the rotor direction.

Ratchet motor

To create the DNA motor described in the *Nature* paper, Dietz and his lab neighbor Friedrich Simmel looked into mechanisms of Brownian ratcheting. The Brownian storm is an inevitable feature of the nanoscale fluid environment, but there are ways to use it to one's advantage. If a time-dependent potential is applied in just the right way, it's more likely than not that the randomness will push a system in the desired direction.

The physics of Brownian ratchets was worked out decades ago.[5] (See the article by Dean Astumian and Peter Hänggi, PHYSICS TODAY, November 2002, page 33.) But when it came to designing a DNA implementation, Dietz says, "We spent a lot of time unsuccessfully with different driving modes, such as rapid laser heating and cooling. But one day it occurred to me that just shaking the system should lead to directional motion and that applying an AC electric field could be a way to power it."

As shown in figure 2a, the motor is made of three DNA-origami components: the rotor blade (yellow), the dock (blue), and the pedestal (white). The pedestal and dock are fixed to a glass surface, while the blade is free to rotate. Once again, Golestanian and Isensee helped elucidate the operating mechanism. The AC field doesn't drive the directed rotation itself, but it shakes the rotor back and forth between the two potentials shown in figure 2b. The blade–dock interaction creates the little potential dips shown at 45° and 225°, and the applied field superposes the flip-flopping sine wave on top of them. The asymmetry of the combination means that when the rotor hops from one dip to the other—aided by the Brownian storm—it almost always turns in the same direction.

The relative positions of the dips and sine wave depend on how the motor is oriented with respect to the field. In an ensemble of motors randomly scattered on a surface, all orientations are represented. So some motors, with the dips at 45° and 225°, turn counterclockwise;

some, with the dips at 135° and 315°, turn clockwise; and still others, with the dips at 0° and 180° or 90° and 270°, show no directed motion. But unlike the turbine, whose symmetry breaking is random, the direction of any given motor can be controlled by adjusting the direction of the field.

Full speed ahead

The *Nature* motor can perform work against a load: The researchers attached the DNA blade to a molecular torsion spring, and they showed that the motor's rotation winds up the spring and stores energy that can be released later. That capability hasn't been tested with the *Nature Physics* turbine—"That would be a fascinating avenue for future experiments," says Golestanian—but just dragging the 500 nm DNA bundle through the surrounding liquid also takes work.

Indeed, both rotor blades were longer, and therefore slower, than they'd likely be in any future molecular-machinery application. They needed to be as long as they were so the researchers could attach fluorescent molecules to the ends of the blades and watch the rotation in real time. The resulting speeds, up to 20 rotations per second for the turbine and four rotations per second for the motor, were slower than those of biomolecular rotors by a factor of 10–100. But shortening the blades would probably make them faster.

Research on synthetic molecular machines is still in the exploratory stages, but researchers have ambitious dreams. On the wish list of what might be possible: docking rotors to biological membranes instead of synthetic ones, finding a way to reverse the turbine action to pump ion currents instead of being driven by them, and using the rotors to mechanically assemble molecules like ATP synthase does. Dietz says, "It feels like with one more missing piece, we could make something really useful, straight out of science fiction."

Johanna Miller

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Giant meteorites could be responsible for Earth's continents

The isotopic composition of ancient Australian rocks may answer a long-standing question about early Earth.

The Pilbara craton, in the Pilbara region of Western Australia, is the best-preserved remnant of Earth's ancient continental crust (see figure 1a). It formed during the Archean eon 4 billion to 2.5 billion years ago. At that time, Earth is believed to have had a water-covered primordial crust that was more or less a single, continuous shell around the mantle. Eventually, the primordial crust transformed into continental crust, which was later joined by its thinner and denser cousin, oceanic crust.

Most present-day oceanic crust is at most 200 million years old, and its for-

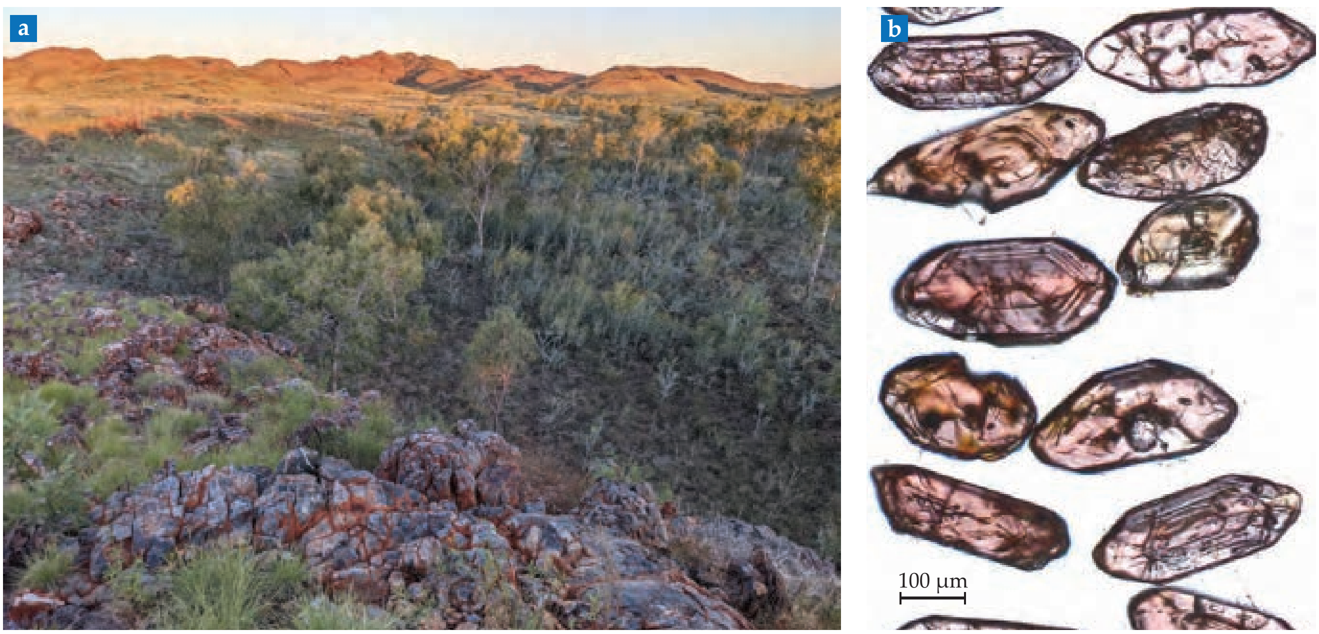

FIGURE 1. THE PILBARA REGION of Western Australia hosts the best-preserved fragment of Earth's ancient continental crust. **(a)** The Pilbara craton formed as far back as 3.6 billion years ago, around the same time as most of today's landmass. It is one of a handful of locations where geological processes between the rocks' formation and the present day haven't erased mineral markers of their origins. **(b)** Zircon grains extracted from Pilbara rocks are particularly useful measures of the craton's past because their composition reveals their age and the conditions at the time of their formation. (Images courtesy of Chris Kirkland.)

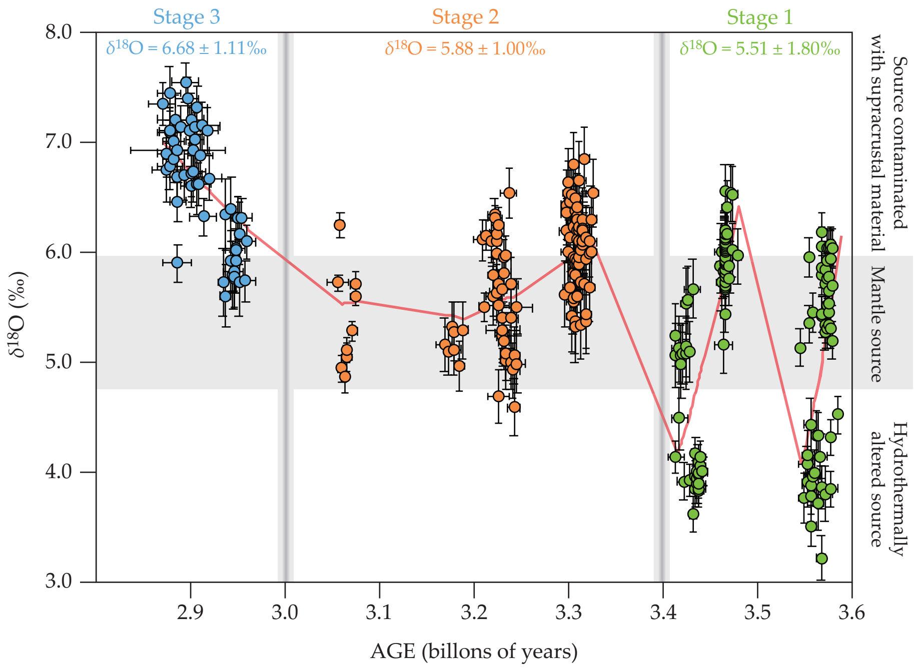

FIGURE 2. OXYGEN ISOTOPES in zircon reflect the source materials that formed the mineral. The ratio of ^{18}O to ^{16}O in secondary-ion mass spectroscopy measurements is compared with a standard reference of distilled seawater to find a relative difference $\delta^{18}O$ in parts per thousand (‰). A useful benchmark is the $\delta^{18}O$ of Earth's mantle (horizontal gray stripe). As indicated by a local regression fit (pink line), zircon grains from the Pilbara craton have $\delta^{18}O$ values that trend with decreasing age, given in stages separated by vertical gray lines, from lower than the mantle in stage 1 (green) to mantle-like in stage 2 (orange) to higher than the mantle by stage 3 (blue). A giant impact could explain the trend. (Adapted from ref. 2.)

mation is ongoing and well understood: When a gap opens between tectonic plates, magma bubbles up into the gap, cools, and spreads out from the initial ridge. Continental crust is much older; three-quarters of the present-day landmass worldwide formed in the Archean as did the Pilbara craton. Because the continents have been around so long, figuring out their genesis is a challenge. Earth's geological evolution gradually and often violently transforms and mixes continental crust until evidence of the distant past is erased.

Since the mid 1960s, one theory has argued that continents formed at the sites of collisions with asteroids tens or a couple hundred kilometers wide.[1] The resulting heating and excavation of the primordial crust would have triggered a sequence of events in which the melted mantle swelled up and overfilled the crater to create a plateau. That seed would then have grown into a continent.

The idea makes chronological sense; the solar system saw a barrage of asteroids around 3.9 billion years ago, a period known as the Late Heavy Bombardment. The Moon's craters are evidence of that period (see the article by Brett Denevi, Physics Today, June 2017, page 38). Earth surely underwent a more ferocious onslaught, as it has more surface area and a larger mass to draw in objects, but the evidence has been limited. And no concrete proof has connected the Late Heavy Bombardment to the formation of continents.

Now Tim Johnson of Curtin University in Australia and his colleagues have found support for the theory that continents formed at the sites of giant impacts.[2] They show that the isotopic composition of Pilbara craton rocks matches what's expected if an asteroid hit the region. Their description of how the craton emerged may explain not only the Pilbara's formation but the making of Earth's continents.

Rock of ages

Johnson, who hails from the UK, arrived in Western Australia in early 2014, just after he had begun thinking deeply about early Earth—that is, the first billion or so years of its four-and-a-half-billion-year existence. He soon met Hugh Smithies of the Geological Survey of Western Australia (GSWA), a division of the state's Department of Mines, Industry Regulation, and Safety. The GSWA was founded over a century ago to gather geological information.

Smithies had long been researching ancient rocks from the Pilbara craton and elsewhere in Western Australia. Those rocks offered an ideal way to study early Earth. Over the course of nearly a decade, Smithies, Johnson, and their collaborators teamed up on a series of projects that used data from Pilbara craton samples. The new study, a culmination of that work, started when Smithies and Yongjun Lu, also from the GSWA, went to Curtin University to discuss some intriguing recent data with Johnson and his colleague Chris Kirkland, an expert on isotope geology.

The team used secondary-ion mass spectroscopy on 26 Pilbara craton rocks that were 2.9–3.6 billion years old. The measurements focused on grains of the magmatic mineral zircon (shown in figure 1b), which is common in igneous rocks. Such grains are useful because they can be dated through the decay of the material's radioactive uranium. What's more, zircon's compositional ratio of oxygen-18 to oxygen-16 isotopes provides a snapshot of its environment—source materials, temperature, and so on—at the time it formed. For the Pilbara samples, the ratios showed three distinct ranges of values that depended on the age of the zircon, as shown in figure 2.

The team wondered whether a giant impact could explain the observation. A strong sign would be that the oldest zircon grains show evidence of forming not from mantle-derived magma originating deeper in Earth but from surface materials melted together by the exceptional heat and compression of an asteroid impact. Such a collision would also produce a whole series of events with potentially discernible influences on the oxygen isotope ratios.

Watered down

The researchers investigated the $^{18}O/^{16}O$ isotope ratio of the zircon samples relative to Vienna Standard Mean Ocean Water, a pure-water benchmark distilled from ocean water gathered from around the globe (see Physics Today online, "Setting standards with old rocks and ocean water," 6 December 2018). The zircon's ratio is then expressed as a relative difference $\delta^{18}O$, typically in parts per thousand (‰).

A useful point of comparison is Earth's mantle: Its $\delta^{18}O$, shown as a gray horizontal stripe in figure 2, is reasonably homogenous and has been stable over time. The mantle serves as an oxygen isotope reservoir, and minerals formed there will more or less share the same $\delta^{18}O$. For minerals formed outside the mantle, $\delta^{18}O$ generally depends on the environmental temperatures.[3] The low-temperature hydrothermal interactions on Earth's surface lead to materials with higher $\delta^{18}O$ than the mantle. Those just below the surface have higher-temperature rock–water interactions and lower $\delta^{18}O$.

Johnson and his colleagues found that for zircon grains older than 3.4 billion years, which they named stage 1, a third have ratios less than that of the mantle. Zircon ages 3.0–3.4 billion years (stage 2) have a higher median $\delta^{18}O$ than that in stage 1, with more than half of the ratios falling in the range expected for the mantle and nearly all the rest higher. For the youngest zircon, with ages less than 3.0 billion years (stage 3), more than three-fourths have $\delta^{18}O$ higher than the mantle.

Johnson and his colleagues argue that the data fit with what would be expected from a giant impact. The low $\delta^{18}O$ values in stage 1 indicate a material source near Earth's surface that was hydrothermally altered at high temperatures, as expected if a burning meteorite crashed into, cracked, and melted a primordial crust covered with ocean water.

The heating and compression from such an impact would spread down to the mantle, which would melt and eventually swell up to fill the crater until it becomes a plateau. That continental nucleus would have crystallizing magmas at its base, which would melt to produce granites with the mantle-like isotope ratios seen in stage 2. Finally, in stage 3, dense near-surface rocks, with their higher $\delta^{18}O$, would sink and end up in a process of intracrustal recycling sometimes called sagduction, akin to subduction but without tectonic plates. From there that continental nucleus would grow.

Additional evidence supports the idea that giant impacts occurred in the region. The Pilbara craton has what's known as spherule beds, a layer of spherical sediment droplets. Spherules are commonly believed to arise from ejected liquid or vaporized rock from a giant impact. The oldest spherule beds in the Pilbara are about 3.4 billion years old, which reassuringly is the same age as a large cluster of low $\delta^{18}O$ zircon grains.

Johnson says that some researchers have been reluctant to accept that giant impacts shaped our planet in any appreciable way, so he suspects that the new work will face opposition in the community. "I'm hoping that the research will stimulate vigorous activity among several groups that will be keen to prove us wrong," Johnson says. "The early Earth is a very controversial scientific endeavor. We're talking about so long ago, and the rocks are so old and have undergone such an uncommonly violent subsequent history."

Any alternative explanation would need to fit the data as well as a giant impact does, though. Two popular alternative theories—that hot matter bubbled up from the mantle to form a continental seed or that plate tectonics were already at play in the Archean—both predict the oldest zircons would have origins from deep below the surface and thus have mantle-like $\delta^{18}O$ values.

Johnson and his colleagues' next step is to investigate other well-preserved ancient rocks in northwest Canada, southern Greenland, and a few other territories to see whether giant impacts could explain all continental masses, not just the Pilbara region. Their initial look at data from the Slave craton in Canada is promising.

Heather M. Hill

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A metamaterial lens traps atoms

Compact, finely textured metasurface optics are coming to a new field of physics.

Atoms are not always small. When excited to a Rydberg state—in which the outermost electron occupies a diffuse orbital that's barely bound to the nucleus—an atom can have macroscopic dimensions of a millimeter or more. Rydberg states' large size and polarizability make them an important tool of atomic physics because they offer researchers a way of controllably switching interactions on and off between atoms in neighboring optical traps. (See the article by David Weiss and Mark Saffman, Physics Today, July 2017, page 44.)

But if an atom is to be stably excited into a Rydberg state, it needs to be held at least several millimeters away from any solid surface, including the surface of the lens that's used to focus the trapping light. For a typical trap size of 1 μm, that's like confining an object to a spot the size of a golf ball from the opposite end of a football field. Conventional optics can meet that demanding requirement, but the precision lenses can take months to design and manufacture, and they must be tailor-made for each new experiment.

Now Cindy Regal of JILA in Boulder, Colorado, and her colleagues have shown that there might be another way.[1] They've created an array of optical traps for single rubidium atoms by focusing light not with smoothly curved glass lenses but with a metasurface, the orange square at the center of figure 1. As shown in more detail in figure 2, the metasurface is made of a thin layer of fused silica topped with subwavelength-sized pillars of amorphous silicon. When the pillars scatter incident laser light, they create an interference pattern that mimics the focusing effect of a conventional lens.

Metasurface optics have been used for years to focus and manipulate light. (See the article by Kai Wang, Maria Chekhova, and Yuri Kivshar, Physics Today, August 2022, page 38.) But designing them to the specifications of atom-trapping experiments was uncharted territory until now. Because metasurfaces can be designed and fabricated quickly and in large numbers, they could make it much easier for cold-atom physicists to adapt their labs to new experiments.

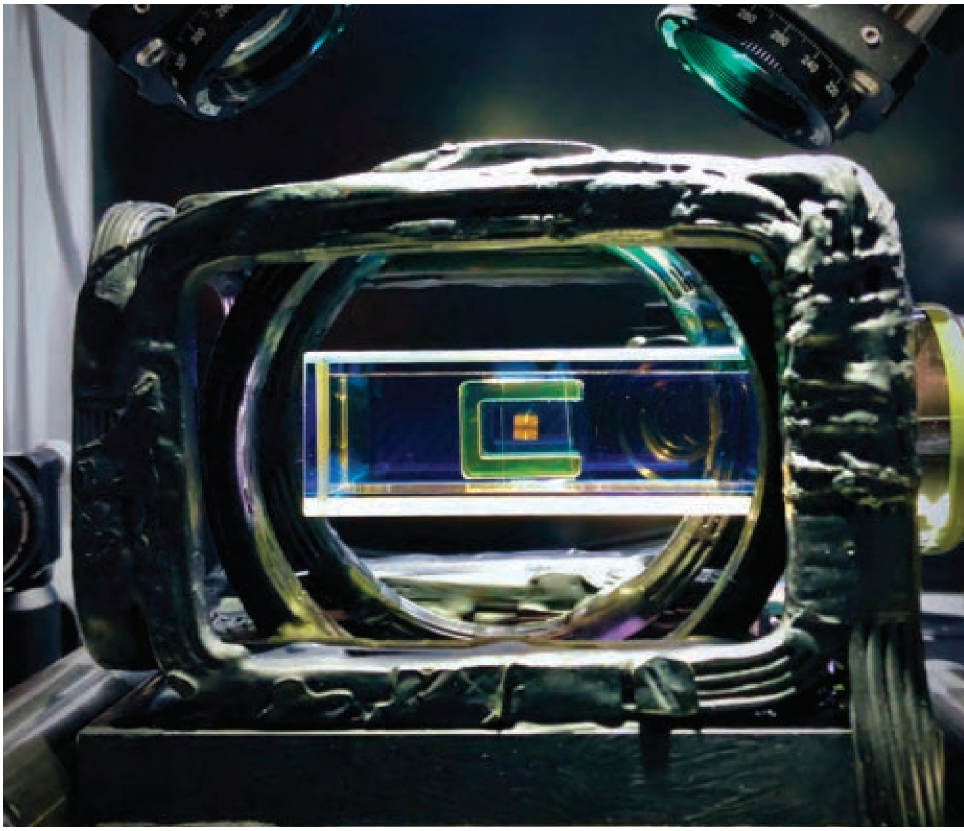


FIGURE 1. A VACUUM CHAMBER for trapping atoms doesn't leave much room for bulky multielement optics. By focusing light instead with a metasurface lens—the central orange square, just 4 mm on a side—researchers can make their experiments significantly more compact. (Courtesy of Ting-Wei Hsu, Scott Papp, and Cindy Regal.)

Faraway traps

A simple convex lens, with spherical curvature on both faces, only approximately focuses light to a point. Its performance is marred by chromatic aberration and spherical aberration, whereby light that has different colors or that strikes the lens in different places is focused to slightly different spots. For many physics experiments that use narrow monochromatic laser beams, simple lenses suffice. But for atom-trapping experiments, which require pinpoint focusing accuracy and often use multiple wavelengths for trapping and imaging, they do not.

One solution is to use aspheric lenses, which can be purchased commercially. But for the greatest flexibility, many researchers opt for multielement lenses, in which several simple lenses are stacked together in a column like a microscope objective. As a general rule, for each additional experimental requirement, such as an additional wavelength or constraint on the trap size, another element must be added to the lens. "So the system gets really big, really fast," says Regal. "You often need huge lenses to do everything you want."

Bulky multielement lenses are complicated to produce, and they constrain experiment design. They are tricky to fit inside the vacuum chamber with the atoms—not just because they are too big, but also because the air pockets between the lens elements are hard to evacuate. As a result, their focal lengths have to be even longer.

Metasurface optics, in contrast, are

admirably compact: The square in figure 1 is just 4 mm on a side. But they introduce a new type of imperfection that conventional lenses lack. Instead of spherical and chromatic aberrations—which are easily eliminated by choosing the right pattern of pillar sizes—they scatter a portion of the incident light into unwanted optical modes. The stray light can excite a trapped atom into an undesired quantum state, or it can create time-varying interference effects that compromise the trapping potential.

Last year Tongcang Li of Purdue University led a collaboration that used a metasurface lens to optically trap a nanoparticle.[2] But that lens wouldn't have worked for trapping atoms. Its focusing efficiency was low, and the majority of the incident light ended up in the wrong optical modes. (That's less of a problem for nanoparticles than it is for atoms, because nanoparticles' internal quantum states aren't as important.) And its focal length was only 100 μm.

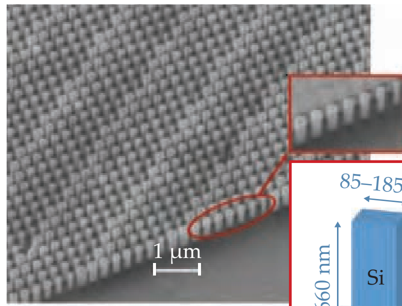
Joining fields

Atomic physics and metasurface photonics are normally the domains of separate research communities. Researchers who design metasurfaces aren't used to thinking about the needs of atom-trapping experiments. And Regal's team of cold-atom researchers wouldn't have been able to design high-efficiency metasurface lenses themselves.

"But the Boulder quantum community has always been broad," says Regal, "with various initiatives to push quantum systems forward." Scott Papp, a collaborator of Regal's at NIST in Boulder, recognized the needs and capabilities of both fields, and he connected Regal with Amit Agrawal of NIST's photonics and optomechanics group in Gaithersburg, Maryland.

The new work grew out of an effort to use metasurface lenses in atomic clocks to make the clocks more compact and portable. The clocks used clouds of cold atoms, not arrays of single atoms, and they didn't use Rydberg states, so the trapping requirements were less demanding. "Then we asked about what trickier tasks metasurfaces could accomplish," says Regal. "Could they produce the really tight spots we needed for optical tweezers?"

Because of the collaborators' complementary ways of thinking about and characterizing lenses, it took a few iterations to come up with a lens that worked. In the end, they used a design with a focal length of 3 mm, a focus size of 1.1 μm or less, and a focusing efficiency of 56–58% for both the 852 nm trapping light and the 780 nm imaging light. Although that may sound like it leaves a lot of stray light unaccounted for, most of the remainder was scattered into modes that don't disrupt trapping. The researchers used an acousto-optic deflector to split the light into an array of nine foci, and they trapped a single rubidium atom in each.



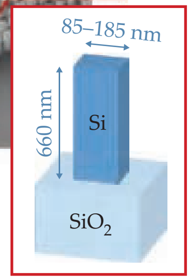


FIGURE 2. A METASURFACE LENS consists of a layer of fused silica topped with an array of amorphous silicon pillars. The size and spacing of the pillars are chosen so that when the pillars scatter incident light, the interference pattern mimics the focusing effect of a conventional lens. (Adapted from ref. 1.)

Encouraged by the proof-of-principle success, Regal and colleagues are now looking to explore new designs that will make full use of metalenses' versatility. The pillars, shown in figure 2, don't have to have square cross sections. By making them rectangular instead, one could create a polarization-selective lens that treats a horizontally polarized trapping beam and a vertically polarized imaging beam separately. Other pillar shapes, such as crosses or donuts, also have potential. "We've shown that the metalens is not necessarily a step backward from conventional optics for atom trapping," says Regal. "Now we want to see if it can be superior."

Johanna Miller

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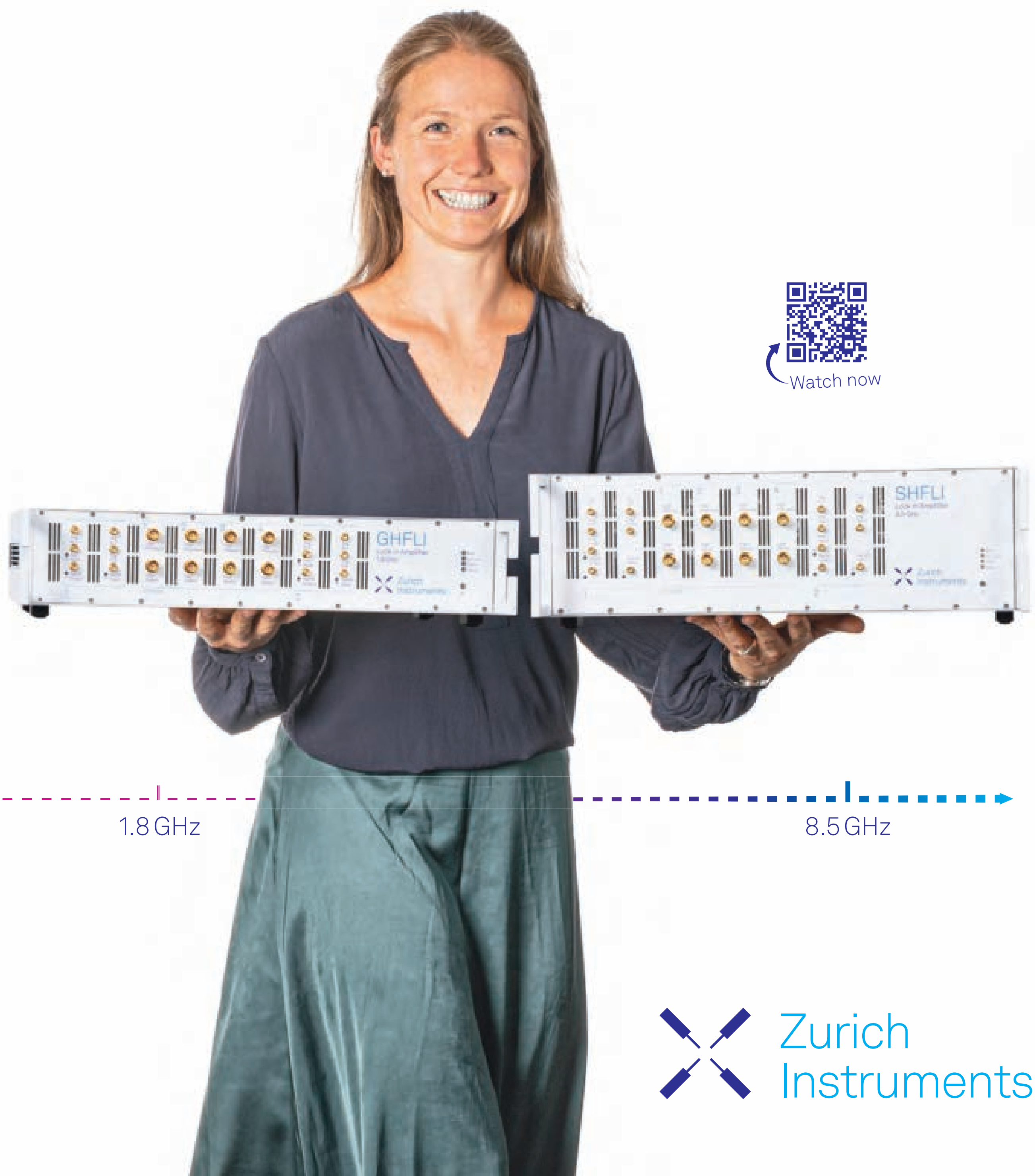
New

Trailblazers.

Meet the Lock-in Amplifiers that measure microwaves.



Zurich Instruments

US particle physicists envision future of the field

In the bottom-up planning process, a collider on US soil garnered enthusiasm; diversity and community engagement also got attention.

JASON HOGAN, THYSSEN MINING INC

EXCAVATION IS UNDERWAY for the caverns that will host the Deep Underground Neutrino Experiment in the Sanford Underground Research Facility in South Dakota. The miner is installing some of the 16 000 6-meter-long rock bolts to provide support in the seven-story-tall underground caverns.

Gordon Watts was nervous when US particle physicists began the most recent grassroots exercise in formulating how to further their science. Watts is a high-energy physicist at the University of Washington and one of the organizers of the 2022 Snowmass process, which began more than two years ago. "I thought people would view the next steps for the field as already decided—for the High-Luminosity Large Hadron Collider at CERN and neutrino experiments in the US—and conclude, 'Why should I spend my time thinking about what's next?' "

Instead, "a glorious range of approaches were presented" over 10 days in July, when about 1200 people met online and in person at the University of Washington, says Watts. "There were 511 white papers! The amount of work that represents is insane. I am very happy to be wrong."

At Snowmass, which takes place roughly once a decade under the aegis of the division of particles and fields of the American Physical Society (APS), particle physicists share ideas for research directions, projects, and facilities. They hone their science goals and find synergies across their subfields.

Some projects and approaches drew clear support and enthusiasm, but ranking them was left for later: Reports from Snowmass will serve as guides for the Particle Physics Project Prioritization Panel (P5), which will rank projects for the US Department of Energy and NSF.

Hitoshi Murayama, a particle physicist at the University of California, Berkeley, is chairing P5. "It's a scary assignment," he says. "We need to be realistic and maximize the science worldwide; the field is international. Community buy-in is key." The P5 recommendations will be due in the second half of 2023.

Neutrino flagship

The 511 white papers spanned 10 "frontier" areas. The science frontiers were energy, neutrino physics, rare processes and precision measurements, cosmic physics, and theory. Crosscutting frontiers focused on instrumentation, computation, underground facilities, accelerators, and community engagement.

Snowmass reaffirmed support for completing the Deep Underground Neutrino Experiment (DUNE) and affiliated lab space, known as the Long-Baseline Neutrino Facility (LBNF). (See "Building a ship in a bottle for neutrino science," by Anne Heavey, PHYSICS TODAY, July 2022, page 46.) The science goals for DUNE include studying neutrino oscillations as a function of energy to reveal the ordering of neutrino masses and whether and by how much neutrinos violate *CP* symmetry. Other goals are to search for proton decay, detect cosmic events such as supernovae, and seek signatures of new physics.

The LBNF/DUNE complex was a priority in the previous P5 in 2014. But cost overruns, delays, and management issues mired the project in controversy. In fiscal year 2021, DOE assigned Fermilab a "C" for program management; the grade wasn't tied explicitly to any one project, but DUNE is the lab's flagship. The cost estimate for the beam, the near detector (at Fermilab), and two of the planned four modules for the far detector (at the Sanford Underground Research Facility in South Dakota) has risen from \$1.3–\$1.9 billion in 2015 to a currently projected \$3.1 billion. And data collection with the neutrino beam, originally planned to start in 2026, is now foreseen for 2031.

Contributing to the cost hikes were difficulties related to excavation, failure to account for the cost of installing the detectors, and a slower-than-anticipated ramp-up on funding, says project director Chris Mossey. "We need to deliver." But, he adds, "the risks we had seven years ago are understood or behind us. What I worry about now is high inflation, the supply chain, the ability to travel, and the ability to get the workforce where we need it."

> "The real danger is that frontier-energy accelerators will end with the LHC."
> —Michael Peskin, SLAC

The plan is to begin operating with two 17-kiloton liquid-argon detectors; two additional detectors would be part of a second phase. The neutrino beam will start at 1.2 MW, and later, for the second phase, it will be doubled in intensity. The near detector will also undergo upgrades. For now, DOE has committed funding for the first phase, and its roughly 30 international partners—major ones include CERN, Brazil, France, India, Italy, and the UK—have signed on assuming the full, two-phase project will go forward. "It would be a disaster to stop now," says Kate Scholberg, a physicist at Duke University and a co-convener of the Snowmass neutrino frontier. "Our ask of P5 will be for support to explore enhancements for phase two. We need phase two to achieve our long-baseline physics goals."

Complications and complementarity

Community support for LBNF/DUNE is complicated by a worry that it could be scooped by Hyper-Kamiokande, under construction in Japan. But the two experiments have different strengths, says Scholberg. The water detector at Hyper-Kamiokande is cheaper and easier to scale up, she explains. And with DUNE's argon "you get fine-grained tracks from neutrino interactions, and you can learn more about the neutrinos." Hyper-Kamiokande is tuned to have good sensitivity for a particular range of neutrino oscillation parameters. "If nature is kind, it will do a very good job. But DUNE will have better sensitivity for a wider range of parameters."

The broader particle-physics community is mostly on board with the full, two-phase LBNF/DUNE project. "If DUNE isn't completed, we are all in big trouble," says Salvatore Rappoccio, a high-energy physicist at the University of Buffalo. The experiment's success will "show the US's technical prowess, engineering skills, and community support," he says. Failure, he continues, would raise the specter of the "black eye" that the US particle-physics community got in 1993 when the Superconducting Super Collider was canceled, and it would make obtaining funding from the federal government for future big projects more difficult.

"So even if the project goes over in price and takes money from other projects, we have to make it succeed," says Rappoccio. He and others express confidence in Lia Merminga, who took the helm at Fermilab in April. "She has the management skills that are required to finalize this project," he says.

Of course, not everyone shares unbridled enthusiasm for LBNF/DUNE. Michael Peskin, a theorist at SLAC, says he finds the project's "ballooning" costs "very disturbing." At Snowmass, he says, the issues with DUNE were "smoothed over, not smoothed out. There are big issues people didn't discuss." Peskin hopes phase one of DUNE will be sufficient "because the project will otherwise consume free energy in the high-energy community. It takes a large bite out of what the US can do in other areas of particle physics—and I have big dreams in other directions."

Going into Snowmass, says Scholberg, "I wasn't sure how DUNE would mesh with other parts of the high-energy-physics community." There are more things people want to do than there will be resources, she says, "but most of our neutrino plans are nearer term, over the next couple of decades. The ambitious and exciting plans in the energy frontier are further out. I think the schedules will work out."

A Higgs factory, now

More than half of US particle physicists work in the energy frontier. Topping their wish list is a Higgs factory, an electron–positron collider dedicated to studying the Higgs boson. A handful of circular and linear collider designs exist worldwide. The community wants whichever proposed machine can be realized most quickly.

The most technically ready design is the International Linear Collider (ILC), which would start at 250 GeV and could be extended to 1 TeV. The project has been in limbo for years, with Japan as host waiting for financial commitments from international partners, and potential partners—including the US—waiting for Japan to proceed with the project (see Physics Today, March 2018, page 25). "Very few people in the US think it will happen," says Peskin, "but as long as you do nothing else, the ILC remains relevant." Mark Palmer, an accelerator physicist at Brookhaven National Laboratory, was involved in the multi-TeV collider discussions for Snowmass. "With funding," he says, "the ILC could be built and running within a decade."

CERN and China have aspirations for circular electron–positron colliders (see Physics Today, September 2020, page 26, and "China plans a Higgs factory," Physics Today online, 17 December 2018). They differ in detail, but each would be about 100 km in circumference, would collide leptons at 240 GeV, and could later be converted to collide hadrons at 100 TeV.

Given existing commitments, 2048 is the earliest a future circular collider could turn on at CERN, the lab's director general, Fabiola Gianotti, said at Snowmass.

China could move faster with its Circular Electron Positron Collider (CEPC). "The design is maturing rapidly," says Palmer, who knows people involved with the project. "If China decides to make it a national initiative in high-energy physics, it could be a contender for the next electron–positron machine."

China has "flexibility, space, and probably money," says Sergio Bertolucci, the Italy-based cospokesperson for DUNE and a former director of research at CERN. China realizes that the CEPC requires international participation, he says, and is receptive to scientists coming to them. "But they cannot expect the international community to go there if they don't also go outside."

GORDON WATTS

MUON COLLIDER ENTHUSIASTS—with T-shirts to show it—assembled at the Snowmass meeting in Seattle in July.

Because of the scope and cost, the community generally believes that at most one huge collider will be built. If China goes ahead with its proposal, international participation is unclear; it's also unclear whether CERN would proceed with its similar project. The CEPC would be a "disrupter," says Palmer.

High-energy physicists are also hyped about a muon collider. The idea is seeing an enthusiastic revival after having been largely abandoned in 2015 following the last P5.

"With muons, you can not only push the energy reach, you can also do precise measurements," says Sergo Jindariani, a senior scientist at Fermilab and one of a half-dozen coordinators of Snowmass's muon collider forum. Muons are about 200 times as heavy as electrons; in a circular machine, they therefore radiate less and can be accelerated to higher energies in a more compact ring. The precision is possible because muons are leptons and, unlike hadrons, produce clean collisions. "We would like to get to 10 TeV collisions with a circumference of about 10 km," he says. Such collisions would be about an order of magnitude higher energy than are possible at the Large Hadron Collider (LHC).

The hitch is that muons are unstable. A muon's rest lifetime is about 2 μs and increases as it's accelerated. "The lifetime is still short, but it's long enough," says Jindariani. Each step in forming an intense muon beam—producing the muons, and then cooling, accelerating, and colliding them—would have to be fast. And each step has challenges.

Muons are also appealing "because you can imagine going to larger rings and getting to much higher energies," says Jindariani. "We know what type of R&D program is needed to be technologically ready for construction in 20 years," he says.

A surprise at Snowmass "was the grassroots support for a collider on US soil," says Priscilla Cushman, a physics and astronomy professor at the University of Minnesota and past chair of the APS division of particles and fields. That support is tied to the promise of the smaller size and price tag offered by either a muon collider or a Higgs factory using new cool-copper linear collider technology.

Among the other high-energy ideas floated at Snowmass were plasma wakefield accelerators (see PHYSICS TODAY, January 2015, page 11) and an underwater collider. More intense R&D on advanced colliders is necessary, says Palmer, "so we can actually bring concepts to maturity for the community to evaluate whether to build or not."

"The real danger is that frontier-energy accelerators will end with the LHC," says Peskin. "We urgently need to figure out how to build something affordable."

"The dark sector"

The cosmic frontier is going "full steam ahead," says Kimberly Palladino, an experimental physicist at the University of Oxford. "We have clear paths to the future." Those paths include covering parameter space of weakly interacting massive particles as much as possible with current technologies and using new ones to explore lower masses, spin dependence, axions, and the matter–antimatter imbalance to possibly illuminate—or be illuminated by—dark matter.

Technology and theory related to dark matter are both exploding, says Palladino. That makes new searches possible, and "the field has become a lot more interesting than people expected." In the past, she says, "we've been treated like a sideshow to the big colliders. But we are just as important—and more affordable."

Some dark-matter experiments need to be underground, notes Palladino, and they could temporarily park in the spots for DUNE's phase-two detectors. "Between us and the neutrino frontier, we need the underground facilities," she says.

Health of the field

For the first time, community engagement was a full-fledged frontier at Snowmass. It encompassed seven topics: applications and industry; career pipeline and development; diversity, equity, and inclusion; physics education; public education and outreach; environmental and societal impact; and public policy and government engagement.

The topics cut across all of physics and other areas of science, notes Kétévi Assamagan of Brookhaven National Laboratory, who convened the frontier with the University of Mississippi's Breese Quinn. As examples of areas that need improvement, Quinn cites academic–industrial relationships, ties between physics and engineering departments, reduction of the field's carbon footprint, and diversity.

But it's a challenge to get people to devote effort to community engagement issues. "There is a tension," says Assamagan, "between what physicists need to do to find jobs, teach, research, and get promotions, and the community engagement issues that impact us all." Palladino, for example, says she was overwhelmed with other professional and family commitments and "felt guilty for not joining the frontier."

> **"We've been treated like a sideshow to the big colliders. But we are just as important—and more affordable."**
>
> **—Kimberly Palladino, University of Oxford**

Structural barriers discourage participation in community engagement, Assamagan notes. "We need to provide incentives, tangible support, and show that the field values work in these areas." The community engagement frontier put together 140 recommendations directed variously at individuals, large research collaborations, institutions, and funding agencies. "Nobody has to do everything," says Quinn, "but everybody has to do something."

Most of the Snowmass recommendations are for P5. But while P5 will try to incorporate community engagement however it can, says Murayama, the panel may not be the best place for recommendations from that frontier. "We are figuring that out," says Quinn. He points to two good signs: P5 is incorporating community engagement in its call for nominations, and Cushman has created a task force within the division of particles and fields to come up with a structure that could shepherd the community engagement recommendations. Says Quinn, "A lot is needed to make our field healthy."

Toni Feder

The race to cut methane emissions ramps up worldwide

Governments, private companies, and nongovernmental organizations are teaming up to eliminate methane leaks and flaring from the oil and gas industry.


FRIENDS OF THE EARTH US

GAS FLARES, like this one in Nigeria, burn methane to safely depressurize oil wells, but they also release toxic gases and particulates and contribute to global warming.

Although carbon dioxide is the primary culprit for global warming, methane also packs quite the punch. It's the second-most emitted greenhouse gas, and ton for ton, CH_4 has a warming potential some 30 times that of CO_2 on century time scales.

At the 26th Conference of the Parties meeting on climate change in Glasgow, UK, in November 2021, the US, European Union, and 11 other countries announced a Global Methane Pledge. The 121 participants have agreed to collectively reduce CH_4 emissions by 30% from 2020 levels by 2030. Those reductions would come from all CH_4 sources and would reduce the global temperature rise by 0.2 °C by 2050. But some of the largest fossil-fuel emitters, including China, India, and Russia, haven't joined the pledge.

Methane is emitted from oil and gas wells, agricultural activity, natural biological processes, and other sources. Emissions from the oil and gas industry are easier to detect and control than those from other sources because they come from well-defined locations. Some one-third of anthropogenic CH_4 emissions come from the production and transport of fossil fuels.

A May 2022 report from the American Physical Society (APS) and Optica explored how best to reduce CH_4 emissions in the oil and gas industry. Researchers have started to develop and demonstrate the CH_4 detection and pipe-repair technologies necessary to hit the emissions-reductions targets specified by the United Nations (UN).

Finding leaks

Methane remains in the air for about a decade, unlike the hundreds or thousands of years that CO_2 lingers. The short lifetime of atmospheric CH_4 paired with its high warming potential means that any emissions reductions of CH_4 will have an outsize effect on air temperatures. In recent years, however, global CH_4 emissions have been rising by 0.5% per year, according to the UN's Intergovernmental Panel on Climate Change. "We need to prioritize methane. . . . If you manage to decrease emissions, you'll see the effect in a decade," says William Collins, a senior scientist at Lawrence Berkeley National Laboratory, who was a lead author for the intergovernmental panel's last three reports and cochair of the committee that wrote the APS–Optica report.

Globally, 30% of CH_4 emissions come from the oil and gas sector. The APS–Optica report (https://doi.org/10.1364/OE.464421) concludes that more than half of those emissions come from leaks or deliberate releases, predominantly from up to a tenth of the oil and gas wells in operation. Targeted policies that focus on that handful of locations could substantially reduce emissions. A 2015 study by Steven Hamburg of the Environmental Defense Fund and colleagues, for example, found that at any given time, 2% of the oil facilities in the Barnett Shale oil and gas field in Texas were responsible for half of the CH_4 emissions in that region. Similar CH_4 super emitters exist in Algeria, Iran, Kazakhstan, and Russia, according to a 2022 paper coauthored by Thomas Lauvaux of France's Laboratory for Sciences of Climate and Environment.

The search for CH_4 emissions and leaks occurs on three spatial scales. At the ground level, technicians may inspect individual pipes or specific locations at an oil well to pinpoint small leaks or deliberate releases. But that's unrealistic for monitoring thousands of wells and millions of kilometers of pipeline.

Remote methods use spectrometers to monitor the IR wavelengths that CH_4 absorbs. The characteristic spectral lines can be used to identify and quantify CH_4 leaks. The active-sensing approaches on low-flying airplanes use onboard light sources to improve the signal-to-noise ratio of CH_4 measurements. Those aircraft can detect small CH_4 leaks, with a discharge rate as low as 1 kg/h.

The largest leaks—those that spew more than 30 kg/h—contribute 60–80% of the CH_4 emissions from oil and gas production and are detectable with satellites. Satellite detection relies on passive radiation from the Sun to record the spectrum of atmospheric CH_4. Although satellite and airplane methods can scan far larger areas than ground-based approaches, they may miss intermittent leaks.

The APS–Optica report calls for a cohesive, multiscale system for monitoring CH_4 from the oil and gas industry: Measurements would be collected continuously, and the data would ideally be freely available so that outside parties could ensure that companies are complying with regulations. In support of that vision, the US Department of Energy's Office of Fossil Energy and Carbon Management announced in August that it will award $32 million toward developing such a monitoring system.

Methane's complexity

Methane may have only five atoms, but the four carbon–hydrogen bonds add many degrees of freedom in which the molecule can vibrate. The many molecular motions translate to various rotation–vibration states, which can be excited when a molecule absorbs IR light.

To obtain a meaningful CH_4 observation in the field, researchers typically compare spectral measurements with known absorption features of the molecule for which temperature, pressure, and other properties are carefully controlled in a lab setting. One of the APS–Optica report's coauthors, Michelle Bailey, works as a research chemist in the optical measurements group at NIST. She and her colleagues measure the spectral features of well-characterized CH_4 and other gas samples with ultrasensitive techniques offering high spectral resolution.

The intrinsic physical parameters that Bailey and her collaborators—and other groups worldwide—collect are used to benchmark theoretical models. The data and models are disseminated in an open-access database called HITRAN; scientists can then use the data to simulate the behavior of atmospheric CH_4.

But clouds, aerosols, atmospheric mixing, and other environmental conditions complicate field measurements and their comparisons with theoretical CH_4 spectra. "As you increase your path length from near surface to the upper atmosphere, the instrument is subjected to a number of potential interferences," explains Bailey.

Nearby non-point-source emissions, particularly agricultural ones, are another challenge to collecting meaningful measurements of CH_4 emissions from oil and gas point sources. Isotope fingerprinting may help. Methane produced from an agricultural source, for example, contains a different mixture of carbon isotopes than CH_4 from an oil and gas source. The difference in molecular mass affects the frequencies of absorbed light, so IR optical-sensing methods can distinguish CH_4 sources.

Patching pipes

In addition to detection improvements, researchers have also been developing technologies to quickly and autonomously repair leaks from oil and gas operations. DOE launched its Methane Mitigation Technologies program in 2016 with the goal of eliminating emissions from the oil and gas supply chain by 2030. The program's priority is to develop technologies that could later be commercialized.

For example, the DOE collaborated with the Southwest Research Institute to repurpose a fixed-laser sensor to scan for CH_4 leaks at wells. The upgraded sensor is mounted on a drone to autonomously estimate emissions. A research manager of the program interviewed for this story said that a lot of R&D has focused on repair technologies for the over 3 million kilometers of pipeline that crisscross the US.

In collaboration with Oceanit Laboratories, headquartered in Honolulu, Hawaii, the DOE program has supported the development of DragX—a friction-reducing, corrosion-resistant, and nontoxic coating that could be applied to existing pipelines. The 100-micron-thick film can reduce surface roughness by some 50% and improve the pipeline's durability. Many of the coating's technical details are confidential, although

preliminary analysis indicates it can last for years.

The DOE program is also supporting the development of robotic repair devices with ULC Technologies in New York. They're designed to travel the length of a pipeline and measure localized pressure changes, which are used as a proxy for material defects. If such a defect is found, the robot magnetically applies a temporary patch, which technicians later replace with a permanent one during a routine evacuation of the pipeline section.

Although many prototype technologies have been evaluated in laboratory settings and have seen success in limited field testing, they may not ultimately be deployed by oil and gas companies. "We do systems analysis to consistently evaluate technical feasibility and cost effectiveness but we don't pick winners," says the DOE program manager for methane-mitigation technologies. "You can't force commercialization on industry, and most all technologies will commercialize as a function of market forces."

The flaring problem

Besides emissions from undetected or unrepaired leaks, oil and gas companies routinely emit CH_4 intentionally. Oil extracted from below the surface often contains CH_4, sometimes referred to as associated natural gas. Even though CH_4 has several uses—either as fuel or as a chemical feedstock in various industrial processes—a pipeline may not be available to transport the gas to a refinery or chemical-processing facility.

Instead, in a process known as flaring, companies burn CH_4 and other unwanted by-products associated with oil extraction. The practice is responsible for up to 20% of the total CH_4 emissions from oil and gas operations, according to the APS–Optica report. To limit flaring, governments, companies, and other stakeholders are exploring economically viable alternatives.

Some flares are large enough to be observed from space by satellites. Oil producers can also self-report them. But the two data sources are often inconsistent. Discrepancies, the APS–Optica report concludes, arise from incomplete monitoring. Many states do not require producers to report flaring activity to regulators, and independent satellite-measured flaring is episodic. Only a few observations can be made per month at a given location because of satellites' orbits.

FORMER WORLD BANK PRESIDENT Jim Yong Kim (center left) and former secretary general of the United Nations Ban Ki-moon (center right) participated in the 2015 Spring Meetings of the World Bank and International Monetary Fund in Washington, DC. The event marked the beginning of a global effort to curb methane emissions: the Zero Routine Flaring by 2030 initiative. (Photo by Dominic Chavez/World Bank; courtesy of World Bank Photo Collection/CC BY-NC-ND 2.0/Flickr.)

To limit and eventually stop the practice of routine flaring globally, the World Bank has set up the Global Gas Flaring Reduction Partnership, made up of governments, oil and gas companies, and nongovernmental organizations. The partnership launched the Zero Routine Flaring by 2030 initiative in 2015. Signatories make a nonbinding pledge to not flare in any newly developed oil fields and to commit to ending routine flaring in legacy locations by 2030.

During the oil-extraction process, the pressure in a well can vary dramatically, and a sudden pressurization can cause an explosion. Gas flaring in those nonroutine situations and in response to immediate safety concerns is excluded by the initiative.

Some 34 governments—including Iraq, Nigeria, Russia, and the US, which are among the top flaring countries—and more than 50 oil companies, including BP, Chevron, ExxonMobil, Saudi-Aramco, Shell, and TotalEnergies, have signed on to the initiative. A 2018 study by the World Bank estimated that the total cost to end routine flaring by 2030 would be at least \$100 billion. A May 2022 press release from the World Bank said that "2021 showed disappointing progress" toward meeting the 2030 target.

Among the contributions to the sticker price are the costs of separating CH_4 from other hydrocarbons and transporting it to energy markets, where it can displace coal and other more-polluting fuels. Zubin Bamji, the program manager of the World Bank partnership, says financing comes from various sources, including project developers, equipment suppliers, strategic investment funds, commercial banks, and private capital funds.

Investing in pricey infrastructure has its own business risks, especially given the strain on energy supplies because of the war in Ukraine. Still, says Bamji, "governments and companies remain committed to zero routine flaring by 2030, and some have even more ambitious targets. We can't lose sight of the need to decarbonize global energy supplies." Bamji also cites an encouraging statistic: Although the past 26 years have seen a 20% increase in oil production, associated gas flaring has fallen by 13% in that time.

Alex Lopatka PT

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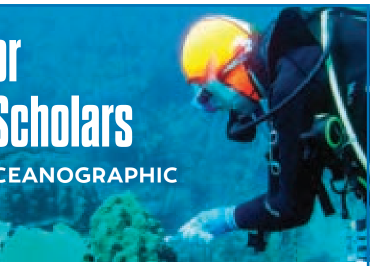

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Careers issue

Christine Middleton was a senior editor at Physics Today from September 2018 to August 2022. She now works as a technical communications editor at ASML.

Stepping into NSF

Christine Middleton

Researchers working as temporary employees at the funding agency bring their technical expertise and take away a deep understanding of NSF's inner workings.

The career options available to physics graduate students largely fall into three sectors: private industry, academia, and government. And although they may change their employer or position, once someone takes their first job in one of those sectors, they're unlikely to move to a different one.[1] (See figure 1 and the article by Anne Marie Porter and Susan White, Physics Today, October 2019, page 32.) But even if a scientist isn't interested in leaving their chosen career path altogether, they may be interested in stepping outside their box to have new experiences, share their knowledge, or gain new expertise. Working as a rotator at NSF is one way to do just that.

The rotator program is not exclusive to NSF, but the agency is by far the heaviest user among US government research agencies. Rotators made up about 15% of NSF's total workforce in 2015, compared with less than 1% at other research agencies.[2] That imbalance can be understood by considering the mission stated in its strategic plan for 2022–26: "NSF promotes the progress of science by investing in research to expand knowledge in science, engineering and education. NSF also invests in actions that increase the capacity of the U.S. to conduct and exploit such research." The mission doesn't dictate a direction in which cutting-edge knowledge and research should expand. To guide its investment in scientific progress, NSF depends on input from experts who have their fingers on the pulse of the research community.

An organized process

NSF was created by the National Science Foundation Act of 1950 to support basic research and education in the sciences. It's unique among government research agencies in that it doesn't hire its own researchers or operate its own facilities. Rather, it distributes most of its budget, which was $8.8 billion for fiscal year 2022, in the form of grants. Deciding how to allocate that budget is the main work of NSF.

At the top of the organization is the NSF directorship (see figure 2), which is currently held by Sethuraman Panchanathan, a computer scientist and engineer. The director and deputy director (currently vacant) are appointed by the president and confirmed by the US Senate. The same process applies to the 24 members of the National Science Board, who, with the NSF director, are responsible for long-range planning and priority setting. The chief operating officer, currently Karen Marrongelle, oversees the planning, budget, and day-to-day operations across the agency.

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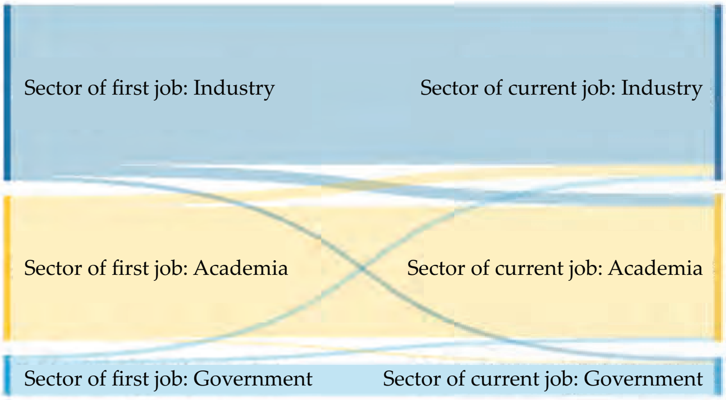

FIGURE 1. THE SECTOR in which a PhD physicist found their first job—private industry, government, or academia—is usually the same sector in which they currently work. By serving as a rotator for NSF, physicists can contribute to federal government work without switching the sector of their primary employment. (Adapted from ref. 1.)

NSF has eight science directorates. Each is led by an assistant director and is focused on funding particular areas of research: biological sciences; computer and information science and engineering; education and human resources; engineering; geosciences; mathematical and physical sciences; social, behavioral, and economic sciences; and technology, innovation, and partnerships. Each directorate's purview is divided into a few divisions. In the Directorate for Mathematical and Physical Sciences, for example, the divisions are astronomical sciences, chemistry, materials research, mathematical sciences, and physics. Those divisions are each headed by a division director and employ program directors tasked with evaluating proposals, facilitating panel reviews, and liaising with researchers.

Rotators typically make up about 25% of NSF's scientific staff, or between 220 and 300 positions.[3] Their terms can span one to four years. They can serve in executive positions, including assistant director and division director in a directorate, and in such nonexecutive positions as program directors and associate program directors. The agency strives to maintain a balance between rotators and federal employees so that everyone can benefit from each other's complementary backgrounds. The permanent scientific staff are subject-matter experts—part of their time is devoted to staying current in their fields and attending scientific conferences and workshops—and they have invaluable institutional memory and procedural knowledge. The rotators bring fresh ideas and perspectives, and although their most obvious assets are their expertise and connections in their field, they can also weigh in on such aspects as internal processes.

NSF has received criticism for how much it uses rotators.[4] Most participants maintain their salaries and benefits they had at their home institutions, and the labor costs to NSF are often higher than the salaries of government employees in the same positions—sometimes by tens of thousands of dollars.[5] Rotators from academia also may not have the experience in administration and management that an experienced government employee would have, and critics cite a lack of oversight and program evaluation. Steps have been taken to address concerns: In 2016, for example, the agency started a cost-sharing initiative in which all home institutions must continue to pay 10% of the rotator's salary.[6]

Maintaining a balance between permanent employees and temporary staff is critical for the rotator program. Some differences between academia and government work, like potentially upgrading one's clothing from the casual uniform of a professor to business attire, are rather minor. But the agency's rigid rules, policies, and procedures—designed to achieve critical goals, such as protecting against conflicts of interest and ensuring that the agency is a good steward of taxpayer dollars—may take some getting used to for professors accustomed to significant job flexibility and autonomy. And gaining significant responsibility on arrival can be both jarring and intimidating. Rotators aren't expected to learn everything on their own, though. Participants receive the necessary training and support from the many administrators and scientists who make up NSF's talented and capable permanent staff.

Everyday tasks

Facilitating the review of grant proposals is a big part of the job for rotators. The process is, broadly, as follows: When a proposal is submitted to a program, it must first be checked to confirm that it meets all of NSF's proposal preparation requirements, such as length limits and margin sizes. Assuming the requirements are met, program directors must find at least three independent reviewers to evaluate each proposal. Having program directors with extended professional networks is particularly

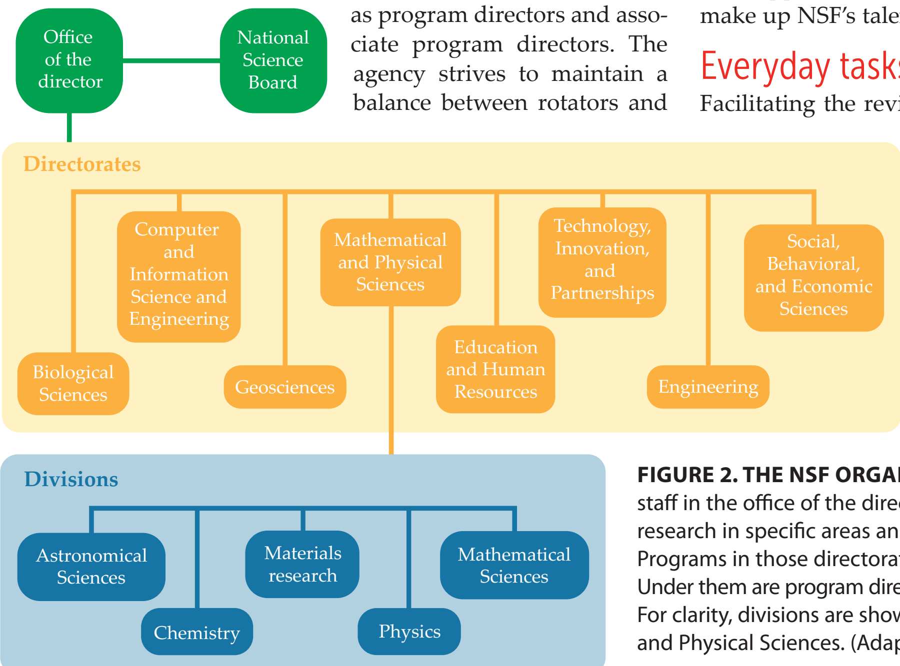

FIGURE 2. THE NSF ORGANIZATION is led by a director and supporting staff in the office of the director. The eight directorates focus on funding research in specific areas and are each headed by an assistant director. Programs in those directorates are each managed by a division director. Under them are program directors who provide oversight of individual grants. For clarity, divisions are shown only under the Directorate for Mathematical and Physical Sciences. (Adapted from the NSF organizational chart.)

Figure 3. NSF headquarters is located just outside Washington, DC, in Alexandria, Virginia. Past rotators moved to the DC area for their tenure at NSF, but like so many other workers, rotators worked remotely in 2020 and have continued to do so. (Courtesy of NSF.)

helpful for that step. Proposals are also reviewed by panels of experts who are willing to spend a few days doing intensive evaluation, and the program directors facilitate the panels. Panel meetings have been hybrid for at least a decade and entirely virtual since the start of the pandemic in 2020, which may make participating on a panel an option for people who wouldn't normally be able to take a week away from their home institution or personal obligations.

Program directors, who may be rotators or federal employees, then use those reviews, together with their own judgment and awareness of related funding requests, to make recommendations to their division director about which proposals to fund. Division directors are responsible for the final funding decisions. They also oversee the proposal evaluation process, prepare and justify the division's budget, and decide how to allocate funds.

Assistant directors each head one of the eight directorates and manage the divisions that fall under it; they can be rotators or federal employees. In the Directorate for Mathematical and Physical Sciences, that means overseeing a staff of approximately 160 people and allocating a budget of $1.5 billion between the directorate's programs. The position also involves big-picture planning, such as setting long-term priorities and planning for new programs and initiatives.

Program directors and division directors also have roles that go beyond evaluating grant proposals in their own divisions. They may participate, for example, in reviewing relevant proposals to agencywide programs, such as Faculty Early Career Development and Major Research Instrumentation grants. They also plan for upcoming grant solicitations and work with colleagues, both in their own division and directorate and throughout NSF, on strategic planning for the agency's future endeavors. Those collaborations can be for interdisciplinary science, but they might involve, say, initiatives to improve education or diversity, equity, and inclusion efforts.

Rotators still attend conferences and network, but in doing so they can't focus on just their own narrow area of expertise. The research covered by even a single NSF division is quite extensive. Although rotators are already experienced researchers with a relatively broad understanding of their field, talking to new people and learning about other research areas is an important part of the position. Being curious and at least somewhat extroverted are therefore helpful characteristics for someone coming into the job.

Incoming rotators should have experience writing and, likely, reviewing journal articles and grant applications. That ability to parse such technical writing and assess it for strengths and weaknesses is important at NSF. The skills needed to direct and manage a research group, such as setting priorities and being flexible when things don't go as planned, transfer to government work as well. But rotators may need to develop other skills—for example, project management and nontechnical writing—to be successful in their new positions.

Getting involved

Postings for rotator positions can be found on the NSF website under About NSF/Career Opportunities/Job Openings and are listed as Dear Colleague letters (although not all such letters are rotator positions); see the box on page 36 for an example. Rotator jobs also can be applied to directly through USA Jobs. They also often get shared through informal channels, such as listservs, and candidates can be nominated by their colleagues. Although rotators often come to NSF in either September or January, corresponding to academic semesters, positions aren't posted on a specific schedule and may not come up annually. Talking to colleagues involved with NSF is a good way to stay informed.

The most common way in which rotators come to NSF is through the Intergovernmental Personnel Act (IPA) Mobility Program. Despite the program's name, IPA rotators don't have to come from other government agencies; at NSF, they often come from academic research institutions. Between 2008 and 2017, about 80% of rotators at NSF came through the program.[2] An IPA rotator is essentially on loan from their home institution, and they continue to receive their usual salary and benefits. That compensation is largely paid for by NSF, though, with a 10% cost share from the home institution. Rotators can also be hired through the Visiting Scientist, Engineer, and Educator (VSEE) Program. In that case, the rotator takes an unpaid leave of absence from their home institution and is paid directly by NSF based on the federal pay scale. In general, both IPA and VSEE participants must be US citizens. (Exceptions are possible for those pursuing US citizenship and require a citizenship affidavit.)

Rotator terms start at one to two years. The grant application cycle is annual, so that sets a natural lower limit for how long they would want to stay at NSF. But once a rotator has experience and training, it's valuable for them to stay around a bit longer, and terms can be extended to a total of up to four years.

Although rotator start times are often synchronized with the start of an academic semester, the applications and offers happen months earlier to allow time for logistics. Faculty members may have to coordinate coverage for teaching and administrative responsibilities in their departments. Then there are questions professors may have to ask themselves regarding their research groups. Examples include the following: Can I continue to lead the group, or will I need to delegate tasks, and if so, to whom? Can I continue to provide sufficient mentorship to my students and postdocs? Will my time at NSF affect my research

In search of a rotator

Below is an excerpt from a Dear Colleague letter posted on NSF's website. The letter advertises a program director position in the materials research division. The qualifications and skills requested in the position description are highlighted.

National Science Foundation

You are viewing a Dear Colleague Letter,

Physical Scientist (Program Director)

Division: Materials Research (MPS/DMR)
Directorate: Mathematical and Physical Sciences (MPS)
Job Type: STEM
Appointment Type: Temporary / Rotator
Pay Grade/Scale: AD-04

Application timeline

Date Posted: August 13, 2021
Closing date: Open until filled

Position description: The position requires an individual with broad knowledge and demonstrated success in the subdisciplinary area of materials research indicated above. Applicants must have a Ph.D. or equivalent experience in the physical sciences or a closely-related field, plus after the award of the Ph.D., a minimum of six or more years of successful independent research. In addition, research administration and/or managerial experience pertinent to the position would be highly desirable. The incumbent should also have an appreciation for interdisciplinary research. For the DMR mission statement and additional information about the above program, please see https://www.nsf.gov/materials.

The position requires effective oral and written communication skills, and familiarity with NSF programs and activities is highly desirable. The incumbent is expected to work effectively both as an individual within the specific NSF program and as a member of crosscutting and interactive teams. The incumbent must also demonstrate a capability to work across government agencies to promote NSF activities and to leverage program funds through interagency collaborations.

program's progress or my participation in collaborations?

NSF has an Independent Research/Development Program that allows rotators to use up to 20% of their time, or one day per week, for outside work, so that time can be used to, for example, maintain the rotator's research group at their home institution. For IPA rotators, NSF also funds up to 12 trips annually from NSF headquarters in Alexandria, Virginia, shown in figure 3, to their home institutions. Still, with less time to focus on scientific questions and with limited access to experiments and facilities, keeping a research group going can be a challenge for both experimentalists and theorists. And between the two jobs, work can easily bleed into evenings and weekends.

Is it for me?

There's no one right time for a researcher to pivot and take on a rotator position, but certain times are better than others. Given the level of disruption working as a rotator can cause in a research program, an assistant professor working toward tenure probably shouldn't take time away from their university to work at NSF. Someone at that career stage also lacks a more senior researcher's breadth and depth of experience and widespread professional connections. But they can still contribute to NSF by reviewing proposals, thereby gaining valuable experience—especially if they do eventually want to work at NSF.[7]

Once a researcher has been granted tenure and is more established, finding a convenient time to do a rotation at NSF is really a matter of personal preference and circumstances. Timing a rotation at NSF with a sabbatical can be a good option. It corresponds to a time when the researcher would likely be away from the department anyway, although rotations often last longer than typical sabbaticals. At that point, the researcher is also far enough into their career that their experiences can truly inform their responsibilities as a rotator—reviewing grants, assembling reviewers, shaping programs, and allocating funds.

Another good time for a researcher to come to NSF is at the end of their career. Although the rotator may have less to gain personally, their wealth of experience is especially valuable to NSF's mission. And the move may be less disruptive—their established research group may have postdocs and senior grad students who need less supervision and who can help train and advise younger students, or they may already be winding their group down.

Family considerations can also affect a researcher's decision about when a good time would be to work as a rotator. The job has generally required one to relocate to the Washington, DC, area for the one to four years they're working at NSF. The move can have implications for their spouse's career—they might be able to transfer or work remotely, but that's not always possible. And rotators with children have additional considerations. They may see temporarily moving to the DC area as a benefit for their children because the city is a unique place and offers many cultural opportunities. But uprooting school-age children can also be a challenge. Families won't necessarily have the same support systems in a new city, and a big move can be disruptive to a child's social development.

Those family concerns may be becoming less important, though, since like many other workers, NSF rotators have been working remotely since the COVID-19 pandemic started in 2020. If the program maintains that level of flexibility moving forward, rotator participation could become accessible to researchers for whom relocation would have been an undue burden.

The benefits

Why might a researcher choose to take time away from their primary job to work at NSF? Given that NSF funds so much research in the physical sciences, many see it as a way to give back to the community. They understand that NSF's renowned merit-review process depends critically on experienced researchers' participation.

But the decision need not be entirely altruistic. Rotators have a lot to gain from working at NSF. They make new contacts and gain a broader perspective on research happening in adjacent fields. Those connections can lead to new ideas and cross-disciplinary collaboration. And the job can be exciting, as rotators are continually in contact with talented researchers pushing the boundaries of scientific knowledge. Although rejecting proposals may be a tough part of the job, getting to say yes and fund innovative ideas is perhaps the most gratifying.

When the rotators return to their institutions, they bring a much deeper understanding of NSF's funding process. Rotators can apply for NSF funding after they leave the agency, although some restrictions apply. They are allowed to direct colleagues to opportunities, help them frame ideas, and provide procedural knowledge. Working as a rotator has been correlated with increased funding for the participant and his or her colleagues over time.[8]

Occasionally rotators learn that they actually prefer government work and decide to leave their research positions. A one-year gap is required between being an IPA rotator and becoming a permanent employee, so there's still time for knowledge transfer to the home institution.

The benefits NSF receives from rotators go beyond just having people to facilitate their grant-review process. Having so many people from the research community participate promotes the agency's mission and helps maintain trust in the process. It also prevents the agency from becoming stuck in a particular direction. Everyone comes to the table with their own biases and preferences, and that can steer funding at the division, directorate, or even agency level in one direction. But having so many members of the scientific community give their input positions the agency for long-term success.

The CAREERS ISSUE continues online. Learn more about opportunities in and related to government by scanning the QR code or visiting physicstoday.org/careers2022.

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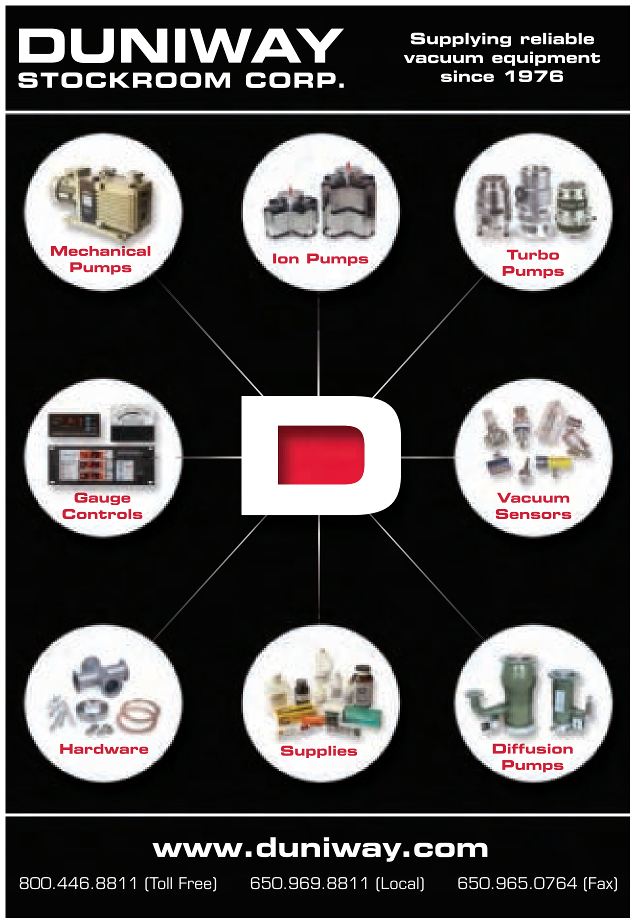
- PhD or equivalent in physics or a closely related field
- A strong interest in science and technology policy
- Active in the physics community
- Must be an APS member

Application deadline: December 1, 2022
go.aps.org/apscsf



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UNIVERSITY OF DENVER

Assistant Professor Tenure-track Position—Experimental Condensed Matter/Quantum Science

The Department of Physics & Astronomy at the University of Denver (DU) invites applications for a tenure-track assistant professor position to begin in September of 2023. We seek candidates with research interests in experimental condensed matter physics whose research and teaching will support an initiative in Quantum Materials and Information Science, which launched with one faculty member already hired in 2022. All areas broadly related to quantum materials and information sciences will be considered, with potential for collaboration with existing research areas on campus and in the surrounding areas a particular plus. The successful candidate will possess enthusiasm for teaching both undergraduate and graduate courses, and demonstrate promise of developing an independent extramurally funded research program that involves both Ph.D. and undergraduate students. Though we intend to focus on experimental candidates, a theoretical or computational candidate with exceptionally strong match to the position and the department may be considered.

Teaching Assistant Professor Position

The Department of Physics and Astronomy at the University of Denver invites applications for a non-tenure track Teaching Assistant Professor position beginning in September 2023. The position is at the Teaching Assistant Professor level, but exceptional candidates with a proven track record in teaching at the college/university level may be considered for a Teaching Associate Professor appointment.

Applications for both positions must be submitted through **https://jobs.du.edu** and should include a cover letter, CV, statements of teaching philosophy and research plans (for the tenure-track position only), one-page diversity statement, and names and contact information for at least three references. Applications completed before January 1, 2023 will be assured full consideration, but the selection process will continue until the position is filled. More information about the department can be found at **https://physics.du.edu**.

The University of Denver is committed to enhancing the diversity of its faculty and staff. We are an Equal Opportunity/Affirmative Action Employer. All qualified applicants will receive consideration for employment regardless of age, race, color, national origin, religion, sex, sexual orientation, gender identity, disability or military/veteran status.

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Cluster Hire in Quantum Information, Materials, Sensors, and Applications

Washington University in St. Louis

Washington University in St. Louis invites applications for a cluster hire of four faculty positions in the broad area of quantum sciences, including two positions in the Department of Physics (expt or theory; one Asst/Assoc, one open rank), one in Electrical and Systems Engineering at McKelvey School of Engineering (open rank), and one in Cell Biology & Physiology at the School of Medicine (open rank). We seek candidates working in topical areas including quantum information, materials, and sensors; quantum optics, advanced spectroscopy and microscopy; and applications to biophysics or other physics, engineering, or medical fields.

Information can be found at https://physics.wustl.edu/, https://ese.wustl.edu/, and https://cellbiology.wustl.edu/. Faculty will be associated with the Center for Quantum Leaps (https://quantumleaps.wustl.edu/), and are encouraged to pursue interactions with the Institute for Materials Science and Engineering (https://imse.wustl.edu/), the McDonnell Center for Space Sciences (https://mcss.wustl.edu/), and the Center for Cellular Imaging (https://wucci.wustl.edu).

Candidates should have a Ph.D. in Physics, Engineering, Biology, or closely related field. Joint applications with a high degree of research synergy will be considered. Candidates for the rank of associate or full professor should have outstanding teaching, service, and publication record commensurate with tenure at that rank. Duties will include conducting research, teaching, advising students, and participating in departmental governance and university service. Diversity and inclusion are core values at Washington University, and we seek to create inclusive classrooms and environments in which a diverse array of students can learn and thrive. Applications consisting of a cover letter; detailed curriculum vitae; statements of research directions (3 pages) and interests in teaching, outreach, and diversity (2 pages); and contact information for at least three references should be submitted to **https://apply.interfolio.com/112603** by **Nov. 14, 2022** to receive full consideration.

Washington University in St. Louis recruits, hires, trains, and promotes persons in all job titles without regard to race, color, age, religion, sex, sexual orientation, gender identity or expression, national origin, protected veteran status, disability, or genetic information.

Careers issue

Tess Jaffe is an astrophysicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland, and the chief archive scientist at its High Energy Astrophysics Science Archive Research Center.

An American's five-country research tour

Tess Jaffe

For one astrophysicist, volunteering for an impromptu transfer to a position in Switzerland turned into a 17-year stint on the European continent.

A year ago former Physics Today editor-in-chief Charles Day asked me to write a narrative of what we termed my "rather bizarre career path." That's a reasonable summation. My first research experience in astronomy was a summer internship I did after my freshman year of college. Having no astronomy background, I applied on a whim and happened to be accepted as their wild card for the year. While modeling stellar atmospheres, I fell in love with the subject. It was a fantastic experience that made me decide to pursue a physics major. But when I returned for my sophomore year, motivated and with a plan, I effectively flunked out of the physics program. That roller-coaster experience turned out to be a microcosm of my career.

Early days in the US, 1997–99

After dropping out of college for a bit, I had much more success during my second go-around, at the University of California, Riverside, where the physics department was a much better fit. I was working on my master's thesis—also at Riverside—when I noticed that an author of a paper I was reading worked at a company called Hughes STX. I still liked astrophysics but felt finished with academia at the time, so I looked into the company and discovered that they provided scientific software developers to NASA's Goddard Space Flight Center.

Somehow I got an interview for a position at Hughes STX working at Goddard for an x-ray astrophysics mission. The Goddard contractors I interviewed with happened to all be women, which was refreshing but gave me an extremely skewed view of the world I was headed into. As the saying goes, fortune favors the foolish, and I got the job. I packed my life into my little pickup truck and drove across the country to Greenbelt, Maryland.

As a 23-year-old who barely knew how to program, working at NASA was amazing. I found my people and my first real

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mentor, and I quickly found that I was pretty good at the job too—helping scientists analyze the data from the *Rossi X-Ray Timing Explorer*. The mission tracked the time variations of astronomical x-ray sources and returned various data types. Scientists needed to reduce the data differently depending on the nature of the source, which meant that the analysis was more complex than is typical for such missions. My group was a mix of scientists and developers who maintained the software and documentation and provided hands-on help to researchers. In return, some of the scientists taught me a bit of astrophysics. I was then able to help create educational materials and answer public questions about the field.

The astrophysics division at Goddard had a large variety of seminars and colloquia, and it paid better than grad school, so in some ways, it was a good interim substitute for a PhD program. The division had several hundred staff and was far larger than probably any university department. But the group I worked in was small, sociable, casual, and collegial. Some of us were contractors for companies like Hughes STX, and some were scientists employed through cooperative agreements with non-NASA institutions like local universities.

It didn't seem to matter at the time what institutional name was on your paycheck. (The important distinctions were things like Linux or Mac and *Star Wars* or *Star Trek*.) In fact, for non-civil servants like myself, our employer's name might change occasionally as the contractor for our positions changed. (Over the course of my seven years at Goddard, I worked for Hughes STX, Raytheon Technologies, and SP Systems.) I worked and socialized with scientists and developers, system administrators and hardware builders, Americans and foreigners. Because our positions were all funded by "soft money"—in other words, dependent on continued funding—they were not permanent. But they could effectively be so if you were useful enough to hop from mission to mission or if you found a long-term project. Goddard was someplace I could have spent my whole career.

Goddard's proximity to several university astronomy departments was something that some of us made use of and some didn't. I took one graduate class in astrophysics while working there, but taking even a single course on top of a full-time job was too much for me to contemplate long term. And as a singleton on an entry-level salary—when I was offered the job, I took the first number Hughes STX offered because I didn't know to negotiate—I'd have been uncomfortable trying to complete a PhD on a part-time salary. The life of a grad student is hard to go back to after adulting for a while.

As much as I liked Goddard, after a few years, I was curious about what else was out there. At the time, the science support group I was in also sent people overseas as part of the US contribution to international scientific projects. One of those individuals was working in Geneva and wanted to come home. I nearly broke my shoulder waving my arm so hard asking them to pick me to replace him. And they did.

Switzerland, 1999–2003

I was hired to take over integrating and testing the data analysis pipelines for a gamma-ray astrophysics mission called *INTEGRAL* (*International Gamma-Ray Astrophysics Laboratory*, still flying!), whose scientific data center was and is run out of a tiny, dedicated institute in Ecogia, a historic hamlet outside

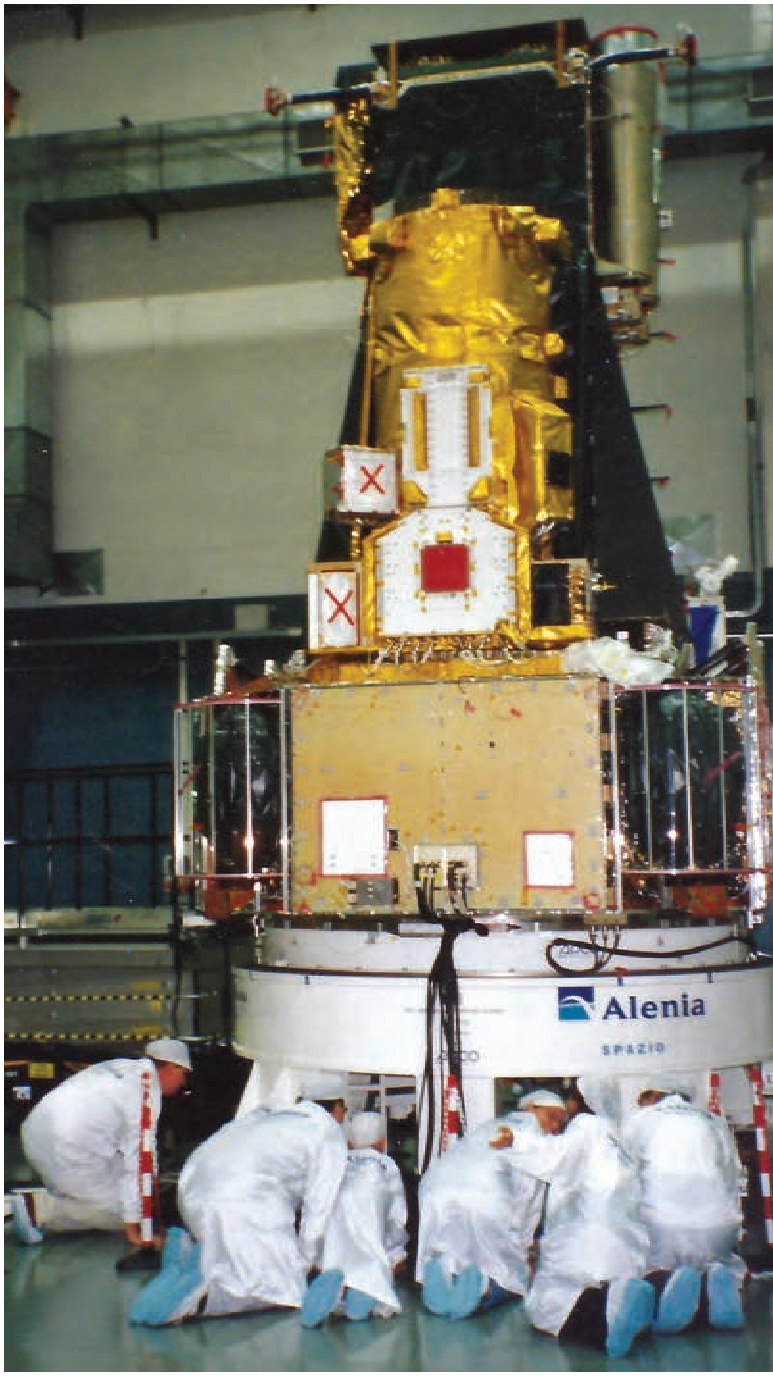

FIGURE 1. MY FAVORITE PICTURE from my time in Switzerland: Part of the *INTEGRAL* (*International Gamma-Ray Astrophysics Laboratory*) software team visiting the hardware before launch. My behind is third from the right. (Courtesy of Peter Kretschmar.)

Geneva. The data center is technically part of the Geneva Observatory and the University of Geneva, but it is largely independent of both institutions. (On the rare occasions I set foot on the university's campus, it was by accident.)

Leaving Goddard was wrenching, and the prospect of moving to Geneva—I had only visited once (for the job interview), I didn't speak much of the language, and I hardly knew another soul on the European continent—was terrifying at the age of 25. Apparently, it was also a bit alarming to the folks in Geneva,

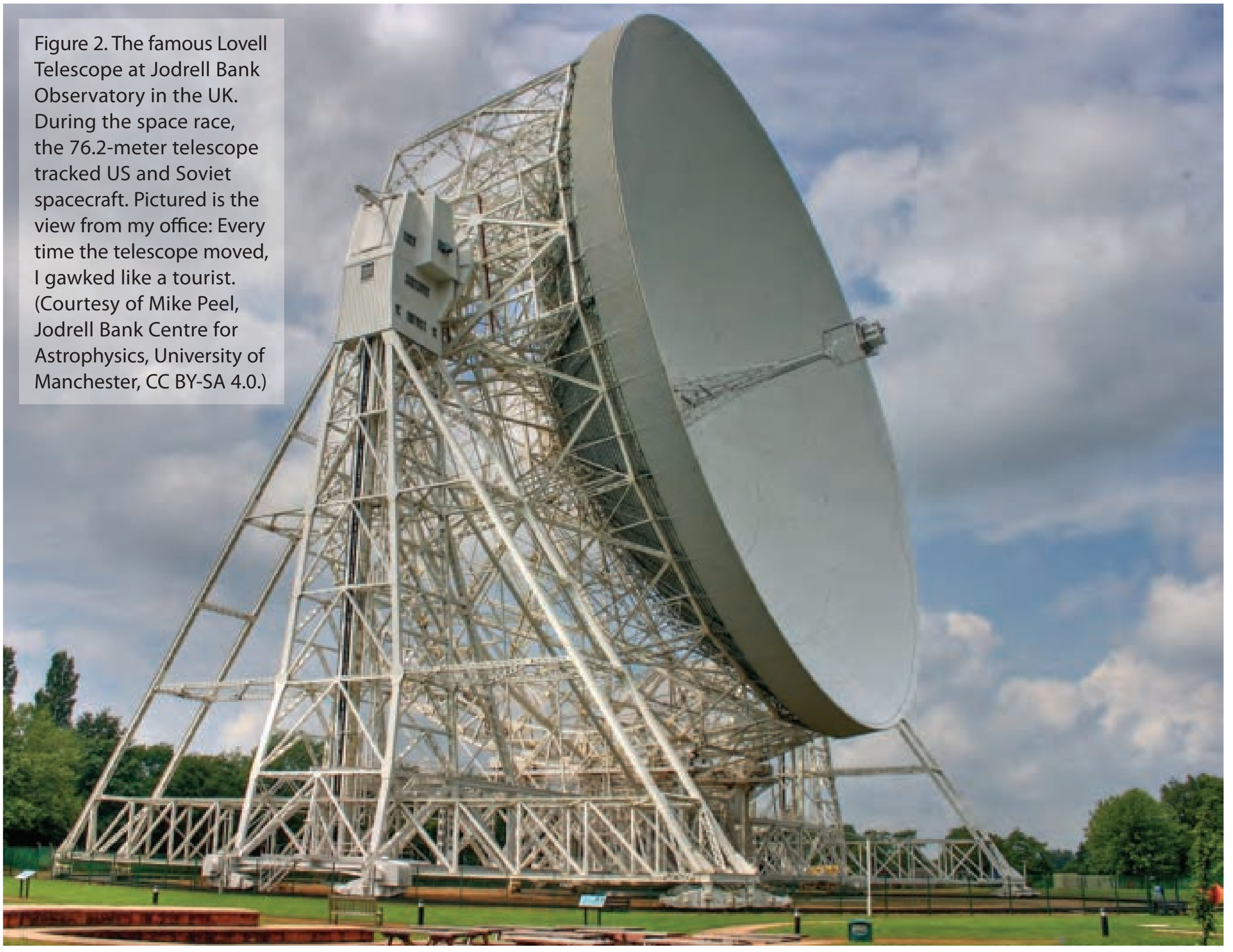

Figure 2. The famous Lovell Telescope at Jodrell Bank Observatory in the UK. During the space race, the 76.2-meter telescope tracked US and Soviet spacecraft. Pictured is the view from my office: Every time the telescope moved, I gawked like a tourist. (Courtesy of Mike Peel, Jodrell Bank Centre for Astrophysics, University of Manchester, CC BY-SA 4.0.)

who wondered what NASA was thinking sending them a child in exchange for an experienced developer.

The staff was international: Like me, most of them had been sent by various countries in the collaboration. Although there were only a few grad students on staff and the atmosphere was a bit more formal than at Goddard, my colleagues at the data center were extremely friendly and welcoming. The staff was used to providing a lot of help to foreigners trying to find apartments and deal with Swiss administrative mysteries without sufficient French language skills. (*Merci, Martine!*) On a side note, despite knowing that having a fling with a colleague is a risky idea in any country, I did it anyway. (I was 25!) I'm now happily married to him, so it worked out well in the end.

I missed my friends at Goddard, but I liked the work and was good at it—and I got to travel in Europe in my spare time, which was the best part. When *INTEGRAL* (seen in figure 1) was launched and the data analysis pipelines were running smoothly, I wasn't ready to go back to the US. With much trepidation, I decided to quit my job (I now had savings) and go back to grad school somewhere in Europe.

That was nontrivial. Now that my French was functional, I looked into some of the high-quality research institutions in France. But at the time, they had limits against funding grad students who began their programs over the age of 25. In Italy, I could have snuck under the age limit of 30 by a few months, and my age didn't matter in Germany. Despite my background in high energy, I decided to head down the electromagnetic spectrum because the newly measured cosmic microwave background (CMB) angular power spectrum was the coolest thing I'd ever seen.[1] (Pun intended.) I was ultimately accepted into a program in Munich to pursue a PhD in the exciting field of CMB anisotropies.

Germany, 2003–06

I did my PhD work at the Max Planck Institute for Astrophysics (MPA), one of more than 80 research institutes operated by the nongovernmental Max Planck Society for the Advancement of Science. Max Planck institutes are well funded and independently run, and their directors have a large amount of discretion over the distribution of each institute's funding.

In physics, that means that grad students (and postdocs) generally do not need to spend much time applying for grants. Instead, they are hired onto a project that typically funds them for a fixed term with its own money or with external funding from a fellowship, such as from the European Union's Marie Skłodowska-Curie Actions.[2] The MPA also had a lot of experience helping foreigners who don't speak enough German. After a few months, my partner managed to get a software-support job at the institute next door and was thus able to follow me from Geneva, which gave us a temporary solution to the two-body problem.

Luckily, I had done a master's degree in the US; European

PhD programs don't generally accept applicants who only have a US undergraduate-equivalent degree. Doctoral programs in Europe focus exclusively on full-time research, and students are generally limited to three years of funding. There are advantages and disadvantages to the European system, but it was important for me to know that I was only setting aside three years and not embarking on an indeterminate project.

Although the MPA had plenty of international personnel, its permanent staff was dominated by Germans. But the institute's graduate program, which is part of one of the International Max Planck Research Schools, was and is set up to recruit international talent, so we were all in the same boat linguistically speaking. The MPA is located amidst a large campus of research institutes in Garching, a suburb of Munich, and the graduate students at those institutes are enrolled at different local universities. I was officially affiliated with the Ludwig-Maximilian University of Munich, but I rarely went to its campus in the center of the city. Unlike in the US, I wasn't able to work with undergraduates, but the point of the three-year limit on European PhD programs is that there's nothing to distract you from your research project.

The fact that there was a majority language group meant that non-German speakers tended to self-segregate a bit by language. There were smaller enclaves of Russians, Italians, and Brits. At the time, I was one of two Americans. By chance, my supervisor happened to be British, and our seminars were in English. (My partner was the only non-German speaker in his group and struggled through their exclusively German-language meetings.) So I'm embarrassed to say that after three years there, my German was never very good, and most of it left my brain when I left the country.

I was lucky because my supervisor was supportive and generous, but some other students faced bullying, not to mention some casual sexism from senior staff (*aber natürlich*), before it became remotely possible to address such issues in research. Overall, however, I was happy. I loved Munich, and I couldn't have asked for a better PhD project.

After two years, our unstable solution to the two-body problem threw my husband out of his job. He took one in the UK while I stayed in Germany for the last year of my PhD. When I was finished, I began to hunt for jobs in the UK. I was again at a fork in the road, and I didn't know if I wanted to continue in research or get a "real" job. After applying to both types of positions, I was offered a postdoc at the Jodrell Bank Observatory, which was part of the University of Manchester, and a scientific software developer position at the Rutherford Appleton Laboratory, the UK national lab in Oxfordshire

Figure 3. My bike commute to work in Toulouse, France, along the historic Canal du Midi.

where my husband was working.

I had gone to grad school not because I had ambitions of an academic career but simply because I wanted to spend three years studying the CMB. I never intended to do any postdocs, but when I got to that point, I decided I might as well do more research since I had the chance. So I took the postdoc at Jodrell Bank. Although the postdoc paid less than the software developer position, I enjoyed the science—and with two incomes, the salary difference wasn't much of an issue.

UK, 2006–09

For the first year of my postdoc, we worked in the beautiful Cheshire countryside, where I had a fabulously distracting view of the Lovell Telescope (see figure 2). My husband was granted a transfer to a closer laboratory so we could live together. But I had a harder time feeling comfortable in my department. My position was funded by a large "rolling grant," which meant that I didn't have to apply for any further funding. In the British system, there aren't many funding options aside from large grants for tenure-track researchers to start a whole group.

FIGURE 4. MY GODDARD COLLEAGUES and I reflected in the mirror of the *James Webb Space Telescope* in 2017. After the telescope was assembled in Goddard Space Flight Center's large clean room, the mirror was deliberately positioned to face the observation hall for several weeks so that we could have the amazing view pictured here.

After a year, we academics moved into a new building in central Manchester, where I shared an office with other postdocs I could talk to, so I felt more integrated into the department. But my project didn't go well. Aside from parenthood, which I was gobsmacked to discover I liked, I didn't have a good time. To make matters worse, after three years, my husband's department was decimated by a budget crisis in the Science and Technology Facilities Council, the UK agency that funded his laboratory.[3] Although he still had a job, he no longer had a group.

So when my former PhD supervisor from Germany moved to a permanent position at a French institute, won a large grant, and offered me a postdoc in sunny Toulouse, I took it. Again, I wasn't intending to search for a permanent academic job. But having felt I'd failed at my first postdoc, I needed to try again to prove that I could do it.

France, 2009–16

So my husband quit his job again, and we moved to Toulouse, where I started working at the Institute for Research in Astrophysics and Planetology (IRAP). One of the independent institutes that arises from a partnership between the CNRS and the Paul Sabatier University, IRAP is located on a large campus south of the city, where the university adjoins several research labs, an engineering school, and part of the French space agency.

My contract was administered by the university, but as in Switzerland and Germany, I barely visited the rest of the campus. IRAP had a healthy population of master's and PhD students and a relatively small number of international postdocs and research staff. But at the time, it was not well set up to support incoming foreigners. Had I not already spoken French, it would have been even more difficult. (Seminars were often in French, and they regularly started with the host asking if anybody in the audience didn't speak French and wanted the speaker to do it in English. That would often be asked . . . *en français*. I've been told things are changing.)

I loved living in Toulouse (see figure 3 for one reason why), and my work went well. My supervisor had guaranteed me the same salary I'd had in the UK, which I believe made me the highest paid postdoc at the time and higher paid than some tenured researchers. After a few months, my husband got a job in Toulouse's large aerospace industry.

We had another child, and I highly recommend Europe for the early years of parenthood. The National Health Service in the UK is great for maternity and childcare, and the French system is good too, although it is, of course, far more bureaucratic (*mon dieu*). In Manchester, day care for one child cost nearly half my salary after taxes, but in France it was subsidized to be a reasonable fraction of our combined income. Having French amounts of vacation was also fantastic, although if I'd taken all of it, my research productivity would have been affected.

As I neared the end of my three-year postdoc contract, we were settled in Toulouse and did not want to leave. Unlike everywhere else I had been, at IRAP it was impossible to find long-term employment by working on a longer project or hopping from project to project: In France, it is illegal to employ people long term without making their positions permanent. So I started applying for permanent positions.

Another unusual aspect of the French system is that most permanent positions in research fields are decided by national competitions judged by a set of panels drawn from one's broader field—in my case, astronomy—much like grant review in the US. Instead of an hour-long job talk, you have less than 15 minutes to present to the panel your entire career and your research plans. The system is meant to be more egalitarian and reduce the effect of the old boys' club.

I applied to two types of positions, which were funded by different agencies that do not have US equivalents. Pure research positions are funded by the CNRS, and positions that are part research, part teaching, and part science support are managed by the National Council of Astronomers and Physicists (CNAP).

Most people apply repeatedly before landing a job, and I ranked highly enough the first time around to think it would be worth trying again. I scrounged some funding so I could apply two more times. In doing so, I ended up being a postdoc at IRAP for nearly seven years (including an extension for maternity leave), under three funding sources. That must be a record at IRAP.

But I was ultimately unsuccessful. I suspect my publication rate was not high enough for the CNRS positions. That was in part because I had worked on a large collaboration with a controlled publication policy, which is unusual in astronomy. For the CNAP positions, it was too late for me to get hired permanently onto the project I proposed working on, and national priorities had shifted to projects I had no "in" with. (Networking remains important in the CNAP application process because the positions are project based.)

My research specialty at that point didn't help either. The study of galactic magnetic fields intersects many subfields of astrophysics without fitting comfortably into any of them.[4] (The story of my life.) I will also note that during the years that I applied (2013–15), the CNRS competition recruited seven men and zero women at my level in astronomy.[5] *Va savoir*.

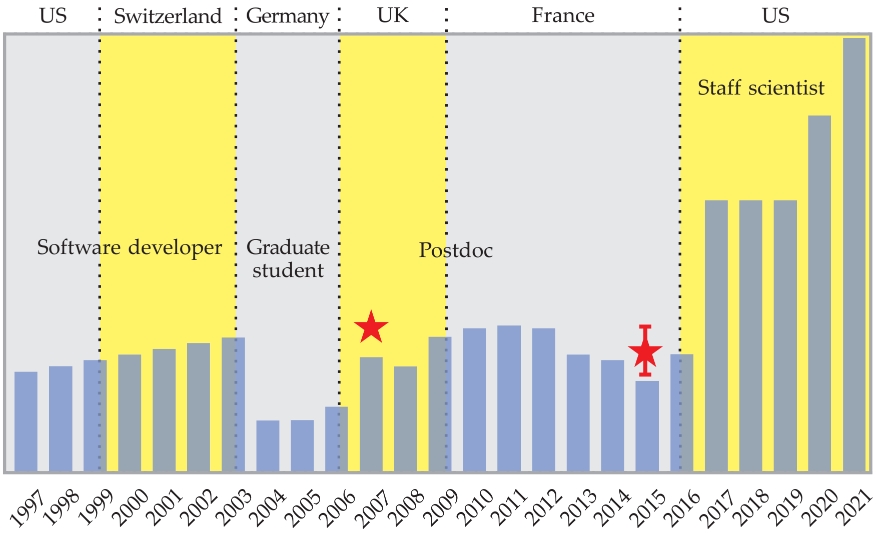

FIGURE 5. MY SALARY HISTORY. Noteworthy elements include the steady salary growth in my first real job (1997–2003) at Goddard Space Flight Center; the huge drop when I went back to graduate school in fall 2003; the drops when my funding agency at the Institute for Research in Astrophysics and Planetology (IRAP) changed (2013 and 2014); the flat salary of a university scientist who only gets a raise when given one by the state legislature (2017–19); and the dizzying rise to stability on the federal pay scale in 2020. The star in 2007 is the salary I turned down at the Rutherford Appleton Laboratory, and the star with the error bar in 2015 is the tenured salary range I would have had if I had received one of the CNRS-funded positions at IRAP.

I was out of research opportunities in France, and I wanted to be closer to my family. So even though I loved living in Toulouse, we decided to move to the US. I hoped to get hired at a place like Goddard, with the kind of long-term but not officially permanent position that is not legal in France. So my husband and I applied to various positions in the US, including at NASA's Jet Propulsion Laboratory and Ames Research Center.

I got lucky: Somebody at Goddard who knew and valued me happened to have an opening for a staff scientist, and the old boys' club ended up working in my favor for once. I tried working my connections for my husband and passed his resumé to everybody I knew, but he ended up landing a job in a Goddard division I knew nothing about—as a contractor for a company I'd never heard of—solely on his own merits.

US, 2016–present

Coming back to the US after 17 years in Europe was extremely difficult. The American lifestyle was not one I wanted to live. I'd driven only a handful of times in the previous decade and didn't miss it. The only American things I missed were proper deodorant and jeans. (Yes, I'm a cliché.) But I was willing to try out what seemed to me to be a strange and not-quite-civilized country to come back to NASA and be closer to family. After all, it was my fifth move to a foreign place, so how bad could it be?

After moving back to the US, things initially got worse and worse for me for reasons entirely unrelated to the job or the location. It turns out that getting mental health treatment can be remarkably effective and is a good idea to do sooner rather than later. I'm far from the only one in astrophysics who's dealt with mental health issues,[6] but I'm one of the few who are willing to talk about it. Note that I could only afford treatment in the US because we had two solid salaries. In the UK or France, it would have been free.

Coming back to Goddard after 17 years was not difficult at all. Now that I'm a scientist and not a developer, I've picked up on a few things I hadn't noticed when I was young and naive—and the government bureaucracy is annoying even to someone who survived seven years in France. But it's the right place for me. Initially, I had a long-term contract position funded by the University of Maryland. I'm now the chief archive scientist at NASA's High Energy Astrophysics Science Archive Research Center, a repository for mission data, so I have to stay current on the research community's needs and the technical tools essential to meet them.

I work with a team of excellent system administrators, developers, and scientists (see figure 4). My favorite part is that we get to learn new technologies on a regular basis so that we can keep up with a changing world. We're currently trying to figure out how to connect a 30-year-old archive to a modern cloud-computing environment without causing too much trauma to our change-averse user community or our funding managers at NASA headquarters.

Some of my previous astronomy collaborations have continued, although I can now devote only a fraction of my time to them. When I was employed by Maryland, I was a bit more involved with the astronomy department. I would go over to campus for occasional seminars, applied for funding using my university affiliation, and looked for students to work with there. It's a nice department, but the academic promotion process is ill-suited for NASA support scientists.

To be fair, I'm biased: The dean refused to promote me from assistant to associate level despite 13 years of post-PhD experience, a recommendation from the promotion committee, and strong support from NASA folks who understood what I did. Unfortunately, NASA's opinions hold no weight with the university when it comes to promotions, which makes sense for the department's academic independence but doesn't work out well for staff in those positions. (I hear that, too, is improving as Maryland better defines promotion criteria for non-tenure-track staff.)

Despite that, I was willing to stay in that position. I was used to being undervalued and underpaid (see figure 5 for my salary history), and the people I worked with knew my worth. Ironically, one year later I landed a top-rung position with NASA. (I can never seem to do things in the usual order.) A NASA civil-servant colleague I was working with retired, and their position opened. I won the competition—and I can now say that I have my dream job, one that matches my whole skill set. I lead a team that provides data access through online tools and programmatic interfaces; ensures our mission data are findable, accessible, interoperable, and reusable; and explores how cloud-computing resources can benefit our community. I also have some time for my own research.

In the end, I got used to driving again—although I mostly biked to work pre-pandemic. My kids are in a French immersion public school that happens to be down the street, and my Belgian husband is pleasantly surprised by the local craft-beer scene. I'm looking forward to a much less adventurous life in the future, or one that's limited to the adventure inherent to living with teenagers, navigating shifting NASA priorities,[7] and working with fast-evolving technologies.

Given my winding career path and the luck I've had, I can't distill my experience into any advice. Nevertheless, I hope it's been useful to see the gory details of a successful yet non-traditional career path.

The CAREERS ISSUE continues online. Learn more about opportunities in and related to government by scanning the QR code or visiting physicstoday.org/careers2022.

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PHYSICS TODAY

PHYSICS TODAY IS LOOKING FOR AN EDITOR-IN-CHIEF

Physics Today, **the most recognized and respected magazine in physics**, published by the American Institute of Physics, will soon be celebrating its 75th year and is looking for an Editor-in-Chief who will chart a course for a future as dynamic as our past.

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Essential among many responsibilities is setting a strategic direction for *Physics Today* to continue to grow beyond publishing a monthly magazine and further diversify our audiences through digital products and channels. In addition to overseeing the editorial content and voice for all products, the EIC serves as the primary "face" of *Physics Today* in the community and at various scientific meetings.

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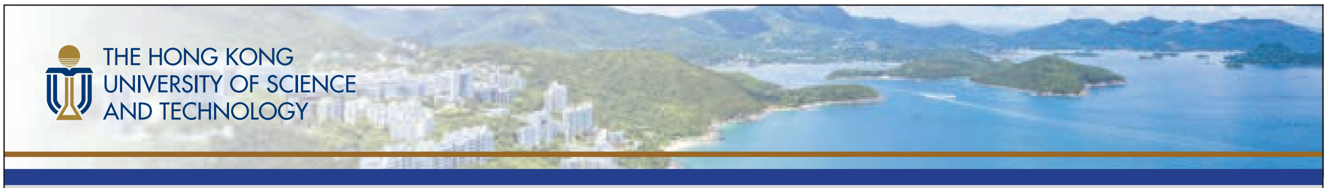

TENURE-TRACK FACULTY POSITIONS IN PARTICLE PHYSICS AND COSMOLOGY

The Department of Physics invites applications for several tenure-track faculty positions at the Assistant Professor level in experimental and theoretical physics. The target areas of the search are Theoretical High Energy Physics and Cosmology, Experimental Particle Physics and Observational Cosmology. Applicants must possess a PhD degree in physics or a related field. The successful candidates should have a strong track record of research (the ones with an interdisciplinary background are especially encouraged to apply). Appointments at the rank of Associate Professor or above will be considered for candidates with an exceptional record of research excellence and academic leadership. In addition to pursuing a vibrant research program, appointees are expected to engage in effective teaching at the undergraduate and graduate levels.

The current faculty in the particle physics and cosmology group at The Hong Kong University of Science and Technology include Professor Andrew Cohen, Professor Tao Liu, Professor Kam-Biu Luk, Professor Kirill Prokofiev, Professor George Smoot, Professor Henry Tye, and Professor Yi Wang. The department is expanding its effort in this area by hiring additional new faculty in theory and experiment. Further information about the Department can be found at http://physics.ust.hk.

Starting salary will be highly competitive and commensurate with qualifications and experience. Fringe benefits including medical and dental benefits, annual leave and housing benefits will be provided where applicable. The initial appointment prior to tenure will normally be on three-year contract terms. A gratuity will be payable upon successful completion of a contract.

Application Procedure: Applicants should submit their applications along with CV, cover letter, complete publication list, research statement, teaching statement, and three reference letters.

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Particle Physics Experiment (PHYS1017P):
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Screening of applications begins immediately, and will continue until the positions are filled.

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Careers issue

Carl Williams is a former deputy director of the Physical Measurement Laboratory of NIST in Gaithersburg, Maryland. He is currently an adjunct professor of physics at the University of Maryland in College Park and a consultant (https://cjwquantum.com).

My journey from academia to the US government and beyond

Carl J. Williams

A career is not meant to be static. Figure out what you are good at and what your strengths are, and never be afraid to try something new.

Physicists usually pursue knowledge for its own sake. But outside of academia, their end goal also is to apply that knowledge to the mission of their employer and to the greater good of society. I have had a truly successful career making contributions to the goals of every organization I worked for while maintaining a personal sense of satisfaction. That personal satisfaction has largely come from working on intriguing projects while interacting with smart and interesting people along the way. In this article I provide a few key lessons from my career path.

The early years

In 1982 I went to graduate school at the University of Chicago in part to live in the ivory tower. As an idealist, I had no desire to face the real world. My thesis adviser, Karl Freed, provided me with numerous opportunities to learn about and understand the academic environment. He was a wonderful, supportive mentor and became a dear friend.

Following graduation in 1985, I took the typical path of securing a postdoctoral position and then another one. Working with Freed, I obtained a research position with the university's James Franck Institute in January 1992 and was allowed to pursue my own interests—focusing on the collisions of ultracold atoms—*if* I could raise the funds. That requirement led to a set of activities that created a growing research relationship with NIST.

Between 1992 and the spring of 1997, I spent roughly 60% of my time working for NIST in the theory group of Paul Julienne while collaborating closely with the experimental group of William "Bill" Phillips, shown with me in figure 1. In the summer of 1995, I moved my family to Gaithersburg, Maryland, so I could work full time with my NIST colleagues.

DONNA PADIAN

Figure 1. Bill Phillips (left) with Carl Williams at Carl's retirement party in 2021.

Figure 2. Katharine Gebbie, executive manager at NIST and founding director of its Physical Measurement Laboratory. (Courtesy of NIST.)

That period was extraordinarily productive and taught me two valuable lessons.

One lesson was that it is not enough to be at the top of your research field. You also need to be able to explain how your work benefits your organization. The other was that true independence rarely exists. Although I had the freedom to choose my own research problems, the need to raise my own funds through grants or contracts, from NIST and elsewhere, meant that I was constrained by what I could convince others to fund.

That financial insecurity increasingly weighed on me. It makes the standard academic job quite stressful, even at the best universities. And although I had several academic opportunities, I finally decided that it was time to find work outside of academia.

Short but valuable side trip

In less than six weeks, I had several offers and decided that my analytical, computer, and modeling skills would align best with the work at the Institute for Defense Analyses (IDA), a nonprofit organization that manages three federally funded R&D centers.

Although I worked at IDA for a little more than a year, it influenced my career profoundly. It opened my eyes to the fact that effective solutions to real-world problems need to address and satisfy multiple considerations. Not only does the solution need to account for technical issues, but it also needs to consider operational, political, and economic factors. Technical solutions are not always sufficient by themselves; sometimes a partial answer today is more important than a complete answer in three months. Realizing that a complete answer can sometimes be too late is a hard lesson for the typical physicist to accept.

During my time at IDA, I worked on two projects. The first involved a large team, and the second was done by a small team that included me and a senior analyst. In both cases, I demonstrated my value through my computational and analytical skills. In the second study, we determined that a mixture of operational and technical factors were key to why a particular US Navy program was in deep trouble. The program office kept spending millions of dollars on better shipborne acoustic sensors. But those in charge of the program had not been looking at the full picture; if they had, they would have realized that they had all the signal necessary and were limited only by the inability to process the data in real time. That problem could have been fixed for less than $100 000 by acquiring a more powerful processing chip.

On the first Tuesday of October 1997, shortly after I began work on the second project, I was driving to NIST when I heard that a local scientist had been named one of that year's recipients of the Nobel Prize in Physics. It was Bill Phillips. By early November, Bill and others with whom I had previously worked were offering me a permanent job at NIST, funded by the extra support given to the new Nobel laureate.

Now I had another decision to make. I had been at IDA for only about eight months, and although I had learned a lot and felt that I was making unique contributions, I still did not fully understand where my career could go if I stayed there. I clearly recognized the possibilities were I to work for NIST. After spending several months talking to both colleagues at IDA and sponsors in the US Department of Defense, I decided that I could not give up the possibility of having ongoing collaborations with a Nobel Prize recipient. Thus I decided to take the job at NIST after completing my second project at IDA.

I had a few additional takeaways from my time at IDA: First, a new job is always fun because you are learning and discovering new things. Second, news stories do not always tell the whole story. My experience at IDA, where I had access to intelligence material, helped me to know when a news reporter managed to get the whole truth about a national security issue and when they were missing or withholding information. Sometimes the hype overshadows the real news, and as a result, scientific truth becomes distorted.

The last major lesson I learned at IDA was from one of my mentors there, Alfred Kaufman. He taught me that it's important to find your own path, because if you don't take control, then you will go only where the flow takes you. Too many people dissatisfied with their careers never do anything about it—either because they don't know how or because they don't

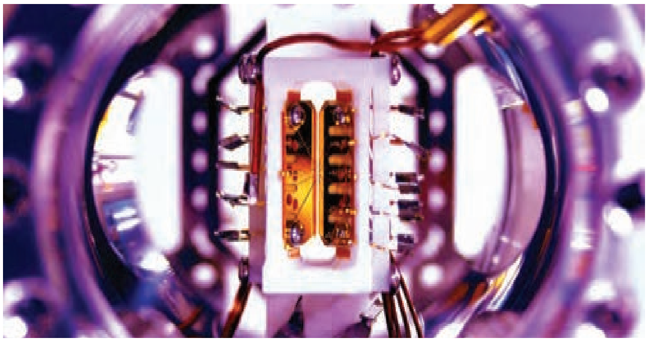

FIGURE 3. AN EARLY ION TRAP used by David Wineland's group that helped establish NIST as a key player in the quantum information science field. (Courtesy of NIST.)

know what they want. Only by understanding yourself can you optimize both your value to your employer and your own job satisfaction.

Life in a government lab

In March 1998 I started at NIST and worked again in Paul's group on cold-atom collisions. My experiences at IDA helped me realize that I needed to direct my own career. That meant learning how NIST operated. To obtain that insight, I received mentoring from Charles Clark, a senior scientist, and the legendary executive manager Katharine Gebbie (see figure 2), while playing in the sandbox surrounded by Bill's dynamic experimental group.

I was at NIST for less than two years when I decided that I wanted to expand my research portfolio. Bill, Charles, and Paul gave me the chance. Charles was probably the principal influence; he had organized the 1994 NIST Workshop on Quantum Computing and Communication,[1] the first anywhere that was solely focused on quantum information science (QIS). After that event, NIST decided that its existing level of activity was sufficient—probably the right decision at the time. But by 2000 my colleagues and I had realized that the organization needed a formal program in QIS.

At NIST, one of the best ways to develop a new research direction is to obtain a "competence" initiative—now called the Innovations in Measurement Science Program—by making a pitch to the NIST director. So in the fall of 2000, Katharine, Bill, and I proposed the idea of building a small quantum processor to then acting director Karen Brown. Karen thought it was a great idea and told us to get started.

Charles, Eric Cornell, Paul, David Wineland, Bill, and I put together a powerful proposal and asked the NIST director for $1.2 million a year for five years. That amount was almost a factor of two more than previous competencies, but it was ultimately fully funded. Eric, in 2001, and David, in 2012, would later receive the Nobel Prize in Physics.

That effort was the beginning of NIST's Quantum Information Program, and I agreed to coordinate it, expecting that it would grow substantially. The following year, Charles and I, together with several other colleagues, raised an additional $700 000 per year for five years from the Defense Advanced Research Projects Agency to initiate an effort in quantum communications. (I was also part of several other quantum computing programs that brought in another $500 000 per year.) As the NIST program rapidly expanded—based on David's demonstration of the first two-qubit gates[2] (see figure 3) in 1995 and the growth prompted by the competence effort and external funding—my new career direction and self-defined path at NIST were solidified.

In 2005, after a couple of promotions, I worked with NIST senior management and successfully prepared the first presidential budget for the Quantum Information Program to NIST. That achievement essentially guaranteed that the program would continue for many years. By the time I retired at the end of 2021, the program was bringing in more than $45 million a year.

Also in 2005, William Jeffrey became NIST's director. Working with him, Katharine, Bill, and colleagues at NIST and the University of Maryland, I helped plan and establish the Joint Quantum Institute (JQI) at the university the following year. As a result, I took on the additional title of NIST codirector of the JQI.

During the first 15 years of my career—through 2000—as a scientist, I published about three papers per year and was satisfied with doing and publishing research. It was a fun but slow process. By 2001 I had moved from ultracold collisions to QIS with a focus on neutral-atom quantum computing and

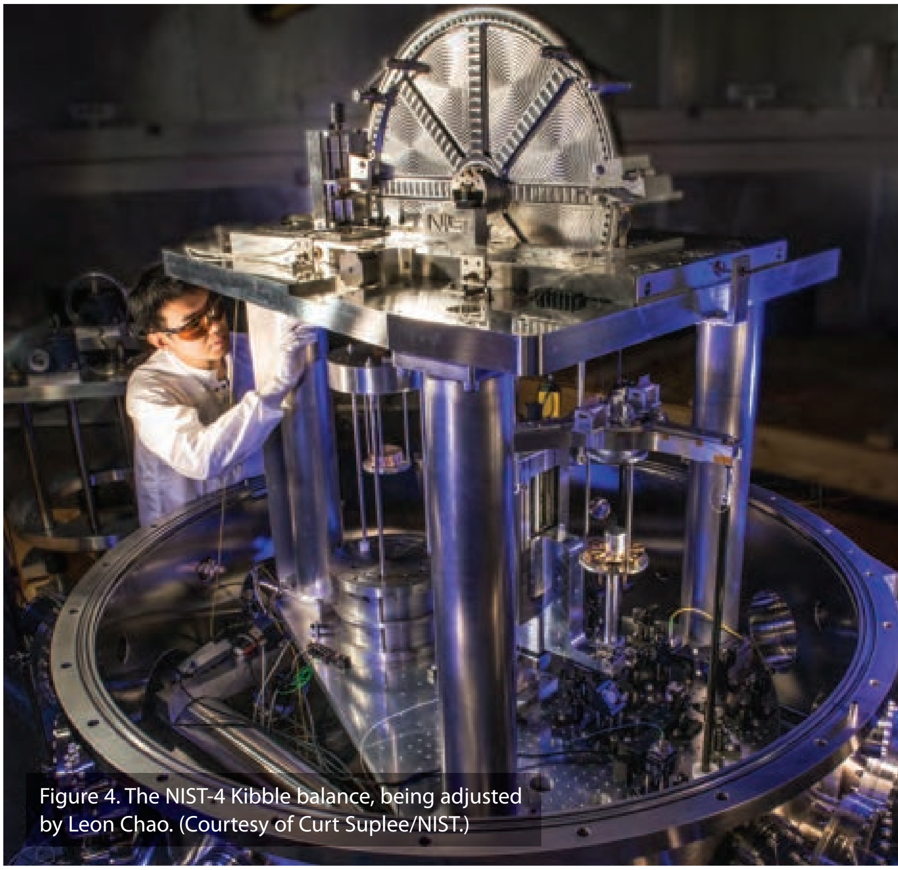

Figure 4. The NIST-4 Kibble balance, being adjusted by Leon Chao. (Courtesy of Curt Suplee/NIST.)

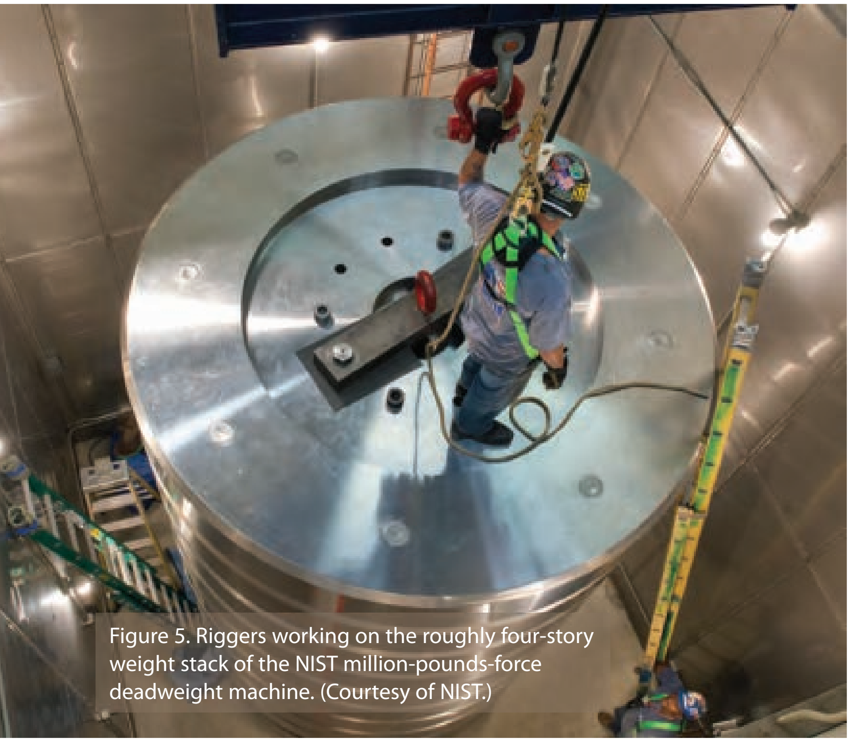

Figure 5. Riggers working on the roughly four-story weight stack of the NIST million-pounds-force deadweight machine. (Courtesy of NIST.)

high-speed quantum key distribution. As I increasingly worked with students and postdocs over the next decade, my productivity doubled.

I was starting to realize that scientific knowledge comes relatively slowly and that the best way to obtain the repeated euphoric highs from a new understanding wasn't by doing research with a small group but by working with larger teams of students, postdocs, and collaborators. I increasingly wanted to build a bigger sandbox so that I could enjoy more of those highs and share the enjoyment of playing in the sandbox with others. I realized it was essential to have multiple good mentors as well—more than one because a senior leader teaches you one thing while a senior scientist or politician teaches you another. Moreover, you need to mentor and recognize those around you.

In late 2007 a new opportunity arose as it became clear that the White House Office of Science and Technology Policy (OSTP) wanted someone to help create a federal vision for QIS. After discussions with the OSTP and with the support of NIST and the US Department of Commerce management, I agreed to a part-time detail with the OSTP, where I would spend the next two and a half years. Although such opportunities are available to academics, most don't know they exist.

Learning policy

In the last year of the George W. Bush administration, I started working at the OSTP. The agreement that I had with John "Jack" Marburger III, then director of the OSTP, was to create a national strategy for QIS by the end of the administration. My first year was spent learning how policy is made within the US government and how to engage with senior policymakers who lead executive agencies.

In March, Jack called the agency principals together for a first meeting. Although I had done my homework well, I misjudged how important it was to be sure that all senior policymakers were on board and thus spent six additional weeks negotiating with the key holdouts. Ultimately, we succeeded in setting a federal vision for QIS. That strategy was delivered in record time and was the last document produced by the OSTP in the Bush administration.[3] One of the best parts to read is the extraordinarily visionary Dear Colleague letter written by Jack at the beginning of the document, as it explains why QIS is so relevant to the nation.

In the Obama administration, I continued to work on QIS and on cybersecurity, another pressing issue deeply tied to US national security. As I dealt with interagency policy committees, I came to understand how important it is to engage with others as policy is deliberated. I also saw how many agency heads had blinders on and only saw issues from their own perspective, while other agency heads navigated the bigger picture. Basically, agencies are much like family members—each with their own personality and approach to problems. Remarkably, most hard policy decisions are negotiated in good faith and end without animosity between parties.

From manager to senior executive

After I returned full time to NIST from the OSTP in 2010, the institute underwent a reorganization. Overnight, I went from having fewer than 30 staff members in three groups to more than 70 and being responsible for more than $30 million annually. With the larger division, I decided to give up the position of codirector of the JQI. Even then, I found I had little time left to do any research. Whenever I set time aside, other pressing managerial matters would intercede.

One of the changes that came with the bigger division was that in addition to research groups, I now had several groups focused on calibration services. They had been starved of resources and were struggling. I thus began an effort to revitalize and integrate them into the rest of the division.

Among the services I inherited were mass and electrical metrologies that included the watt balance, now known as the Kibble balance, shown in figure 4. It was NIST's approach to a quantum-based, nonartifact replacement for Le Grand K—the mass prototype that internationally defined the kilogram—kept in a safe at the International Bureau of Weights and Measures (BIPM). During the first two to three years of the new division, I worked hard at creating an inclusive culture, a tiring task but something that gave me great personal satisfaction as division staff members grew to trust each other and become a tight team.

As part of revitalizing measurement services, I pulled together a new team to build the fourth-generation NIST-4 Kibble balance.[4] The planning, design, and purchasing for it started in earnest in early 2012, but construction delayed the actual assembly of the new apparatus until December 2013. Within 18 months, the team had not only finished assembly but also provided a new value for Planck's constant. The effort demonstrates the great value of teamwork and an inclusive culture.

As NIST-4 was being put together, I received some other startling news: The NIST million-pounds-force deadweight ma-

FIGURE 6. THE PAVILLON DE BRETEUIL, home of the International Bureau of Weights and Measures in Sèvres, France, where Le Grand K—the mass prototype that formerly defined the kilogram—is kept. (Courtesy of BIPM, CC BY 3.0 IGO.)

chine,[5] shown in figure 5 and used to calibrate large force sensors, had developed galling—a form of adhesive wear between two moving surfaces—after nearly 50 years of operation. I learned the news from Rick Seifarth, the man responsible for large force calibrations at NIST, and he told me that it needed to be repaired before it was permanently damaged.

In spring of 2014, I pulled together NIST senior leaders, including those from the physical plant and acquisitions, to explain the Herculean task that was to come. The disassembly and refurbishing of the world's largest dead-weight machine, 10 stories high (including its hydraulic lift and test infrastructure), was an amazing experience. I recall one tense moment when the enormous scope of the task became evident. Rick began to worry that while dismantling the machine, we could damage it. We talked for a few minutes and I told him what he already knew—that we needed to forge ahead to salvage a national treasure. I could see Rick relax as he knew I had his back. Again, the great value of a team.

The BIPM is based at the Pavillon de Breteuil, shown in figure 6, in the park of Saint-Cloud in Sèvres, a southwestern suburb of Paris. Between 2012 and 2018, I made 14 trips to Paris, primarily for meetings at the BIPM as I worked with international colleagues to create the foundation for the most dramatic change to the Treaty of the Meter since its signing in 1875.

The redefinition included removing the last artifact, Le Grand K, that helped to define the International System of Units. That was achieved by fixing the value of a constant of nature—the value of Planck's constant as determined by the NIST-4 Kibble balance and other instruments around the world. In November 2018 in Versailles, France, the treaty members voted to redefine the SI units. After the redefinition came into force on 20 May 2019, the 144th anniversary of the signing of the Treaty of the Meter, the NIST-4 Kibble balance became NIST's instrument for realizing the kilogram. (See the article by Wolfgang Ketterle and Alan Jamison, Physics Today, May 2020, page 32.)

Being part of that piece of history was another highlight of my career, for which I credit many of the skills I had developed at the OSTP. Those skills allowed me to both advance the concept of the redefinition and convince other countries to support the effort. A world-class team of mass and electrical metrologists worked alongside talented precision engineers from my division to enable its success.

More policymaking

When I came back to NIST from the OSTP in 2010, I continued to engage in policymaking. In 2012 the National Research Council released the report *Optics and Photonics*.[6] As it was being rolled out, I arranged a meeting of government-only staff with Gerald Blazey, who was then at the OSTP. That interaction led in April 2013 to the establishment of a fast-track action committee (FTAC) under a subcommittee on which I was the NIST representative. I arranged for a fellow NIST division chief, Gerald Fraser, to cochair the FTAC, which produced the report *Building a Brighter Future with Optics and Photonics*.[7]

Simultaneously with the meeting of the FTAC, several professional societies came together to create the National Photonics Initiative (NPI; www.lightourfuture.org) to advocate for photonics in the US. Some leg work in the administration led to the announcement in July 2015 of the creation of AIM Photonics, a manufacturing innovation institute established by the Department of Defense. My continued work with the professional societies involved with the NPI led to a discussion about a year later that it should propose an initiative around QIS in support of the recommendation made in *Advancing Quantum Information Science*.[8]

In the fall of 2016, the NPI drafted a white paper and then drafted the original text of what became the National Quantum Initiative (NQI) Act. Its completion was the first time in the physical sciences that professional societies managed to draft a key piece of legislation in support of science. I was then invited to testify before congressional committees about US leadership in quantum technology.[9] The testimony led the following year to the NQI draft being signed into law on 21 December 2018.

Late in 2017, after a request from the OSTP, I recommended that they interview NIST physics theorist Jacob "Jake" Taylor to become the first assistant director for QIS at the OSTP. Jake took on the task of further driving the NQI forward. The act mandated the establishment of the Quantum Economic Development Consortium (QED-C), a diverse set of industry, academic, and other stakeholders whose mission is to grow a robust commercial quantum-based industry and supply chain in the US.

I enjoyed leading, but management was not all I wanted. My former small division had allowed me to lead and still do research. The management that was involved was *manageable.* Toward the end of my career at NIST, I spent roughly half my time coordinating and driving forward QIS activities at NIST and the QED-C and across the federal government. But I spent too much time dealing with the bureaucratic headaches associated with being part of a laboratory with more than 600 permanent staff and a budget that surpassed $200 million annually.

My time at NIST had many highlights—helping to establish the JQI, coordinating the Quantum Information Program, creating the first interagency subcommittee at the OSTP for QIS, redefining SI units, and creating the National Quantum Initiative and the QED-C. I would not change anything.

Lessons learned

I retired from NIST at the end of 2021, but I did not retire. Instead, I set up a consulting company, CJW Quantum Consulting, to engage with startups, companies, nonprofit organizations, and others that will ultimately become part of the US economy's future. My goal is to help solve problems that will allow the nascent quantum economy to grow and become robust (see "What's under the hood of a quantum computer?," PHYSICS TODAY online, 5 March 2021). I focus not on any specific company but on the broader needs of the community.

In the eight months since I started the company, I have gotten eight clients. I am taking all that I have learned during my career and using it not only to help guarantee the success of this new US industry but for the good of the world. I expect that the next 5 to 10 years will see me grow in completely new ways.

A career is not meant to be static. Figure out what you are good at and what your strengths are, and don't ever be afraid to try something new. A great career is about a lot more than making money. It is about affecting those around you and creating a better world for your employer, your coworkers, and society at large.

With the evolving quantum industry, young physicists have many opportunities beyond academia and the government. Many of them are going into industry and doing both basic and applied research to create the technology that they (and I) hope will ultimately shape the 21st century. Some of them go to startups, some go to established companies, and some create their own companies. I hope to influence that evolution and to play in the quantum sandbox. That's something that I could not have even imagined when I agreed to lead the NIST Quantum Information Program more than 20 years ago.

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PHYSICS TODAY

A 1906 geological map of Iceland.

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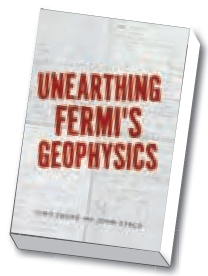
An anachronistic new textbook

Unearthing Fermi's Geophysics
Gino Segrè and John Stack
U. Chicago Press, 2022. $35.00



Known for his seminal works on statistical mechanics, beta decay, and slow neutrons, Enrico Fermi was already a towering figure in 20th-century physics by the time he emigrated to the US in 1939. He entered the annals of world history in 1942 when he directed the construction of the first experimental nuclear reactor, Chicago Pile-1. But it is far less known—and was previously unknown to me—that the protean Fermi not only was a pioneering nuclear physicist but also had a deep interest in the less glamorous field of geophysics.

The context and content of the physicist's curiosity about Earth science is the central theme of *Unearthing Fermi's Geophysics*, an informative and lucid book by two professors emeriti of physics, Gino Segrè and John Stack. Many readers of Physics Today will be familiar with Segrè's books on the history of physics, which include the prize-winning 2007 *Faust in Copenhagen: A Struggle for the Soul of Physics* and a 2016 biography of Fermi coauthored with Bettina Hoerlin, *The Pope of Physics: Enrico Fermi and the Birth of the Atomic Age*. Segrè's coauthor, John Stack—a particle physicist at the University of Illinois at Urbana-Champaign—is a theorist with extensive teaching experience.

Although Fermi never published any papers on geophysics, he taught a course on the subject at Columbia University during his first few years in the US. In *Unearthing Fermi's Geophysics*, the two authors use his handwritten lecture notes to develop a complete textbook on introductory geophysics in the way that Fermi might have done had he written one at the time. To do so, they also use another source: Fermi's notes from the Sixth Washington Conference on Theoretical Physics, held in 1940, which focused on the physics of Earth's interior.

The authors sensibly endeavored to write a textbook that faithfully reflects what was known about Earth physics around 1940. But as they admit, they couldn't resist expanding on several of the topics discussed by Fermi and adding a few new ones of their own. Indeed, throughout the book there are references to much later literature and modern data, which makes perfect sense from a pedagogical point of view but is problematic from a historical perspective.

Readers may find it unclear which parts of the book come from the authors and which ones are by Fermi.

Fortunately, inquisitive readers can freely consult Fermi's authentic notes online at the University of Chicago Press's website. If they do so, they will discover that very little of the Segrè–Stack book is actually based on Fermi's notes, which mostly consist of formulas, tables, and numerical data. Moreover, the notes also contain references that were left out for some reason, presumably because Segrè and Stack believed they would be irrelevant for modern readers. For example, at one point in the lecture notes, Fermi refers to the geologist and physicist John Joly, who in 1909 tried to explain Earth's heat budget with a cyclic theory in which radioactive decay continually increases and decreases. Joly's long-forgotten theory was apparently of some interest to Fermi, but it is not mentioned in the book.

As Segrè and Stack point out, the topics Fermi chose to cover in his lectures on geophysics were somewhat idiosyncratic. They differ not only from those presented in modern textbooks and lectures but, more importantly, from the content covered in most geology books published in Fermi's day. For example, his lectures did not cover orogeny—namely, mountain formation—a topic of great interest to physical geologists both then and now.

But the authors make no attempt to place Fermi's lectures in the context of 1940s geophysics. How representative were his lectures of contemporary mainstream geophysics? Readers are left guessing. It would have been interesting if the authors had compared Fermi's physics-oriented view of geophysics with more geology-oriented views of the field, such as the one articulated by the geologist Arthur Holmes in his classic 1944 textbook *Principles of Physical Geology*.

Despite its shortcomings, at least from a historian of science's perspective, *Unearthing Fermi's Geophysics* is a welcome contribution to the literature on Fermi and 20th-century geophysics. First, it opens a window into Fermi's surprising interest in and broad knowledge of a completely different field than the ones upon which his fame rests. Second, Segrè and Stack have produced a concise and excellent textbook on classical geophysics as the subject stood around 1940.

But even though the book was inspired by Fermi's lecture notes, its 17 self-contained chapters—which cover such topics as liquid-drop physics and atmospheric plasma—substantially deviate from the notes. Nevertheless, *Unearthing Fermi's Geophysics* will be appreciated by not only historians of geophysics but also teachers of physics because of its clarity and pedagogical style.

Helge Kragh
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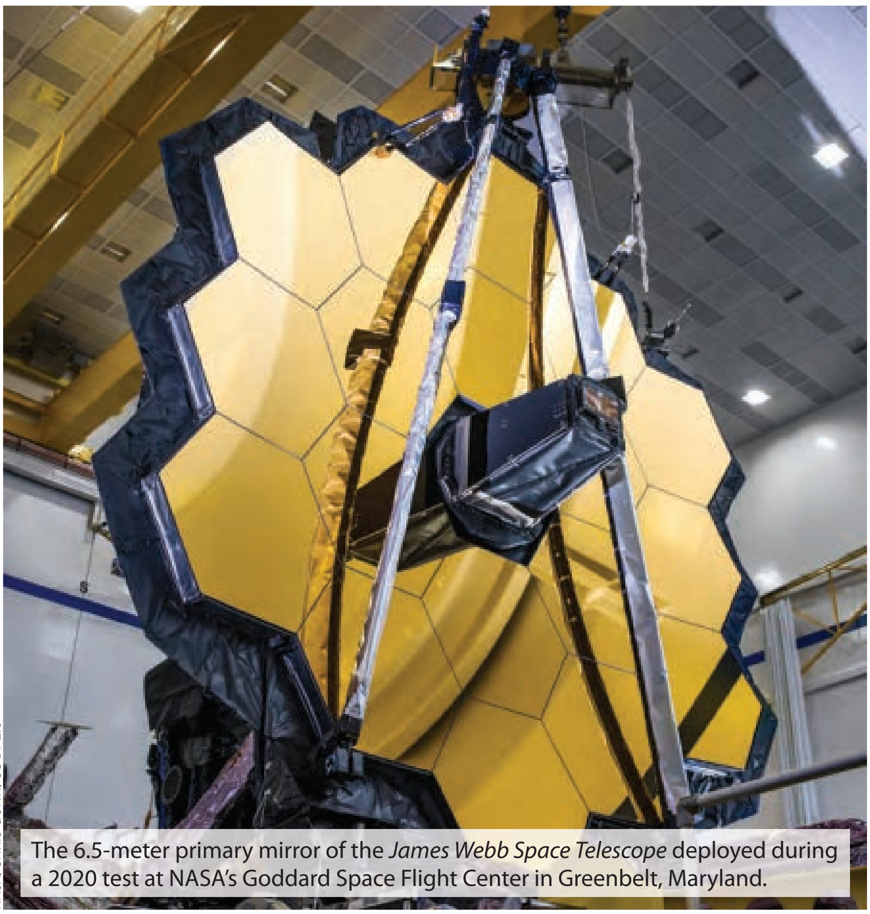
An introductory astronomy textbook for majors



NASA/CHRIS GUNN/CC BY 2.0

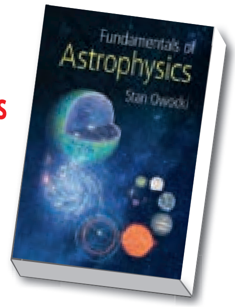
The 6.5-meter primary mirror of the *James Webb Space Telescope* deployed during a 2020 test at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

Most astronomy departments offer two introductory courses: one for majors and one for nonmajors. Stan Owocki's new textbook, *Fundamentals of Astrophysics*, is designed to accompany the former. A professor at the University of Delaware, Owocki is well known for his research in the field of stellar astrophysics and has extensive experience teaching undergraduate courses. He intends his new book to fill in the gap between textbooks for nonscience majors and upper-level astrophysics textbooks. But does it succeed?

I'll get to the point: I really like *Fundamentals of Astrophysics*. Will you? I think it depends on what purpose you think a textbook serves. Is it meant to be a tome that you'll refer to for an entire career or a readable book that might need to leave out some rigor in the name of clarity? In other words, should a textbook include every possible topic or equation you might want to cover so you can pick and choose which sections to assign? Or should the book remain simpler and be supplemented by classroom instruction?

Fundamentals of Astrophysics falls firmly in the simple and concise, but readable, category, which I believe is a good thing.

Fundamentals of Astrophysics
Stan Owocki
Cambridge U. Press, 2021. $99.99



My own biased view is that undergraduates are unlikely to read a textbook if it's not approachable, and Owocki's book is conversational and supremely readable. Readers will feel both the author's excitement for the material and his depth of experience explaining concepts at the undergraduate level. For me, it brought back memories of reading physics textbooks by David J. Griffiths, a rare author who isn't afraid to speak to students in casual language.

Not insignificantly, a physical copy of *Fundamentals of Astrophysics* also weighs a lot less than comparable introductory astrophysics textbooks. It totals only 290 pages and is available as an extremely portable softcover. Perhaps, like me, you (or your students) will find yourself toting this book with you to coffee shops or perusing it on your couch. One particularly nice, unique feature of Owocki's text is its division into many short subchapters, each of which is accompanied by "Quick Questions" alongside the more standard, substantial "Exercises."

That said, there were moments when I worried that Owocki's language would be unclear to an undergraduate seeing this material for the first time. Terms like "angular size," for example, pop up early in the book without prior introduction. Moreover, some of my enjoyment while reading came from seeing Owocki make connections between concepts often presented in separate contexts by turning them around and looking at them from different angles. But trying to understand those sophisticated connections might overwhelm some students. Owocki also often resorts to unfortunate turns of phrase like "It should become obvious," which physics professors have become infamous for. In that regard, the proof is likely in the pudding—I'd want to share this book with my students to get their direct feedback.

In my anecdotal experience, professors who teach introductory astrophysics for majors do not agree on a go-to textbook. Two common alternatives to Owocki's book are *An Introduction to Modern Astrophysics* (2nd ed., 2007) by Bradley Carroll and Dale Ostlie and *Astronomy: A Physical Perspective* (2nd ed., 2003) by Marc Kutner.

Carroll and Ostlie's book sits squarely in the category of comprehensive introductory textbooks and thus includes significantly more physics than Owocki's. For example, when discussing spectroscopy, Owocki merely mentions that it provides a "bar code" that encodes atomic abundances. But Carroll and Ostlie's coverage mentions the Bohr model, quantum mechanics, the Rydberg formula, and Zeeman splitting. On the flip side, Owocki discusses concepts that professors might take for granted but that undergraduate students may have not yet internalized, such as the idea that telescopes are "light buckets" and that the number of photons they can collect thus scales directly with the mirror's area.

Kutner's book sits between the other two. Although it's more comprehensive than *Fundamentals of Astrophysics*, it too is clearly aimed at early-stage undergraduates. It's the only one of the three to walk students through mathematical derivations and example problems. It also includes many color illustrations and has extensive coverage of solar-system astronomy.

All three textbooks cover stellar astrophysics and galactic structure and evolution, but Owocki's discussion of solar-system science and planet formation is lacking compared with the other two books. He falls into the trap of providing too many facts but little in the way of unifying planetary-related physics. His section on cosmology, on the other hand, is more extensive and up to date than the coverage by either Carroll and Ostlie or Kutner.

In short, *Fundamentals of Astrophysics* is a welcome addition to the world of undergraduate astronomy textbooks. It may be a good fit for you if you teach astrophysics to majors. But before assigning it to your class, you should peruse it to make sure it covers your preferred topics. Whether you choose to adopt Owocki's book or not, you'll enjoy the read.

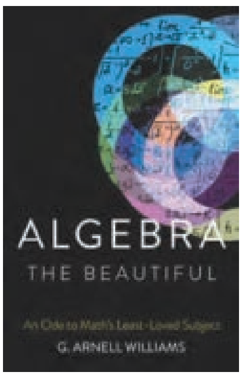
Colette Salyk
Vassar College
Poughkeepsie, New York

NEW BOOKS & MEDIA

The Bomb

Rosa Ellis, host
BBC Sounds, 2022 (Season 2)

The second season of this BBC podcast focuses on the infamous atomic spy Klaus Fuchs. A communist refugee from Nazi Germany, Fuchs found refuge in the UK, where he studied under Max Born, a fellow émigré. During the war, Fuchs was sent to Los Alamos as part of the British contribution to the Manhattan Project, and while there, he passed intelligence to the Soviets. Only in 1949 was he unmasked as a spy. Although the script lapses into hyperbole all too often, *The Bomb* uses interviews with family members such as Fuchs's nephew, Klaus Fuchs-Kittowski, to present a nuanced depiction of his story. The family connections don't stop there: The podcast host, the journalist Rosa Ellis, is the grandniece of Fuchs's handler, Ursula Kuczynski. —RD



Algebra the Beautiful

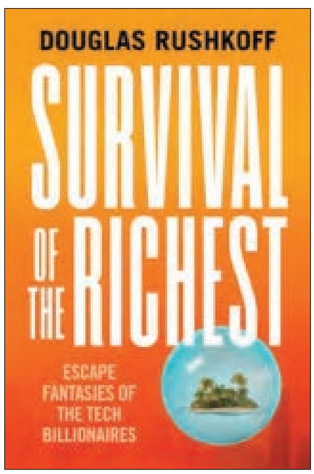
An Ode to Math's Least-Loved Subject

G. Arnell Williams
Basic Books, 2022. $32.00

Algebra, a dreaded subject for many students, is the focus of this popular-science book by G. Arnell Williams, a math professor. Recognizing that many adults still struggle to understand it, Williams adopts a narrative approach aimed at nonspecialists to demystify algebra's concepts and rules. In addition to providing a thorough explanation of what algebra is and how it differs from arithmetic, he walks the reader through numerous word problems and demonstrates how to translate expressions and ideas into variables and equations. Whether that approach turns readers into algebra converts or not, they should at least gain a better appreciation for one of the most important branches of mathematics. —CC

Survival of the Richest

Escape Fantasies of the Tech Billionaires



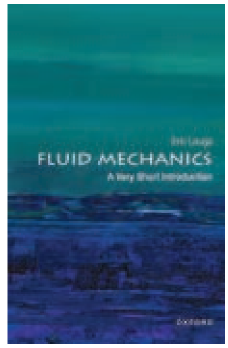
Douglas Rushkoff
W. W. Norton, 2022. $26.95

Even as governments attempt to regulate their companies, tech billionaires continue to sail toward their next missions—be it Mars colonies, ocean communities, or launching cars into outer space. In *Survival of the Richest*, the self-proclaimed Marxist media theorist Douglas Rushkoff criticizes the cyclical nature of digital capitalism, which creates distractions and immersive realities that alienate consumers from the environmental and socioeconomic repercussions of unbridled technological development. Juxtaposing tech billionaires' extravagant plans with the toll they take on the environment and the global poor, Rushkoff calls out offshore "slave labor" and argues that governmental deregulation helped create today's tech oligarchs. Rushkoff's razor-sharp language is refreshing, and readers will most likely enjoy his brutal honesty. —GD

Fluid Mechanics

A Very Short Introduction

Eric Lauga
Oxford U. Press, 2022. $11.95 (paper)



Despite its ubiquity in nature, industry, and everyday life, fluid dynamics is often overlooked. So it is perhaps unsurprising that it took 27 years and more than 700 volumes before the subject was covered in Oxford University Press's long-running Very Short Introductions series. Fortunately, the resulting book was worth the wait. Authored by Eric Lauga, the lead editor of *Physical Review Fluids*, the new title covers such topics as viscosity, pipe flows, boundaries, vortices, and instabilities. A final chapter describes current areas of research in the field. Although Lauga includes more equations than one might expect of a title in the Oxford series, the book provides a great overview of the remarkable properties of fluids. —RD

Geopedia

A Brief Compendium of Geologic Curiosities

Marcia Bjornerud
Princeton U. Press, 2022. $16.95

From "Acasta gneiss" to "zircon," this pocket-sized encyclopedia comprises 74 geologic terms selected by the professor of geology Marcia Bjornerud "because they are portals into larger geologic stories." The entries represent a mix of rocks, landforms, locations, and geologic periods and phenomena, each of which serves as a springboard to launch into discussions of etymology, geological and human history, and interesting geophysical events. Aimed at general readers who want to learn more about an oft-neglected subject, *Geopedia* strives to convey, in a few short words, an understanding of how Earth works, how it has coevolved with life, and how much we have learned about it so far. —CC PT

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NEW PRODUCTS

Focus on test, measurement, quantum metrology, spectroscopy, and spectrometry

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

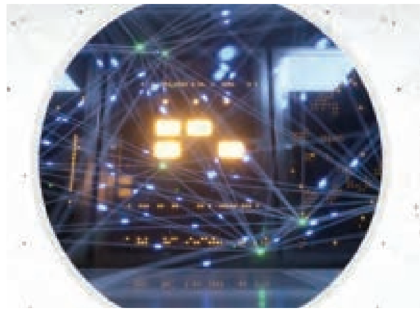
Pulse processing unit for quantum computing

Quantum Machines has developed a cloud infrastructure for universal quantum computing that is based on its new pulse processing unit (PPU), Hadamard. Integrated with the company's OPX Quantum Orchestration Platform—a scalable solution for the control and operation of quantum computers—the PPU facilitates the execution of advanced quantum computing algorithms and enables quantum error correction in real time. The multicore PPU consists of classical logic gates that constitute a unique, highly specialized processor architecture. Each of the 18 pulser cores generates the pulses that operate the qubits, receives the data from the qubits, and enables the algorithm to run efficiently. According to the company, since the new PPU-powered OPX platform runs on the time scales of the qubits, it can orchestrate protocols that were not previously possible in real time and, thereby, significantly speed up run times. ***Quantum Machines***, *Yigal Alon St 126, Tel Aviv-Yafo, Israel, www.quantum-machines.co*

Wideband EMI testing in real time

Rohde & Schwarz now offers a hardware extension that it says will allow its ESW EMI test receiver to operate at the fastest speed and provide the largest bandwidth in the industry, while maintaining a high dynamic range and measurement accuracy. To shorten measurement time and provide a more careful analysis of interfering signals, the fast-Fourier-transform bandwidth of the ESW EMI test receiver can be increased to 350 MHz with the ESW-B350 option and to 970 MHz with the ESW-B1000 option. The 970-MHz-wide spectrum is measured in real time; users benefit from a truly gapless spectrogram. Infrequent emissions can be observed over a much longer time and are detected with a much higher probability. All emissions, even the shortest pulses, from equipment under test going through a duty cycle are recorded over a broad spectrum of 970 MHz. ***Rohde & Schwarz GmbH & Co KG***, *Muehldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Digital wideband-transceiver test solution



Keysight has launched a digital wideband-transceiver test solution designed to reveal the true RF performance characteristics of mixed-digital RF devices. Defense radars, satellite communications, and the 5G cellular network all use phased-array antennas to meet performance and versatility requirements to millimeter-wave frequencies. Keysight's test solution compares digital and RF signals between device input and output and measures the transmitter and receiver responses independently of other test instrumentation. It comprises Keysight hardware and software, such as the N52xxB PNA/PNA-X vector network analyzer, VXG vector signal generator, S94601B device-measurement eXpert software, and S94610B digital wideband-transceiver analysis software. According to the company, its test solution maintains high measurement accuracy of gigahertz bandwidth in millimeter-wave frequencies and can enable users to accelerate the design cycle. ***Keysight Technologies Inc***, *1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

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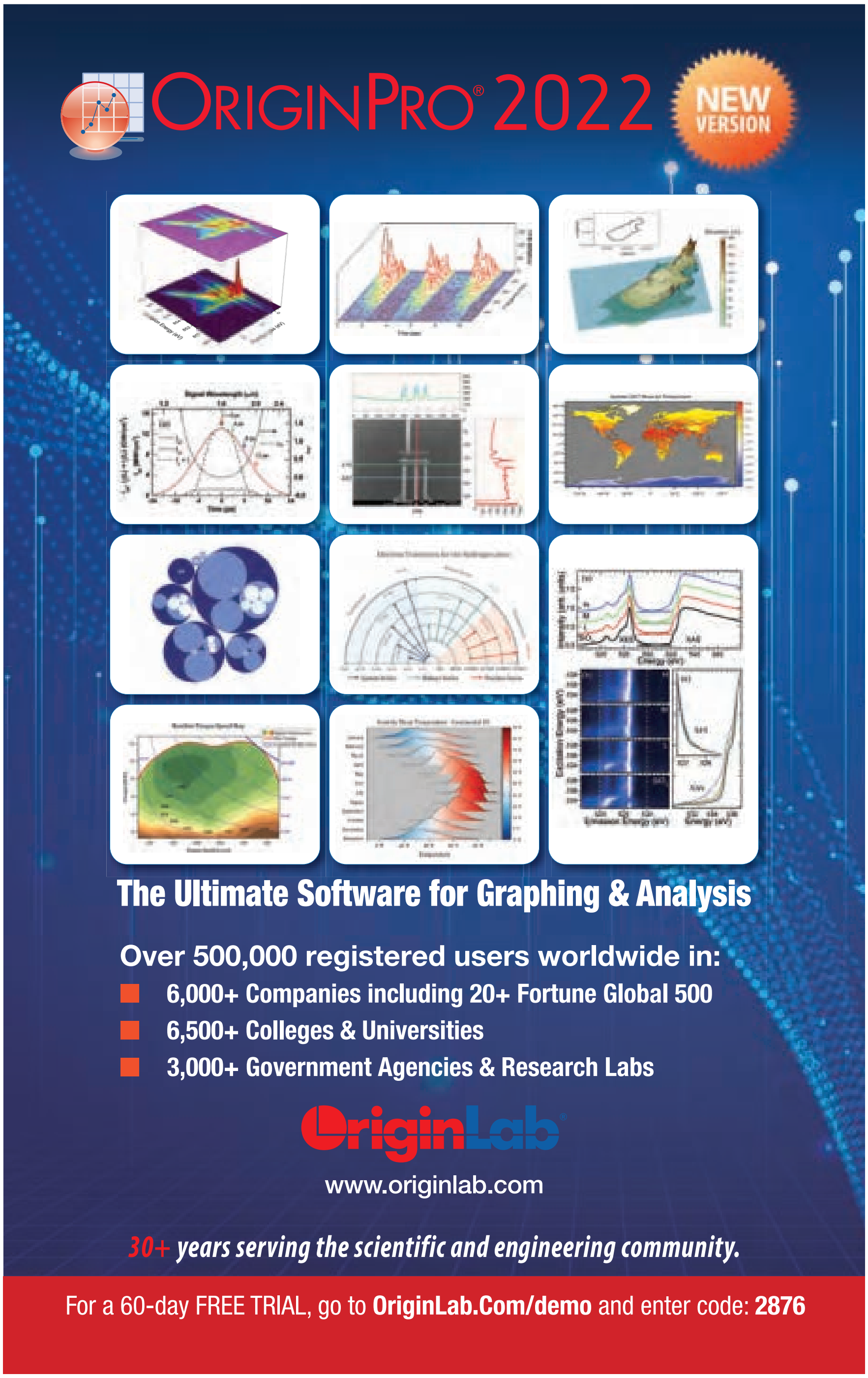
Benchtop NMR spectrometer

New capabilities for Oxford Instruments' X-Pulse broadband benchtop NMR spectrometer increase its ease of use, throughput, and remote-working capability while reducing costs. The combination of the new X-Auto automatic sample changer, which allows up to 25 samples to be preloaded, and new functionality in the SpinFlow 3.1 software ensures that users can add individual experiments or long queues to each sample with a few simple clicks. By reordering experimental queues, short-duration experiments can be prioritized to quickly determine whether longer-duration ones should be continued, which maximizes efficiency. Advanced modular architecture makes the X-Pulse a fully configurable, upgradable, and cost-effective instrument for core science, advanced analytical research, quality-control optimization, and teaching. ***Oxford Instruments plc****, Tubney Woods, Abingdon OX13 5QX, UK, https://nmr.oxinst.com*



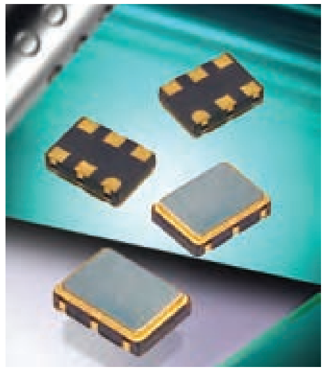
Compact OEM OCT spectrometer

Wasatch Photonics has expanded its Cobra optical coherence tomography (OCT) spectrometer product line with a new spectrometer that OEMs can easily integrate into OCT imaging systems. Despite its small size, it delivers performance comparable to that of the company's flagship Cobra-S OCT spectrometer. The small, lightweight Cobra OEM is optimized for 800 nm spectral-domain OCT imaging. It is suitable for ophthalmology and eye surgery, materials processing and laser welding, and industrial inspection of surface topology and microelectronics packaging. The Cobra OEM OCT spectrometer is offered in multiple bandwidths centered at 840 nm, each matched to commercially available superluminescent diode light sources. The spectrometer can be read at speeds of up to 250 kHz using Wasatch Photonics' rapid-access software development kits for C++, C#, LabVIEW, and MATLAB. The Cobra OEM uses a high-efficiency optical design optimized for high sensitivity and low roll-off and leverages Wasatch Photonics' patented technology for volume-phase holographic gratings. ***Wasatch Photonics****, 808 Aviation Pkwy, Ste 1400, Morrisville, NC 27560, https://wasatchphotonics.com*

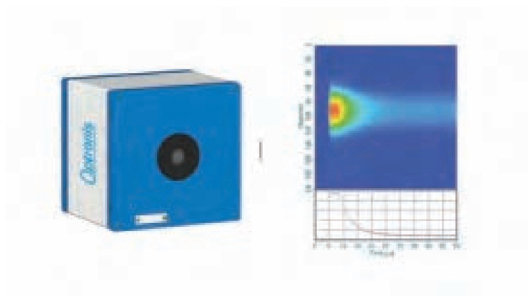
Vacuum transducer for harsh environments

Thyracont has enlarged its USB transducer range by adding the model VSC43USB, a compact transducer with a chemical-resistant ceramic sensor and FKM (fluorocarbon elastomer) sealing. It is resistant to dirt and suitable for rough industrial environments. The VSC43USB measures vacuum pressure independent of gas type. It offers an extended measuring range for absolute pressure of 2000 mbar to 1 mbar and for relative pressure of −1060 mbar to 1200 mbar, which makes it appropriate for a broad range of applications. The robust ceramic sensor displays precise results immediately, without a warm-up period. Since it offers a short response time—a maximum of 20 ms—it can improve production-process efficiency. The USB interface allows for a plug-and-play connection to all common computers and Android smartphones, so the measured vacuum can be displayed quickly and precisely, and no separate power supply is required. ***Thyracont Vacuum Instruments GmbH***, *Max-Emanuel-Str 10, 94036 Passau, Germany, https://thyracont-vacuum.com*

Mini temperature-compensated oscillators



Saelig has launched a range of surface-mount temperature-compensated crystal oscillators (TCXOs) that offer a frequency stability of as low as ±2.5 ppm. Made by frequency specialist Euroquartz, the EM211T TCXO series is available with CMOS outputs in frequencies of 10–60 MHz. The standard output frequencies available are 12, 20, 24, 25, 26, 40, 50, and 60 MHz. The components are housed in a standard-format six-pad 2.0 mm × 1.36 mm surface-mount-device ceramic package with a hermetically sealed metal lid. The EM211T series oscillators are suitable for use in applications that require high accuracy and a miniature footprint, such as embedded and portable systems. With low-voltage CMOS output into a 15 pF load, frequency-dependent tolerances of ±2.5 ppm to ±10 ppm are available over a temperature range of −40 °C to 85 °C. Typical single-sideband phase noise at 25 °C is between −85 dBc/Hz and −154 dBc/Hz for a 50 MHz frequency output. ***Saelig Company Inc***, *71A Perinton Pkwy, Fairport, NY 14450, www.saelig.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 significant growth fields 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 less than 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*

Power meter for laser-beam measurement

Miro Altitude, an advanced display device for laser power and energy measurements from Gentec-EO, features a 10-inch, high-resolution, antiglare touch screen and a modern, intuitive user interface. It is housed in a strong, durable metal casing suitable for transport and field use. Three display modes include one that lets users check past data points without interrupting the current measurement session and another with extra-large digits that can be viewed from a distance. The Miro Altitude's XNR Anticipation feature can improve the natural response of detectors by a factor of 10, depending on the detector. That is especially useful for power measurements in the kilowatt range, since the natural response of those detectors can be over a minute. Miro Altitude is compatible with all Gentec-EO detectors. Connection possibilities include Ethernet, RS232, external trigger, sync out, analog out, and USB-C. ***Gentec Electro-Optics Inc****, 445 St-Jean-Baptiste, Ste 160, Quebec City, QC G2E 5N7, Canada, www.gentec-eo.com*

Short-pulse measurement system

According to APE, the latest iteration of its autocorrelator product line, the pulseCheck NX, is easy to use and delivers state-of-the-art data processing and evaluation for analyzing, monitoring, and optimizing short-pulse laser systems. The NX provides plug-and-play capability via USB and Ethernet connections that enable integration into automated test and measurement environments. Low-noise analog electronics and fast digital components allow for excellent signal-to-noise ratios and seamless data transfer. Temporal resolution is down to 50 as. New analog signal-processing electronics and an 18-bit digital architecture ensure fast, reliable detection of details, a high dynamic range, and low latency. Tracking of measurement and quality parameters are among the time-saving data analysis tools in the included software; integrated fitting algorithms make it easier to evaluate data. ***APE GmbH****, Plauener Strasse 163–165, Haus N, 13053 Berlin, Germany, www.ape-berlin.de*

Multichannel event timers

PicoQuant has upgraded its MultiHarp multichannel event timers with a free gateware and software update. The addition of multifunction event filters that work in real time enables higher throughput. The new feature is particularly aimed at demanding applications that use information spread across several channels, such as coincidence counting in quantum sciences. Hardware-based event filters reduce the amount of data sent to a computer, which is important for experiments that require working at high count rates. Users can select which channels are subjected to the filter, and the filter offers many degrees of freedom: The length of the coincidence time window can be set to up to 160 ns in steps of 5 ps, and the filtering order of coincidence events can be adjusted up to sixfold. The onboard filters can thus be used to obtain a data stream for efficient real-time coincidence analyses. The filter logic can also be inverted to eliminate bursts of events, coincidences, and the like. ***PicoQuant****, Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

Compact microspectrometer

According to Ocean Insight, its Ocean ST microspectrometer provides excellent UV response, high-speed spectral acquisition, and high signal-to-noise-ratio (SNR) performance for applications ranging from DNA absorbance to color measurement. At 42 mm × 40 mm × 27 mm and weighing 70 g, the Ocean ST microspectrometer is suitable for integration into devices and setups that require a very small instrumentation footprint. Despite its size, it delivers full spectral analysis at a performance level comparable to larger and more costly spectrometers. The Ocean ST microspectrometer is available in three models that span the spectral ranges 185–650 nm, 350–810 nm, and 645–1085 nm. Wavelength-appropriate options are offered for applications such as fluorescence measurement and plasma monitoring. Its rugged design and thermal stability make the Ocean ST suitable for both using in a laboratory and embedding into OEM instrumentation in challenging environments. ***Ocean Insight****, 3500 Quadrangle Blvd, Orlando, FL 32817, www.oceaninsight.com* PT

Thomas Ferbel

The renowned high-energy physicist Thomas Ferbel, of the University of Rochester, passed away peacefully at his home in Friendship Heights, Maryland, on 13 March 2022.

Tom was born in Radom, Poland, on 12 December 1937. After frequently relocating during World War II, his family emigrated to New York in 1949. Tom attended the Bronx High School of Science and did his undergraduate studies in chemistry at Queens College, City University of New York, before switching to physics at Yale University, from which he received his PhD in 1963.

A summer program at Brookhaven National Laboratory inspired Tom to focus his PhD studies on experimental high-energy physics (HEP). The early 1960s was a uniquely propitious time to be entering the field. Brookhaven had recently begun operating the first high-energy accelerator using strong focusing, and it also had pioneering exemplars of the recently invented technology of liquid-hydrogen bubble chambers. The HEP group at Yale was ideally positioned to take full advantage of those unique opportunities.

Tom's studies at Yale were carried out under the guidance of Jack Sandweiss and Horace Taft, with the latter serving as his official adviser. His thesis work focused on proton–antiproton inelastic scattering without strange particles in the final state. In analyzing those data, Tom discovered the first evidence for production of baryon–antibaryon resonances.

After receiving his degree, Tom remained at Yale as a postdoc for two years before joining the University of Rochester as an assistant professor in 1965. Together with one of us (Slattery), who went to Rochester as a research associate in 1967, Tom built a highly successful bubble-chamber program, which proved especially suitable to adapt to new physics opportunities. In addition to discovering and investigating the properties of several hadronic resonances, their group was one of the first to study the systematics of one- and two-body inclusive reactions, a prelude to their subsequent work investigating multiparticle dynamics. They used the 30-inch bubble chamber, which they had been early advocates for taking to Fermilab to provide an initial survey of that unexplored energy domain.

The Ferbel–Slattery group, with Rochester colleague Frederick Lobkowicz, subsequently turned their attention to studying radiative meson decays using the first liquid-argon calorimeter employed in the US for HEP experimentation. Several of the resulting measurements were either the first, or the most precise, such determinations at the time they were made.

The culminating phase of the Rochester group's liquid-argon-based experimentation involved measuring photons directly produced in hadronic collisions, as distinguished from those originating as decay products of other particles. Those measurements were made using the group's 3-m-diameter liquid-argon calorimeter, the largest such device in operation at the time. A principal result of the work was the demonstration of the importance of initial-state gluon radiation to the understanding of how direct photons are produced.

In the meantime, fundamental theories, such as the standard model and quantum chromodynamics, were being developed rapidly, moving the energy frontier from energies accessible to fixed-target experiments to collider experiments. In response, Tom joined the DZero experiment at Fermilab and was a major player in the discovery of the top quark.

Tom's many contributions to HEP were recognized by institutions and organizations around the world. He was selected for a Humboldt Research Award in 1994. He was a scientific associate at CERN, a guest scientist at the Central Design Group of the Superconducting Super Collider, and a visiting scientist at the Max Planck Institute for Physics. Tom held visiting professorships at the University of Paris–Sud and at the Johannes Gutenberg University Mainz and the University of Freiburg. He served as the manager of the US Department of Energy's physics program at the CERN Large Hadron Collider from 2004 to 2008.

For the American Physical Society, Tom served as the secretary-treasurer of the division of particles and fields in 1983–86 and on the editorial board of


Thomas Ferbel

UNIVERSITY OF ROCHESTER

Physical Review D. He also was on the editorial board of *Zeitschrift für Physik* (*Journal for Physics*) *C Particles and Fields*. Tom served on program advisory committees at SLAC and Brookhaven and as chair of DZero's Institutional Board. Tom also was associate dean for graduate studies in Rochester's School of Arts and Sciences. With the other of us (Das), also at Rochester, Tom coauthored the widely used textbook *Introduction to Nuclear and Particle Physics* (2nd edition, 2003), which has been translated into several languages.

Tom was an inspiring teacher and an exceptional mentor of graduate students and postdocs. He not only personally advised 24 graduate students, some of whom went on to become highly successful in HEP, but also advised many graduate students officially supervised by his colleagues. Recognizing the educational difficulties confronting students working in HEP laboratories, Tom founded, and directed for 20 years, the biennial Advanced Study Institute on Techniques and Concepts of High Energy Physics, with all but one school held in Saint Croix, US Virgin Islands, and funded by NATO. Thus Tom had a major influence on an entire generation of high-energy physicists.

Most especially, Tom was a kind and large-hearted person whose presence will be greatly missed.

Ashok Das
Paul F. Slattery
University of Rochester
Rochester, New York

Ben Roy Mottelson

The American Danish theoretical physicist Ben Roy Mottelson, one of the pioneers of nuclear structure theory, left us on 13 May 2022. We lost one of the greatest minds and one of the finest people. Ben combined his passion for physics and his great and unusual gift for doing science with a warm, enthusiastic, and open-minded personality, leaving an indelible impact on colleagues and future generations of younger researchers alike.

Ben was born on 9 July 1926 in Chicago and grew up nearby in La Grange, Illinois. He was sent for officer training at Purdue University by the US Navy during World War II. After getting his BS at Purdue in 1947, he earned his PhD in nuclear physics from Harvard University in 1950; his doctoral adviser was Julian Schwinger. Ben became a professor at Nordita, the Nordic Institute for Theoretical Atomic Physics, in Copenhagen in 1957. In 1971 he obtained citizenship in Denmark.

The close scientific collaboration between Ben and Åge Bohr began in 1950 immediately after Ben arrived in Copenhagen to spend his graduate fellowship from Harvard at the Institute for Theoretical Physics (now the Niels Bohr Institute). Their unique collaboration continued until Bohr died in 2009. Their way of understanding physics can be seen in their seminal 1953 article "Collective and individual-particle aspects of nuclear structure." Seventy years after its publication, the paper continues to earn citations, and their work became known as the Bohr–Mottelson theory. They published the monograph *Nuclear Structure* in two volumes: *Single-Particle Motion* in 1969 and *Nuclear Deformations* in 1975. The books are not usual textbooks but more like enormous papers full of original ideas on nuclear structure and related research areas. Today they are among the most widely used monographs on the theory of many-particle quantum systems.

Ben Roy Mottelson

Ben was awarded the Nobel Prize in Physics in 1975 with Bohr and James Rainwater for finding the connection between collective and single-particle motions in atomic nuclei and developing the theory of the atomic-nucleus structure. Their work fundamentally changed the understanding of nuclear structure and set a landmark for the general theory of many-particle quantum systems. It also shows how fundamental theory needs to work hand in hand with experiment. During his Nobel banquet speech, Ben remarked that it is the combination of individual and collective processes that promotes science through the interplay of ideas—such an allusion to nuclear structure was characteristic of his humor.

From 1993 to 1997, Ben was the founding director of the European research institute ECT*. Typical of his later work, Ben brought concepts from one field of physics to another. For example, he applied the concept of supershell structure to electrons in metallic clusters.

Ben was among the first to realize that ultracold atomic quantum gases offer new and unprecedented prospects to study bosonic and fermionic many-body quantum systems, which he sometimes called "artificial nuclei." His 1999 work on the "yrast" physics of rotating Bose–Einstein condensates spurred a new field of research. Ben's work on pairing mechanisms in atomic Fermi gases demonstrated the universality of concepts earlier developed for the nucleus. Around 2000, Bohr invited Ben to join the work on genuine fortuitousness as the leading postulate in quantum theory.

Ben's playful and unbounded creativity provided an inspirational and enjoyable atmosphere to the people around him. In discussions and collaborations alike, it was clear that authority had no role to play, and physics always came first. Ben was remarkably gifted at motivating his students and colleagues alike—with him at the blackboard, new ideas often appeared crystal clear, but proving them right could take days and weeks of follow-up hard work and calculus. Ben's intuition was extraordinary, and he inspired many generations of researchers with his contagious joy of doing physics.

A marvelous example is Ben's lectures in the 1960s and 1970s at the Niels Bohr Institute, associated with Nordita, which one of us (Hamamoto) remembers as very special: Ben's deep thinking and remarkably clear teaching style left a great impression on his young students, who came from all over the world—some listening to a lecture in English for the first time. He inspired many to engage in research on nuclear structure. In his lectures, he also put great effort into teaching younger theoreticians the crucial importance of learning from experimental data and of communication between theory and experiment for making fundamental progress.

One gets an impression of Ben's forward spirit from an occasion when he joined the other of us (Reimann) and her family on their sailboat, which he did several times. As they headed across the strait of Øresund from Denmark to Sweden, the wind got strong, and it became advisable to reef the sails. But Ben strongly protested because he wanted all the fun: to go fast and get wet—at the age of 86.

To us, he was a close friend—we sorely miss him and are deeply thankful for the time shared. The science and joy that Ben shared with us about the "wonderful world of finite quantal systems," as he often called it, will always keep him entangled with our minds.

Stephanie M. Reimann
Ikuko Hamamoto
Lund University
Lund, Sweden

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PHYSICS TODAY | JOBS

Ethan Williams is a geophysics graduate student in the Seismological Laboratory at Caltech in Pasadena, California.

Listening to the seafloor with optical fibers

Ethan Williams

Using telecommunications cables that already traverse the ocean floor, geophysicists can observe ground motion, ocean waves, and hydroacoustic signals in unprecedented resolution.

Measurements of seismic ground motion at the seafloor provide critical insights into earthquake and tsunami hazards, deep-Earth structure, plate tectonics, submarine volcanism, and interactions between the ocean and solid Earth. Yet ocean-bottom seismometers (OBSs) and observatories are exceedingly scarce: Although about 70% of Earth's surface is covered by water, less than 1% of the global network of permanent broadband seismic stations is installed at the seafloor (see "Deploying seismometers where they're needed most: Underwater," Physics Today online, 24 May 2019).

The emerging field of fiber-optic seismology offers a promising new paradigm for ocean-bottom instrumentation: distributed sensing rather than point sensing. Submarine fiber-optic cables for intercontinental telecommunications and power transmission traverse the global oceans and can be harnessed for distributed sensor networks. As seismic and ocean waves stretch and compress optical fibers at the seafloor, the light traveling through them encodes valuable information. With distributed acoustic sensing (DAS) and other new fiber-seismic methods, that information can be exploited for geophysical monitoring (see Physics Today, March 2018, page 24). This Quick Study explains how.

What is DAS?

The individual optical fibers in a telecommunications-grade cable contain small, inherent density fluctuations that locally perturb the index of refraction and cause Rayleigh scattering. As a pulse of light propagates down the cable, each scattering point reflects a minuscule amount of light back along the fiber. The accumulation of light from numerous scattering points constitutes a measurable backscatter trace. From that trace, one can map the arrival time of light to its scattering position in the fiber.

Whereas many DAS implementations exist, the general principle for all of them is similar. The method starts with an interrogator unit, the instrument that regularly transmits laser pulses into an optical fiber—typically at a rate of 1–10 kHz—and the corresponding backscatter trace for each pulse is recorded by a photodetector. By comparing consecutive traces, one can extract the change in phase of backscattered light from one pulse to the next as a function of distance along the fiber. The number and distribution of scatterers is predetermined by the fiber's manufacturing process, so changes in the phase of backscattered light are caused only by changes in the optical path length between scatterers. Consequently, any internal deformation in the fiber can be calculated from the differential phase by a simple linear relationship.

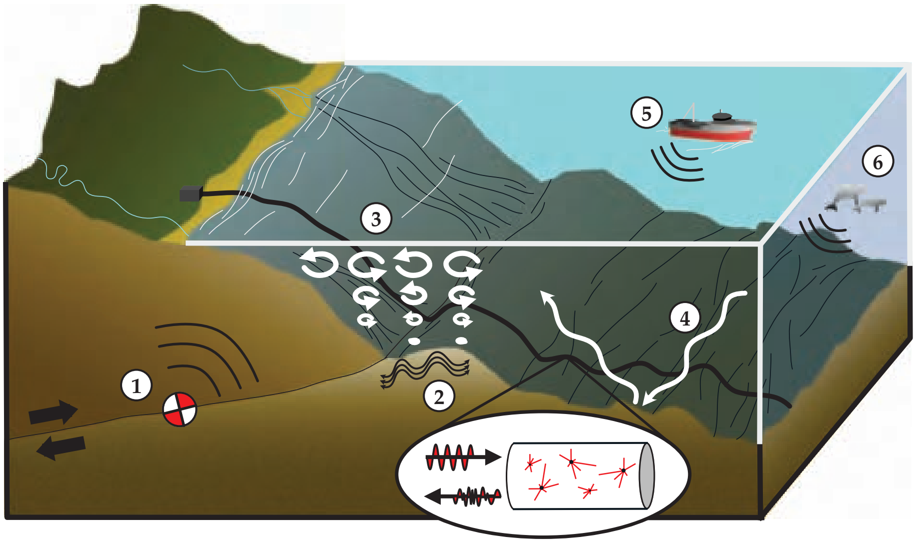
The result is a two-dimensional data set of the strain or strain rate measured at thousands of locations along the fiber and thousands of times per second. Think of DAS as analogous to a dense linear array of conventional seismometers, except that each channel measures the distributed deformation over a finite distance instead of the particle motion at a single point. To date, DAS networks on land have recorded natural and human-generated earthquakes, detected icequakes on glaciers, imaged subsurface geologic structures, characterized soils for geotechnical analysis, and even monitored urban traffic patterns. Now scientists are turning to the oceans as the next frontier in fiber-optic seismology.

From point sensing to distributed sensing networks

The first pioneering effort to put seismometers on the seafloor was carried out by Maurice Ewing aboard the *Atlantis* in September 1935. After dropping a 1280-m-long string of seismic instruments through roughly 5 km of water to the bottom of the Atlantic Ocean, Ewing and colleagues detonated several explosives in an attempt to generate enough seismic waves to image the oceanic crust. Subsequent efforts to bring seismic instruments to the seafloor were delayed by the outbreak of World War II. It wasn't until the 1960s that the need to monitor international nuclear-testing programs reignited interest in offshore seismic observatories. That interest led to the fundamental blueprint for OBSs that is still used today.

The majority of modern broadband OBSs are deployed over a period of one to two years. During that time, they operate autonomously: Using power from battery packs dropped to the seafloor, OBSs record their data to onboard storage. At the end of a deployment, an acoustic transponder prompts an OBS to return to the surface, where it is recovered and reconfigured for a new deployment. A benefit of the approach is that multiple research groups leverage the same pool of instruments to study diverse seafloor environments.

The temporary operational framework, however, limits the capabilities of OBSs relative to permanent terrestrial seismic networks. Only a handful of large (above magnitude 7.0) earthquakes occur worldwide over the span of a deployment, and typical OBS arrays contain fewer than 30 instruments. Seismic waves from smaller, more frequent earthquakes travel shorter distances through Earth, so the number of seismic ray paths traversing deep Earth that can be obtained by OBS arrays is small. Furthermore, because the data are trapped at the seafloor for the duration of the experiment, temporary OBSs cannot be incorporated into real-time systems that provide early warnings of earthquakes and tsunamis.



DISTRIBUTED ACOUSTIC SENSING (DAS) takes advantage of a fiber-optic cable's small, inherent defects, which light encounters when propagating through the cable. Some of that light scatters back along the fiber, and its travel time is a proxy for the deformation, or strain, of the fiber over time. The geophysical and environmental phenomena that may be observed by an ocean-bottom DAS array (black cable) include (1) earthquakes and (2) ambient seismic noise from ocean–solid Earth interactions; oceanographic signals, such as (3) surface gravity waves and (4) internal gravity waves; and acoustic signals from (5) shipping traffic and (6) marine mammals.

Over the past two decades, significant work has gone into developing alternative sensing networks that circumvent those challenges. One of the most successful approaches has been the establishment of cabled observatories in which seismometers installed at the seafloor are connected to land by a dedicated cable that provides unlimited power to the seismometer instruments and transmits real-time data back to operators. The cost of installing and maintaining such observatories, however, renders them impractical for global-scale applications.

Fiber-optic seismology offers a fundamentally different framework for monitoring the ocean bottom. A single DAS interrogator unit is connected to a seafloor fiber-optic cable at its landing station, and the laser pulse illuminates the fiber with thousands of effective sensors that record the vibrations of the seafloor in real time. Because the instrument itself is located on land, the deployment duration is unlimited, and data telemetry occurs at the speed of light. Both advantages allow DAS to be integrated into earthquake and tsunami early warning systems. Although the acquisition range of DAS systems is presently limited to signals no more than 100 km from the interrogator, other complementary fiber-seismic methods that are under development, such as polarization-based sensing, can span thousands of kilometers across entire ocean basins.

The distributed nature of ocean-bottom DAS measurements motivates a new approach to seismic data processing. Conventional OBS networks are sparse, with stations often spaced greater than 10 km apart. Those networks use multicomponent instrumentation—that is, three orthogonally oriented seismometers and a pressure gauge—to differentiate oceanic signals from solid-Earth signals and infer the properties of the seismic wave field. On the other hand, DAS networks are dense (1–10 m channel spacing), but they record only a single measure of seafloor motion at each sensing location. DAS networks are thus inherently multiscale and spatially coherent. They render data that are well suited for analysis by image-based algorithms, which remove noise from the data, separate wave-field components, and automate earthquake detection.

Bridging seismology and oceanography

Over the past four years, seismologists have designed ocean-bottom DAS arrays at diverse sites—from a wind farm in the Belgian North Sea to Monterey Canyon offshore of California. Those experiments have detected earthquakes ranging from a tiny magnitude 1.9 about 90 km away to a massive magnitude 8.2 whose source was more than 16 000 km away, identified previously unrecognized offshore fault zones through use of scattered waves, and mapped the velocity structure of the shallow crust by employing tomography.

Perhaps the most interesting findings pertain not to the seafloor but to the oceans. Pressure perturbations and thermal forcing from waves and tides can deform fiber-optic cables at the seafloor and be recorded by DAS. Since the 1930s, seismologists have known that ocean waves are the principal source of Earth's quiet hum, called ambient seismic noise or microseism. But the generation mechanism remains a subject of considerable debate largely because of the absence of *in situ* observations. Three independent studies published in 2019 all observed surface gravity waves in the ocean with ocean-bottom DAS and demonstrated a clear link between the ocean waves and ambient seismic noise recorded on the same arrays.

Other oceanographic observations reported to date include ocean swell waves from distant storms; tidal bores and internal wave breaking; wave–current interaction, which allows DAS to measure ocean currents; and hydroacoustic signals from ship traffic, distant earthquakes, and marine mammal vocalizations. Identifying and separating such diverse signals, which are often indistinguishable on conventional OBS networks, is made possible by the dense and distributed nature of ocean-bottom DAS arrays.

Although fiber-optic seismology is still a nascent field, the success of early experiments has brought the geophysics community much closer to realizing the vision of permanent, telemetered seismographic and oceanographic monitoring across the oceans.

Additional resources

▶ M. R. Fernández-Ruiz et al., "Distributed acoustic sensing for seismic activity monitoring," *APL Photonics* **5**, 030901 (2020).

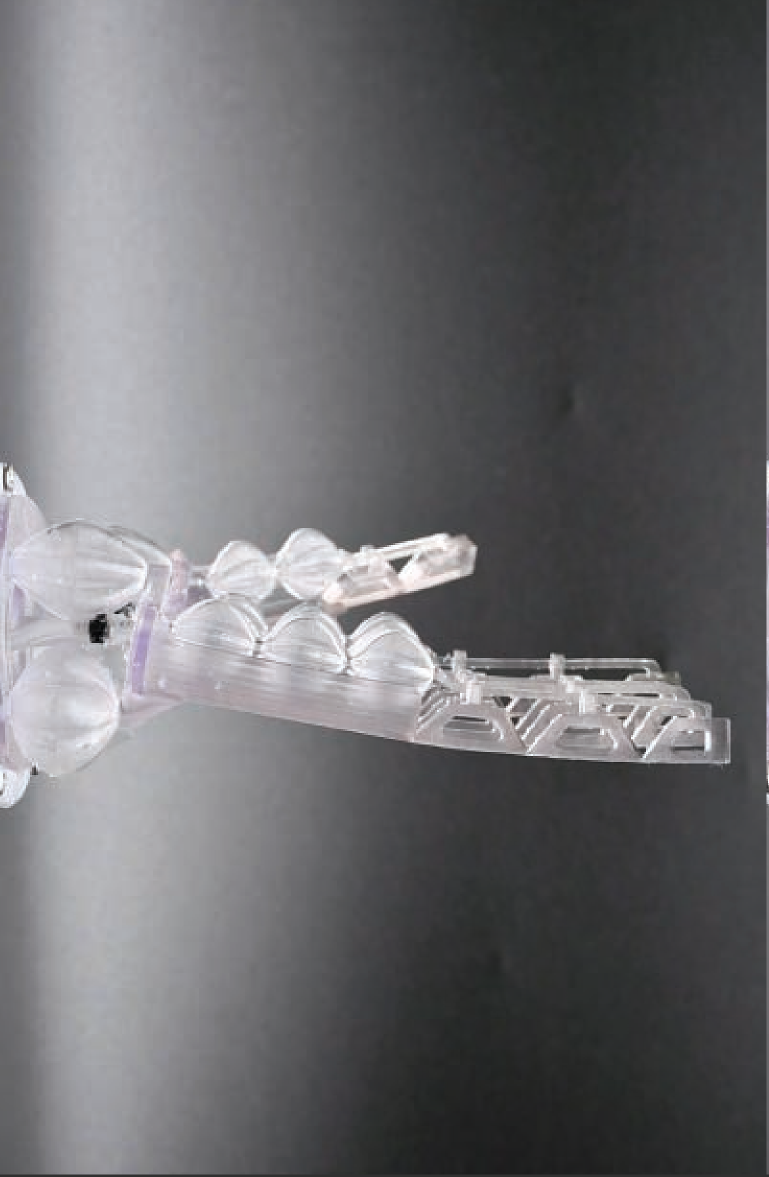
▶ N. J. Lindsey, T. C. Dawe, J. B. Ajo-Franklin, "Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing," *Science* **366**, 1103 (2019).

▶ N. J. Lindsey, E. R. Martin, "Fiber-optic seismology," *Annu. Rev. Earth Planet. Sci.* **49**, 309 (2021).

▶ A. Sladen et al., "Distributed sensing of earthquakes and ocean-solid Earth interactions on seafloor telecom cables," *Nat. Commun.* **10**, 5777 (2019).

▶ E. F. Williams et al., "Distributed sensing of microseisms and teleseisms with submarine dark fibers," *Nat. Commun.* **10**, 5778 (2019).

BACK SCATTER



Artificial hands make lifelike movements

Barbara Mazzolai, of the Italian Institute of Technology in Genoa, studies how plants and animals form so that she can develop bioinspired robotic devices. Mazzolai, her PhD student Corrado De Pascali, and colleagues constructed the 3D-printed, human-sized robotic hands seen here, each with 18 individual artificial muscles that extend and contract like those of a person. Those movements are enabled by a pneumatic mechanism first developed in the 1950s. When the air inside of a stretchable cylindrical membrane pressurizes, the membrane expands radially, and its length parallel to the fingers contracts. Traditionally, researchers have attached stretch-resistant fibers to the membrane to translate its volume changes to specific axial movements.

Mazzolai and her colleagues constructed their membrane differently: It is made of one of various commercially available plastics with regularly occurring folds that perform the same job as the stiff fibers. Without the fibers, the monolithic design can be used to build more flexible and customizable artificial muscles at a larger range of spatial scales. Depending on which particular plastic is used, the new artificial muscles can lift weights that are orders of magnitude heavier than the muscles themselves. An 8 g sample in a lab test, for example, lifted an 8 kg weight. (C. De Pascali et al., *Sci. Robot.* 7, eabn4155, 2022; images courtesy of the Italian Institute of Technology.) —AL

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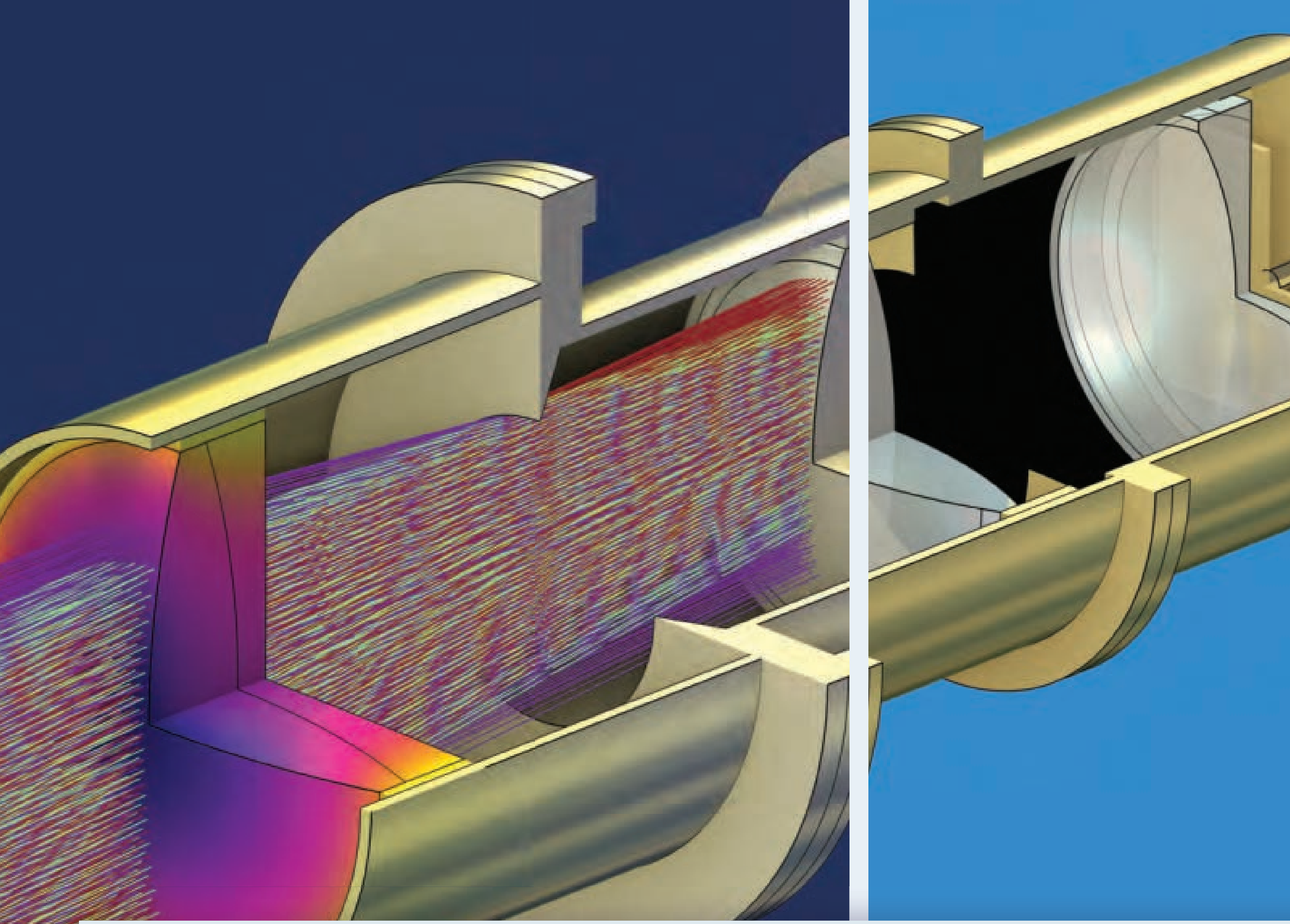

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Semantic segmentation for wildlife conservation.