PHYSICS TODAY

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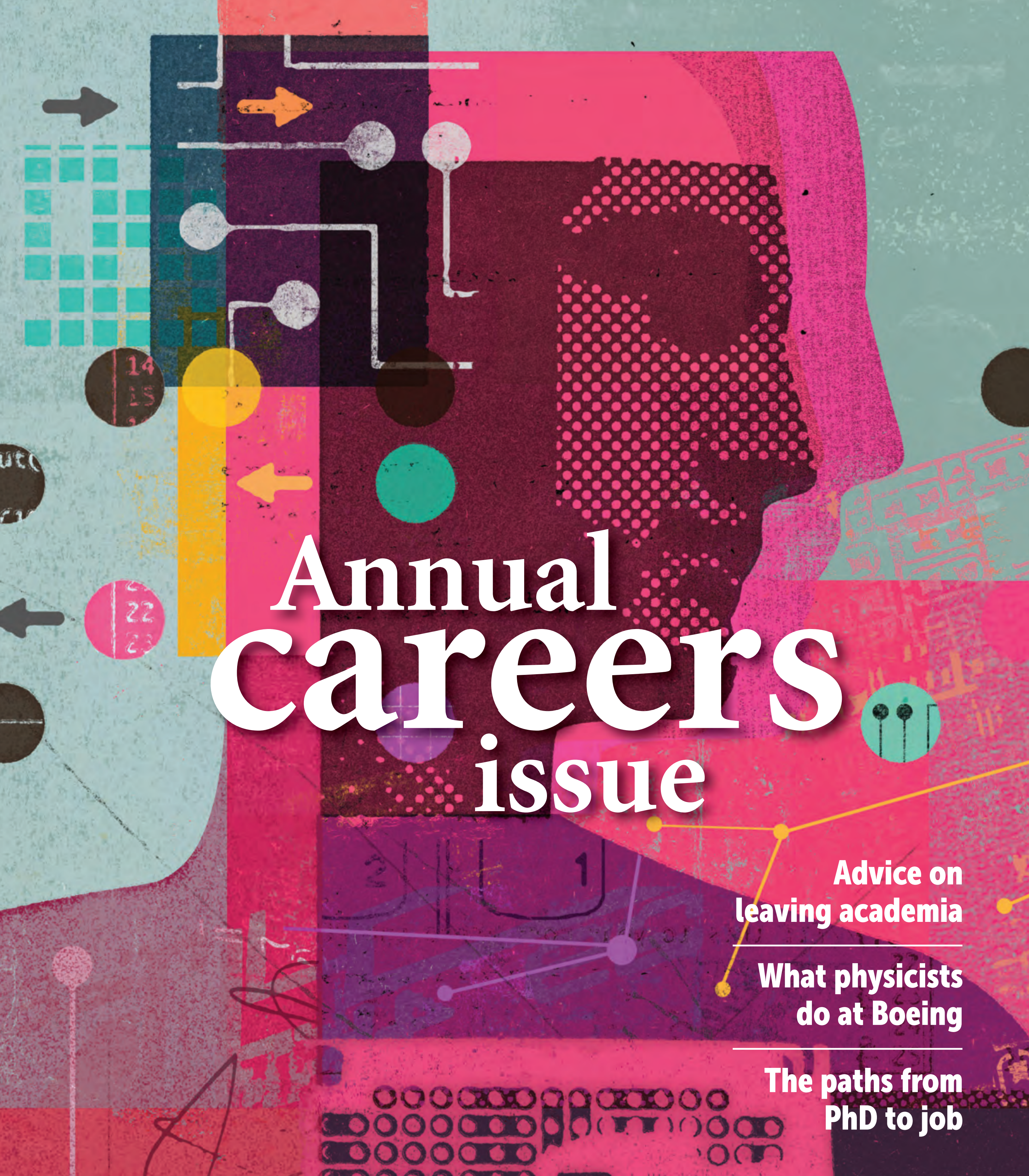
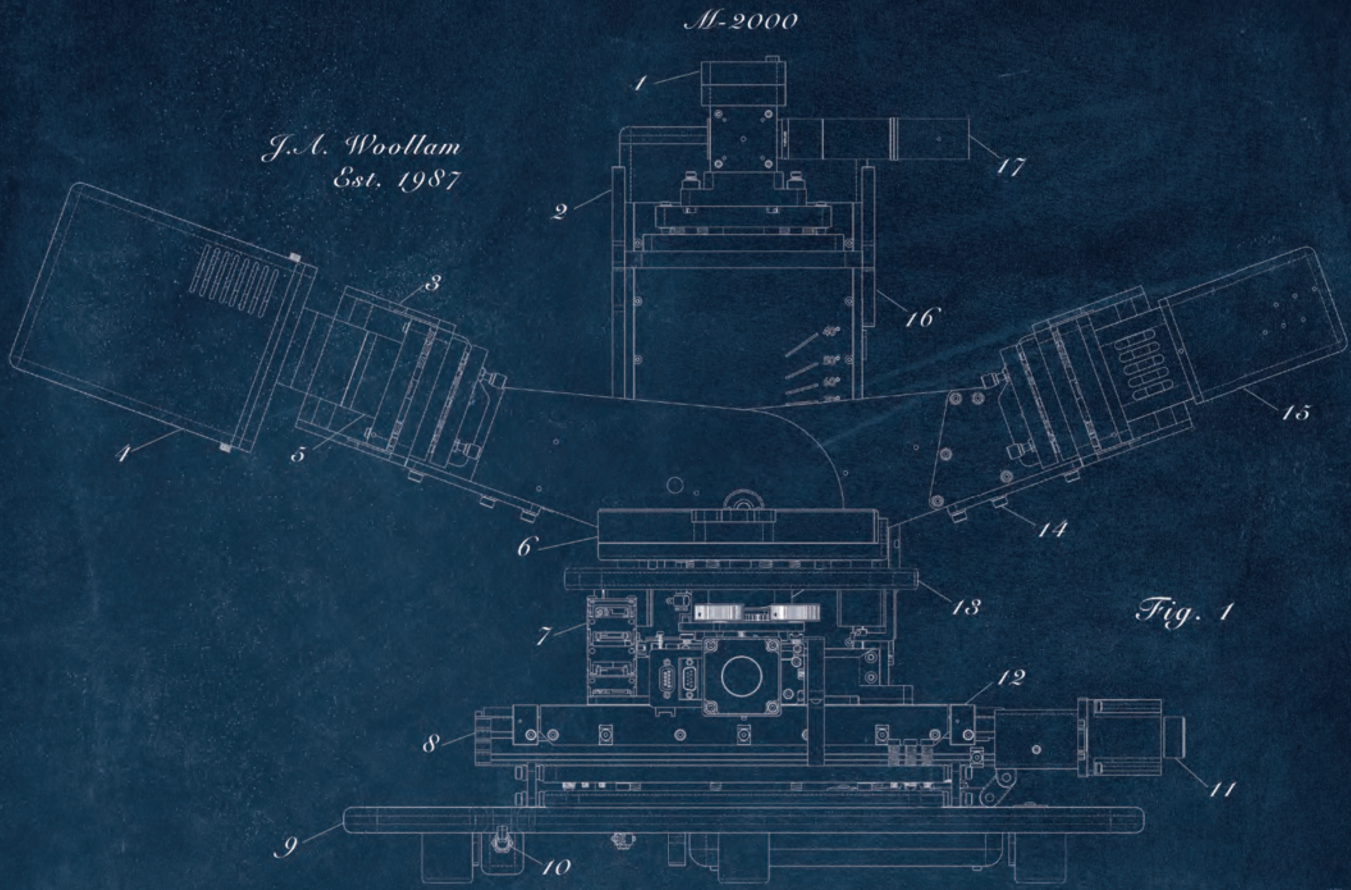


Annual careers issue

Advice on leaving academia

What physicists do at Boeing

The paths from PhD to job



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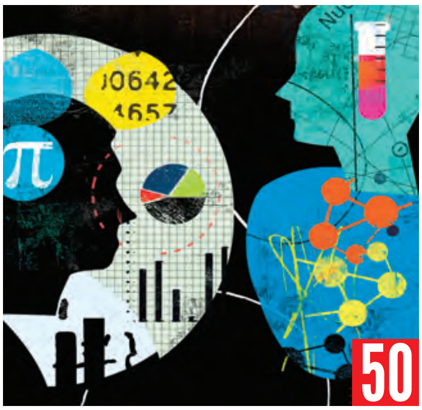

Careers issue

ON THE COVER: Our first annual careers issue focuses on three aspects of becoming and being a physicist: the paths that physical scientists pursue 10 years after obtaining their PhD, the case for including innovation and entrepreneurship in the undergraduate physics curriculum, and the efforts of a consortium of California colleges and universities to boost the number of women and underrepresented minorities in graduate school. Be sure also to turn to Elizabeth Frank's commentary on **page 10** and the news stories starting on **page 24**. (Image by Stuart Kinlough/Alamy Stock Photo.)

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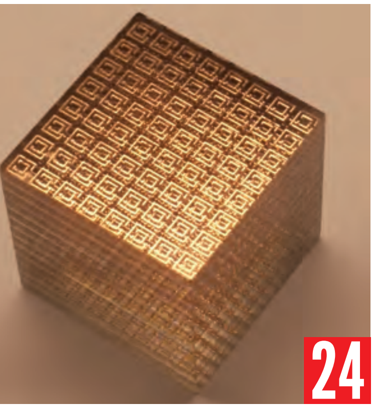
DEPARTMENTS



Address
American Center for Physics
One Physics Ellipse
College Park, MD 20740-3842
+1 301 209-3100
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FROM THE EDITOR

Options and choices

Charles Day

In September 2018 my niece Miriam emailed me the first draft of the personal statement that she needed to submit with her UK university applications. She opened with a description of the aftermath of a food festival held in our hometown of Conwy. The plastic dishes, plates, bottles, cups, and cutlery that overfilled garbage cans and littered the town's streets shocked and appalled her. They also inspired her to develop new sustainable materials and sources of energy. This month Miriam takes a step toward that goal as she starts a bachelor's degree in natural sciences at Durham University.

In my 22 years at PHYSICS TODAY, I've acquired a broad overview of science, including energy and materials. I've interviewed hundreds of scientists about their research and about what motivates them. But if Miriam chooses not to pursue an academic career, I'm all but clueless when it comes to offering her career advice. What's more, as I recounted in my November 2018 editorial, in pursuing my own career in astronomy, I didn't actively seek or follow advice. Rather, I took the most attractive option that was in front of me.

This special issue is the first of what will become an annual series on careers. Its goal is to illuminate the options that physical scientists have and the choices they make. The focus of the inaugural issue is on education and early careers. Future ones will explore other aspects of careers, including career advancement and retirement.

Careers content kicks off on page 10, where you'll find Elizabeth Frank's commentary, "Lessons learned from leaving academia." After realizing during her postdoc that academic research was not for her, Frank joined an asteroid mining startup that subsequently failed. Now she's thriving as an applied planetary scientist—her term—at an engineering consultancy.

STUART KINLOUGH/ALAMY STOCK PHOTO

"The road taken," which starts on page 32, is the Robert Frost–inspired title of Anne Marie Porter and Susan White's feature article. It summarizes the results of a recent survey conducted of physicists who had obtained their PhDs in the late 1990s and early 2000s. On the whole, survey respondents reported high job satisfaction and low job mobility.

In their feature article beginning on page 40, Crystal Bailey and Douglas Arion describe a movement by some physics professors to make innovation and entrepreneurship a vital component of the undergraduate physics curriculum. Even though few physics majors go on to found companies, all of them, Bailey and Arion contend, will benefit from learning the skills of a successful, socially minded entrepreneur.

Getting into graduate school is arguably when students commit to becoming physicists. Unfortunately, women and underrepresented minorities do not take that step in proportion to their numbers. In his feature article on page 50, Alexander Rudolph describes how Cal-Bridge, an alliance of community colleges and universities in California, is succeeding in tackling that problem.

The commentary and feature articles in this issue were written well in advance of the publication date. That's not the case for David Kramer's news report about Boeing on page 28. Kramer visited the aerospace company's offices in Seattle, where he interviewed some of the 90 physicists who work there. When I read the first draft, two things struck me. First was the variety of the work that Boeing's physicists do. Figuring out how to protect a composite fuselage from lightning and boosting the efficiency of robots on the factory floor are just two examples.

The second thing that struck me was the near-perfect resonance between the goals of teaching physics majors about innovation and entrepreneurship, as outlined by Bailey and Arion, and what Boeing's Minas Tanielian told Kramer: "Physicists are not as expert in terms of how to do some specialized things, but we understand the core of how things happen or interact with each other, especially in a multidisciplinary environment." PT

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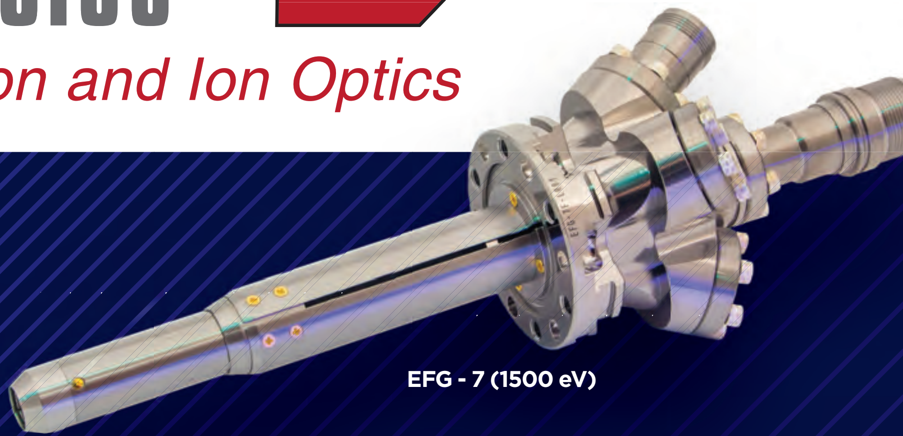

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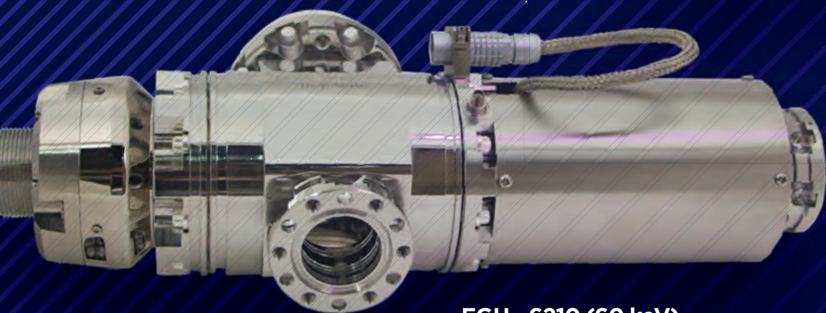

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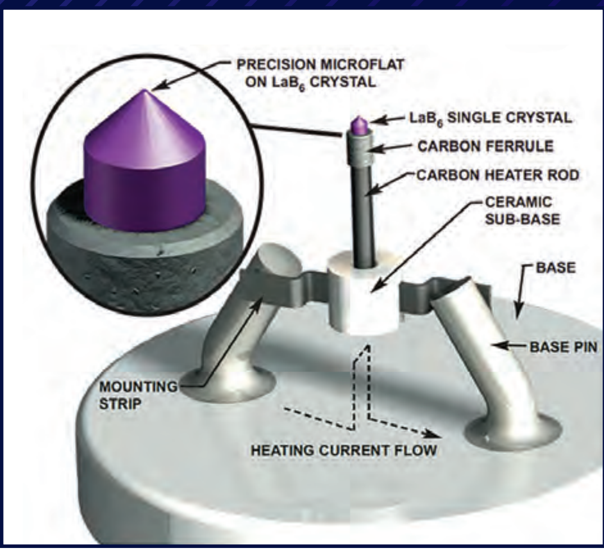

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Commentary

Lessons learned from leaving academia

I've come to dislike the interview cliché, "Where do you see yourself in five years?" In 2014 I had just defended my dissertation in planetary geochemistry at the University of Colorado Boulder and was gearing up for a postdoc, the standard next step for a career in planetary science research. I certainly couldn't have guessed then that my next five years would include an asteroid mining company, unemployment, and an engineering consulting startup.

ELIZABETH FRANK, APPLIED PLANETARY SCIENTIST and author of this commentary, with a pallasite, her favorite meteorite type.

I've known since high school that I would become a scientist. I had long wanted to work on a NASA mission, and an internship at the Jet Propulsion Laboratory during graduate school confirmed that interest in spades. By the time I'd finished my PhD, however, I'd started to become disenchanted with academia. Early in graduate school, I realized a professorship wasn't for me, but the idea of relying heavily on grant money as a research scientist, the most probable alternative, for the rest of my career was not appealing either.

I brushed those feelings aside when I began a postdoc at the Carnegie Institution for Science, where I worked on NASA's *MESSENGER* mission to Mercury. Although I was living my dream as a NASA team member, I still wasn't enamored with the realities of being a research scientist. I couldn't see spending my career pigeonholed into a narrow range of projects, having only papers to show as my primary deliverables, enduring the typically very slow rate of research progress, and writing proposals to pay my salary.

Unfortunately, I had had no exposure to career options beyond academia and no one to turn to on how to make that transition; my education had been tailored to students on an academic or research career trajectory. In preparation for a career transition, I spent much of my free time during my postdoc researching career options, studying the industry job search process, and networking. I hoped to be a good candidate when the right opportunity arose.

My hard work paid off. Immediately after my postdoc, I joined Planetary Resources Inc (PRI), the asteroid mining company, as a geospatial analyst. Initially I was supporting PRI's Earth observation campaign. When the company refocused on asteroids, I was promoted to director of data products. In that role I was the lead scientist on the development of an asteroid prospecting mission.

The pace of the work was dynamic, the people became like family, and I was using my expertise and professional network in planetary science to address practical problems. I learned about spacecraft engineering and how companies operate, exposure few academic scientists get. The job wasn't perfect—none ever is—but I learned that, overall, industry offered a much better setting for what I want out of a job.

Given PRI's lofty goals and startup status, I knew going in that there was a risk the company would fail. That risk became reality when the entire staff was laid off in early 2018 due to a funding shortfall. The time leading up to the layoffs had been incredibly stressful as well. Rather than searching for a job right away, I took a few months off to travel and decompress, a luxury I'd never had before.

In the meantime, 11 of my former coworkers founded an engineering consulting startup called First Mode. Six months later business was taking off, and I was invited to join the team. I had worked with these people at PRI, so there was no application or interview.

Now I'm an applied planetary scientist. I picked the title because it reflects that while I no longer do research, I still use my academic training. My work involves a mix of technical support, project management, and space business development. Working at any young company carries inherent risk, but the risk-to-reward ratio is worth it to me, whereas that of a soft money career was not.

The road to get here was hard won. To help make the journey easier for others, I offer three of the most important lessons I've learned.

▶ **Loving a subject is not the same as loving a job.** Those who pursue PhDs are typically driven by an innate curiosity about a particular topic. They tend to form their professional identity around

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that passion, self-identifying, for example, as a Mars expert or a dark-matter expert. Building a successful career in academia or research is so demanding that it can be difficult to disentangle your professional identity from your identity as a multifaceted human with a personal life.

I believe that the conflation of value and expertise is one reason for the stigma associated with leaving academia. Academics tend to internalize the message that if you are "good enough," you'll put up with any negative aspects of the career path. Deciding to take a different direction can lead to thoughts of inadequacy or incompetence, when really the issue is job fit.

Every job has its inanities: I left academia behind but the drudgery of unproductive teleconferences and a demanding email inbox remains. What I gained, however, is a fast pace, project diversity, and work products that feel more tangible and impactful than publications. The trick in finding the right job for you is to strike the balance between pros and cons, which are different for everyone. I still love planetary science, but I would not enjoy the day-to-day realities of being a professor or a research scientist—preparing lectures, grading papers, churning out proposals, writing papers. And that's okay. Being passionate about a subject is not the same as being passionate about a job.

▶ **The framework for evaluation is different in nonacademic careers.** The fact that academics form their professional identities around their research is reflected in the curriculum vitae (CV), which is different in structure and intent from a resumé. A CV proves expertise by listing a person's education, employment, grants awarded, publications, presentations, affiliations, and more. It is static in structure and simply grows in length with each new example of expertise. I've seen CVs from senior scientists and professors that were more than two dozen pages long.

With resumés, the intent is to demonstrate a person's competence rather than expertise. A resumé should be no longer than two pages, detailing the person's skills and—most importantly—the results they have obtained in each position. To show your potential value to a company or organization, a resumé's content should be customized for the position you're applying for. Most nonacademic job applications will require a resumé unless otherwise specified.

▶ **Leaving academia doesn't make you a failure.** Innumerable career paths are open to those with a PhD besides being a professor or researcher, but the antiquated academic system continues to produce more trained academics than it can employ. Simultaneously, graduate students are not educated about nonacademic career options and opportunities.

Some people may leave academia willingly, like I did. Others may feel forced out because the job market is saturated: There simply are not enough academic jobs for the number of qualified applicants. Either case can leave a person with an internalized sense of failure even if they successfully chart a unique, nontraditional course.

For those considering alternate career paths, remember that you don't have to justify your motivations to anyone but yourself. Any reason is sufficient as long as it's yours. And you may not realize it, but to earn a PhD, you were trained in skills that can bring value to a future employer.

Although by all appearances I've done well for myself outside academia, unlearning a decade of messaging that my professional success is contingent on a traditional academic or research role has been difficult. I have never once regretted my decision to forge an alternative career path, and I continue to be grateful for the opportunities that have allowed me to stay involved in planetary science. I hope that by sharing my journey, I can inspire others to discover career paths that bring them joy and balance.

Now where do I see myself in five years? I have no idea, and I like it that way.

Elizabeth Frank
(elizabeth@firstmode.com)
First Mode
Seattle, Washington

LETTERS

Interpretations of quantum mechanics

Jean Bricmont's review of Travis Norsen's *Foundations of Quantum Mechanics: An Exploration of the Physical Meaning of Quantum Theory* (Physics Today, April

2018, page 58) stresses the virtues of Louis de Broglie and David Bohm's pilot-wave interpretation of quantum mechanics, also referred to as Bohmian mechanics (BM), but the review omits mention of some of that interpretation's rather serious defects. As Bricmont notes, in BM the standard Schrödinger wavefunction $\psi(\mathbf{r}, t)$ for a particle is augmented with a classical trajectory $\mathbf{r}(t)$ that is interpreted as the actual precise physical position of the particle as a function of time. Sometimes that Bohmian trajectory can provide a helpful intuitive picture, but in other cases it is quite misleading.

John Bell presented an example of how Bohmian trajectories can mislead: a modified double-slit experiment with a lens placed right after each slit so that the emerging beams cross on their way to two distant detectors located beyond the crossing point.[1] The beam from the lower slit arrives at the upper detector, and that from the upper slit at the lower detector. If a particle arrives at the upper detector, which slit did it pass through?

Bell claims that the naive answer—that the particle came from the lower slit, based on the intuition that particles move in straight lines in a vacuum—is wrong. He notes that a Bohmian particle cannot cross the symmetry plane separating the upper slit and detector from their lower counterparts, and thus a particle arriving at the upper detector actually came from the upper slit: first it moved downward, but when it arrived in the region where the beams cross, it "bounced" back upward toward the upper detector.

Years ago I published an analysis that contradicted Bell and showed that the answer he regarded as naive—the particle passes through the crossing region without bouncing—was perfectly good quantum mechanics.[2] I am still waiting for someone in the Bohmian community to publish a reply.

Norsen is troubled because the nonlocal, often superluminal influences needed to make sense of BM are hard to reconcile with special relativity. Indeed, the widely accepted no-signaling principle of quantum mechanics asserts that those influences cannot transmit information, so a direct experimental detection of them is out of reach. Defenders of BM say they know that nonlocal influences exist because quantum mechanics violates Bell's inequalities. But as I and others have pointed out, the hidden variables used in derivations of Bell inequalities are fundamentally classical,[3] in contrast to the representation of quantum properties by Hilbert subspaces, as introduced by John von Neumann.[4] Projectors on those subspaces do not generally commute, which clearly distinguishes quantum physics from classical. Thus that feature, rather than a failure of locality, is why Bell's inequalities do not agree with quantum theory and experiment.

The BM particle trajectories are instances of classical hidden variables, so the nonlocality of the pilot-wave interpretation of quantum mechanics is not surprising. Indeed, when proper account is taken of noncommutativity, one can show that quantum theory satisfies a principle of locality that Albert Einstein might well have agreed with: Objective properties of an isolated individual system do not change when something is done to another, noninteracting system.[3] Thus a consistent Hilbert-space formula-

tion of quantum theory without hidden variables removes any worry about a conflict with special relativity.

Although Bohmian mechanics was worthy of consideration and has been useful in the development of quantum foundations, ignoring more recent developments is not the way to honor the memory of one of the great physicists of the last century. I hope that a second edition of Norsen's well-written book will take account of more recent work.

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Robert B. Griffiths
(rgrif@cmu.edu)
Carnegie Mellon University
Pittsburgh, Pennsylvania

▶ **Bricmont replies:** I find it odd, as the reviewer of a book, to be criticized because I did not discuss a theory that was not mentioned in the book. But I'll answer Robert Griffiths point by point.

In Bohmian mechanics (BM), it is simply a mathematical fact, noted by John Bell in chapter 14 of reference 1 of the Griffiths letter, that in the delayed double-slit experiment Griffith describes, particles cannot cross a symmetry plane but instead bounce back from it.[1] Offering a different theory in which particles follow a different trajectory does not refute that fact.

In standard quantum mechanics (QM), particles do not have trajectories; that fact was emphasized by, among others, Richard Feynman[2] and Lev Landau and Evgeny Lifshitz.[3]

The theory by Griffiths, based on the idea of "consistent histories," is therefore not standard QM but is instead, like BM, an attempt to complete QM, by adding histories that consist of real events that occur independently of any measurements made on the quantum system (a measurement means an interaction with that system that may affect what would happen to it in the absence of measurements). Unfortunately, Griffiths's attempt runs into contradictions, as shown in particular by Sheldon Goldstein in his two-part feature for Physics Today (March 1998, page 42, and April 1998, page 38).

Griffiths misses the first step in Bell's proof of nonlocality: the Einstein-Podolsky-Rosen (EPR) dilemma that perfect correlations between distant events cannot be explained unless one supposes either that some form of action at a distance occurs or that the events are predetermined by antecedent causes. The latter assumption is *not* a "classical" one; it is one part of the EPR dilemma. But Bell showed with his inequalities that the assumption leads to a contradiction. Hence, nonlocality follows. For more details, see, for example, references 1 and 4 and Travis Norsen's book.

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Jean Bricmont
(jean.bricmont@uclouvain.be)
Research Institute in Mathematics and Physics
Univrersity of Louvain
Louvain-la-Neuve, Belgium

Temperature inversions in theory and in Pittsburgh

I recently read Tony Sadar's Quick Study, "Waking up to temperature inversions" (Physics Today, October 2018, page 74). I write to clarify a couple of points that could be misunderstood, and I have an important and interesting addition about the way that inversions form around Pittsburgh, Pennsylvania.

The Quick Study's figure 1 could be read as indicating that sunlight intensity increases linearly from zero at 6 am to a maximum at solar noon and then decreases linearly to zero at 6 pm. In fact, sunlight intensity is not linear through the day; it follows a sine function from sunrise to sunset.

Similarly, the plot should not be understood as saying that temperature rises and falls linearly. To a first approximation, air temperature near Earth's surface follows a sine curve from a minimum temperature near sunrise to a maximum temperature two hours after solar noon and declines along the sine curve until sunset. After sunset, air temperature falls exponentially to a minimum near sunrise.

I would also like to mention an important part of inversion formation in complex terrain. A hilltop cools much faster than the valley floor, and as a result, cooler, denser air flows downhill and into the valley. Cooler air pooling in the valley undercuts warmer air and creates an inversion, as shown in panel c in the Quick Study's figure 2. As Sadar notes, Pittsburgh is surrounded by hilly environs.

Dale Edward Linvill
(dlinvill@nctv.com)
Clemson University
Clemson, South Carolina

▶ **Sadar replies:** I appreciate Dale Linvill's thoughtful comments. His mention of the downward flow of cold air that can form substantial ground-level temperature inversions in valleys is a good example of inversion formation in complex terrain.

As for his critique of the diurnal-temperature and sunlight-intensity graphs, his description provides helpful details of thermal and solar-impact changes throughout a 24-hour period. However, the graphs were stylized and simplified to convey the general nature of conditions that affect the formation of surface-temperature inversions. In addition, the temperature graph roughly mimics actual measurements observed in the Pittsburgh area.

Tony Sadar
(anthony.sadar@alleghenycounty.us)
Allegheny County Health Department
Pittsburgh, Pennsylvania

Correction

August 2019, page 66—In figure 1, the eclipse path labeled 2021 June 10 should read 2021 December 4. A corrected map can be found online. —Jay Pasachoff

Wind analysis links West Antarctic ice loss to humans

Anthropogenic warming is reversing the predominant winds over the region and could explain the ice sheet's destabilization.

The thinning of the West Antarctic Ice Sheet (WAIS) is contributing to global sea-level rise at a current rate of about 0.5 mm per year,[1] and the situation will probably only get worse (see PHYSICS TODAY, July 2014, page 10). Ice from Pine Island Glacier (see figure 1), the Thwaites Glacier, and others drain the WAIS into the sea. The glaciers melt more quickly than usual if winds diverted eastward by human activity drive warmer circumpolar water onto the continental shelf and underneath the floating ice.

Given rising greenhouse gas concentrations, that chain of events could already be under way. Average global temperatures have risen by about 0.8 °C since 1880. In the Arctic, warm air temperatures are directly responsible for the increased melting of glaciers. But for West Antarctica, determining the rate of ice loss is difficult because of episodic fluctuations. The region's climate swings between warm and cold cycles. The air pressure at sea level over the Amundsen varies more than any other place in the Southern Hemisphere.[2] And over a 10-year period, the amount of warm ocean water reaching the glacier there can fluctuate by about 50%.

The natural climate variability in the Amundsen Sea stems from year-to-year change associated with the tropical Pacific Ocean's El Niño–Southern Oscillation (ENSO; see the article by David Neelin and Mojib Latif, PHYSICS TODAY, December 1998, page 32). When tropical sea-surface temperature anomalies alter the prevailing wind patterns, the winds around West Antarctica also change. Records lack enough years of data to clearly separate how natural variability and human activity cause West Antarctic winds to change and consequently increase the rate of ice loss.

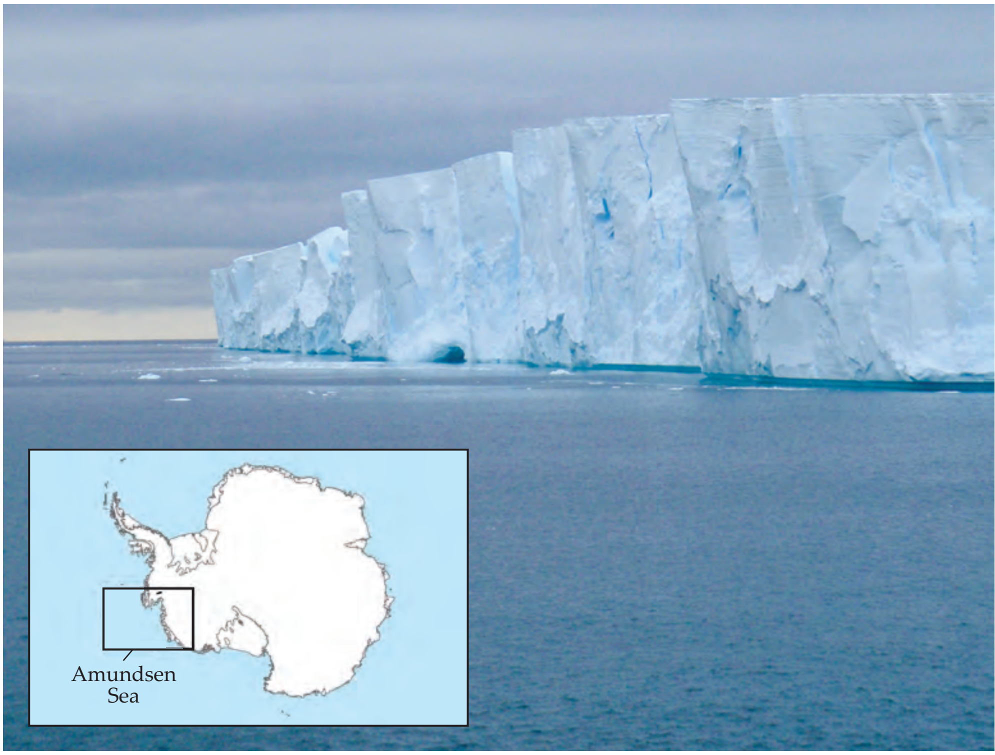

FIGURE 1. PINE ISLAND GLACIER, at the edge of the Amundsen Sea in West Antarctica, shown in the inset. More eastward winds caused by human activity drive warm, circumpolar water onto the continental shelf, where the underside of the glacier can become destabilized, lose mass, and accelerate sea-level rise. (Photo by Pierre Dutrieux; inset by Polargeo/Wikimedia Commons.)

Now Paul Holland of the British Antarctic Survey and his colleagues have disentangled the causes and established a clear connection between WAIS loss and human-induced climate change.[3] The researchers combined satellite-derived data and model simulations so they could study trends over the 20th century. Their analysis indicates that an anthropogenic reversal in the direction of local winds is accelerating the ice-loss rate of the WAIS.

Tropical data mining

On-the-ground climate data around the Amundsen Sea are limited. "It was in the early 1990s that serious observations really began," says Eric Steig, a glaciologist and geochemist at the University of Washington and a coauthor of the new paper. "And that is not a very long time in terms of climate change." The available wind data over the Amundsen Sea came from an analysis by the European Centre for Medium-Range Weather Forecasts, which uses a meteorological model to blend satellite observations from 1979 to the present.

To extend the wind record back before the satellite era, Holland and his colleagues took advantage of a climate connection between West Antarctica and the tropical Pacific Ocean. Water-temperature data have been collected by ships since at least the mid 19th century, with relatively reliable coverage and frequency starting in the early 20th century.[4] Wind speed over West Antarctica is significantly correlated with tropical Pacific sea-surface temperature because ENSO brings tropical wind patterns to the poles by atmospheric Rossby waves.

Climate models can use the connection to fill in the gaps where past wind observations are lacking. At the National

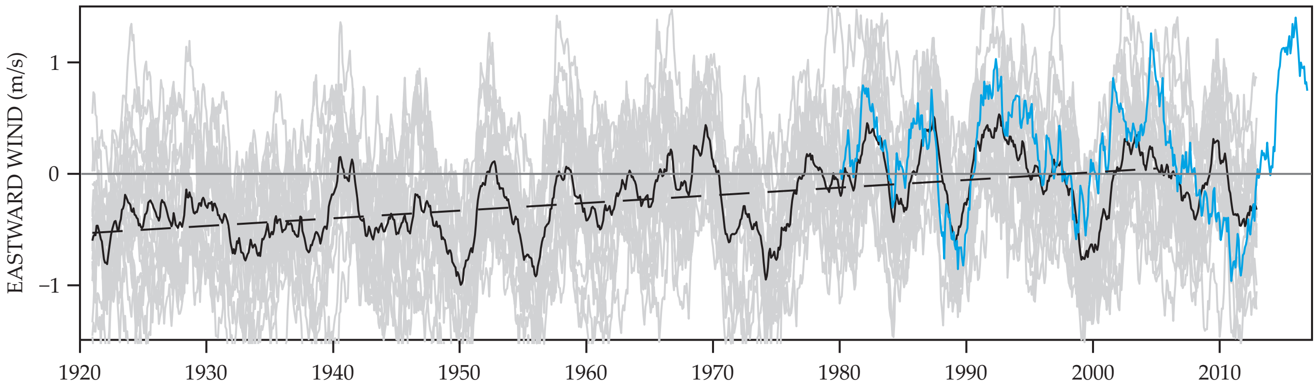

FIGURE 2. A REVERSAL OF THE PREDOMINANT WINDS over the Amundsen Sea may be thinning the West Antarctic Ice Sheet. The average winds (black solid line) of 20 climate simulations (gray) from the Community Earth System Model agree with observed winds (blue solid line) obtained from an analysis by the European Centre for Medium-Range Weather Forecasts. The trend (dashed black line) of 0.7 m/s over much of the 20th century shows that the winds changed from westward-flowing (negative values) to predominantly eastward-flowing (positive values). Rising greenhouse gas concentrations contributed 0.5 m/s to the eastward winds. (Adapted from ref. 3.)

Center for Atmospheric Research (NCAR) in Boulder, Colorado, the Community Earth System Model (CESM) incorporates historical ocean data to simulate the wind speed and direction back to 1920. There's nothing specific to how the CESM physically models the atmosphere, land, and ocean that makes it more accurate at simulating Antarctic climate than other models. Researchers have run the CESM repeatedly to more clearly separate human activity from natural variability in West Antarctica.[5]

"I've been trying to think of a way of writing this paper," says Holland, and the CESM was the tool he needed. The first 20 simulations Holland and his colleagues analyzed were constrained by the historical tropical Pacific sea-surface temperature data. Using the same data for each simulation means that the average of those 20 runs is reflective of both natural and human climate variability.

Which way the wind blows

The results of the 20 simulations, plotted in figure 2, show the strong decadal variability in the simulated wind speed and the observations. The simulations' average speed increased at a rate of 0.7 m/s per century. That change corresponds to a decrease in westward winds and an increase in eastward winds over the 20th century. The reversal in direction brings more warm water to the glaciers and consequently more WAIS ice loss.

To separate the long-term anthropogenic trend from the noisy natural variability in the time series, Holland and his colleagues analyzed a second set of 40 simulations that was not constrained by the historical sea-surface temperature data.[6] In those runs, the average only indicates the anthropogenic warming because the natural variability is random and cancels out.

Holland and his colleagues determined that the once-predominant westward winds have weakened by about 0.5 m/s over the past 100 years because of human activity. "Many studies have hypothesized that a link might exist" between anthropogenic climate change and the winds around West Antarctica, says Nerilie Abram of the Australian National University. "This study now clearly demonstrates the link."

The magnitude of the anthropogenic effect is about the same as the natural variability of the winds, estimated by the spread in the simulations. The result underscores the necessity of the model simulations. Observations alone didn't cover enough time, and measurements of winds and ice loss will continue to be strongly influenced by natural variability from the tropical Pacific for decades to come. Humans are changing the climate in West Antarctica to be sure, but until now the natural variability has been large enough to obscure the signal.

The not-so-distant future

Now that there's clear evidence that eastward winds in West Antarctica have increased, Holland wants to better understand how the Amundsen Sea responds to the atmosphere on a longer time scale. Using an ocean model that precisely simulates the dynamics of each ocean layer in the region, he is exploring what happens to the flows when they are forced by the eastward winds simulated in the CESM. Once the observed rate of ice loss is reproduced, he can test whether the same atmosphere–ocean processes that operate on decadal time scales also apply to centennial time scales.

Knowledge of the processes that control ice loss on decadal and longer time scales can inform future climate change forecasts. Holland and his colleagues suggest that if humans continue to increase carbon dioxide emissions in a business-as-usual scenario, the Antarctic wind trend they found for the 20th century will continue into the 21st century.

However, the worst effects of climate change may be averted if such a trend can be avoided. In a 21st-century scenario in which greenhouse gas emissions are rapidly reduced, the Antarctic winds stabilize to the present-day state. "Reversing the change," says Holland, "is a much bigger challenge."

Alex Lopatka

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Massive galaxies from the early universe found hiding in plain sight

Detection at a new wavelength reveals ancient galaxies in higher numbers than observed previously or predicted.

FIGURE 1. ANTENNAS FROM THE ATACAMA LARGE MILLIMETER/SUBMILLIMETER ARRAY are on an elevated desert plateau ideal for measuring wavelengths from the far-IR to radio. The 66 antennas can cluster together for higher-sensitivity measurements or spread over tens of kilometers to zoom in on details. (Courtesy of W. Garnier/ALMA/ESO/NAOJ/NRAO.)

Opened in 2012, the Atacama Large Millimeter/Submillimeter Array (ALMA), shown in figure 1, measures the portion of the spectrum straddling the boundary between radio and IR—a range which is easily absorbed by water in Earth's atmosphere. The array's location is ideal. Not only is Chile's Atacama Desert the driest place on Earth (excluding the poles) but it also has a wide plateau whose 5000 m elevation reduces absorption by water vapor and whose flatness allows the array's 66 large antennas to be easily moved around and reconfigured. ALMA researchers have published numerous results in the intervening seven years (see, for example, PHYSICS TODAY, December 2016, page 22). The array is also part of the network of facilities that make up the Event Horizon Telescope, which recently captured the first image of a black hole (see "What it took to capture a black hole," PHYSICS TODAY online, 11 April 2019).

Now Tao Wang of the University of Tokyo and his colleagues have used ALMA to find a missing link in the story of galaxy formation.[1] Before he and his team made their discovery, the low number of massive galaxies, with masses above 10^{10} solar masses, observed from the first 2 billion years after the Big Bang could not account for the significantly higher number observed from the next billion years. ALMA's wavelength range is perfect for finding those ancient massive galaxies not visible in previous measurements, and Wang and his team did just that.

Redshift your perspective

Because the universe is expanding, emitted radiation from galaxies redshifts to longer wavelengths the farther away it starts from Earth. A wave's journey to us takes time, so to observe a redshifted wave is to look into the past. Redshifts are determined by identifying an emission line in a galaxy's spectrum and measuring how far its peak wavelength, λ_{obs}, has shifted from its rest-frame value, λ_0. Redshift z is defined as $(\lambda_{obs} - \lambda_0)/\lambda_0$. Although spectral features broaden in their long journey across the universe, the redshift is still identifiable. Radiation with $z = 3$ was emitted when the universe was 2 billion years old.

In its rest frame, a galaxy's visible-to-UV emission spectrum drops off suddenly for wavelengths shorter than 912 Å. Light with shorter wavelengths than that limit ionizes hydrogen gas in and around the galaxy before it escapes. As the radiation gets redshifted, the sudden break in the spectrum shifts to higher wavelengths—even into the UV range measurable from Earth. Astronomers identify high-redshift galaxies, with $z > 3$, by filtering the emission and comparing its higher signal in the visible range with its much lower signal in the UV. Galaxies discovered using that method are known as Lyman-break galaxies (LBGs).

Previous measurements performed with the *Hubble Space Telescope* and at Las Campanas Observatory in Chile found many massive galaxies with redshifts z of 2–3, which existed 2 to 3 billion years after the Big Bang.[2] But far fewer have been found from earlier stages in the universe's evolution, with $z > 3$. Those found thus far either are LBGs with much smaller stellar populations than later galaxies or are extreme starburst galaxies, which have high star-formation rates and are brighter than a typical massive galaxy. Together they are too small or too few to have made all the galaxies seen with a z of 2–3.

The Lyman-break selection method overlooks some galaxies. For the break to appear precipitous and therefore be identifiable in Earth-based visible and UV images, a galaxy must emit enough at wavelengths just above the Lyman break. That condition is unlikely to be met by massive galaxies because the surrounding dust dims the outgoing emission or because their stars are older and emit less right above the break to begin with. Detectors that have higher sensitivity and are able to measure into the mid- and far-IR provide a higher signal to compare with UV images. But the exact wavelength ranges one compares are important. Galaxies at lower redshifts can mimic those with higher redshifts if their spectrum is pushed to a redder color by attenuation from high levels of dust or is intrinsically redder because it comes from an active galactic nucleus rather than stars.

Hiding in plain sight

A few years ago, Wang and his team hunted for those missing massive galaxies in the mid-IR.[3] They found a specific combination of filters capable both of finding galaxies too faint for Lyman-break selection and of distinguishing between older galaxies and younger mimics. Using the *Spitzer Space Telescope*'s Infrared Array Camera, they captured an image at 4.5 μm, which they subtracted from existing *Hubble Space Telescope* measurements in the near-IR. A difference in the intensity above a certain threshold indicated the location of a potential galaxy in the distant universe. Through that method, Wang and company identified 63 potential ancient massive galaxies not found using *Hubble*'s measurements alone.

But the galaxies are still very faint at 4.5 μm, and measurements with better spatial resolution and at multiple wavelengths would reveal more about their properties. The researchers knew they needed a facility such as ALMA, with detection in the far-IR. Taken in the summer of 2016, their ALMA images resolved the galaxies and confirmed that 39 of the previously identified objects are star-forming massive galaxies invisible in the *Hubble* images: Four are shown in figure 2. "While we did expect that many of these galaxies would be at high redshift, the high detection rate with ALMA is still surprising," says Wang.

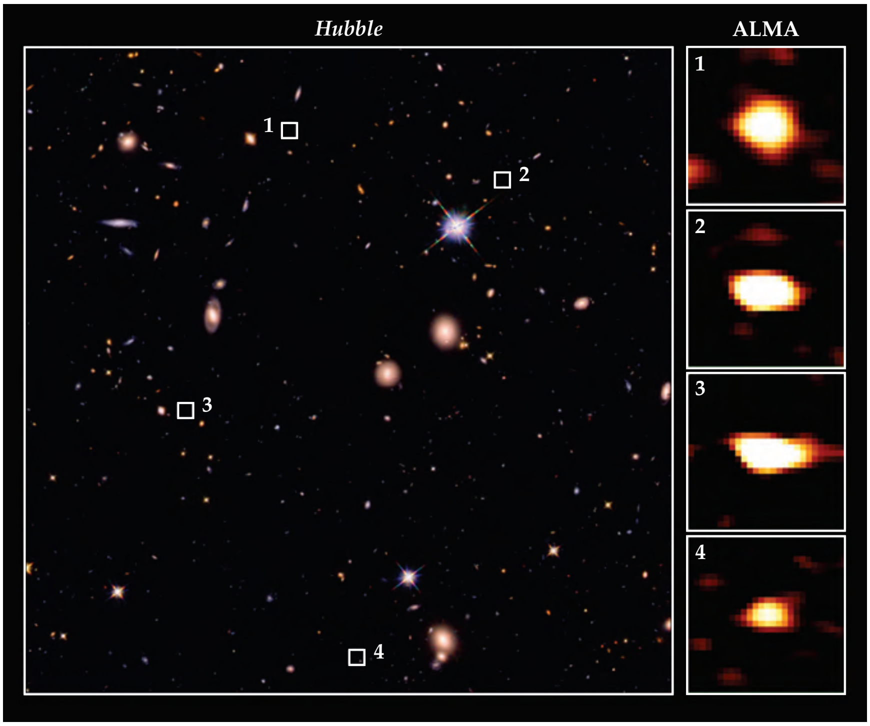

FIGURE 2. ANCIENT MASSIVE GALAXIES visible with the Atacama Large Millimeter/Submillimeter Array (right) in the far-IR are invisible to the *Hubble Space Telescope* (left). (Courtesy of Tao Wang.)

Once older massive galaxies are identified, there's still the question of figuring out their exact redshift. It's much harder to measure a full spectrum, so many observatories stick with radiation that is detected through a broad filter and not spectrally resolved. Such a measurement gives just one number—the intensity—rather than the individual spectral lines necessary to calculate the redshift. Instead, the data need to be fitted with an expected spectral energy distribution to find what is called the photometric redshift, which has a larger uncertainty than redshifts found from spectroscopy.

Corentin Schreiber of Oxford University in the UK was in charge of figuring out the redshift in the team's ALMA measurements—a tricky task because most photometric methods use measurements in the UV to visible rather than in the far-IR. By combining different photometric methods and cross-correlation with galaxies known to be of the same age, Schreiber found that the median redshift was $z = 4$, corresponding to radiation emitted about 1.5 billion years after the Big Bang.

The galaxies are faint, below the detection limit of a single antenna, and massive, with most in the range from 10^{10} to 10^{11} solar masses, an order of magnitude larger than the average LBG. The shape of their spectral energy distribution indicates the rate at which they produce stars, and on average they churn out 200 solar masses' worth of stars per year—that's about 10% of the rate previously found for LBGs and starburst galaxies of the same age but one to two orders of magnitude higher than LBGs of similar masses. Their star-formation rate coupled with their densities of 2×10^{-5} galaxies per cubic megaparsec, two orders of magnitude higher than starbursts', mean the new galaxies are responsible for the majority of the stars produced by massive galaxies in the early universe.

The problem for theorists

Although the newly found ancient galaxies help explain the presence experimentally of so many, and such large, massive galaxies at lower redshifts, they present a problem for most galaxy-formation theories (see the article by Jeremiah Ostriker and Thorsten Naab, PHYSICS TODAY, August 2012, page 43). Semianalytic models—those that tune simple phenomenological descriptions of astrophysical processes to match the abundance, clustering, redshift, and other observed properties of the galaxy population—underestimate the density of massive galaxies in the early universe by one to two orders of magnitude. And hydrodynamic simulations of galaxy merger rates predict no massive galaxies at all. Although previously observed LBGs and starburst galaxies already challenged those theories, the abundance and star-formation rates of the new galaxies render the disagreements harder to ignore.

"More and more observations show that a large population of massive galaxies and supermassive black holes has already been established in the young universe," says Wang. "In general, the young universe is more efficient in forming big things than we thought." To reconcile theory with observations, astronomers will need more accurate redshift measurements and better characterization of the physical properties for a larger sample of galaxies so they can put more stringent constraints on galaxy-formation models.

Heather M. Hill

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A molecular clock for testing fundamental forces

The vibrational frequencies of trapped ultracold molecules can serve as a check on what we think we know about the universe.

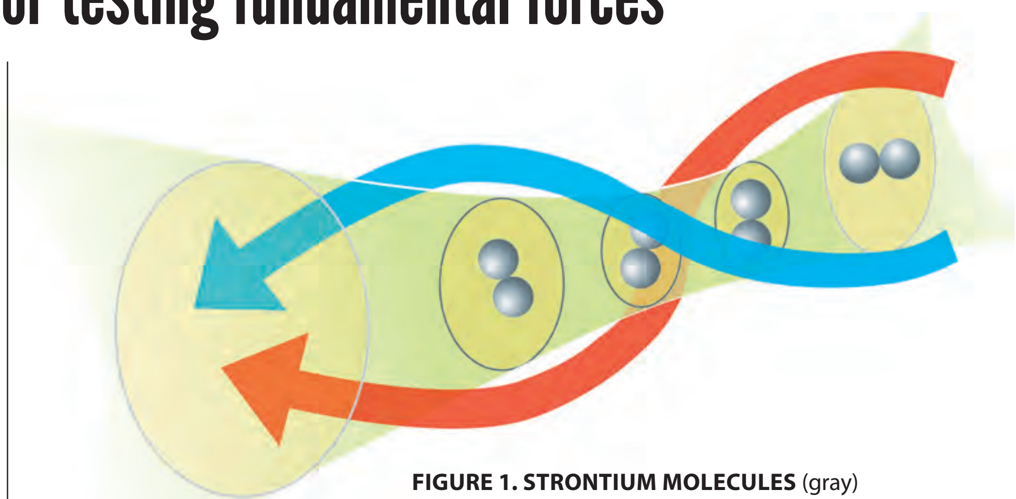

FIGURE 1. STRONTIUM MOLECULES (gray) held in a one-dimensional lattice of optical traps (yellow) are probed by a pair of Raman lasers (red and blue). Ultraprecise measurements of their vibrational frequencies reflect the fundamental forces acting on the nuclei and electrons.

Gravity over macroscopic distances is well understood. The simple inverse-square law, proposed centuries ago by Isaac Newton, continues to accurately describe the force at scales across the nonrelativistic regime, from laboratory-scale torsion balance experiments to the motions of stars and galaxies. It's been especially well tested at the scale of the distance from Earth to the Moon.

Short distances—microns or less—are another matter. In microscopic experiments, electromagnetic forces are so overwhelmingly dominant that the force of gravity at small scales has never been directly measured. All we have are upper bounds on its strength, some of which are astonishingly large. According to the best experimental constraint so far, the gravitational attraction between two objects 1 nm apart is no more than 10^{21} times what Newton's law says it is.[1]

It's not so outlandish to imagine that the force of gravity could follow the inverse-square law over large distances but deviate from it over small ones. Theories of extra dimensions through which only gravity can propagate, for example, allow just such a functional form. (See the article by Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, PHYSICS TODAY, February 2002, page 35, and the Quick Study by Lisa Randall, PHYSICS TODAY, July 2007, page 80.) To help test and constrain those theories, experimenters have been working for decades to chip away at the possible parameter space of short-range non-Newtonian gravity. Their techniques include measurements of the Casimir force (see the Quick Study by Jeremy Munday on page 74 of this issue) and neutron scattering off atomic nuclei.

Now Columbia University's Tanya Zelevinsky and colleagues are adding a new experimental method to the mix with their ultraprecise measurements of molecular vibrations.[2] Because their experiment, shown schematically in figure 1, is similar to that of an atomic optical-lattice clock (see PHYSICS TODAY, March 2014, page 12), they call it a molecular lattice clock, even though precision timekeeping isn't among their immediate goals. Although theoretical details remain to be worked out, the researchers estimate that with their current experimental capabilities—measuring a 25 THz vibrational resonance to within just 1 Hz—they'll be able to constrain predictions of nanometer-scale gravity to within 10^{18}–10^{19} of its Newtonian value.

Cold-molecule spectroscopy

Relative to atoms, molecules are complicated. Not only can their electrons be excited into more energetic states, but their vibrations and rotations are also quantized. The resulting hierarchy of quantum levels lends itself to probing many aspects of fundamental physics (see the article by Dave DeMille, PHYSICS TODAY, December 2015, page 34). But it also makes molecules hard to control. Whereas it's straightforward to optically cool atoms to a fraction of a kelvin, doing the same for molecules means keeping track of a vast tangle of states to make sure the cooling lasers aren't inadvertently pumping energy into the molecules instead of pulling it out. (See PHYSICS TODAY, January 2010, page 9.)

Molecular-physics experiments don't always require ultracold samples; sometimes it suffices to use a molecular beam, in which collisions cool the molecules to a relatively balmy few kelvin. Zelevinsky and colleagues needed lower temperatures than that, though, so they used an established trick in the cold-molecule field. Rather than cooling the molecules directly, they first cooled a gas of atoms, then optically coaxed the atoms into diatomic bound states. (See the article by Debbie Jin and Jun Ye, PHYSICS TODAY, May 2011, page 27.)

That approach is limited to the elements compatible with cold-atom techniques, though, so their molecule—the strontium dimer, Sr_2—isn't one that's often found outside of cold-molecule experiments. It's held together not by a covalent bond but by the weaker van der Waals force, so it's an order of magnitude larger than a covalently bound molecule such as nitrogen or oxygen, and its binding energy and vibrational-level spacing are accordingly smaller. Otherwise, it behaves much like any other diatomic molecule.

To probe the energy difference between two vibrational states, shown in blue and orange in figure 2, the researchers use Raman spectroscopy, a two-photon process that connects the two states by way of a higher-energy virtual state. The difference between the Raman laser frequencies can be stabilized to better than

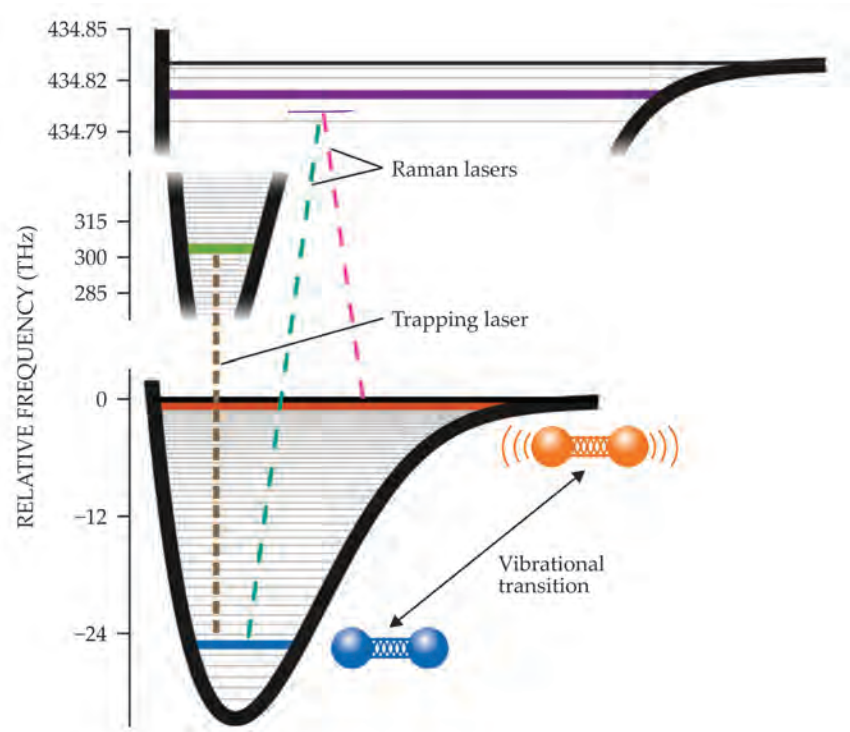

FIGURE 2. IN THE HIERARCHY OF MOLECULAR QUANTUM STATES, each electronic state (thick black curves) contains a series of vibrational levels (horizontal lines). To probe the frequency of the vibrational transition between the levels marked in blue and orange, Tanya Zelevinsky and colleagues use a pair of Raman lasers that drive the transition by way of a higher-energy virtual state (thin purple line). To eliminate both Doppler broadening and AC Stark shifts, they optically trap the molecules at a so-called magic frequency that's nearly resonant with yet another excited state (green solid line). (Adapted from ref. 2.)

0.1 Hz. The technique's precision is thus limited by molecular, not optical, effects.

Magic trapping

One potential source of uncertainty comes from Doppler broadening. Molecules moving toward or away from the source of the Raman lasers are excited at slightly different frequencies. Cooling slows their relative motion, but even at 2 μK, the molecules move enough to broaden the resonance by 30 kHz. So the researchers confine the molecules to a one-dimensional optical lattice formed by the standing wave of a near-IR trapping laser, shown in yellow in figure 1.

Lattice trapping eliminates Doppler broadening, but it introduces its own problem. Through the AC Stark effect, the trapping laser field separately shifts each vibrational state's energy by an amount that depends on the state's frequency-dependent electric polarizability and the trapping light's intensity. Molecules in different parts of the lattice can have their transition energies shifted by different amounts, and the overall resonance can be broadened by tens or hundreds of kilohertz.

Fortunately, the cold-atom community had already worked out a solution: Set the trapping laser to a so-called magic frequency at which the two states have the same polarizability. The Stark shifts then cancel, and the transition frequency can be measured with high precision.[3]

It's not always possible to find a convenient magic frequency, especially for a pair of molecular vibrational states, whose polarizabilities tend to parallel each other without crossing. The exception is for frequencies close to a resonance between one of the states of interest and a higher-energy electronic state (shown in green in figure 2). Near-resonant fields make a molecule's polarizability fluctuate rapidly as a function of frequency, so crossing points become plentiful.

But near-resonant trapping is risky, because the trapping laser can slowly excite molecules out of the vibrational state of interest and into the higher-energy metastable state. The excitation's slow destruction of the sample isn't such a problem: The researchers' spectroscopic technique requires them to destroy and re-form the sample for every data point anyway, and the process takes only a few seconds. What's worse is that the near-resonant excitation degrades the coherence lifetime of the vibrational transition. Because the sharpness of a spectroscopic line is fundamentally limited by the transition coherence time, anything that reduces the lifetime of either state cuts down on the measurement precision.

Zelevinsky and colleagues went for it anyway. With their near-resonant magic trapping, they obtained a coherence time of 30 ms, corresponding to a resonance linewidth of 32 Hz. For a transition frequency of 25 THz, that's a quality factor of nearly 10^{12}, a record for any vibrational measurement. Still, it's several orders of magnitude less than has been achieved in atomic measurements—where quality factors have reached 10^{16}—and less than Zelevinsky was hoping for. "We were surprised that the near-resonant trapping shortened the coherence time as much as it did," she says. "There's clearly something that's not very well understood, and we take it as our new challenge to figure it out." Because the molecules have so many excited states, there are many more near-resonant magic frequencies to explore that could perform better.

The hunt for new physics

A linewidth of 32 Hz doesn't mean that the measurement precision is limited to 32 Hz. Zelevinsky and colleagues estimate that with a reasonable integration time, they can find the center of the line to within 1 Hz. That's enough for them to start making meaningful measurements of fundamental forces. Strontium has several stable spin-0 isotopes that range in mass number from 84 to 88. Looking at each of them in turn should allow the researchers to isolate what observable effect, if any, gravitational mass has on interatomic forces.

Before they do those experiments, though, they want to have a good handle on all the other ways vibrational frequencies can depend on mass. Heavier nuclei have more inertia, so they respond more sluggishly to the forces of the surrounding atoms (see, for example, PHYSICS TODAY, September 2018, page 17). To help isolate the influence of gravity, the experimenters are working with theorist Robert Moszyński and colleagues at the University of Warsaw to calculate contributions to that isotope effect that are usually ignored, including the effects of relativity and coupling between nuclear and electronic motion.

Non-Newtonian gravity isn't the only fundamental-physics measurement the experimenters have in their sights. They're also interested in testing the stability of the proton–electron mass ratio over time.[4] The ratio could change if, for example, the strong nuclear force is not constant: The proton, unlike the electron, is not a fundamental particle, and its mass depends on how its constituent quarks interact. So far, there's been no sign of such a drift in the proton mass, but as Zelevinsky explains, "It's not strictly ruled out, and therefore scientists are actively looking for it, since there are many things about the universe we know we don't understand."

If the proton–electron mass ratio does change, one natural place to look for it is in molecular vibrational frequencies, which straightforwardly depend on both bond stiffness (a consequence of the quantum mechanical behavior of electrons) and nuclear inertia. Most constraints to date have come from astrophysical spectra of distant galaxies, which are sensitive to small fractional drifts in the ratio (on the order of 10^{-16}/yr) averaged over billions of years.[5] But the ratio doesn't necessarily drift at a constant rate. To complement the astrophysical constraints, Zelevinsky and colleagues are working toward an Earth-based measurement that has comparable precision but is focused on the present-day drift rate.

Johanna Miller

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A folding protein gets caught in the act

Time-resolved NMR spectra paint a picture of structural transformation with millisecond resolution.

To transform from linear chains to three-dimensional structures, *in vivo* proteins somehow navigate tortuous free-energy landscapes. Their final configurations must be just right for them to function properly; protein misfolding is thought to underlie some allergies as well as neurodegenerative diseases such as Parkinson's and Alzheimer's.

X-ray crystallography and NMR are well-established methods for accessing the detailed structure of a protein's final folded configuration. Gathering dynamical information about the folding process itself requires real-time techniques such as fluorescence, circular dichroism, and hydrogen exchange; acquiring information that quickly, however, comes at the expense of structural detail. Molecular dynamics simulations are also a valuable tool for studying protein configurations (see PHYSICS TODAY, December 2013, page 13), but because of computational limitations they fail to capture either the complete atomistic detail of real proteins or the complete process of folding.

Now Jaekyun Jeon, Robert Tycko, and coworkers at the National Institutes of Health in Bethesda, Maryland, have introduced a new way to track a protein's folding.[1] Their experimental setup, shown in figure 1, can start and stop the folding process quickly enough to trap proteins in transitory configurations. With the help of a signal-enhancing NMR technique, the researchers generated 2D spectra to track the formation of helices and dimers by melittin, a protein found in bee venom.

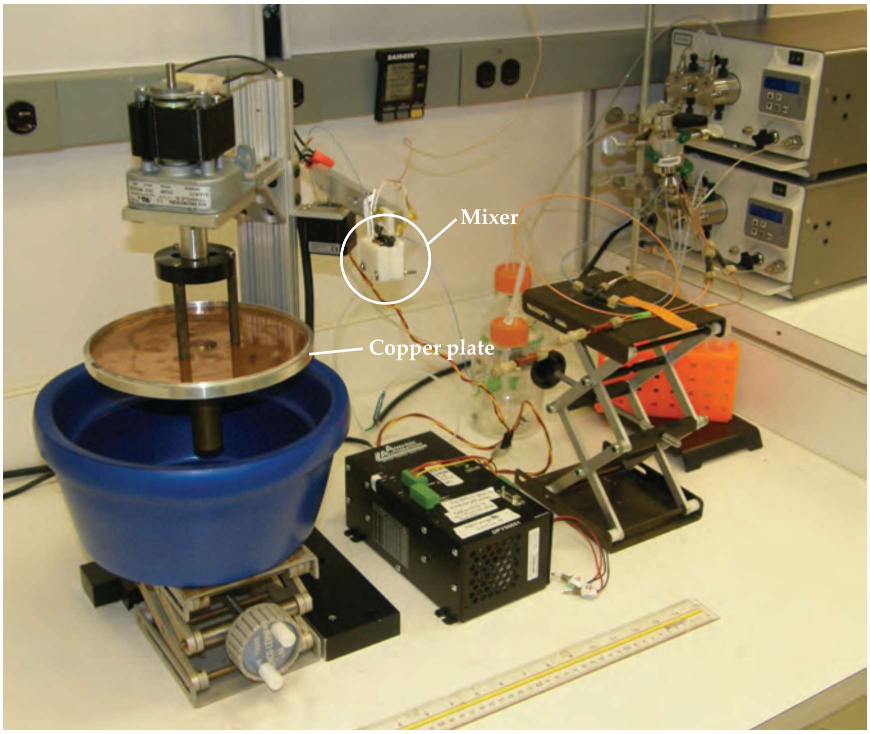

FIGURE 1. A RAPID-MIXING DEVICE starts and stops the protein-folding process with millisecond resolution. The mixer combines two pumped solutions, producing a high-velocity jet that freezes when it hits a liquid-nitrogen-cooled rotating copper plate. The frozen samples are subsequently analyzed using solid-state NMR. (Adapted from ref. 1.)

Their data, which have both high spatial and temporal resolution, challenge the previously accepted picture of melittin's structural development.

One moment in time

Melittin is a small protein—a peptide—with only 26 amino acids. At low pH, the peptides are linear chains, but in neutral to high pH, each peptide forms a bent helix. The helices form antiparallel dimers, which pair to make tetramers, melittin's native configuration.[2] The entire transition happens in less than 10 ms, so whether those steps happen concurrently or sequentially has been hard to discern.

Tycko's group developed a rapid mixer to change the solution's pH and initiate the protein-folding process. It mixes two solutions in just 1.6 ms—not quite instantaneous on the protein-folding time scale, but fast enough to capture a narrow spread of folding times. Although it's conceptually simple, the mixer is a critical part of their technique. "We've been working on these kinds of experiments for a while, and that was always one of our stumbling blocks," says Tycko. The microfluidic devices the researchers tried previously were expensive and had to be discarded when they inevitably became clogged. In addition to being inexpensive, their small homemade mixer, made from standard chromatography fittings, is reliable and can be easily disassembled and rebuilt if it becomes clogged. And, importantly, it yields reproducible results.

The device will likely be useful for a wide range of future experiments because rapid mixing is a versatile way to trigger protein structural changes. The same mixer that Tycko's group used to quickly change a solution's pH could also be used for rapid dilution to alter a protein's structure by changing the concentration of salt or of a denaturant such as urea or guanidine. Two interacting components could also be mixed to initiate complex formation.

To start melittin's self-assembly process, the researchers mixed a low-pH solution of unfolded melittin with a high-pH buffer to produce a neutral solution. To stop the folding process, the mixer ejected the solution onto a liquid-nitrogen-cooled rotating copper plate that froze the solution—and the protein's configuration—in less than 0.5 ms. The speed of the fluid leaving the mixer and the distance to the copper plate determined the protein's structural evolution time. In experiments, the proteins were frozen after 2.2, 4.6, 9.4, and 29 ms. The initial low-pH solution provided measurements of the unfolded state, and a pre-mixed neutral solution represented the final folded configuration.

The researchers used carbon-13 isotope labeling to track the locations of three amino acids on each peptide: glycine-3, leucine-6, and isoleucine-20. Helix formation in melittin brings Gly3 and Leu6 close together, and dimer formation brings Leu6 and Ile20 close together, as illustrated in figure 2. The proximities of those amino acids therefore served as proxies for structural developments.

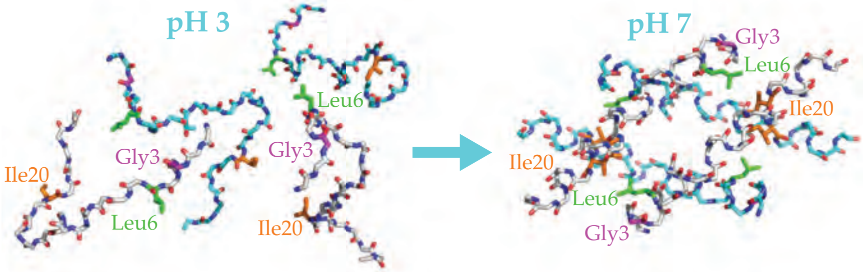

FIGURE 2. MELITTIN PEPTIDES FOLD AND UNFOLD in response to changing pH. At low pH they are extended chains (left), but at neutral to high pH they form ordered structures (right). Each chain forms a helix, the helices form antiparallel dimers, and the dimers pair into tetramers. The blue and white backbones indicate dimer pairs. Helix formation brings two labeled amino acids on a single peptide, glycine-3 (Gly3; purple) and leucine-6 (Leu6; green), closer together. When dimers form, the labeled isoleucine-20 (Ile20; orange) on one peptide gets close to the Leu6 on the other. (Adapted from ref. 1.)

Freeze frame

Once they had a time series of frozen protein configurations, the researchers still faced the challenge of extracting structural information from their samples. Using NMR to discern the structures of biological molecules is a tried-and-true technique; Kurt Wüthrich received half of the 2002 Nobel Prize in Chemistry for developing such methods (see PHYSICS TODAY, December 2002, page 19). But frozen proteins necessitate solid-state NMR (ssNMR), and those spectra have broad peaks compared with those from liquids (see the article by Clare Grey and Robert Tycko, PHYSICS TODAY, September 2009, page 44). To further complicate matters, the melittin solutions had to be highly diluted to fold properly, so they produced weak signals.

Jeon, Tycko, and coworkers enhanced the ssNMR signal with dynamic nuclear polarization. DNP takes advantage of the fact that electrons are much easier to polarize than nuclei; the gyromagnetic ratio of an electron is about 2500 times that of a carbon nucleus. The electrons are irradiated with microwaves at the resonant frequency of their precession—263 GHz in the 9.4 T field from the lab's homemade NMR setup—which flips some of the spins and reduces the electron polarization. When the electrons flip back to align with the field, they couple with the nuclear spins and, because they're preferentially flipping in one direction, increase the nuclear polarization.

DNP is not a new technique—the underlying nuclear Overhauser effect was postulated and experimentally demonstrated[3] in lithium metal in 1953. But, as Tycko explains, it has had a renaissance in the past 10–15 years because of its newfound utility in biologically relevant experiments and improvements in microwave sources.[4] Applying DNP to time-resolved ssNMR made detailed protein measurements feasible: Previous experiments without DNP could not follow the evolution of intermediate structures.[5] The researchers achieved adequate NMR spectra in less than eight hours, whereas without DNP the same measurements would have taken a month or longer.

Come together

Jeon, Tycko, and coworkers used 2D NMR to track the development of helices and dimers in the melittin samples. They used a pulse sequence that transferred nuclear spin polarization between ^{13}C atoms so that at the beginning of a measurement they observed the nuclear resonance from one atom, and at the end they observed that from another nearby atom. That's what gives the technique its two dimensions—polarization transferring from one nucleus to another. The nuclei in different locations resonate at different frequencies, so the signal shows up as an off-diagonal peak, or crosspeak, in a two-dimensional NMR spectrum. The NMR pulse sequence was tailored such that nuclear polarization transfer between atoms in the labeled amino acids happened only when they were close enough (see PHYSICS TODAY, October 2016, page 19). Because the labeled amino acids were chosen such that their proximity indicated helix and dimer formation, the amount of transfer between them grew as those structures developed.

Figure 3 shows the buildup of nuclear polarization transfer between the labeled amino acids, which is quantified by the crosspeak volume ratio. Growth of the Gly3–Leu6 crosspeak indicates helix formation; the Leu6–Ile20 crosspeak shows antiparallel dimer formation. Exponential fits to the data give buildup times of 8.7 ± 4.1 ms and 6.1 ± 2.8 ms, consistent with the two processes happening concurrently instead of sequentially. Helices in monomeric proteins typically form much faster than that, which suggests that for melittin, intermolecular interactions are necessary to stabilize the helical

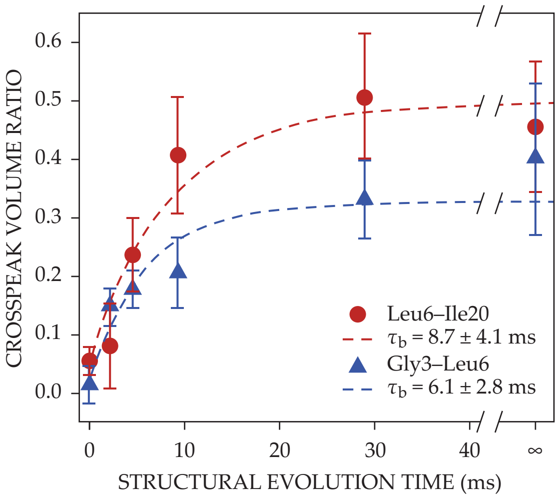

FIGURE 3. HELIX AND DIMER FORMATION increase the transfer of nuclear spin polarization between labeled amino acids glycine-3 (Gly3), leucine-6 (Leu6), and isoleucine-20 (Ile20); the polarization transfer is quantified by the crosspeak volume ratio. The Gly3–Leu6 crosspeak, which indicates helix formation, and the Leu6–Ile20 crosspeak, which indicates dimer formation, both grow with the protein's structural evolution time. The buildup times τ_b from exponential fits (dashed lines) are consistent with concurrent development of the two structures. (Adapted from ref. 1.)

structures. That prerequisite could have to do with the hydrophobic core created by melittin's full tetrameric structure—shielding each peptide's hydrophobic side chains may partially drive the folding process.

Time-resolved ssNMR was not used to track the protein's full tetrameric structure. That experimental choice highlights one of the NMR technique's limitations: The 2D spectra can be hard to interpret because the peaks are broad, particularly early on, when the protein is more disordered. Labeling more sites exacerbates the problem; the number of structural features that can be studied at once before the spectra become intractable is therefore limited. Although they could have done additional time-resolved ssNMR measurements with different labeled sites, the authors instead monitored tetramer formation using a less precise real-time fluorescence technique. Those measurements were consistent with tetramers forming along with the helices and dimers instead of the previously accepted sequential folding pathway. The unexpected result will inform theoretical models of protein folding dynamics.

Tycko sees time-resolved ssNMR as complementary to existing ways of studying protein folding. "There are a lot of other great techniques," he says, "but they don't give you the same kind of detailed molecular structural information that NMR can give you." Now that they've demonstrated their method, the researchers are extending it to other protein-folding problems, such as complex formation by calmodulin (see PHYSICS TODAY, May 2006, page 18), a ubiquitous protein that can bind to various target proteins in response to changes in calcium concentration.

Christine Middleton

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PT

Ongoing mentorship works for retaining minorities in STEM

Improving the academic environment for marginalized groups is aided by a holistic approach and dedicated resources.

"There are a million summer internships around, but they haven't had much impact in retaining underrepresented students in the natural sciences," says Richard Anthes, former president of the University Corporation for Atmospheric Research, which oversees the National Center for Atmospheric Research (NCAR) for NSF. Twenty-five years ago he conceived of the Significant Opportunities in Atmospheric Research and Science (SOARS) program to tackle the problem.

"SOARS had a huge impact on my career trajectory," says Dereka Carroll-Smith, who participated for three summers early this decade; her comments about the program are typical among the more than 200 alumni. "I credit the program with preparing me for graduate school, and building a network that I still use today," she says. A scientist who splits her time between NCAR and Jackson State University in Mississippi, she models tropical cyclone hazards and the effects of severe weather on society.

A signature feature of SOARS is that interns can return. They are eligible to join after their sophomore year in college and can participate for up to four summers. About 80% of them go on to graduate school or pursue a career in STEM (science, technology, engineering, and mathematics) after earning their bachelor's degree. Given the program's success, it's surprising how little it has been emulated. Recently, though, SOARS has begun seeding satellite programs. In a different field altogether, the Stewart Blusson Quantum Matter Institute (QMI) at the University of British Columbia in Canada has launched a program modeled on SOARS. And related activities at various institutions are gaining traction.

Not a summer vacation

SOARS was born of the question "What more can you do?" posed by Neal Lane, then NSF director, during a visit to NCAR in the 1990s. He wanted to attract more minority students to STEM. "The stuff they were doing was so interesting—storms, weather, clouds," he says. "I thought it was the kind of thing that could get kids excited regardless of their educational or home background." In response, Anthes realized that NCAR's existing internships weren't long enough. Students would come to Boulder, Colorado, for two months and then go back to their home universities. "I interpreted their experience as a nice summer vacation," he says. So he sketched out a model that he hoped would "actually influence these young people's lives."

SOARS covers the travel and living expenses of up two dozen participants a year. The program pays for students to present their work at national conferences and provides financial assistance for college or graduate school. "It's important that they don't have to decide between working at McDonald's or coming to Boulder," says Thomas Windham, the inaugural director and now a senior adviser to the program. SOARS is the rare internship program that hires full-time staff and provides year-round mentoring. NSF funds the program; the current five-year grant is a bit more than $3 million.

Any undergraduate who is a US citizen can apply; the focus on underrepresented groups is addressed through the recruitment and selection processes. As a member of the steering committee, SOARS alumnus Matthew Paulus reviews applications. "I'm a Hispanic male," he says. "Graduate school was dominated by 'pale, stale, male.' I try to look beyond the numbers by looking at personal statements. I try to find people who are passionate about diversity and who want to give back to the community." Among the categories NSF considers underrepresented are African Americans, Native Americans, Hispanics,

LEADERSHIP TRAINING EXERCISES at the Significant Opportunities in Atmospheric Research and Science mentoring program in Boulder, Colorado, are a way for participants to get to know each other. This group activity took place on 22 May 2018.

women (for many fields), veterans, first-generation college students, people with disabilities, and sexual and gender minorities.

The 11-week summer program kicks off with activities intended to promote bonding through group physical and mental challenges. In the second week students join their research groups, which are usually at NCAR, NOAA, and the University of Colorado Boulder. But for returning students, research can involve fieldwork anywhere from Juneau to the Galápagos Islands. Fridays are reserved for workshops in communications, computation, and professional development. SOARS participants present their work in poster and talk formats.

Each SOARS participant has up to five volunteer mentors: for research, communication, computation, and community, plus a peer mentor. The program is set up to be holistic, says NCAR director for

SOARS STAFF

education and outreach Rebecca Haacker, who was SOARS director in 2011–17. “Students have the opportunity to see who they click with most.” She regards the teacher–apprentice model as flawed because success depends completely on one person. “Across SOARS and the geoscience community, we are trying to break down this old model.”

Curtis Walker studies surface transportation meteorology as an NCAR postdoc. Before SOARS, he says, he would have ended his academic career after a bachelor’s degree. “I thought I would be a broadcaster or forecaster. SOARS introduced me to research.” The group of mentors is invaluable, he says. “It’s one thing to have help with science, but you also have help with data analysis and programming if you need it, and with writing.” The peer mentor is important too. “It’s helpful to know that others were in your shoes of feeling uncertain.”

The repeat experiences and focus on the whole person make SOARS feel like a family, say many alumni. They gather at conferences, which helps solidify their connections, especially across years. “It’s like a big SOARS reunion. I feel very connected to other alumni,” says Paulus, an associate scientist at NCAR. “In graduate school is when I found a need for support,” says Talea Mayo, an assistant professor of civil engineering at the University of Central Florida. “I still lean on the SOARS community, as a tenure-track faculty member, and I talk to others going up the career ladder.”

This year 105 people applied for eight spots for newcomers; another dozen students returned. “A key part of my vision was that it not be a remedial program,” says Anthes. “We look for students with demonstrated potential, and we challenge them to go on to become leaders in the field.” Many outcomes constitute success, notes Haacker, including when someone realizes they don’t want to do science. Today, nearly 25 years on, SOARS alumni are senior scientists and professors, they hold leadership roles in NOAA and other federal agencies, and they work in the private weather and climate sectors. Two alumni hold elected positions on the council of the American Meteorological Society.

What makes SOARS successful, says Haacker, “is that we adapt and evolve.” As examples she lists the program’s addition of financial support at the undergraduate level, adjustments in its mentoring options, and seminars in time and stress management. “The overarching goals are to broaden participation and improve the quality of science by bringing in diverse perspectives,” she says. It is also critical, says Windham, that the program has had both top-down and bottom-up support and that the research community was prepared and accepting of SOARS from its inception. He describes the program’s attitude as, “We are here to facilitate your success, but it’s on you.”

Long-term commitment

The SOARS model is duplicable, Windham says. At universities successful examples exist that use some of the same features. Given variables such as the size and cohesion of the research community and the availability of equipment and

TALEA MAYO

TALEA MAYO (center), an assistant professor at the University of Central Florida, runs a spinoff of the Significant Opportunities in Atmospheric Research and Science (SOARS) program. Her first recruit was Cindi-Ann Findley (right). In 2018 they presented their computational work on the nonlinearities of tides and hurricane storm surges at an NSF event on Capitol Hill, where they posed with Karen Saxe of the American Mathematical Society.

PAUL JOSEPH, UBC

STUDENTS IN QUANTUM PATHWAYS, a new multiyear internship program at the University of British Columbia's Stewart Blusson Quantum Matter Institute.

funding, the best approach is to adopt the aspects of SOARS that make sense, he says. "You don't need to replicate the exact same model, but you do need to have an environment where the soil is enriched and welcoming."

Perhaps closest to SOARS is Research Experiences in Solid Earth Science for Students (RESESS), a spinoff at UNAVCO in Boulder that became independent more than a decade ago. It hosted eight students this year, two of whom were returning. The program limits participation to two summers to reach more students.

Tight funding makes for a tricky trade-off between the number of students and repeat participation; programs tend to maximize the number of students. For example, NSF discourages repeat participation in its Research Experience for Undergraduate (REU) programs, a prime vehicle for increasing participation of marginalized groups in STEM.

For their part, SOARS alumni and administrators swear by the continuity of the program. During a broad external review of the QMI in Vancouver a few years ago, Anthes mentioned in passing that committing to students over time is what makes SOARS different and that it has had a huge payoff. The institute's 22 faculty members in physics, chemistry, and electrical engineering grabbed the idea. In 2018 they launched Quantum Pathways, which hosted two students its first year. They both returned, and the total jumped to 15 this year.

Quantum Pathways accepts applications from across Canada and beyond. Mentoring students for multiple years is a "win-win," says QMI physicist Douglas Bonn, "because once they have experience they can contribute more effectively to research. It's a better investment than a one-off." And having them come from elsewhere widens the potential source of future graduate students, he adds.

Quantum Pathways offers training in science communications, career panels, and career advice, but not as intensively as SOARS. The program is tailored to QMI needs: Students take a machine-shop course and participate in boot camps to learn specific skills, such as materials synthesis; working in ultrahigh vacuum, cryogenic temperatures, or with sensitive electronics; and modeling nanoscale systems.

A few years ago, SOARS was awarded a grant to form satellites as a way to increase its reach. So far two alumni, Mayo in Florida and Deanna Hence at the University of Illinois at Urbana-Champaign, have established small programs; additional satellites are in the works. Mayo recruits individual students to work with her during the school year. Her first student modeled hurricane storm surges and then got into the main SOARS program. Her current student is focusing on machine learning for storm surge data. "I'm trying to be all the mentors for them," she says.

With her satellite program, Hence is targeting transfer students from a nearby community college, which is a large source of diversity. She wants to develop and formalize existing activities to "mimic the mentorship that SOARS is known for." SOARS was "life-changing for me," Hence says. "But not everyone can go to NCAR for 10 weeks. We want to create something similar at home institutions."

The big picture

Broadening participation of people from underrepresented groups in STEM has been a goal of US funding agencies, universities, and professional societies for decades, but the urgency with which it is pursued fluctuates. In physics, for example, the number of women earning physics PhDs each year has more than doubled in the past two decades, although in terms of percentage the increase is smaller: from 13% to 20% of all PhDs awarded in the field, according to the Statistical Research Center of the American Institute of Physics (which publishes PHYSICS TODAY). Over that period, the number of African Americans earning physics PhDs each year has hovered around 12 (with a peak of 22 in 2012), while the number of Hispanic Americans earning physics PhDs has more than quadrupled to about 40.

Dedicated master's programs and the American Physical Society's bridge program are routes for underserved students to pursue higher degrees in physics. (See the articles by Alexander L. Rudolph on page 50 of this issue and by Ted Hodapp and Kathryne Woodle in PHYSICS TODAY, February 2017, page 50, and the news story from April 2019, page 22.)

One new approach seems to be making a difference: a student-initiated club, Physics Undergraduate Women and Gender Minorities at Stanford or PUWMAS. Now in its third year, it's branching out to include other underrepresented groups. "Our goals are to promote diversity by creating community, create a space to discuss issues related to physics and STEM, and provide help with career and academic development," says club co-president Kathlynn Simotas, a first-generation college student with a dual major in music and physics.

Risa Wechsler, a Stanford University physics professor and chair of the department's equity and inclusion committee, says that PUWMAS is having a positive effect. "Now, even before students have a chance to get discouraged, someone has already reached out to them. A few years ago, we had zero Black, Latinx, or Native American women students in the major; there are now several."

Wechsler notes that students tried to set up a similar group some years back, but it didn't take. The difference may in part reflect greater societal awareness of sexual harassment, racism, and other inequity issues both in academia and more broadly, she notes. "And we now have a critical mass of supportive faculty. Many institutions are doing things, with various degrees of success, budget, and enthusiasm."

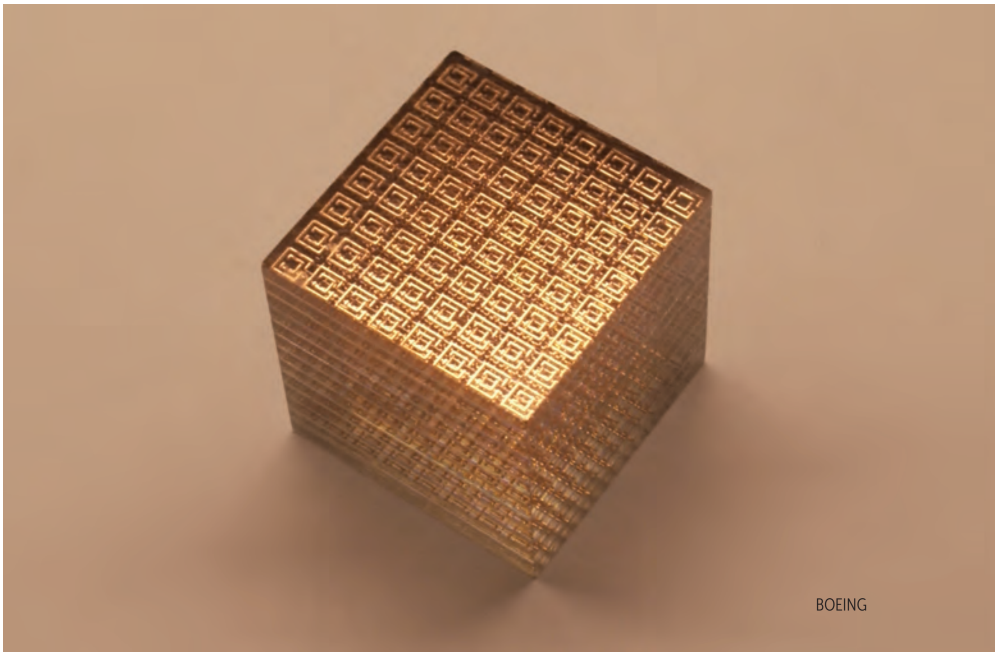
The challenge of diversifying STEM fields "is so big, it's beyond what anyone can do at a single institution," says SOARS alumnus Chris Castro, a professor at the University of Arizona who focuses on regional climate modeling. He favors a decentralized approach with hubs around the country. In the Southwest, for example, "you could then do deeper outreach to colleges and educational entities that otherwise do not have access to atmospheric and other STEM research—that could be community colleges and tribal colleges."

Castro asserts that to increase diversity in STEM, "you have to create a safe place within your home institution." In part that means that faculty need dedicated time for such activities. "Nothing happens without resources," he says. And a significant hindrance is that "the incentives and professional metrics are at odds with the purpose of broadening participation of underrepresented groups."

Toni Feder

Physics at Boeing runs the gamut from lightning strikes to neuromorphic processors, with a dash of metamaterials

Physicists are uniquely qualified to solve problems that require an understanding of the bigger picture.



BOEING

THIS 2.5 CM METAMATERIAL CUBE was fabricated by researchers at Boeing and the University of California, San Diego, and other universities under a 2004 Defense Advanced Research Projects Agency contract. The object demonstrated that scientists could engineer a material with specific properties in a format that resembles a real material.

Every hour during an airliner flight, dozens of sensors monitoring thousands of parameters produce around 1.5 terabytes of information. As more sensors are added in next-generation aircraft to detect maintenance issues before they become a problem, the volume of data is expected to increase 10-fold, and more than a petabyte of information could be generated during a 10-hour flight.

Jay Lowell is a Boeing senior technical fellow and one of more than 90 physicists who work at Boeing Research & Technology, the aerospace giant's central R&D organization. He and his team will have to cope with that growing data avalanche. He believes neuromorphic processors—chips configured like neural networks—can help address the onboard data-processing crunch and flag abnormal situations. "They are exceedingly efficient for machine learning and artificial intelligence applications," he says.

But running machine learning and artificial intelligence programs with current processor technology would require tens or hundreds of kilowatts of power, compared with the 50 watts typically used by today's planes to process maintenance data. There will never be enough bandwidth to transfer all that data from a fleet of aircraft to the cloud for processing, Lowell adds, noting that around 10 000 Boeing 737s alone are currently in service.

The data problem is one of the challenges Boeing physicists are working on under the rubric of the company's initiative on disruptive computing and networks. A second thrust seeks to advance high-performance computing architectures by pairing central processing units with coprocessors such as graphics processing units. GPUs are "exceedingly more efficient" than CPUs at performing a smaller number of specific tasks, Lowell says. Boeing is looking at architectures that use a wider variety of coprocessors than today's top-performing supercomputers do. Looking further out, Boeing sees a future in quantum sensing and computing to address such problems as optimization in manufacturing.

Besides computing, Boeing physicists tackle problems that range from handling aircraft lightning strikes to protecting factory workers from static shocks. But they don't dwell on one problem or topical area indefinitely. Whether they work on a problem for two months or two years, once they hand off solutions for implementation by engineers, their next assignment is likely to bear little resemblance to the last. "Our job is to work ourselves out of a job," says Lowell.

One of Lowell's first assignments at Boeing in 2016 was to improve the functionality of a robotics system on the factory floor. "What they needed was somebody who could approach the problem like a physicist and understand the fundamental principles involved." It turned out, says Lowell, that he needed to apply the principles of metrology to understand how the robots were making measurements and to use classical mechanics to help identify and characterize the robots' limitations in performing their tasks. Physics also helped him capture data and build a picture to provide insight into the processes that were occurring. "You then had to perform analysis on the data you captured to model the entirety of the system at the scale of the factory," he says. In the end, his suggestions for changes and fixes made the factory floor much more efficient.

The Boeing physicists who spoke with PHYSICS TODAY declined to discuss their role in returning the 737 MAX airliner to service, saying only that employees with many backgrounds are working on the problem. In March the aircraft was grounded by governmental authorities after two crashes that killed all 346 passengers and crew aboard. The accidents have been attributed to faults with the onboard Maneuvering Characteristics Augmentation System, which repeatedly caused the planes to turn their noses down.

Problem solving

The real-world environment encountered by a Boeing physicist is unlike an academic setting, says Lowell, who previously worked as a US Air Force Academy instructor and as a program manager at the Defense Advanced Research Projects Agency (DARPA). For one, university scientists tend to be focused on a narrower range of research. Moreover, says Lowell, "we get to apply physics research to a problem that's concrete enough that we don't have to make a lot of assumptions. We don't have to toy the problem down to the point where it's trivial."

Compared with most academic research, Boeing's requirements are greater both in scale and in the level of detail. Modeling the fluid dynamics of a wing, for example, must take into account the winglet, gaps, and flaps, says Dejan Nikic, a physicist who joined the company in 2006. Simulating the flutter and elasticity of a wing as it flexes during flight adds to modeling complexity.

The computational resources needed for wing modeling, however, pale when compared with what's needed for figuring out how aircraft components, engines, and airflow around the aircraft combine to propagate noise to the ground. Those problems can take months for the most powerful supercomputers to solve, Lowell says. The benefits to airlines from cutting noise levels in half would be enormous; many airports could ease or eliminate bans on overnight takeoffs and landings.

Unlike their academic counterparts, Boeing scientists rarely publish their research, most often because it's proprietary. Publishing also has the potential to provoke changes to regulations, notes Nikic, whose interests include the electromagnetics of plasma physics and pulsed power. He's worked on such topics as laser weapons and lightning strikes.

DENNIS DUGAY, an electrophysics engineer at Boeing, is in an anechoic chamber at the company's laboratory in Huntington Beach, California. Dugay develops and tests RF and microwave components for airplane communications systems.

On average, airliners are struck by lightning once or twice a year, says Lowell. As manufacturers have begun incorporating more composite materials for weight savings, building a Faraday cage to safely dissipate lightning and keep it out of the cabin has become more complex. For metal airplanes, that's easy, says Lowell. "The lightning follows the metal skin of the plane. It doesn't penetrate to the interior of the plane, or maybe a few hundred amps do. Composites are not nearly as conductive, and thousands of amps could flow through the interior."

Physicists are well-equipped to understand how the current will flow between structural members, down to the microscopic details of the fasteners that hold them together. Says Nikic, "We've done things like understanding the plasma density and temperature when lightning hits a surface, what that plume contains, how far the lightning penetrates a given material, and the erosion rate. That is all basic physics."

One way to protect a composite airplane is to boost the skin surface conductivity by incorporating a layer of metal foil in the composite stack. Doing so reduces the amount of current that transfers into the airplane substructure, which itself is designed to handle any transferred current. Boeing adds other proprietary features to provide a redundant layer of protection.

More mundanely, Nikic was called in to address complaints from factory workers who routinely received harmless but annoying static shocks when peeling sheets of plastic off of wing panels after they are cured in autoclaves. The solution entailed altering how panels were unbagged, changing what workers wore, and other steps. "Every other person who tried to approach this wasn't able to make headway," Lowell says.

A different model

Minas Tanielian is a somewhat atypical Boeing physicist; throughout his 30-plus years at the company, he has specialized in organizing consortia with universities, DARPA, and other federal agencies. He's also worked on wireless systems, microsystems, autonomous systems, quantum devices, and laser-powered systems, among other areas. He holds 65 patents and has published more than 60 scientific articles. Currently he's working under contract with the Air Force Office of Scientific Research on a university–industry collaborative program on power beaming.

Nearly 20 years ago, after reading a news story in PHYSICS TODAY (May 2000, page 17) about left-handed materials—now called metamaterials—Tanielian contacted the researchers at the University of California, San Diego. "I put a team of university researchers together and we started the metamaterials program at DARPA," he says. "Initially, the concept of metamaterials was somewhat controversial among the engineering community, but within six months we conducted an experiment which verified that they were real and published the results. The program eventually went to a second phase at DARPA called negative-index materials, where we focused on applications." Tanielian subsequently identified an application for the technology in Boeing's defense business, which he says he can't discuss for proprietary reasons.

Some of the modeling tools developed for the DARPA program were later used in developing electrically small antennas for cell phones. Lowell says that's an example of how basic physics often transitions by "bank shot" from basic physics to application: "It's not that what you do always goes directly to a place you might think but somewhere that's one step removed."

The reductionist approach physicists employ is ideal for troubleshooting, the Boeing scientists say. "When you get called in, the physicist approaches the problem by asking, How do I reduce the system down to its bare core physics and build the complexity up?" Lowell notes. "The engineer starts with the complexity and looks at the system at that level and sometimes struggles to simplify things enough to see what's going on."

Physicists also help bridge knowledge gaps that occur among different types of engineers and other scientists working on multidisciplinary programs, says Tanielian. Just as an electrical engineer may not understand the mechanical-engineering, thermal, or other aspects of a program, a mechanical engineer likely has trouble with electronics, he explains. "Physicists are not as expert in terms of how to do some specialized things, but we understand the core of how things happen or interact with each other, especially in a multidisciplinary environment."

Getting the word out

Boeing wants people with experimental backgrounds and those with theoretical backgrounds, people with analytical skills and people with numerical skills, says Lowell. "The breadth of problems in a company our size is large, so the breadth of skills we need is broad and deep."

Lowell expects that the company's disruptive computing and network organization alone will require at least a dozen new physicists over the next two years. Quantum physicists—those who have worked in supercomputing and those with modeling experience—are in particular demand. High-energy physicists who deal with large amounts of data and codes that take advantage of different kinds of processors are also needed.

"We have a problem in trying to recruit young physicists to industry and specifically to Boeing, which is essentially an engineering company," says Tanielian.

David Kramer PT

Anne Marie Porter and **Susan White** are survey researchers in the Statistical Research Center at the American Institute of Physics in College Park, Maryland.

The road taken

Anne Marie Porter and Susan White

Survey data show that PhD physicists find satisfaction in a wide range of careers, from academia to government to industry.

Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference.

—Robert Frost, 1916

In his poem "The Road Not Taken," Robert Frost famously wrote about choices. For graduate students in physics, the most familiar road is the academic path, but many other career paths are available to PhD physicists—far more than Frost's two roads. According to NSF's Survey of Doctorate Recipients, almost half of the 130 000 PhD physical scientists living and working in the US in 2017 were employed in the private sector, about 40% were employed in academia, and 9% worked in government settings (see figure 1).

STUART KINLOUGH/ALAMY STOCK PHOTO

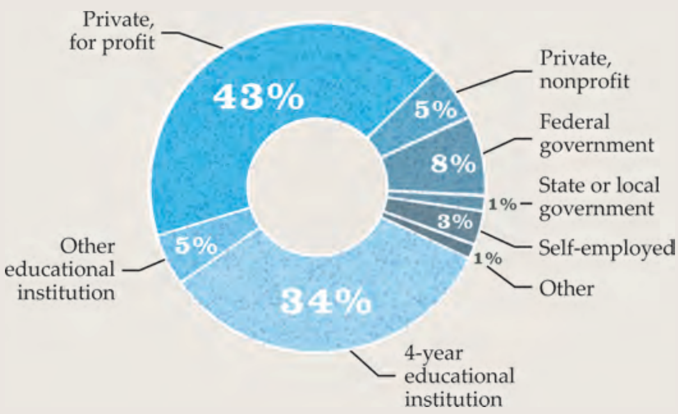


FIGURE 1. EMPLOYMENT OF PHYSICAL SCIENCES PHDS BY SECTOR, 2017. (Adapted from NSF, National Center for Science and Engineering Statistics, Survey of Doctorate Recipients, 2017.)

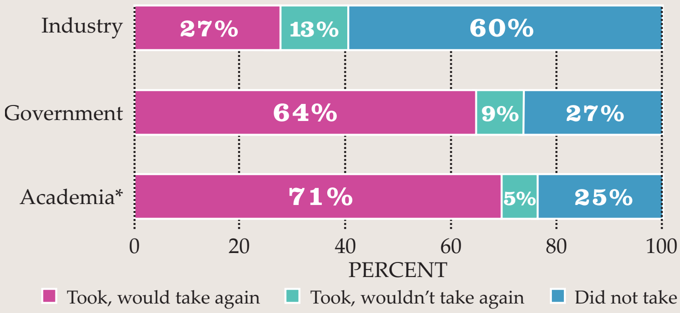


FIGURE 2. PERCENTAGE OF PHD PHYSICISTS IN EACH SECTOR WHO ACCEPTED POSTDOCTORAL POSITIONS, physics PhD classes of 1996, 1997, 2000, and 2001. Respondents were also asked if they would accept their postdoc again if given the chance.

*Percentages do not total 100 due to rounding.

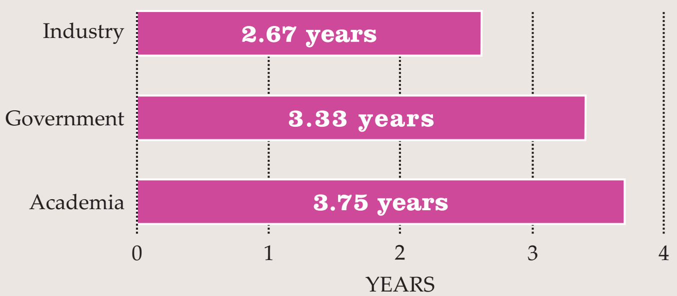


FIGURE 3. NUMBER OF YEARS IN POSTDOCTORAL POSITIONS BY SECTOR, physics PhD classes of 1996, 1997, 2000, and 2001. PhD physicists in academia spent the most time in postdoc positions; those in industry spent the least.

In this article we examine the different career paths of PhD physicists working in private industry, academia, and government, and we describe what physicists in different sectors find rewarding about their chosen careers.

In the first-ever 10-year follow-up survey of physics PhD recipients, the Statistical Research Center at the American Institute of Physics (AIP), which also publishes PHYSICS TODAY, contacted physics PhD recipients from the classes of 1996, 1997, 2000, and 2001 who were in the US during 2011. Data used in this article were collected from more than 1800 respondents who participated in that PhD Plus 10 Study. We asked a variety of questions about respondents' postdoctoral positions, their first jobs after receiving their doctorates, and their jobs at the time of the survey. Respondents reported whether they worked in academia (universities or other two- or four-year institutions), for the government (military; national labs; or a local, state, or federal agency), or in the industrial sector (government contractor, private company, or self-employed).

Who pursues a postdoc?

The first step in a new PhD's career is typically the decision of whether to pursue a postdoc. According to AIP's most recent follow-up survey of physics degree recipients in 2015–16, 47% of PhD graduates accept postdoc positions. Not all physicists pursue postdocs, and our PhD Plus 10 data show that postdoc decisions were different across sectors. We found that far fewer physicists working in industry accepted postdoc positions. When we asked if they would do so again, nearly a third of industrial physicists who took a postdoc said they would not (see figure 2). Furthermore, those in in-

ONLINE RESOURCES

If you are interested in reading more about the careers of PhD physicists or gaining inspiration for job searches outside academia, the following reports are available on the American Institute of Physics website.

▶ **Who's Hiring Physics PhDs** (www.aip.org/statistics/whos-hiring-physics-phds) lists employers who have recently hired a physics PhD in various sectors, along with common job titles, salaries, and skills needed.

▶ **Common Careers of Physicists in the Private Sector** (www.aip.org/sites/default/files/statistics/phd-plus-10/PhysPrivSect.pdf) contains data on salaries and skills used in eight types of industrial jobs.

▶ **Physics PhDs Ten Years Later: Duties and Rewards in Government Positions** (www.aip.org/sites/default/files/phd%2B10-gov-duties nrewards.pdf) indicates the job titles of physicists in government positions and what those jobs entail.

▶ **Physics PhDs Ten Years Later: Duties and Rewards in Academic Positions** (www.aip.org/sites/default/files/phd%2B10-acad-duties nrewards.pdf) indicates the job titles of physicists in academic positions and what those jobs entail.

dustry who did accept a postdoctoral position spent the least amount of time in it (see figure 3).

Of the physicists in our survey, 8% declined postdoc offers and reported their reasons for doing so. They made that choice because they found permanent positions elsewhere, they were no longer interested in an academic career, the postdoc salary was too low, they could not relocate, or they wanted to start a family. Those responses suggest that financial and family considerations are important factors in a PhD physicist's decision to pursue the postdoctoral path.

Do careers change over time?

Since we knew PhD physicists' first and current jobs, we were able to look at different types of movement across careers. Our survey analysis focused on three questions about career movement:

- Did respondents move across sectors during their careers?
- Did respondents stay with the same employer?
- Did respondents change fields during their careers?

We found little movement across career sectors. Almost all PhD physicists were still working in the same broad sector—industry, academia, or government—in which they had accepted their first job after a postdoc (see figure 4).

We saw wide variation in physicists' tendency to switch employers depending on their job sector (see figure 5). About two-thirds of the physicists working in the academic sector were with the same employer who gave them their first non-postdoctoral job, and almost three-fourths of government employees were still with the same employer. Those working in industry, however, were more likely to have moved; less than 40% were still with the same employer.

Lastly, we examined movement between job fields (figure 6). How common was it for physicists to, for example, move from a physics-focused job to an engineering-focused job or to a nonscience position? Most academic and government physicists began their careers in the field of physics or astronomy, and the majority stayed in their job field. Most industry physicists worked in engineering fields, and those who began in physics or astronomy were more likely to move to a nonscience field. It's possible that trend reflects a tendency for industry physicists to move to management or nonscience business positions as their careers progress.

What rewards do jobs in the different sectors offer?

We also asked physicists, "What are the most rewarding aspects of your current job?" In examining more than 1300 quotes from our respondents, we found far more similarities than differences across the three sectors (see figure 7). For example, PhD physicists in all three sectors felt rewarded when they collaborated with others, mentored younger employees or students, helped society with their work, and had the autonomy to decide their research and work schedules. Regardless of which job path physicists choose, it appears that working in academia, government, and industry can be fulfilling in similar ways.

Each sector is also unique, and physicists in the three sectors identified specific aspects of their jobs as rewarding. For example, academic physicists felt rewarded when teaching

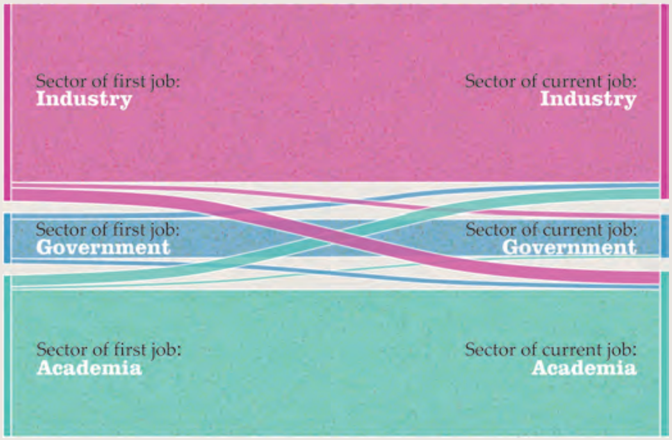


FIGURE 4. MOVEMENT BETWEEN FIRST AND CURRENT JOB SECTORS, physics PhD classes of 1996, 1997, 2000, and 2001. The width of the bar corresponds to the proportion of people in a particular sector.

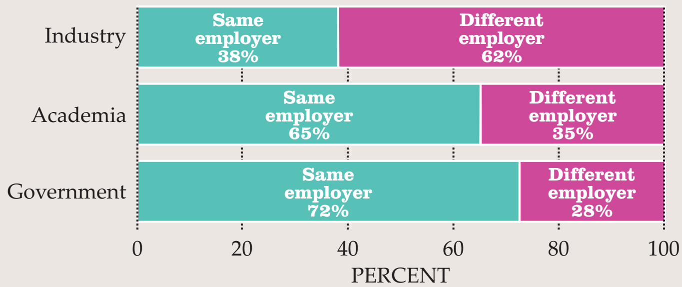


FIGURE 5. MOVEMENT BETWEEN EMPLOYERS BY SECTOR, physics PhD classes of 1996, 1997, 2000, and 2001. PhD physicists working in industry were more likely to have changed employers than those in the academic or government sectors.

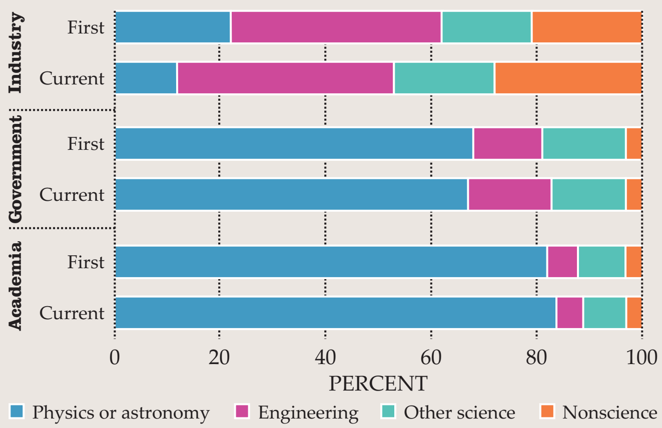


FIGURE 6. MOVEMENT BETWEEN EMPLOYMENT FIELDS BY SECTOR, physics PhD classes of 1996, 1997, 2000, and 2001. Most PhD physicists working in industry were in a field other than physics or astronomy.

JOB REWARDS IN ALL SECTORS

Mentoring • Collaborating • Helping society • Learning
Problem solving • Developing new ideas and technology
Having job autonomy • Performing research

Industry Job Rewards

Creating or supporting a business
Helping clients
Receiving financial benefits
Managing projects
Conducting research faster
Traveling

"Creating brand new technology used by hundreds of thousands of human beings across the world"

"Interacting with customers to understand their problems and provide and implement solutions"

Academic Job Rewards

Teaching
Conducting public outreach
Helping department
Helping scientific field
Publishing • Traveling
Having job security

"Seeing the amazement in my students' eyes when they understand a concept"

"Helping students advance, find rewarding work, or further their science education"

Government Job Rewards

Having job security • Publishing
Managing projects
Conducting research faster
Working on climate change, public health, or national security

"Shaping the future direction of research conducted to improve the Nation's security"

"Working on a problem, climate change, that is of utmost importance for humanity and the planet"

FIGURE 7. JOB REWARDS BY SECTOR, physics PhD classes of 1996, 1997, 2000, and 2001. Some job rewards are universal across sectors; others tend to be mentioned more often by PhD physicists working in a specific sector.

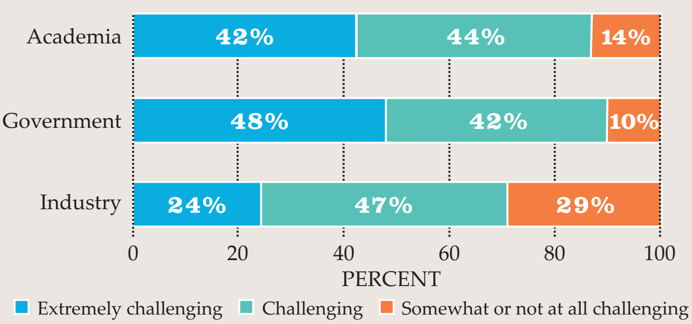


FIGURE 8. RESPONSES TO THE QUESTION "IS THIS JOB INTELLECTUALLY CHALLENGING?" by sector, physics PhD classes of 1996, 1997, 2000, and 2001. Even though PhD physicists working in industry were less likely to report that their job was intellectually challenging, they did not report lower job satisfaction than their peers in the academic or government sectors.

students, performing public outreach to improve science literacy, and helping their departments or the larger scientific field. Industry physicists felt rewarded when helping their clients, supporting their company, and receiving financial benefits like higher salaries and stock options. Government physicists appreciated that they had more job security and conducted research at a faster pace than academics; they also felt rewarded when addressing larger societal issues such as climate change and national security.

When we asked PhD physicists whether they found their jobs intellectually challenging, those in government and academic positions were more likely to respond in the affirmative than those in industry (see figure 8). However, there is no evidence that industrial physicists are less satisfied with their jobs than their counterparts in academia and government. Although industry physicists may feel less intellectually challenged, they may encounter different types of problems that they enjoy tackling and solving.

Diverging or converging roads?

The career options available to PhD physicists are varied. Our data provide insight into the satisfaction that midcareer PhD physicists have found (see online resources on page 34). We should, however, note that the past does not necessarily predict the future. The pace of technological change suggests that career options that do not currently exist may be viable options in 2040. In the same vein, current occupations may become obsolete. Therefore, we cannot give a comprehensive overview of the career paths that today's PhD students may travel.

The roads in Frost's poem diverge, and the narrator chooses one. Later, the narrator notes, "Yet knowing how way leads on to way, I doubted if I should ever come back." We do not know whether the narrator ever went back. Can a PhD physicist? We have seen that most remain in the same sector as their first full-time job. However, some do change their career path over time. The options are many and varied. Which road will you take? PT

THEORETICAL HIGH-ENERGY PHYSICS FACULTY POSITION

The Department of Physics, Colorado State University, seeks to hire at least one tenure-track faculty member at the rank of Assistant Professor in **theoretical high-energy physics**. Exceptional candidates will be considered for positions with a more senior rank. Candidates whose research complements the CSU program in experimental high-energy and particle astrophysics (HEPPA) are strongly encouraged to apply. Candidates must hold a Ph.D. in physics or an equivalent degree and have a documented potential for outstanding teaching, scholarship, and research. Postdoctoral and/or other substantial experience beyond the Ph.D. is expected. Complete applications consist of a cover letter, detailed CV, descriptions of research plans and teaching interests, and three letters of reference. Your references will be contacted immediately upon submission of application and will receive an email with a link to submit their letter. Applications must be submitted online. For more information,including application instructions, see **https://jobs.colostate.edu/postings/71002**. Applications completed by November 13, 2019 will receive full consideration, but applications will be accepted until the position is filled. Colorado State University is an EO/EA/AA employer and will conduct background checks on all final candidates.

KOREA INSTITUTE FOR ADVANCED STUDY (KIAS)

Assistant Professor & Research Fellow in Theoretical Physics at KIAS

The School of Physics at Korea Institute for Advanced Study (KIAS) invites applicants for the positions at the level of KIAS assistant professor and postdoctoral research fellow in theoretical physics. Applicants are expected to have demonstrated exceptional research potential, including major contributions beyond or through the doctoral dissertation.

The annual salary starts from 50,500,000 Korean Won (approximately US$45,500 at current exchange rate) for Research Fellows, and 57,500,000 Korean Won for KIAS Assistant Professors, respectively. In addition, individual research funds of 10,000,000 Korean Won for research fellows and 13,000,000 Korean Won for KIAS Assistant Professors are available per year. The initial appointment for the position is for two years and is renewable once for up to two additional years, depending on research performance and the needs of the research program at KIAS.

Applications are normally reviewed twice a year and the respective deadlines are June 1st and December 1st. In addition, unexpected vacancies may be filled with exceptional candidates throughout the year. Applications must include a curriculum vitae with a cover letter, a list of publications, a research plan, and three letters of recommendation. Your application materials may be sent to phys@kias.re.kr or submitted via Academic Jobs Online at https://academicjobsonline.org/ajo.

FELLOWSHIP OPPORTUNITIES FOR Ph.D. STUDENTS

Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship

DEADLINE: 1/8/2020
www.krellinst.org/ssgf

Department of Energy Computational Science Graduate Fellowship

DEADLINE: 1/15/2020
www.krellinst.org/csgf

Department of Energy National Nuclear Security Administration Laboratory Residency Graduate Fellowship

DEADLINE: 3/4/2020
www.krellinst.org/lrgf

BENEFITS

- Generous yearly stipend
- Payment of full tuition and required fees
- Annual professional development allowance
- Yearly program review participation
- 12-week practicum experience(s)
- Renewable up to four years

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U.S. DEPARTMENT OF ENERGY

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FACULTY POSITION IN EXPERIMENTAL PARTICLE PHYSICS

The Department of Physics and Astronomy in the College of Science at Purdue University seeks applications for a faculty position at the level of Assistant Professor in the area of experimental particle physics. All areas of experimental particle physics will be considered. We are interested in outstanding scientists with an established track record, international stature, a commitment to leading a preeminent research program, and a clear vision for future developments that will complement the current efforts within the department. Purdue has major involvement in the CMS, Mu2e, XENON1T/nT, LBECA, STAR and LSST experiments. Synergies exist with groups in astrophysics, theory, nuclear physics and condensed matter physics. The department offers a state-of-the-art in-house facility with resources applicable to silicon detector design, development and fabrication.

Qualifications: Applicants must have a Ph.D. in particle physics or a closely related field, an outstanding record of research accomplishments, and evidence of potential excellence in teaching at both the undergraduate and graduate levels. Candidates are expected to develop vigorous research programs, supervise graduate students, and teach both undergraduate and graduate level courses.

The Department and College: The Department has 57 tenured and tenure-track professors, 150 graduate students, and over 250 undergraduates. Over the last 5 years the Department has added 14 faculty and significant investment has been made in our key areas of discovery. The College and Department have launched initiatives in new emerging areas, such as Data Science and Quantum Information Science, and committed the resources necessary to make the new growth impactful.

Physics and Astronomy is part of the College of Science, which comprises the computing, physical, and life sciences at Purdue. It is the second-largest college at Purdue, with over 350 faculty and more than 6000 students. Purdue itself is one of the nation's leading land-grant universities, with an enrollment of over 41,000 students primarily focused on STEM subjects. For more information, see **https://www.purdue.edu/purduemoves/initiatives/stem/index.php**.

Application Procedure: Applications need to be submitted to **https://career8.successfactors.com/sfcareer/jobreqcareer?jobId=7330&company=purdueuniv&username=** and must include (1) a complete curriculum vitae, (2) a publication list, (3) a brief statement of present and future research plans, and (4) a statement of teaching philosophy. In addition, candidates should arrange for at least 3 letters of reference to be sent to ppsearch@purdue.edu. Questions regarding the position and search should be directed to neumeist@purdue.edu. Applications completed by November 15, 2019 will be given full consideration, although the search will continue until the position is filled.

Purdue University's Department of Physics and Astronomy is committed to advancing diversity in all areas of faculty effort, including scholarship, instruction, and engagement. Candidates should address at least one of these areas in their cover letter, indicating their past experiences, current interests or activities, and/or future goals to promote a climate that values diversity and inclusion. A background check will be required for employment in this position.

Crystal Bailey heads career programs at the American Physical Society in College Park, Maryland. **Douglas Arion** is professor of physics and astronomy and of entrepreneurship at Carthage College in Kenosha, Wisconsin.

Teaching physics for tomorrow

Equipping students to change the world

Crystal Bailey and Douglas Arion

Why should engineers have all the fun?

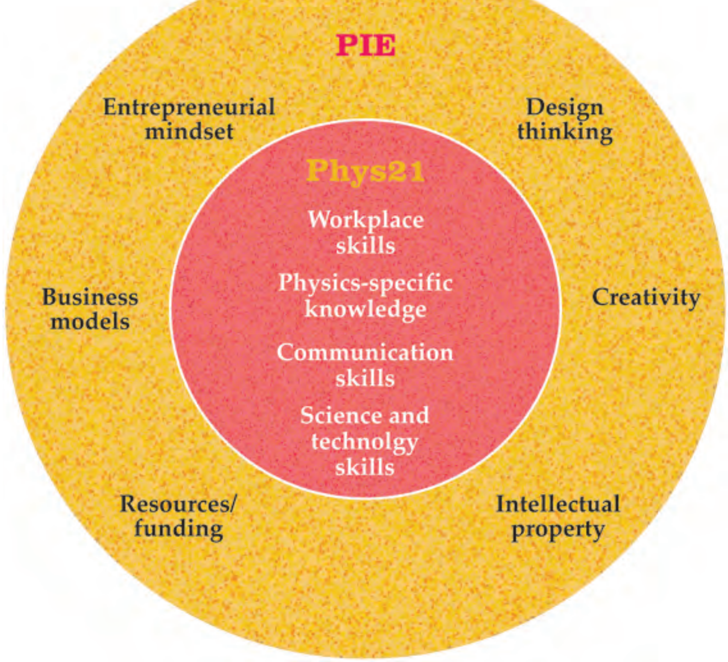
On a fine spring day in a hotel in downtown Washington, DC, a conference room full of educators listen raptly to a group of undergraduate students. One by one the students describe new technologies they developed—a process for eliminating fossil fuels from the production of synthetic materials or smart clothing that detects the physiological precursors of meltdowns in autistic children—and the companies they launched to market those technologies. Students recount how creating their product and launching their business was a deeply empowering and fulfilling experience, despite the hard work and uncertainty. They articulate how meaningful it is to create technologies that can improve human life.

STUART KINLOUGH/ALAMY STOCK PHOTO

Every student in that room is an engineering major; not a one a physics major.

Such was the scene at the March 2019 Open conference, held by an organization called VentureWell, where educators from across disciplines gathered to learn the latest in the pedagogy of innovation and entrepreneurship. The absence of physics students was odd, considering that so many major technologies that significantly affect human life started through research in physics. Wouldn't it make sense to see physics students applying their physics knowledge and ability to solve real-world problems?

Those trained in physics are able to solve problems, to apply mathematical and modeling skills, and to integrate and apply multiple technologies; their abilities make them particularly sought after by employers in many industrial and research environments. Only 5% of physics bachelor's degree recipients will ultimately become tenured physics faculty; the rest will apply their skills in a diverse range of careers, the vast majority in the private sector.[1] The same is true for recipients of physics PhDs. More than 60% of them also work in nonacademic environments.[2] If physics students received intentional training in innovation and entrepreneurship, and if they developed the mindset and vision to apply their skills, think of all the world's problems that could be solved!



THE SCOPE OF PIE (physics innovation and entrepreneurship) encompasses the recommendations of *Phys21: Preparing Physics Students for 21st-Century Careers*, the 2016 report of the Joint Task Force on Undergraduate Physics Programs.

Besides enhancing student skills and opportunities, other factors make innovation and entrepreneurship education even more important now. Pressure is increasing on undergraduate education to produce financial value for graduates, especially as more and more first-generation students from diverse cultural backgrounds enroll in college. The closures of Mount Ida College, Daniel Webster College, and Green Mountain College and the search by Hampshire College to find sustaining partners bring home the message: Colleges have to adapt if they are to survive.

Seven years ago, a group of individuals met serendipitously at a session at the March Meeting of the American Physical Society (APS) that focused on careers. There they discovered a shared and deeply held interest in developing a new approach to teaching physics, one that intentionally taught the skills, knowledge, and mindset to equip physics students to have more impact as scientists in the workforce. From that initial meeting, an informal working group formed. It has since blossomed into a community of practitioners of what we call physics innovation and entrepreneurship (PIE) education.

What PIE is—and what it isn't

PIE consists of experiences, courses, and research opportunities that convey leadership, communication, and other professional skills; that develop deep technological expertise and the confidence to translate it into innovative solutions to problems; and that create familiarity with intellectual property, return on investment, and other workforce-relevant concepts—all in the context of an undergraduate physics degree. PIE encompasses many of the skills and knowledge that will be relevant to future careers, but it also includes the mindset and knowledge that will enable physics students to recognize opportunities to address human needs and to translate their ideas into scalable solutions.

Don't be misled by the presence of "entrepreneurship" in PIE. Few physics students will go on to start their own companies. Even so, all students will benefit from understanding how to create value propositions, marshal funding and other resources, manage teams, think strategically, and deal with uncertainty. That's because the majority of them are destined for the private sector. And those students who do have entrepreneurial dreams will be far better positioned to realize them. What's more, the same skills are often essential for success in academic research environments. Integrating them into the physics curriculum will also serve the 5% of physics undergraduate degree recipients who pursue academic careers.

Despite the manifest benefits of PIE, faculty members wonder how they can incorporate its ideas while struggling with ever-tightening budgetary and time constraints. They also worry about preserving the "soul" of physics as a discipline. One of the earliest conversations our working group had with skeptical faculty members took place in 2015 at a panel on PIE at the APS March Meeting. Most of the attendees were undergraduates, graduate students, and postdocs, the demographic which tends to be in the majority at events with "entrepreneurship" in the title. However, a small number of highly engaged—even combative—physics faculty were also present. They voiced two major questions. Are you advocating turning our physics students into engineers? What physics will I leave out in order to teach PIE instead?

Since that session, the growing community of PIE practitioners has been continually revisiting the two questions. In short, the answer to the first question is no. The mathematical facility, problem-solving ability, and breadth of technical expertise that are hallmarks of physicists and distinguish them from engineers are what make physicists powerful innovators; they are enhanced through PIE education, not depleted. The answer to the second question is that PIE can be incorporated into the student experience in ways that do not reduce the qual-

Box 1. Examples of Curricular Materials

PIE Modules for Introductory Physics Courses

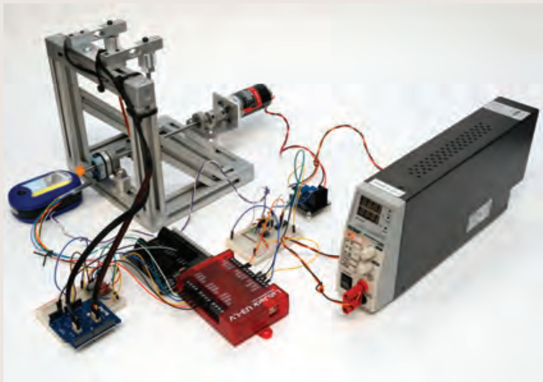
Led by Bahram Roughani
Loyola University Maryland (LUM)

These modules use design-thinking, which includes creative and appropriate attention to human needs while demonstrating the application of physics knowledge in real-world, human-focused applications. One module is based on the Hyperloop, the high-speed transport system proposed by a joint team from Tesla and SpaceX. Another module is based on a series of problems and exercises around human-powered pumps that have been developed and subsequently used for irrigation in sub-Saharan farming communities. In both modules, students are guided through a decision tree involving open-ended questions that combine physics with feasibility, such as energy output of humans, the distance to the river, and the area of the land to be irrigated. The activities embrace ambiguity, which is unavoidable in the real world. A course on technical innovation and entrepreneurship has also been developed and offered by the physics department to its own majors and others at LUM since 2016.

Technical Competencies Supporting Physics, Innovation, and Entrepreneurship

Led by Randall Tagg
University of Colorado Denver (CUD)

Prototyping requires integrating several technical competencies, including electronics, mechanical systems, sensors, actuators, optics, and computer-aided data acquisition and control. In some cases, vacuum systems, microwave systems, feedback control, and plasma generation are also needed. To introduce first-year physics majors to a basic range of competencies, the PIE initiative at CUD developed a two-semester sequence of applied physics labs. The formal lab work is augmented by informal opportunities to learn procedures, such as soldering, CAD, and 3D printing. A "grand finale" experiment from the module appears in the accompanying photograph. Designed to measure the speed of a DC motor in response to changes in frictional torque, the experiment incorporates, among other things, Python code to run it, a LabJack computer data-acquisition interface, and a converted LED flashlight used as a strobe. CUD's lab staff Devin Pace and Kris Bunker designed and built the apparatus.



Pop-Up Courses on Industry and Innovation

Led by Linda Barton
Rochester Institute of Technology (RIT)

At RIT we have experimented with what we call pop-up courses—short, informal workshops that introduce students to new topics in a low-pressure, casual atmosphere. Pop-up courses are typically self-contained, interactive, exploratory, and not highly scripted. At RIT, pop-ups have covered basic hands-on technical competencies such as electronics assembly, introductory metal working, and programming Arduinos (which was very popular, with student interest leading to additional activities on Linux installations and BASH scripting). We have also used pop-ups to explore career development topics, including resumé writing, job searching, elevator pitches, and networking (largely based on the Society of Physics Students Careers Toolbox). Whenever possible, we schedule career pop-ups to coincide with career fairs. Pop-up classes can serve as a vehicle for faculty development of curricular modules that could later be integrated into more traditional courses. Alternatively, the classes can stand alone as a fun way to broaden the training of physics students beyond the usual canon of traditional problem sets on traditional topics. The pop-up format makes it easy to introduce innovation and entrepreneurial elements (or any other material of interest) into the physics curriculum.

Agile Project Management in Physics Design Projects

Led by Wouter Deconinck
William & Mary

At William & Mary we developed capstone design projects in which student teams of three to five physics seniors solve research and technology development problems. Faculty researchers or external partners provide the problems and their contexts. To avoid analysis paralysis, we use concepts drawn from the agile approach to managing software development—namely, sprints (short, iterative bursts of development), scrums (brief daily meetings to share progress reports), and kanban (bulletin boards to track progress). Teams are required to demonstrate an increasingly functional prototype after each three-week sprint. The team generates and prioritizes a list of tasks at the start of the sprint. Every second day the team gathers for a 10-minute stand-up meeting (the scrum) to review a task-tracking board (the kanban) led by one of the students who is the scrum master. Each sprint ends with a prototype demonstration to the product owner (the faculty member or external partner) and a retrospective session, in which the team reflects on collaboration and performance. Together, the scrums, demos, and retrospectives give students opportunities to practice and improve their oral communication skills. They also instill self-motivation and project ownership better than do our traditional individual senior research projects.

ity and content of the physics education. Indeed, the core of our work is to develop educational approaches that teach innovation and entrepreneurship while retaining the factors and features that make a physics education so valuable.

Baking PIE: The APS PIPELINE Network

Several activities have occurred in the past few years to help those interested in PIE. Among them was a conference held in 2014 at the American Center for Physics in College Park, Maryland, attended by faculty from more than 40 institutions. One of the meeting's outcomes was a set of recommendations for how the value of innovation and entrepreneurship education could best be communicated and disseminated to other institutions. Recommendations included holding sessions at society meetings, creating a newsletter for communication, and creating and disseminating approaches for implementing PIE education. Out of those recommendations came a road map for the next steps that ultimately became a project called the Pathways to Innovation & Physics Entrepreneurship: Launching Institutional Engagement (PIPELINE) Network.

Box 2. Faculty Views of PIE

Forty faculty members from seven institutions participated in a study that assessed their perceptions, awareness, and experiences with physics innovation and entrepreneurship (PIE). Many of the challenges, such as boosting the role of computation and increasing the use of research-based instructional strategies, are shared by other efforts aimed at changing the way physics is taught. The commonality of challenges suggests that many effective ways developed to support those other initiatives could also work for PIE.

Sixteen faculty members whom we surveyed reported challenges in implementing PIE at their institutions. The following themes, ranked in order of prevalence, emerged.

1. **Lack of knowledge about nonacademic careers** limited faculty's ability to develop and deliver PIE-related curricula.
2. **Lack of recognition for faculty** who integrate PIE and career-focused elements into their teaching reduced motivation.
3. **Lack of interest among colleagues** and, more broadly, their departments left PIE champions feeling isolated.
4. **The physics major is already full,** leaving little room for new topics, such as PIE.
5. **Resources were lacking,** including connections to alumni who work in the private sector, time and funding to develop and implement PIE, and curricular materials.

Response	Are you aware of PIE?	Have you faced challenges implementing PIE?
Yes	53%	40%
Not sure	35%	20%
No	15%	40%

Meanwhile, activities focused on the career development of physics students have also taken place in the past few years. In 2014 APS and the American Association of Physics Teachers (AAPT) convened a joint task force on undergraduate physics programs (J-TUPP). Released in 2016, the task force's report, *Phys21: Preparing Physics Students for 21st-Century Careers*, identified the technical, communication, and workplace-relevant skills that physics students need besides expertise in physics.[3] (The report is outlined in the article by Laurie McNeil and Paula Heron, PHYSICS TODAY, November 2017, page 38.)

PIE aligns perfectly with the recommendations of *Phys21*. As awareness of the report has spread within the physics education community, increasing numbers of physics faculty are beginning to consider incorporating PIE in their teaching.

In September 2016 APS launched the NSF-funded PIPELINE Network. The collaborative, three-year project unites the efforts of seven institutions (William & Mary, George Washington University, Loyola University Maryland, Rochester Institute of Technology (RIT), Worcester Polytechnic Institute, Wright State University, and University of Colorado Denver) to develop and disseminate PIE materials and to seed a nascent community of experienced PIE practitioners. PIPELINE is guided by educators who have already established successful innovation and entrepreneurship programs for physics students, including one of us (Arion), whose ScienceWorks entrepreneurship program at Carthage College launched in 1994; Ed Caner, who is with the physics entrepreneurship master's program at Case Western University; and Dan Ludwigsen at Kettering University. PIPELINE's work has also been guided by an advisory board of industrial physicists who have extensive experience as entrepreneurs and in the private sector.

A primary goal of PIPELINE has been the development and testing of several sets of curricular materials. Some of them are described in detail in box 1. The courses have received enthusiastic reviews from students who took them, and many additional student-driven projects have sprung from those initial activities. Some have caught cross-campus attention and created new opportunities for collaboration among departments and disciplines; many institutions value such opportunities.

Our second goal, increasing engagement of physics faculty in the PIE community, has been more challenging to achieve and measure, despite our monthly PIE newsletter, our talks at numerous invited sessions at APS and AAPT meetings, and the articles we've written for APS publications. In 2017 a general survey went out to members of the APS Forum on Education. Of the 68 who responded, at least half indicated that they would take advantage of resources that would help them implement PIE. Yet the number of physics educators at PIE-focused workshops and sessions at annual APS meetings remains dwarfed by the number of students and early-career physicists who see the value of the entrepreneurial mindset and the broader application of their physics training.

Why educators seem reticent to fully engage is revealed by a third goal of PIPELINE: an assessment and evaluation process that looked at the attitudes toward PIE of both faculty and students. As detailed in box 2, many physics faculty seem to recognize the general value of PIE and are interested in learning more. (The findings in boxes 2–4 come from research by Benjamin Zwickl of RIT and Anne Leak of High Point University.) Yet obstacles to implementation remain, including a lack of familiarity with PIE concepts, lack of recognition and support for such activities at the institutional level, and the perception that physics content will be lost by incorporating PIE into the curriculum.

Many faculty members don't realize that they don't have to teach both physics and PIE themselves, so it's not a zero-sum game when it comes to their time. Students can gain PIE skills through a variety of on- and off-campus experiences. The physics curriculum can still address all of the core topics, skills, and abilities that make physicists so valuable while also preparing students for careers in industry.

That principle of combining core physics with entrepreneurship and innovation is exemplified by a module developed at Loyola University Maryland, and based on Hyperloop, the high-speed transportation system being explored by Tesla and SpaceX. Hyperloop envisions sending trains of pods containing people or freight through airless tubes. Instead of teaching kinematics by having students solve an arbitrary projectile motion problem, the module guides students through problems of increasing complexity associated with the feasibility of operating a train moving at 730 km/h in an evacuated tunnel. As the students tackle the problems, they have opportunities to exercise their creativity by devising innovative ways to ensure that design or

Box 3. Student Views of PIE

The seven essential aspects of PIE label the columns of the chart on the right. Students learn, think they learn, or fail to learn about them through various channels (rows) and at different rates (numbers), as the chart and quotations illustrate.

"Sometimes design skills may be needed in a lab and will most likely be needed in research. However, you usually don't learn too much in the actual physics class."

"I am a leader on my volleyball team at school, so I think I have learned team efficiency strategies from there and have incorporated them into my academic work."

"I have learned a lot about technology during my research. It has helped me specifically understand how computer programming works."

"I haven't learned any business skills in my physics classes. The only place I have absorbed business skills is from my financial accounting class."

"Being a TA allows me to have time to thoroughly explain my reasoning behind physics topics to others with little experience."

"Homework has provided me the most opportunity for creativity in physics because there are usually multiple ways to approach a problem. We have to figure out which approach is best."

"The only place where I have heard about the impacts of physics on society is in my science, technology, and values class, where we have been learning about the making of atomic bombs."

"After attending meetings for both SPS and Women in Science, I get a very clear picture of what my life might be like after my physics degree."

Number of respondents: 40 30 20 10 0

	Business	Communication	Creativity	Design	Leadership	Social impact	Technical skills
Lab courses in physics	6	30	25	37	26	10	47
Extracurriculars	22	23	21	16	40	18	13
Research/internship	20	27	25	17	15	14	30
Courses outside physics	31	15	20	24	8	18	21
Teaching/learning assistant	10	32	16	3	33	13	6
Physics homework	5	12	26	10	11	5	13
Lecture courses in physics	2	10	10	8	2	32	12
Professional association	19	10	3	1	19	20	0

physics considerations do not impair the technology's desirability. What's more, the module deliberately asks open-ended questions and leaves crucial quantities undefined. For example, students are to assume that the train accelerates at a "comfortable" rather than specified rate. The tactic familiarizes students with ambiguity and encourages them to make reasonable, well-informed estimates. The ability to confidently move beyond the boundaries of what is known and make good guesses is a characteristic of physicists. Students who take the module acquire the essential mindset of a physicist while solving a real-world problem, and they do so at the start of their physics education.

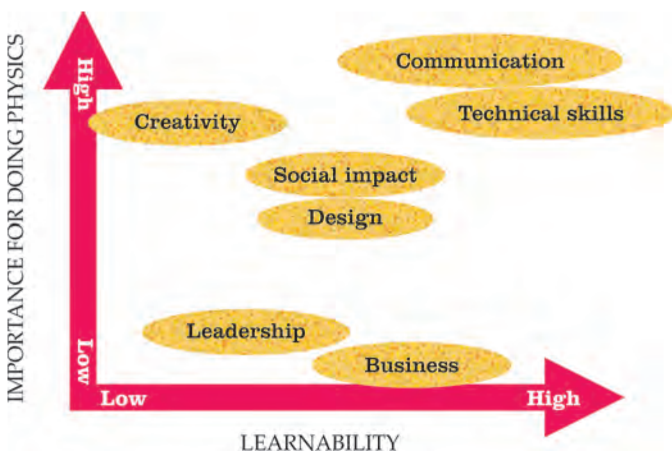
Students also harbor misconceptions about PIE. As boxes 3 and 4 detail, our research revealed that students' perceptions differ from those of experts. In particular, students did not believe that some aspects of innovation and entrepreneurship were—or even should be—taught within physics. They did not gain an understanding of the discipline's benefits to society. They maintained a belief that the disciplinary boundaries between, for example, physics, engineering, and business are real and that their physics education doesn't require understanding design and learning cross-disciplinary topics.

That last revelation is especially unfortunate because cross-disciplinary skills are essential even for careers in fundamental physics research. More importantly, when most students go out to work in the private sector, they will be working on interdisciplinary teams. Part of their value as generalists is to be able to speak lots of different disciplinary "languages." Their perception that they should let arbitrary boundaries define what they can and can't do diminishes that value.

In addition to attitudinal roadblocks among faculty and students, there is also a dearth of tested, effective PIE materials that can be used by practitioners with different experience levels. Also lacking among physics faculty are knowledge of and comfort with teaching PIE concepts. Encouragingly, 89% of the respondents to the APS Forum on Education survey said that they would take advantage of an online platform for sharing and developing PIE curricula.

How to make this happen

To reiterate: PIPELINE aims to prepare students for 21st-century career options and to make them more effective at solving the



IMPORTANCE AND LEARNABILITY of seven aspects of PIE as perceived by students.

Box 4. How Experts and Students Define the Seven Aspects of PIE

I&E aspects	Expert definitions	Student definitions
Business	Goal-driven, client-oriented, consideration of costs and systems	Consideration of cost, awareness of audience, social interactions important
Communication	Teamwork, audience and purpose, working with clients, asking questions, documentation, presentations	Teamwork, explaining physics clearly and concisely, focused on oral communication more than written communication
Creativity	Novel ideas and solutions, innovation in products and processes	Essential for solving problems, especially complex ones with unclear solutions
Design	Awareness of end user and purpose, modeling and software, systems thinking	Creating experiments and computational models, using design software
Leadership	Project or team management, initiative, organizational mindset	Collaboration with peers, leading group work, teaching physics to others
Social impact	Considering impact on people and communities, making positive change	Negative impacts of physics, advancing science through physics discoveries, relating physics to personal experiences
Technical skills	Programming, hardware, specialized tools/equipment, hands-on making	Programming, software, lab equipment

problems of today and tomorrow. To accomplish that vision, it's important to help physics faculty understand the value of teaching PIE, help physics faculty who are interested do so effectively, and help physics students understand that the skills, knowledge, and mindset they gain through PIE will bring them closer to realizing their dreams.

To expand the community of practice to include more faculty (and departments) that are invested in adopting PIE, we first want to create mechanisms that facilitate the successful implementation of existing PIE curricula. Physics faculty members who are interested in teaching PIE should have access to resources that will enable them to at least experiment even if they aren't experienced practitioners.

We also want to create scaffolding for physics faculty members who are currently implementing and developing new approaches to PIE. By using the scaffolding, the developers of PIE materials can share what they have created with others, who in turn can build approaches that work in their particular landscape of resources and barriers. When the initially "PIE-curious" begin to feel comfortable creating new approaches and mentoring the next rounds of adopters, we will see our promotional efforts turn a corner toward a self-sustained and self-led community. Eventually, what we believe is a long-overdue evolution in physics pedagogy will not only help physics graduates get jobs but will also inspire and empower them to make positive changes in the world.

All PIE approaches developed under PIPELINE, including the ones mentioned in box 1, can be found on our website (go.aps.org/innovation). Educators are heartily invited to use and adapt the materials and to submit approaches that they develop. Through early 2020, APS will be hosting a series of webinars that introduce each of the existing PIE approaches and provide advice on implementation. The webinars will include a Q&A session during the live broadcast, and the recording of the presentation and discussion will be available with the source material. You can sign up to receive notifications of the broadcasts by subscribing to APS *PIE News*, a monthly newsletter featuring newly developed PIE curricular approaches, fresh opportunities to learn more or get involved in PIE, and resources available through APS and other organizations, such as the American Society for Engineering Education and VentureWell. To join the newsletter mailing list, visit the PIE website. Lastly, we have compiled a PIE speakers' list, which is also available on the PIE website. Here you can find people who can describe the materials they have developed, provide advice on your efforts, and help you build institutional support.

Building a successful 21st-century workforce, maintaining the relevance of the study of physics, and adapting education to the shifting demographics and pressures on institutions are keys to the success of physics as a discipline and the future of higher education. We hope that you will join us in these efforts.

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2. National Science Foundation, *National Survey of College Graduates*, NSF (2017).
3. Joint Task Force on Undergraduate Physics Programs, *Phys21: Preparing Physics Students for 21st-Century Careers*, American Physical Society (October 2016).

PT

UNIVERSITY OF NOTRE DAME

Accepting applications for faculty positions in physics

TENURE-TRACK PROFESSOR IN PHYSICS

The Department of Physics at the University of Notre Dame invites applications for a tenure-track faculty position. Experimentalists and theorists in all areas of physics are encouraged to apply. The principal research areas in the department are astronomy/astrophysics, biophysics, condensed matter physics, high-energy physics, network science, and nuclear physics. Candidates in other research areas, as well as interdisciplinary research, will also receive full consideration.

The successful candidate must demonstrate the ability to develop a highly successful research program, attract independent research funding, and to teach effectively at both the graduate and undergraduate level. Salary and rank will be commensurate with the successful applicant's experience and research accomplishments. The expected start date is August 2020.

Applicants should submit a curriculum vitae, list of publications, detailed research plans, and a statement of teaching interests. Candidates must also arrange for at least three letters of recommendation. Applications must be received by November 1, 2019.

Apply at: **https://apply.interfolio.com/66465**

TENURE-TRACK FACULTY IN CONDENSED MATTER PHYSICS

The Department of Physics at the University of Notre Dame invites applications for up to two tenure-track faculty positions in Condensed Matter Physics. Experimental and theoretical Condensed Matter Physicists are encouraged to apply. Applications from tenured/senior researchers will also be considered.

The condensed matter group at Notre Dame consists of 7 experimental and 4 theoretical faculty, doing research in hard condensed matter, quantum materials, complex networks, and biophysics. The successful candidate should have a strong track record in condensed matter research, will be expected to attract independent research funding and to teach effectively at both the graduate and undergraduate level. Salary and rank will be commensurate with the successful applicant's experience and research accomplishments. The expected start date is August 2020.

Applicants should submit a curriculum vitae, list of publications, detailed research plans, and a statement of teaching interests. Candidates must also arrange for at least three letters of recommendation. Applications received by November 1 will receive full consideration.

Apply at: **https://apply.interfolio.com/66898**

The Department of Physics has 43 tenured and tenure-track faculty; another 23 research, teaching and concurrent faculty; more than 100 graduate students; and about 120 undergraduate physics majors. Additional information about the department and the College of Science can be found at **http://physics.nd.edu** and **http://science.nd.edu** respectively.

Equal Opportunity Employment Statement: The University of Notre Dame seeks to attract, develop, and retain the highest quality faculty, staff and administration. The University is an Equal Opportunity Employer, and is committed to building a culturally diverse workplace. We strongly encourage applications from female and minority candidates and those candidates attracted to a university with a Catholic identity. Moreover, Notre Dame prohibits discrimination against veterans or disabled qualified individuals, and requires affirmative action by covered contractors to employ and advance veterans and qualified individuals with disabilities in compliance with 41 CFR 60-741.5(a) and 41 CFR 60-300.5(a).

FACULTY AND POSTDOCTORAL POSITIONS

International Center For Quantum Materials
Peking University, China

The International Center for Quantum Materials (**http://icqm.pku.edu.cn**) invites applications for tenured/tenure-track faculty positions and postdoctoral positions in the fields of condensed matter physics; atomic, molecular, and optical (AMO) physics; solid-state based quantum information science (QIS); material physics and related areas. During the next phase of enhancement, the center has a number of faculty lines and postdoctoral positions open for applications.

Candidates must have a Ph. D in a relevant discipline, outstanding record of research accomplishments, and capability to lead an independent research group. The position offered will be commensurate with individual's work experience and research track-record.

All newly hired faculty members will be offered competitive resources and office/lab spaces. Annual salaries for faculty positions are competitive with US research universities. Peking University provides employee benefits package. Postdoctoral fellows will be provided with competitive annual stipends based on individual's experience and research performance. Housing subsidies will be provided.

Applicants for a faculty position should send full curriculum vitae; copies of 3-5 key publications; 3 letters of recommendation; and a statement of research to Prof. Nanlin Wang at **ICQM@pku.edu.cn**. Application for a postdoctoral position should be directly addressed to an individual prospective advisor.

UMBC

Department of Physics, Atmospheric Physics Program (ATPH), invites applications for a tenure-track assistant professor position with a research focus in one or more of the following research areas: regional to global scale climate modeling with emphasis in boundary layer processes, numerical simulation of aerosol-cloud interactions, computational fluid dynamics, or other areas related to numerical weather/climate simulation to begin on or before August 2020. Exceptionally qualified candidates may also be considered at a higher level of appointment. Candidates are expected to contribute to the diversity and excellence of the department and group through research, teaching and service. We seek candidates who have the capacity to establish a vigorous, externally funded research program that complements existing faculty research interests, and who are able to teach effectively both the undergraduate physics curricula and graduate atmospheric courses in the ATPH program. A PhD in Physics or in a closely related field is required. Interested candidates should upload an application letter, a CV, detailed research and teaching plans, a statement of commitment to Inclusive Excellence in Higher Education, and the names and addresses of at least three references on the Interfolio website at apply.interfolio.com/65991. Applications will be received until a suitable candidate is identified. Applications received by November 1, 2019 will receive full consideration.

Massachusetts Institute of Technology

Come work with us!

The Physics Department of the Massachusetts Institute of Technology, located in Cambridge, Massachusetts invites applications for the faculty positions described below. Faculty members at MIT conduct research, teach undergraduate and graduate physics courses, and supervise graduate and undergraduate participation in research. Candidates must show promise in teaching as well as in research. A Ph.D. in physics or physics-related discipline is required by the start of employment. Preference will be given to applicants at the Assistant Professor level.

The application deadline for all faculty positions is November 15, 2019. Applicants should submit a curriculum vitae, a list of publications, and a brief description of research interests and goals (the latter NOT TO EXCEED 3 PAGES IN LENGTH) at the following web site: http://www.academicjobsonline.com. Applicants should also arrange for three letters of reference to be uploaded to the same site. Only web submissions will be accepted.

Candidates who are uncertain whether they fit into a particular search should contact the most relevant search chair.

Astrophysics: The Astrophysics search is unrestricted with respect to area of specialization, but has a particular interest in candidates working in astrophysics theory. Current astrophysics faculty are active in broad areas of observational and theoretical astrophysics, including optical/IR, radio, and high energy astronomy; studies of exoplanets; gravitational wave science; and observational and theoretical cosmology. MIT hosts the Kavli Institute for Astrophysics and Space Research, whose faculty and research staff contribute instrumentation for and conduct research using several facilities including the Laser Interferometer Gravitational-Wave Observatory (LIGO), the Magellan telescopes, the Hydrogen Epoch of Reionization Array (HERA), the Chandra X-ray Observatory, the Neutron Star Interior Composition Explorer (NICER), and the Transiting Exoplanet Survey Satellite (TESS), as well as an in-house high-performance computing cluster. Enquiries should be directed to Prof. Scott Hughes, Search Committee Chair, sahughes@mit.edu.

Soft Condensed Matter and Biological Physics: We invite applications for a faculty position in the fields of Soft Condensed Matter and Biological Physics. Preference will be given to individuals with a significant theoretical component to their research. Any enquiries should be directed to Professor Mehran Kardar, Search Committee Chair, kardar@mit.edu.

Theoretical Physics: The Center for Theoretical Physics at MIT is seeking applications for a junior faculty appointment in high-energy, nuclear, and/or quantum physics. We encourage applicants doing relevant research at any energy scale, including areas such as quantum computing and quantum information; cosmology, dark matter, and astroparticle physics; particle theory in and beyond the standard model; quantum field theory and amplitudes; QCD including strongly coupled matter; and string theory, gravity, holography, and mathematical physics. Candidates will be evaluated on the basis of potential contributions to theoretical physics research, and to the undergraduate and graduate teaching programs of the MIT Department of Physics. Interviews will occur in February 2020. Any inquiries should be directed to Professor Jesse Thaler, Search Committee Chair, at ctp-facultysearch@mit.edu.

MIT is an equal employment opportunity employer. All qualified applicants will receive consideration for employment and will not be discriminated against on the basis of race, color, sex, sexual orientation, gender identity, religion, disability, age, genetic information, veteran status, ancestry, or national or ethnic origin.

http://web.mit.edu

Alexander L. Rudolph is a professor of physics and astronomy at California State Polytechnic University in Pomona and the director of the Cal-Bridge program.

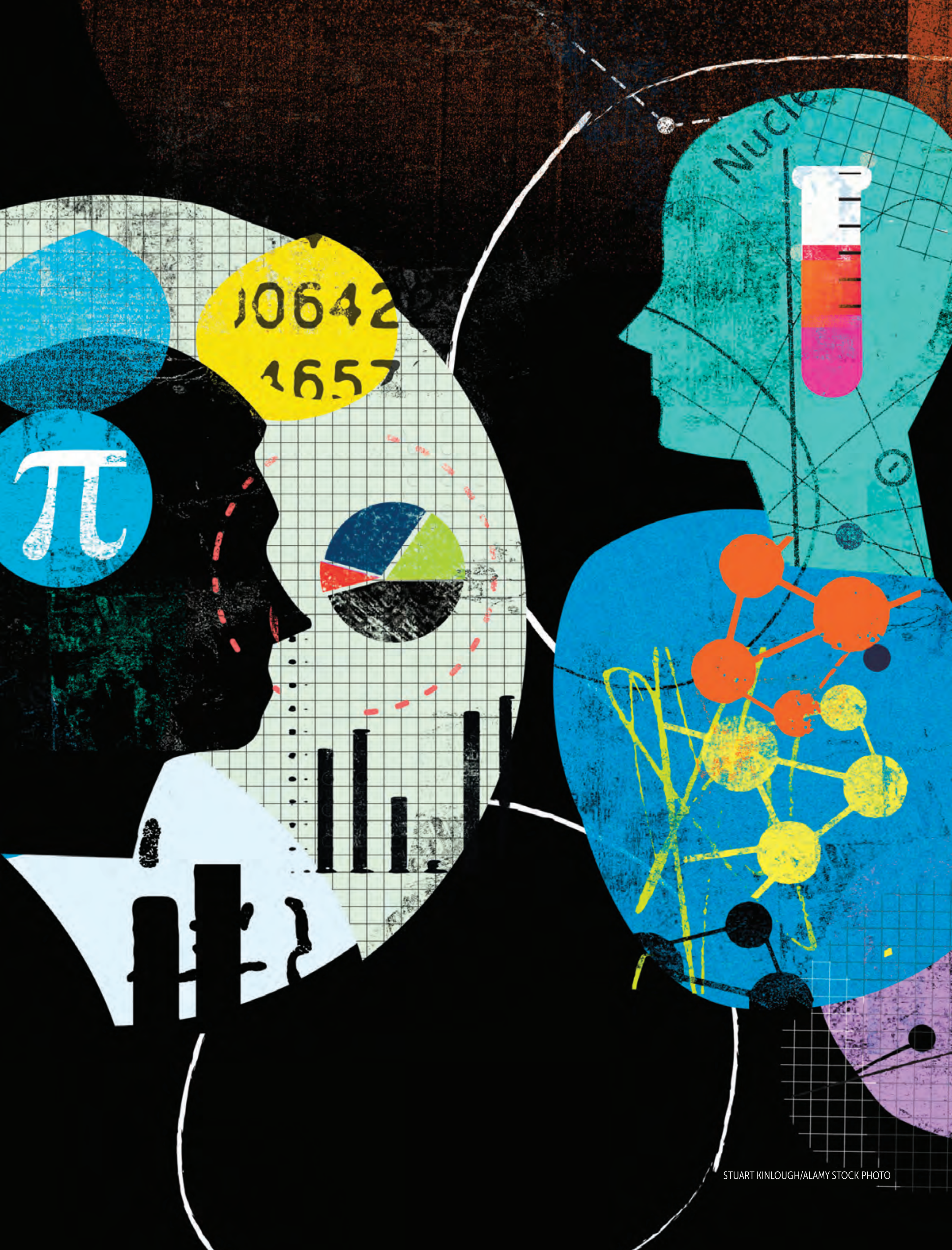
Cal-Bridge

Creating pathways to the PhD for underrepresented students in physics and astronomy

Alexander L. Rudolph

The Cal-Bridge program connects promising juniors and seniors from underrepresented groups with STEM faculty mentors to help smooth the transition from undergraduate to graduate programs.

The challenge of creating equal representation in STEM (science, technology, engineering, and math) is a long-standing one that has resisted improvement. The problem is especially stark at the PhD level. The number of underrepresented minorities (URMs), comprising the groups Latinx or Hispanic, Black or African American, and Native American, receiving STEM PhDs has remained around 14%, even though those groups make up more than 30% of the US population.[1] The problem is even more acute in physics and astronomy, where the percentage of PhDs awarded to URMs in 2016 was only 6% of the total. Women are also underrepresented, making up only 20% of PhDs in physics and astronomy, lagging even the rest of the STEM fields (see figure 1).



STUART KINLOUGH/ALAMY STOCK PHOTO

Attempts to address the lack of representation have had limited success. However, some recent programs are beginning to make progress. One of them is the Cal-Bridge program, a partnership between 9 University of California (UC), 16 California State University (CSU), and more than 30 community college campuses in California. The mission of Cal-Bridge is to increase the numbers of traditionally underrepresented groups in PhD programs in physics, astronomy, and closely related fields. More than 160 physics and astronomy faculty from the three systems participate in the program. The Cal-Bridge model has the potential to improve representation and inclusion in STEM PhD programs.

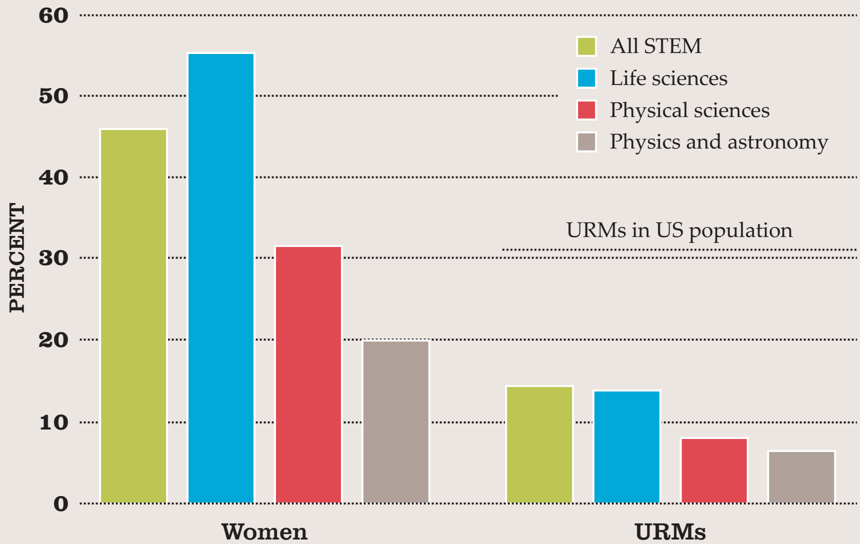


FIGURE 1. PERCENTAGE OF STEM PHDS AWARDED IN 2016 to women and to members of underrepresented minorities (URMs). Numbers of PhDs awarded to members of both groups (for example, women of color) are even lower and are not reported separately by NSF. (Adapted from ref. 1.)

Problems and progress

Reducing inequities at all educational levels is crucial both for creating equal opportunities and for ensuring the future health of the US scientific community. In the National Academies report *Expanding Underrepresented Minority Participation*, the authors note that "the S&E [science & engineering] workforce is large and fast-growing: more than 5 million strong and projected by the U.S. Bureau of Labor Statistics to grow faster than any other sector in coming years. This growth rate provides an opportunity to draw on new sources of talent, including underrepresented minorities, to make our S&E workforce as robust and dynamic as possible."[2]

Students with STEM degrees have a wide range of careers open to them (see the article in this issue by Anne Marie Porter and Susan White, page 32), and unemployment rates decrease rapidly with increasing education, from 5.3% for high school graduates, to 2.5% for those with a bachelor's degree, and even lower for those with advanced degrees.[3] About 12% of PhDs in STEM eventually attain faculty jobs,[4] where they become the teachers and role models for the next generation of college students. Although that percentage is relatively small, diversifying the faculty in physics and astronomy is an important goal. Studies have consistently shown that a lack of faculty role models dissuades students from underrepresented groups from choosing a STEM major.[5] In physics and astronomy, only 16% of faculty are women and 5% are URMs.[6] Inequalities in the professoriate and workforce are thus intertwined.

The percentage of URMs and women in physics and astronomy PhD programs has been slow to change, and the problem is even more acute for those with multiple underrepresented identities, such as women of color, even as the physics community recognizes those percentages as a problem (see the article by Jennifer Blue, Adrienne Traxler, and Ximena Cid, PHYSICS TODAY, March 2018, page 40). But some recent efforts are beginning to bear fruit. For example, there has been a small increase in the number of Hispanic PhDs in those fields in the past few years,[1] possibly due to the growth of PhD bridge programs such as Cal-Bridge, the Fisk–Vanderbilt Master's-to-PhD Bridge Program,[7,8] Columbia University's Bridge to the PhD Program, and the American Physical Society (APS) Bridge Program.

Other than Cal-Bridge, those programs are all based on a postbaccalaureate model. The oldest, Fisk–Vanderbilt, is an innovative partnership between Fisk University, a prominent historically black institution, and Vanderbilt University, a top research university located only two miles away. The program focuses on the master's degree as a key pathway to the PhD for URM students. Minority students are approximately 50% more likely to seek a master's degree on their way to a PhD than are nonminority students.[9] The Fisk–Vanderbilt program currently grants 10 times the national average of URM PhDs in astronomy and 5 times the national average in physics.

The APS Bridge Program recruits candidates nationally and matches them with dozens of vetted graduate programs, mostly PhDs, in physics. Two-thirds of applicants to the APS program had not been admitted to a PhD program; the other third had not applied at all, often due to perceived deficiencies in their GPA or physics GRE score. As of 2019 the program had placed more than 200 applicants into bridge programs or partner sites, including 40 students in 2016 alone, the last year they reported (see the article by Ted Hodapp and Kathryne Woodle, PHYSICS TODAY, February 2017, page 50).

Cal-Bridge: A different model

The bridge programs described above serve postbaccalaureate students who did not transition directly to a PhD program after

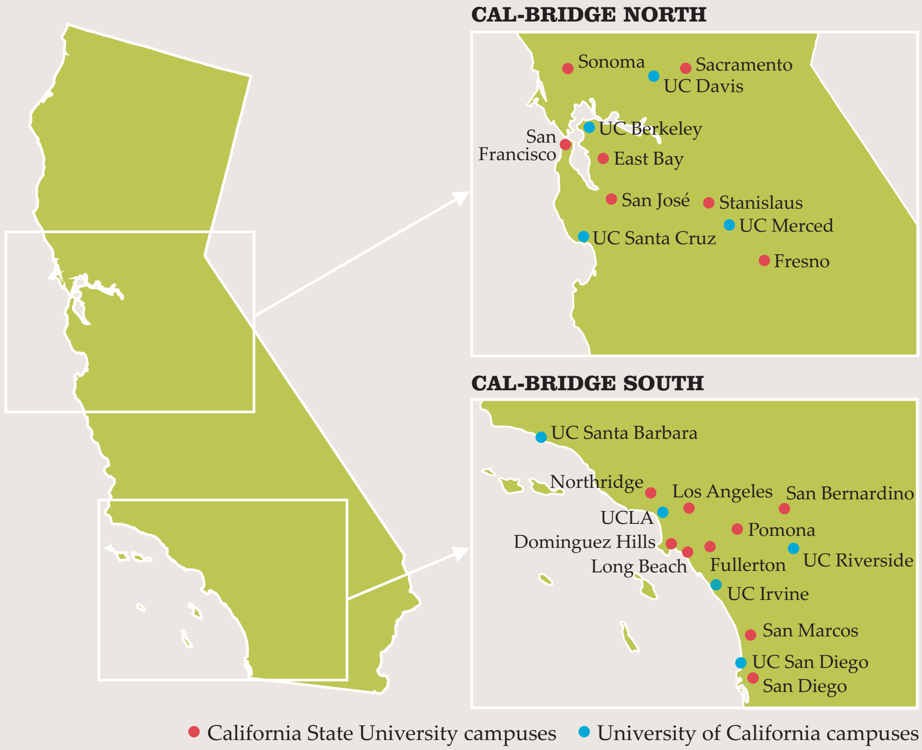


FIGURE 2. LOCATIONS OF CAL-BRIDGE CAMPUSES.

receiving a bachelor's degree. The Cal-Bridge model offers a different approach: ensuring adequate preparation and broadening faculty attitudes in the PhD admissions process *before* students graduate with a bachelor's degree.

To achieve that end, the Cal-Bridge program recruits and supports students entering their last two years of undergraduate studies. In 2015 almost 70% of undergraduate URM students interested in STEM did not complete their STEM degree, and few proceeded to pursue a PhD.[10] Given the high attrition rate, it is critical to support students as early as possible. Our hope is to eliminate the necessity for the detour many underrepresented students take by obtaining master's training at one university before obtaining a PhD at another institution. We also hope to identify and recruit students who never even make it to the stage of applying to programs like Fisk–Vanderbilt and APS Bridge, let alone a PhD program, because they struggled early in their undergraduate career or lacked awareness of the PhD as a possibility.

The Cal-Bridge program is divided into two parallel subprograms, Cal-Bridge South and Cal-Bridge North (see figure 2). Recruiting takes place at the 16 participating CSU campuses, plus more than 30 community colleges that are primary feeders for transfer students to CSUs. Faculty mentors at the CSUs and one or more liaisons at each community college are the primary program recruiters. They are responsible for identifying, cultivating, and mentoring potential applicants. That form of active recruiting is critical to increasing diversity; we have found that many students from underrepresented groups lack basic knowledge about a PhD as a path to follow or do not feel welcome in our fields unless specifically encouraged.

Cal-Bridge selects scholars using a model similar to Fisk–Vanderbilt, which is based on social science research and employs specific criteria and practices.[5] Applications are submitted online and include three essay questions designed to elicit information about the motivation and capabilities of the applicants. Each region has its own steering committee, which consists of UC, CSU, and community college faculty. The steering committees for each region review the initial applicant pool. A group of finalists is selected for in-depth 30-minute interviews via video conference with two steering committee members, one from a CSU or community college and one from the UC system. The steering committees then meet to select the Cal-Bridge scholars for their region based on the criteria in the interview protocol.

During the process, steering committee members review the applicant's personal essays and letters of recommendation to assess the student's work ethic, initiative, focus, and perseverance; consider their academic performance in math and physics courses; and evaluate their community service, leadership, and outreach activities as indicators of motivation and long-term goals. Committee members also focus on the student's academic potential as evidenced by performance in individual courses and improvement over time, and take into account situations where a student might have an uneven record due to external demands like work, family, or psychosocial stressors.

Program structure

The National Academies report *Expanding Underrepresented Minority Participation* highlights two key priorities for broadening participation in the STEM workforce. To address the first priority, undergraduate retention and completion, the report proposes that higher education institutions provide "strong academic, social, and financial support . . . along with programs that simultaneously integrate academic, social, and professional development."[11] For the second priority, transition to graduate study, it encourages programs that support the transition from undergraduate to graduate education and provide support in graduate programs.

The design and implementation of Cal-Bridge reflects those priorities and solutions by building the program on four pillars: financial support, mentoring, cohort building and professional development, and research experiences. In addition, faculty at both the scholars' home institutions and at the institutions where the scholars hope to matriculate to obtain their PhD are active participants. We next describe the resources for scholars and participating faculty under each pillar.

FIGURE 3. CAL-BRIDGE NORTH (LEFT) AND SOUTH (BELOW) SCHOLARS at fall 2018 orientation. (Courtesy of the Cal-Bridge program.)

Financial support

Most applicants to Cal-Bridge have demonstrated financial need beyond the aid they already receive from the state and federal governments. Based on 2016–17 data, 80% of CSU students receive financial aid, despite the relatively low cost of attendance: In-state resident tuition and fees are about $7000, and, depending on housing arrangements (on campus versus off campus), the full cost of attendance ranges from $15 000 to $25 000, including room, board, books, and so on. Of the CSU students receiving aid, 61% received Pell Grants. Average parental income of students receiving aid in the CSU system is under $45 000.

Cal-Bridge scholars are given two years of need-based scholarship support, up to $10 000 per year, at their CSU campus to supplement any grants or scholarships they receive. The average need-based grant of Cal-Bridge scholars has been $9400. Most CSU students work to pay for their education and to help provide financial support to their families. Many scholars have been working 20 to 30 hours per week during their first two years of college, and some even hold full-time jobs that take valuable time away from their studies and from research and mentoring opportunities. As a condition of participation, Cal-Bridge scholars are limited to working fewer than 10 hours per week; thus financial support from Cal-Bridge allows students to remain engaged in their classes and in program activities.

Mentoring

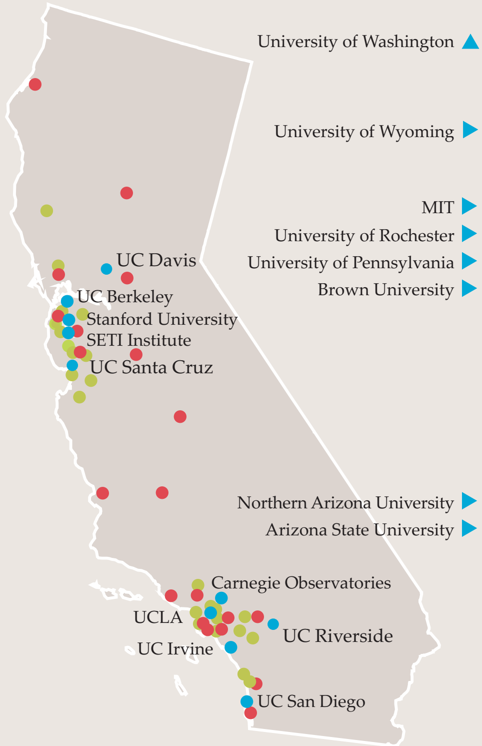
Following the Fisk–Vanderbilt model, each scholar is formally assigned two mentors: a CSU faculty member at their home institution and a UC faculty member. Mentoring programs have been shown to improve persistence, student performance, and academic self-esteem.[12,13] Joint mentoring is the best way to track student progress and to ensure scholars' readiness for PhD-level graduate work. Mentoring takes place via twice-monthly meetings between each scholar and their two mentors. The CSU faculty mentor gives academic advice on course selection and study habits, guides students toward research opportunities, and helps them apply to graduate school. The UC mentor performs similar functions and is also especially qualified to provide guidance toward readiness for graduate school.

The participation of a UC faculty mentor is a novel and critical piece of the Cal-Bridge model. Exposure to regular advice and validation from a faculty member at a PhD program gives added weight to the encouragement and guidance students receive. The UC mentor also advises the scholars on what is expected in a graduate school application and guides them through the application process.

Mentors also obtain monthly feedback from each scholar's instructors in order to track academic progress and catch problems early. That system allows for intervention when necessary; for example, mentors might help scholars work on their study habits or connect them with UC graduate student tutors, paid for by the program. To ensure that Cal-Bridge mentors implement research-based best practices, mentoring experts provide training workshops for Cal-Bridge faculty participants. Experienced faculty mentors also act as "near-peer" mentors to newer Cal-Bridge faculty.

Cal-Bridge also facilitates regular meetings among the faculty and students from different campuses and systems. Those meetings enable an exchange of information about how undergraduates should train and prepare for graduate school. Students and CSU and community college faculty members gain insight into graduate admissions decisions with the help of UC faculty who sit on PhD admissions committees.

Simultaneously, the UC faculty members gain reciprocal insight into the lives of CSU students, which greatly increases the faculty's awareness of both the challenges those students



CALIFORNIA STATE UNIVERSITIES

Cal Poly Pomona
Cal Poly San Luis Obispo
CSU Bakersfield
CSU Channel Islands
CSU Chico
CSU Dominguez Hills
CSU East Bay
CSU Fresno
CSU Fullerton
CSU Long Beach
CSU Los Angeles
CSU Northridge
CSU San Bernardino
CSU San Marco
CSU Stanislaus
Humboldt State
Sacramento State
San Diego State
San Francisco State
San José State
Sonoma State

COMMUNITY COLLEGES

Cabrillo College
Cerritos College
Chabot College
Chaffey College
City College of San Francisco
College of the Canyons
College of San Mateo
Cypress College
De Anza College
Diablo Valley College
El Camino College
Evergreen Valley College
Foothill College
Gavilan College
Glendale College
Hartnell College
Los Angeles Southwest College
Mendocino College
MiraCosta College
Mt San Antonio College
Norco College (Riverside)
Palomar College
Pasadena City College
Rio Hondo College
Riverside Community College
San Diego Miramar College
San José City College
Santa Monica College
Santa Rosa Junior College
Skyline College

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Carnegie Observatories
Northern Arizona University
SETI Institute
Stanford University
UC Davis
UC Irvine (SURF program)
UC Riverside (MSRIP program)
UC San Diego (STARS program)
UC Santa Cruz
University of Rochester
University of Wyoming
CHAMP program:
- Arizona State University
- Brown University
- MIT
- UC Berkeley
- UCLA
- University of Pennsylvania
- University of Washington

FIGURE 4. LOCATIONS OF COLLEGES AND UNIVERSITIES IN THE CAMPARE NETWORK. CAMPARE, a sister program to Cal-Bridge, matches promising undergraduates with summer research opportunities in STEM fields. The CAMPARE HERA Astronomy Minority Partnership (CHAMP) is a subprogram of CAMPARE that partners with the Hydrogen Epoch of Reionization Array (HERA) project.

face and the strengths they can bring to a graduate program, strengths that may not be reflected in a paper application. When those UC faculty members evaluate applications to their PhD programs, their experience with Cal-Bridge may broaden the network of institutions and faculty recommenders that they trust to endorse qualified applicants. That familiarity can minimize the perceived risks of admitting students from institutions whose reputations UC faculty are less familiar with.[14] Identifying changes to the recruiting and admissions process that smooth the transition of underrepresented students into graduate school and building an institutional apparatus to support those changes are primary long-term goals of the Cal-Bridge program.

Cohort-building and professional development

To foster holistic support for young scholars, Cal-Bridge also holds regular monthly cohort-building, skill-building, and professional development workshops. Most are combined with a visit to a UC campus. The geographic compactness of the Cal-Bridge schools in each region, as seen in figure 2, makes it feasible for Cal-Bridge scholars to attend in-person workshops. That attendance in turn supports the creation of a peer cohort among Cal-Bridge scholars, an essential program element that increases retention.[15]

In the new scholar orientation, newly selected students (see figure 3) are introduced to the program and presented with the Cal-Bridge scholar contract, which outlines the obligations of the program and establishes clear expectations. Returning scholars work on developing a list of graduate schools to which they plan to apply and on refining their graduate school admissions essays. Other workshops are held throughout the year; topics include Python programming and cultivating a growth mindset.

Every spring, two workshops are held on graduate admissions essay writing. Scholars in their junior year learn the best practices for writing such essays at the first workshop and revise their drafts at the second. Over the summer their essays are reviewed by their peers, then by an eight-member UC faculty committee, and finally by their mentors before they submit them to graduate programs in the fall. All senior-year scholars are also required to apply for an NSF Graduate Research Fellowship. Seven scholars, representing 26% of Cal-Bridge scholars who applied, have received a fellowship in the past four years.

Research experiences

Numerous studies have documented the benefits of undergraduate research in catalyzing interest in graduate education.[16,17] Cal-Bridge scholars participate in supervised research both in the summer and during the academic year, and junior-year scholars learn about opportunities for summer research from our annual presentation on those opportunities.

One valuable opportunity is the Cal-Bridge summer research program, also known as CAMPARE (see figure 4). That program, which has been running since 2009, provides research opportunities for students from 21 CSU campuses and more than 30 community college partners to conduct summer research at one of 18 research sites around the country, including 7 UC campuses. Other scholars have obtained their own research placements with independent undergraduate research programs such as the Harvard–Smithsonian Astronomical Observatory, Northwestern CIERA, MIT Haystack Observatory, and

The importance of mentoring

Cal-Bridge scholars highly value the mentoring they receive from the program. In our independent NSF grant evaluator's report, mentoring is listed as the most valuable part of the program, and scholars mention it twice as often as they mention the program's substantial financial support. Cal-Bridge graduates consistently say that they might not have reached their current levels of academic success without the Cal-Bridge program. The quotes below encapsulate the importance of Cal-Bridge mentoring for the students. (Photos courtesy of Cal-Bridge.)

The network of mentors and peers Cal-Bridge has helped me create has been invaluable in my pursuit of an astrophysics PhD! I now have an incredible support system of similarly underrepresented astro grad students and mentors who actively work to build a more inclusive community.

—**Katy Rodriguez Wimberly** (BS, CSU Long Beach 2015; astronomy PhD candidate, UC Irvine; NSF Graduate Research Fellow)

If not for the immense support provided by all my mentors and peers in Cal-Bridge, I probably would have given up on my dream to go to grad school. They kept me moving forward.

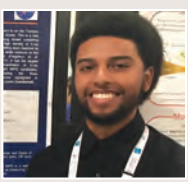
—**Luis Nuñez** (BS, Cal Poly Pomona 2018; astronomy PhD candidate, the Pennsylvania State University)

Cal-Bridge opened up doors for me that led to great experiences which helped lead to where I am now. As a first-generation college student, they offered great resources and mentoring that helped guide me through school, internships, and graduate school.

—**Becky Flores** (BS, CSU Northridge 2019; astronomy PhD candidate, Georgia State University)

"Help" is an understatement for what Cal-Bridge has done for me. Cal-Bridge prepared me academically and mentally to become a PhD candidate at UCI. Despite being an alumnus scholar, I still benefit from Cal-Bridge as I can connect with many other current and alumni scholars. My dream is to become a professor at a minority-serving institution. Cal-Bridge and CAMPARE have contributed to making this dream my career.

—**Jeffrey Salazar** (BS, CSU San Bernardino 2018; astronomy PhD candidate, UC Irvine)



Cal-Bridge is turning my dream of a PhD in Astrophysics into a tangible reality through required mentoring, personal academic support and substantial financial support. I would have never thought that a program like this was made for folks that resemble me and my background.

—**Evan Nuñez** (BS, Cal Poly Pomona 2019; astronomy PhD candidate, Caltech; NSF Graduate Research Fellow)

the National Astronomy Consortium led by the National Radio Astronomy Observatory.

Working with UC faculty offers two distinct benefits to Cal-Bridge scholars. First, a summer research program gives the scholars a window into the type of research they might conduct if they attend that UC campus for graduate school. Second, a UC faculty member can get an in-depth look at a Cal-Bridge scholar in a research setting, so that they can speak to that scholar's capabilities in a letter of recommendation for graduate programs. The Cal-Bridge summer research program also acts as an additional recruiting mechanism for the main Cal-Bridge program by helping identify students who are likely candidates for it.

All Cal-Bridge scholars are expected to present the results of their research at regional and national conferences, such as the American Astronomical Society meeting or the APS March Meeting. Attending conferences and presenting research results are critical for students' professional development. A 2007 study of undergraduate research students noted that students who "became involved in the culture of research—attending conferences, mentoring other students, authoring journal papers, and so on—were the most likely to experience 'positive' outcomes," such as increased interest in pursuing a research career and increased likelihood of obtaining a PhD.[16]

In the fall of each year, Cal-Bridge hosts an annual research symposium together with our sister CAMPARE summer research program. Participants in both programs present their research results. Scholars' families are invited in order to enlist support for the students as they make their career choices, including the possible decision to pursue a PhD in physics or astronomy. Family support is critical for all students, but especially for URM and first-generation college students.[18]

Outcomes

The Cal-Bridge program has already had a positive effect on the number of students from underrepresented groups pursuing physics and astronomy PhDs (see the box at left). The program has selected 59 scholars over the past five years. They include 34 Latinx, 7 African American, and 25 women students, with 15 of the women coming from underrepresented minority groups. Thus over 25% of Cal-Bridge scholars are women of color. Of the 59, 44 are first-generation college students. We were recently able to double our size, to 25 scholars per year, through a five-year, $5 million grant from NSF's S-STEM program. Growth is expected to continue with a long-term target of 35–40 scholars selected annually from across the state.

In the past four years, 27 of 33 (82%) Cal-Bridge scholars who graduated with a BS while in the program have begun PhD programs in physics or astronomy. Four others are enrolled in an APS Bridge Program or a master's degree program, and most are hoping to eventually earn a PhD. One scholar was accepted into a PhD program but chose to teach high school physics instead.

Of the 27 scholars who are in a PhD program, 10 are attending five UC programs: Davis, Irvine, Merced, Santa Barbara, and Santa Cruz. The other 17 scholars are attending 14 non-UC PhD programs across the country, including those at Caltech, Harvard, University of Maryland, Northwestern University, University of Pennsylvania, the Pennsylvania State University, and

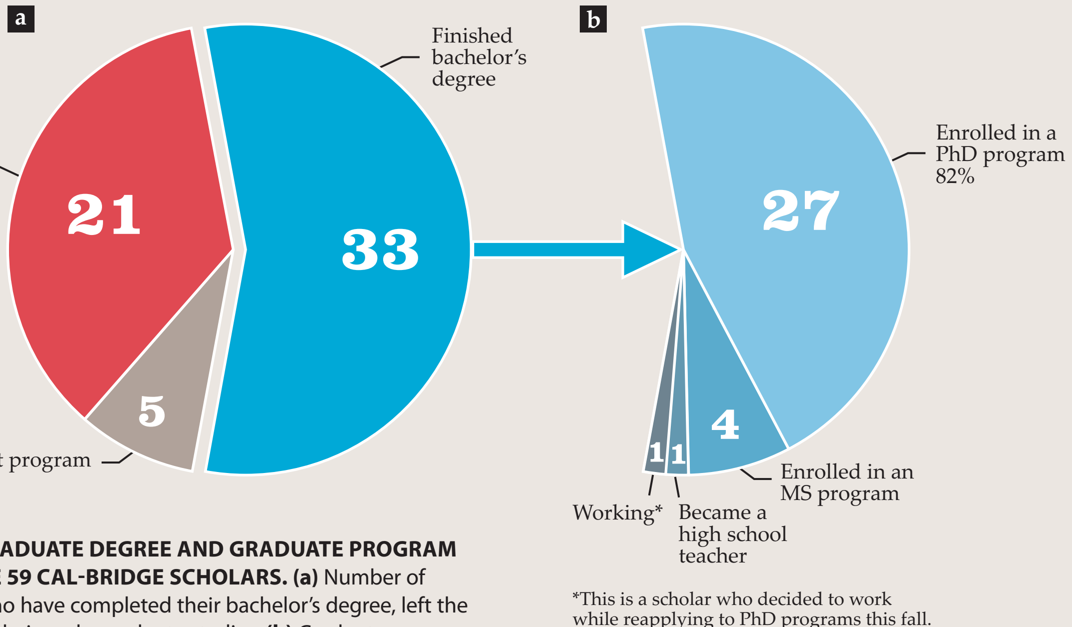


FIGURE 5. UNDERGRADUATE DEGREE AND GRADUATE PROGRAM OUTCOMES FOR THE 59 CAL-BRIDGE SCHOLARS. (a) Number of Cal-Bridge scholars who have completed their bachelor's degree, left the program, or continue their undergraduate studies. **(b)** Graduate program outcomes for Cal-Bridge students with bachelor's degrees.

University of Wyoming, among others. As mentioned previously, seven scholars have won NSF Graduate Research Fellowships, and four more received an honorable mention. Figure 5 shows the outcomes for the first five years of the program.

Looking ahead

If Cal-Bridge expands to 40 scholars per year, we might expect 25–30 URM students from the program to pursue a PhD per year. That would increase the number of URM PhDs in physics and astronomy nationally by almost one-third.[1]

Administrators in both the CSU and UC systems are helping with plans to expand the program's reach in two ways: by expanding to other STEM fields, and by promoting emulation in other geographic regions. Program leadership has already reached out to faculty in computer science, mathematics, and engineering to talk about creating additional bridge programs in those fields, which have diversity issues similar to those of physics and astronomy.

In addition to expanding to other fields, we hope that this new model of an undergraduate–graduate PhD bridge, created as a network of regional universities, will be replicated in other parts of the country. Numerous regions of the US have high concentrations of minority-serving and Hispanic-serving institutions. Those regions include Texas and the southwestern US; the southeastern US, where many historically black colleges and universities are found; Florida, home to many Hispanic-serving institutions; and the New York metropolitan and Atlantic coast area. Cal-Bridge leadership is prepared to help any such regional partnership get off the ground with technical and other support, including sharing materials we developed and lessons learned.

To solve a problem as large and intractable as the lack of diversity in STEM in the US will require varied approaches and many programs. If the support for existing, successful programs continues and additional programs are created, we may achieve true equity in access and accomplishment in STEM fields.

The author acknowledges the many faculty members at all three levels of the California public higher education system who have devoted countless volunteer hours to the success of the Cal-Bridge scholars. The author extends his deepest gratitude to the scholars of the program. Without their hard work and perseverance, the program would not be the success it has become.

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UNIVERSITY OF ALABAMA at BIRMINGHAM (UAB)

Open-Rank Professor Position – Condensed Matter Physics

The UAB Department of Physics, https://www.uab.edu/cas/physics/, invites applications for an Open Rank, open tenure, faculty position that will strengthen the Department's program in **Theoretical or Experimental Condensed Matter Physics**. Research areas of interest include, but are not limited to, the physics of quantum & biological materials using ultrafast spectroscopies, extreme pressure and electromagnetic fields, or quantum/data-driven computing. The new faculty member must have an outstanding publication record and strong commitment to excellence in teaching and supervising research at both graduate and undergraduate levels. The rank will be commensurate with the applicant's track record. We particularly welcome applicants from groups underrepresented in physical sciences. Screening of applications will begin immediately and continue until the position is filled. Full consideration will be given to all applications received by January 5, 2020, that include: (i) short letter explaining the applicant's research, extramural funding ideas, and qualifications relevant to this position; (ii) full curriculum vitae; (iii) statement on planned and past research projects; (iv) statement on teaching and mentoring; (v) three reference letters. All applications will be handled through **http://uab.peopleadmin.com/postings/5502**. For more information, please contact the search committee chair, Prof. Yogesh Vohra, at **ykvohra@uab.edu**.

The University of Alabama at Birmingham is a comprehensive urban university, with the nation's third-largest public hospital, that rapidly evolved into a world-renowned research university and health care center. Times Higher Education ranked UAB #1 young U.S. university for two years in a row, top 12 worldwide. With over 22,000 students and a campus covering more than 100 city blocks, UAB is focused on the future of research, teaching, health care, and community service. We are also a founding partner of Innovation Depot, the largest high-tech incubator in the southeast. Our research-driven, student-centric Physics Department currently has 20 faculty and instructors. It has experienced recent growth by focusing on (i) Modeling & Simulation using high-performance, data-driven & quantum computing, (ii) Advanced Materials properties under extreme environments and stimuli, (iii) Photonics & Lasers, and (iv) Technology-Enabled Physics Education.

UAB is an Equal Opportunity/Affirmative Action Employer committed to fostering a diverse, equitable and family-friendly environment in which all faculty and staff can excel and achieve work/life balance irrespective of, race, national origin, age, genetic or family medical history, gender, faith, gender identity and expression as well as sexual orientation. UAB also encourages applications from individuals with disabilities and veterans. — A pre-employment background investigation is performed on candidates selected for employment.

Assistant Professor in Experimental Soft Matter Physics
University of Pennsylvania

The Department of Physics and Astronomy at the University of Pennsylvania seeks applications from outstanding candidates for an appointment as Assistant Professor in experimental soft matter physics, broadly defined. The successful candidate will develop an innovative research program that attracts the participation of students and creates collaborative links with other Penn scientists and engineers. The candidate should have a Ph.D. at the time of appointment, and will be expected to teach, to attract external research funding and to contribute actively to the Laboratory for Research on the Structure of Matter. Applicants must apply online at **http://apply.interfolio.com/67423**. Required application materials include: curriculum vitae with a list of publications, a research statement, a teaching statement, and three letters of recommendation. Review of applications will begin no later than November 1, 2019 and will continue until the position is filled. It is anticipated that the position will start July 1, 2020.

The Department of Physics and Astronomy is strongly committed to Penn's Action Plan for Faculty Diversity and Excellence and to creating a more diverse faculty (for more information see: **http://ww.upenn.edu/almanac/volumes/v58/n02/diversityplan.html**). The University of Pennsylvania is an equal opportunity employer. Minorities/Women/Individuals with disabilities/Protected Veterans are encouraged to apply.

TMT

The Thirty Meter Telescope (TMT) project has been established to design, build and eventually operate an Extremely Large Telescope (ELT) with a primary mirror diameter of 30 meters. ELT's will be the successors of the present day 8-10 meter world class telescopes. When complete TMT will be the largest ground based optical/infrared telescope in the Northern Hemisphere providing the capability to study exciting astronomical problems from the nature of extra-solar planets to the first stars in the universe. An international collaboration consisting of the University of California, the California Institute of Technology, Canada, Japan, India and China has been formed to deliver this exciting project. The design and build of the various telescope systems will be distributed amongst the TMT partner institutions, collaborators, industry, and the Project Office.

TMT is looking for self-motivated individuals who are excited by the opportunity to join a highly-visible international project that will significantly advance our understanding of the universe.

ADAPTIVE OPTICS TECHNICAL PROJECT MANAGER

Oversee and monitor either a work-package agreement and/or contract(s) with vendor(s) for either a first light AO system or AO components and will be responsible for the successful delivery of the system and/or components to TMT. It is expected that his/her first assignment will be the technical management of the deformable mirror contract (sub-contracted to CILAS, France).

M1 CONTROL SYSTEM TECHNICAL PROJECT MANAGER

Guide and oversee the design and integration, and monitor the progress, of the Primary Mirror Control System (M1CS) development, fabrication, and integration efforts, Work closely with the M1CS design teams, TMT Project Office staff, and TMT partners to develop a production-ready M1CS design and to ensure the successful delivery and integration of the M1CS at the telescope site.

PRODUCTION SUPPORT ENGINEER

Monitor manufacturing in India of critical precision components and assemblies for the M1 System. Insure that quality control and assurance processes are being followed and that production schedules are being met. Identify risk and problem areas and work with TMT partners in India and the Project Office to develop and implement mitigation plans. Identify and work with Project Office teams to correct any deficiencies in production drawings and related documentation.

SCIENCE INSTRUMENTS PROJECT MANAGER

Oversee the development of IRIS, an adaptive optics (AO)-assisted imager and spectrograph, and WFOS, an optical spectrograph and envisioned as a workhorse instrument that operates over a wide field-of-view in a seeing-limited capacity, respectively. A hybrid role where the individual will play the dual role of providing contract oversight from within the Project Office but also serve as the instrument's overall Project Manager and as such work directly within the design team.

SENIOR ENGINEER—PRIMARY MIRROR CONTROL SYSTEM

Work as an integrated member of the Primary Mirror Control System design team. Work with industrial and TMT partners as well as other teams within the TMT Project Office. Hands on experience in design, build, test and integration is required. Broad based engineering background and familiarity, and expertise in one or more, of the following, analog and digital electronics, embedded and high level control software, control systems, and mechanical systems.

SYSTEMS ENGINEERING GROUP LEADER

Lead in the scientific and technical aspects of system engineering and system science for complex scientific detector, telescope or aerospace systems with significant experience in mechanical, optical and controls technology. Plan, coordinate and supervise the systems engineering activities required for the design, construction, assembly, integration and testing of the TMT Observatory System.

SYSTEMS SAFETY ENGINEER

Oversight and leadership for safety and environment protection for all sub systems during the design, fabrication, assembly and early operation of TMT. Perform review of systems designs and work with engineers to ensure compliance with all TMT safety programs and policies including all applicable regulatory and legal polices and laws for work place safety.

Positions are located at the TMT project office in Pasadena, CA. For detailed job descriptions and/or to apply online, please visit www.tmt.org. TMT is an equal opportunity employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, or national origin, disability status, protected veteran status, or any other characteristic protected by law.

The former headquarters of I. G. Farben, now part of the Goethe University Frankfurt campus.

Technological reparations in the aftermath of World War II

Taking Nazi Technology
Allied Exploitation of German Science after the Second World War
Douglas M. O'Reagan
Johns Hopkins U. Press, 2019. $54.95

As the Allied armies fought their way across Europe in February 1945, leaders of the Big Three—the US, UK, and Soviet Union—met at Yalta in Crimea to plan the postwar occupation of Germany. After carving up the country into four occupation zones, with the fourth going to France, they set their sights on the destruction of Germany's war potential, denazification and war crimes trials, and extensive reparations to the Allied nations. Although each of the occupation powers tended to pursue its own policies, reparations were a common goal as they snapped up technological weapons, documents, and personnel to whisk them out of Germany for their own use and deny them to rival Allies.

Those efforts resulted, as Douglas O'Reagan writes in *Taking Nazi Technology: Allied Exploitation of German Science after the Second World War*, in "the largest-scale technology transfer program in history, aimed at almost every field of industrial technology and academic science." O'Reagan leaves to others the important moral, legal, and economic issues surrounding the "taking" of German technology, some of which was produced by enslaved laborers, and of German personnel, some of whom were Nazi Party members. I would like to have seen at least a brief discussion of those issues. O'Reagan's archive-based history focuses instead on the nature and process of the technology transfer. He places particular emphasis on the crucial discovery that technology transfer cannot succeed without the human element—what the Americans called skilled know-how and is today often referred to as tacit knowledge.

Moreover, writes O'Reagan, "in the postwar world, this focus on the know-how element took on a life of its own, shaping business, law, and politics around the world." To support that bold statement, O'Reagan leaves the occupation far behind to explore the legacy of know-how that grew out of the technology transfer. He examines such later developments as the rise of information science, US international aid programs, and the Atoms for Peace initiative. Those chapters are intriguing, but a complete discussion of such movements and programs requires fuller consideration of the many other factors involved beyond tacit knowledge.

Amid the growing literature on postwar reparations and occupation policy, this book is admirably unique in that it offers an in-depth comparative history of technology transfer in all four occupation zones. O'Reagan devotes a chapter apiece to each. In the US zone, hundreds of military and civilian technicians swarmed over German universities and industrial facilities, including the infamous I. G. Farben chemical conglomerate. The Americans were in search of "intellectual reparations" in the form of documents, blueprints, and patents rather than equipment. Reportedly, they sent home 55 tons of such material. They also transported tens of thousands of on-site investigative reports.

Improved microfilm technology eventually streamlined the process. Because documents and patents no longer needed to be shipped back home, they were used to aid the West German economy as the Cold War set in. American agents also sent German technicians to the US. The enormous transfer enabled US engineers to fully use valuable technologies they did not already possess in such fields as aerospace technology and chemical manufacturing.

Technical know-how played a different role in the French zone. France pursued a policy of "exploitation in place," sending French students to train in German institutes while German experts visited French industries. That approach enabled the French to monitor the Germans while learning directly from them. Rather than extracting documents, Soviet occupiers pursued both exploitation in place and the literal transfer to the Soviet Union of entire buildings together with all the equipment and the people who worked in them, willingly or not.

But it was in the British zone, as O'Reagan recounts, that scientific know-how became the basis for the revival of academic research in West Germany. The zone included the University of Göttingen and several Kaiser Wilhelm research institutes—soon renamed after Max Planck. It also had many of the most prestigious scientists still in Germany, among them Otto Hahn, Werner Heisenberg, and Max von Laue. German scientists lobbied for the revival of German science under Allied control, which fit well with British plans to use a science-enhanced zonal economy in support of the British economy, now bankrupted by the war. With British support, German scientists founded new scientific institutions and revived old ones important for the future Germany. They also gained connections in the American zone that aided the founding of the Federal Republic of Germany in 1949.

Technology transfer across boundaries and cultures is difficult to accomplish. In the end, O'Reagan concludes that despite its vast scale and scope, the German technology transfer was only partially successful. Much of the technology was already known, many of the US microfilm reels remained unread for lack of content indices, many of the buildings sent to the Soviet Union remained unbuilt for lack of blueprints, and many of the displaced scientists remained underused for lack of need.

O'Reagan's masterful study of the Allies' technology transfer in all four zones and in all of its many facets, successes, and shortcomings is a most welcome contribution to Allied occupation history and to the history of technology in general.

David C. Cassidy
Hofstra University
Hempstead, New York


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Creating atomic nuclei on a lattice

Nuclear Lattice Effective Field Theory
An Introduction
Timo A. Lähde and Ulf-G. Meißner
Springer, 2019. $59.99 (paper)

A major goal of contemporary nuclear physics is to explain the structure of atomic nuclei and their reactions in a microscopic way. That approach, also known as the *ab initio* method, starts from two- and many-body forces between protons and neutrons and applies quantum many-body theory to deal with the multitude of nucleons. Many methods, including Faddeev–Yakubovsky equations, the no-core shell model, coupled cluster methods, many-body perturbation theory, and quantum Monte Carlo, have been designed to treat such strongly interacting multiparticle systems.

The methods listed above use continuous spacetime coordinates. A recent alternative approach instead represents a physical system in a finite volume with discrete spacetime coordinates subjected to sampling by Monte Carlo methods. That sounds simple and straightforward, but it is not, as the new book by Timo Lähde and Ulf-G. Meißner, *Nuclear Lattice Effective Field Theory: An Introduction*, explains thoroughly. Meißner, a professor of physics at the University of Bonn in Germany, is well known for his research on effective field theories in nuclear and particle physics. Lähde, a staff member at the Research Center Jülich in Germany, has been heavily involved in lattice calculations in condensed-matter and nuclear physics.

The text's first two chapters provide helpful background information not specifically about lattice calculations. One offers a general introduction to effective field theories (EFTs), and the other introduces nuclear forces in chiral EFT. The authors give several beautiful examples that demonstrate the basic ideas underlying an EFT. The section entitled "A Short Recipe for the Construction of an EFT" is a remarkably concise and clear explanation of the concept. The book's introduction to chiral EFT-based nuclear forces, in which nucleons and pions are the typical active degrees of freedom rather than quarks and gluons, is also clear and accessible.

The main body of the book consists of six chapters that present lattice methods in a systematic way. The first of those chapters introduces the basic mathematical concepts of the lattice approach, such as Grassmann fields, transfer matrices, and auxiliary fields. The next chapter addresses chiral nuclear forces, with a special focus on how they are put on the lattice. The discussion evolves from leading order to next-to-leading order and finally next-to-next-to-leading order. Each order is presented in small steps that make the chapter easy for the unacquainted reader to follow.

Subsequent chapters are devoted to the characteristic problems that arise with increasing numbers of nucleons. The authors discuss at length methods for how to extract phase shifts on the lattice for two and three nucleons, and they carefully weigh the advantages and disadvantages of the Luescher, spherical wall, and auxiliary potential methods. Increasing the number of nucleons beyond three, as the authors show, creates the need for Monte Carlo sampling of lattice calculations. The last chapters move up to medium-mass nuclei and to chiral forces up to next-to-next-to-next-to-leading order. The authors report on some of the first attempts to solve these thorny problems, but they acknowledge that actual solutions are still in the future.

Lattice methods are technical and beset by a cumbersome mathematical apparatus. Thus any explanation of them could be difficult to read for outsiders or newcomers to the field. However, Lähde and Meißner manage to get the complex material across in a digestible way by breaking it up into small steps and knowing when repetition is helpful. They also introduce from scratch such basic concepts as phase shifts, without referring the reader to another book. Such care makes *Nuclear Lattice Effective Field Theory* self-contained, which is a great practical advantage to the reader. The six appendices further enhance the self-contained character of the text by summarizing notations and conventions and providing more details about useful mathematical functions, nuclear force properties, and the application of Monte Carlo methods.

Nuclear Lattice Effective Field Theory offers interesting insight into the endless problems that the pioneers of lattice methods had to confront during the past 20–40 years, such as rotational symmetry breaking, the sign problem, and the unfavorable scaling of Monte Carlo algorithms. Solutions have been worked out for most hurdles, and thus we can say that nuclear lattice EFT has come of age; the field is ready for more comprehensive and systematic applications in nuclear theory.

Apart from work by some of the authors' collaborators, the method has not yet been applied widely in nuclear theory. Lähde and Meißner's helpful primer has the potential to stimulate increased efforts by serving newcomers as an essential guide to the field.

Ruprecht Machleidt
University of Idaho
Moscow

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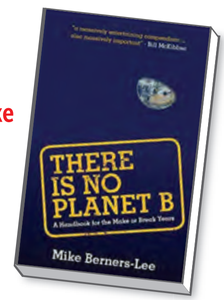
The challenges and opportunities of the climate crisis



There Is No Planet B
A Handbook for the Make or Break Years

Mike Berners-Lee
Cambridge U. Press, 2019.
$12.95 (paper)

People are causing Earth's climate to change and climate changes create serious risks for humanity. We have a wide range of well-studied response options, and the expected benefits from many of them greatly exceed the expected costs. Those conclusions result from multiple independent lines of evidence and have been reaffirmed by hundreds of comprehensive scientific assessments. Subject-matter experts examined the evidence, independent scientists reviewed the findings, and scientific organizations stood behind the processes and outcomes. I am not aware of any scientific institution with relevant subject-matter expertise that has looked at the evidence and reached contradictory conclusions.

Despite the robustness of those scientific conclusions, we continuously fail to respond to climate change. We struggle even to have an effective public conversation about whether to respond and, if so, how. That may be the most ominous implication of climate change—that our social institutions aren't up to the task of addressing major issues, even when we have unambiguous scientific information in favor of doing so.

But climate change is, possibly, also an opportunity. If we figure out how to approach our climate problem, we might create a template for addressing a wide range of challenges and opportunities facing humanity in the 21st century. That is the key insight and basic premise of Mike Berners-Lee's book *There is No Planet B: A Handbook for the Make or Break Years*. It's a terrifically important idea that may be the key step in the pathway toward humanity's future.

Berners-Lee emphasizes that climate

change is one of several global social and environmental changes that are currently underway. Additional examples of global environmental changes are the loss of biodiversity and the redistribution of species throughout the world, stratospheric ozone depletion, land conversion, and nutrient deposition. The climate problem is thus both hugely important on its own and reflective of a bigger challenge: Our increasing capacity to disturb the planet means that we need new and better ways to work together and to harness human ingenuity. Addressing climate change could show us the way to tackle the larger set of issues that we face.

There Is No Planet B will resonate most with those who are already deeply focused on the climate system, the impact people are having on it, and our path forward. Unfortunately, the book largely misses the mark for a broader audience. Although it identifies the critical issues, the discussion of them is too often weak and underdeveloped.

The book's approach to discussing social values illustrates some of its shortcomings. Berners-Lee emphasizes that he is trying to initiate a conversation and that he hasn't figured it all out. That is the right idea; we will need to have an open discussion in which everyone has a chance to participate and learn from one another.

But Berners-Lee asserts the need for particular values instead of leading a critical examination of the options and their implications. That is a mistake. Ultimately, individuals and societies must determine which values they adopt. No one person can set them. By championing values at the outset, *There Is No Planet B* misses the opportunity to encourage and empower readers' exploration of societal values. It becomes too easy for readers to reject the book's espoused values and to uncritically stick with their own.

For example, Berners-Lee asserts that a commitment to equity is central to solving climate change. That view generally resonates with me, but it would be more compelling as a conclusion that follows from a hard exploration of alternatives and the potential futures those alternatives imply for humanity. As offered, Berners-Lee's assertion is unlikely to impact any preexisting beliefs that readers have.

The challenges we face are daunting. Climate is a critical life support system, and we have no reason to conclude that it will be resilient against the massive disturbance to which we are subjecting it. None of us acting alone is likely to solve the problem; we will have to work together. That interdependence makes climate change hard for individuals to face.

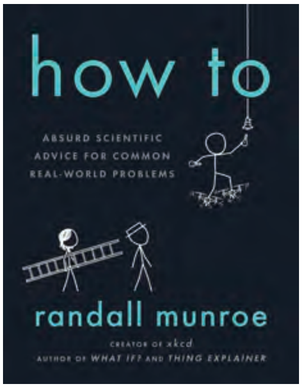
But we are also awash in good news. Science has provided us with remarkable insight into how the climate system works, the impact that people are having on it, and the ways that we can respond. Even better, if we get our approach to climate change right, then humanity will be poised to continue our remarkable run well into the future. *There Is No Planet B* may not be able to get us to that potential future, but it provides a hint of what we will need.

Paul Higgins
American Meteorological Society
Washington, DC

Supernova Era

Cixin Liu, trans. Joel Martinsen
Tor, 2019. $27.99

Science fiction author Cixin Liu won the 2015 Hugo Award for Best Novel for *The Three-Body Problem*, which combined a gripping science-fiction mystery with a haunting meditation on the aftermath of the Cultural Revolution. A similar eerie melancholy winds its way through his new novel *Supernova Era*, which imagines a world in which a supernova causes irreparable damage to the cells of anyone over 13, meaning that within a year only the world's children will be left alive. The novel critiques existing national and international political systems, but Liu's post-adult world is no "children are the future" utopia; conflict and violence endure even with the grown-ups gone. It's not soothing bedtime reading, but fans of *The Three-Body Problem* will be eager to get their hands on Liu's latest. —MB



How To

Absurd Scientific Advice for Common Real-World Problems

Randall Munroe
Riverhead Books, 2019. $28.00

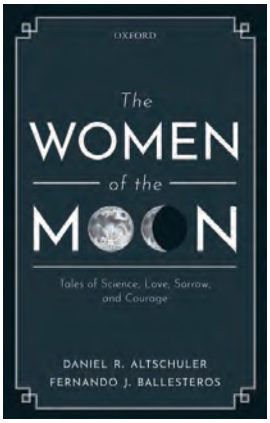
Former NASA roboticist Randall Munroe is the mind behind xkcd.com, arguably the internet's most popular science-related comic strip. Munroe brings his distinctive stick-figure art into the delightful *How To*. Each chapter considers the physics-related obstacles associated with an unlikely undertaking—say, returning an online order from outer space or flying your house to a new location by quadcopter. Munroe even puts some of his scenarios to the test—for example, he recruits tennis legend Serena Williams to determine how effective a tennis serve would be at hitting a small drone out of the air. The book is a great coffee-table read, and Munroe's use of physics calculations also makes it a potential source of teaching material for introductory physics classes. —MB

The Cosmic Mystery Tour

A High-Speed Journey through Space and Time

Nicholas Mee
Oxford U. Press, 2019. $24.95

"Mystery tour"—a short trip that people take for pleasure without knowing where they are going—aptly describes this brief introduction to the universe by theoretical physicist Nicholas Mee. In fewer than 200 pages, Mee covers a lot of ground: He discusses the history of the cosmos and the laws governing it, recent cutting-edge research and instrumentation, and the giants of science who have worked to make sense of it all. The information is delivered in sections of just a few paragraphs each and illustrated by more than 100 photos, diagrams, and images. Rather than study it cover to cover, readers can open it up anywhere and plunge in. —CC



The Women of the Moon

Tales of Science, Love, Sorrow, and Courage

Daniel R. Altschuler and Fernando J. Ballesteros
Oxford U. Press, 2019. $26.95

Of the 1586 lunar craters named after philosophers and scientists, just 28 are named for women, write physics professor Daniel Altschuler and astronomer Fernando Ballesteros. *The Women of the Moon* centers on those 28, their lives, and scientific contributions. Beginning with a history of the Moon, the authors dedicate each of the subsequent chapters to a different woman, starting with Hypatia, a mathematician and astronomer born circa 355 CE, and continuing chronologically to modern-day Valentina Tereshkova, the first woman in space. Although many of the subjects are well known, such as astronomer Caroline Herschel, others are more obscure, like Anne Sheepshanks, an astronomical philanthropist. The biographical sketches include black-and-white images of the women and their namesake craters. —CC PT

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Faculty Position in Experimental Biological Physics

The Department of Physics and Astronomy in the College of Science at Purdue University seeks applications for a faculty position at the level of Assistant Professor in the area of experimental biological physics. All areas of experimental biological physics will be considered. Successful candidates will have a joint appointment in both the Department of Physics and Astronomy and the Department of Chemistry (75:25 appointment). We are interested in outstanding scientists with an established track record, a commitment to leading a preeminent research program, and a clear vision for future innovation. Current research efforts within the department apply a variety of experimental and theoretical techniques to investigate intracellular dynamics, cell growth, cell sensing, and structural and electron dynamics in a variety of systems. The department is looking to integrate a creative scientist into the cutting-edge interdisciplinary environment provided by the Purdue University Life Sciences Institutes, including the Purdue Institute of Inflammation, Immunology and Infectious Disease (PI4D) and the Purdue Institute for Integrative Neuroscience (PIIN).

Qualifications: Applicants must have a Ph.D. in physics, chemistry, biophysics or a closely related field, an outstanding record of research accomplishments, and evidence of potential for excellence in teaching at both the undergraduate and graduate levels. Candidates are expected to obtain significant research funding, develop vigorous research programs, supervise graduate students, and teach courses at the undergraduate and graduate level.

The Departments and College: The two Departments have over 100 tenured and tenure-track faculty, more than 300 graduate students, and over 500 undergraduate students between them. Over the last 5 years the two departments, Chemistry and Physics and Astronomy, have added more than 20 faculty and significant investment has been made in key areas of discovery. The College and the Departments have launched initiatives in new emerging areas, such as Data Science and Quantum Information Science, and committed the resources necessary to make the new growth impactful. For more information, see **http://www.physics.purdue.edu/** and **https://www.chem.purdue.edu/**.

Physics and Astronomy and Chemistry are part of the College of Science, which comprises the computing, physical, and life sciences at Purdue. It is the second-largest college at Purdue, with over 350 faculty and more than 6,000 students. Purdue itself is one of the nation's leading land-grant universities, with an enrollment of over 41,000 students primarily focused on STEM subjects. For more information, see https://www.purdue.edu/purduemoves/initiatives/stem/index.php.

Application Procedure: Applications need to be submitted to **https://careers.purdue.edu/job/Assistant-Professor-of-Physics-and-Astronomy-Experimental-Biological-Physics/590654600/?locale=en_US** and must include (1) a cover letter that includes a diversity statement. (2) a complete curriculum vitae, (3) a publication list, (4) a brief statement of present and future research plans including funding strategy, and (5) a statement of teaching philosophy. Applicants should also arrange for at least three letters of recommendation to be sent to **bpsearch@purdue.edu**. Questions regarding the position and search should be directed to **bpsearch@purdue.edu**. Applications completed by November 1, 2019 will be given full consideration, although the search will continue until the position is filled.

Purdue University's Departments of Physics and Astronomy and Chemistry are committed to advancing diversity in all areas of faculty effort, including scholarship, instruction, and engagement. Candidates should address at least one of these areas in their cover letter, indicating their past experiences, current interests or activities, and/or future goals to promote a climate that values diversity and inclusion. A background check will be required for employment in this position.

Purdue University is an EEO/AA employer. All individuals, including minorities, women, individuals with disabilities, and veterans are encouraged to apply.

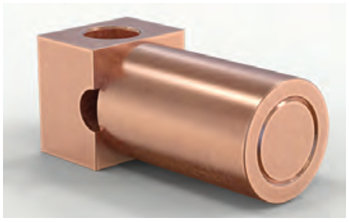
NEW PRODUCTS

Focus on materials, semiconductors, vacuum, and cryogenics

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 the product description. For all new products submissions, please send to ptpub@aip.org.

Andreas Mandelis

Cryogenic temperature sensor



Lake Shore Cryotronics has introduced its Rox RX-102B-RS ultralow-resistance temperature detector for operation below 10 mK. Suitable for advanced dilution-refrigerator applications, the RX-102B-RS builds on the capabilities of Lake Shore's previous-generation Rox sensor. The company has refined the package to improve thermal connections and has added optical radiation shielding to reduce unwanted sensor heating. When paired with Lake Shore's model 372 AC resistance bridge and temperature controller, the RX-102B-RS can be used for simplified monitoring or control in any application below 50 mK. Certain calibration configurations allow temperature readings down to 5 mK. ***Lake Shore Cryotronics Inc****, 575 McCorkle Blvd, Westerville, OH 43082, www.lakeshore.com*

Compact energy-efficient vacuum pumps

Pfeiffer Vacuum has launched its HiLobe series of Roots pumps for low- and medium-vacuum applications, such as electron-beam welding, vacuum furnaces, coating, and freeze drying. With a new drive concept and frequency converters, the series achieves approximately 20% shorter pump-down times than Pfeiffer's conventional Roots pumps. That fast evacuation capability makes the pumps suitable for load-lock chambers and leak-detection systems. The HiLobe pumps' energy-efficiency class IE4 drive, special rotor geometries, and sealing concept combine to yield maintenance and energy costs more than 50% lower than standard Roots pumps. Flexible air cooling allows the pumps to operate at ambient temperatures of up to 40 °C and thus avoid the need for costly water cooling. ***Pfeiffer Vacuum Inc****, 24 Trafalgar Sq, Nashua, NH 03063, www.pfeiffer-vacuum.com*

Plasma deposition platform

Oxford Instruments Plasma Technology has designed a high-volume manufacturing solution that uses plasma atomic-layer deposition to address key challenges, such as a consistently high-quality gate passivation, in the gallium nitride power-device industry. To enable demanding device performance in areas such as 5G networks and renewable energy conversion, the Atomfab single-wafer platform delivers excellent passivation and dielectric properties, according to the company. A patent-pending fast remote-plasma source yields reduced cost per wafer. Remote plasma delivers a reproducible GaN interface; Atomfab precisely controls the plasma to protect the underlying sensitive GaN substrate, and its high-deposition-rate process delivers high throughput. ***Oxford Instruments Plasma Technology****, N End, Yatton, Bristol BS49 4AP, UK, https://plasma.oxinst.com*

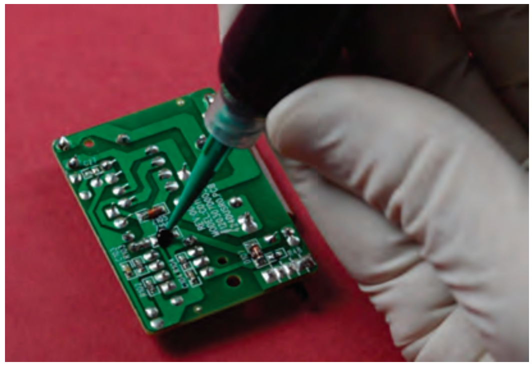
Fast neutron detectors

Inrad Optics has unveiled a suite of 1- to 5-inch-diameter Scintinel stilbene radiation detectors for fast neutron detection. They integrate a stilbene scintillation crystal into a photomultiplier tube with voltage divider electronics in it. The main advantages of Scintinel stilbene are its high sensitivity to neutrons and ability to discriminate with high efficiency between neutrons and gamma-ray radiation. According to the company, those properties allow users seeking special nuclear material to avoid false calls caused by benign gamma sources. Because of its lower energy thresholds and higher neutron efficiency, stilbene—a solid-state, nonhazardous material—performs better than liquid and plastic scintillators. Applications for stilbene are found in nuclear security and applied physics research. ***Inrad Optics****, 181 Legrand Ave, Northvale, NJ 07647, www.inradoptics.com*

Semiconductor wafer metrology

Semilab has released a new set of applications for its existing EIR instruments. Models EIR-3000 and EIR-2200 use nondestructive Fourier-transform IR spectroscopy to perform thick dielectric monitoring in the semiconductor industry. The new offering includes dielectric composition of borophosphosilicate and fluorosilicate glass and silicon nitride, which, according to the company, can help reduce wafer requirements and conditions for measurement. For example, backside wafer finishing is not required, and production wafers can be used. Semilab claims that the new capability will help users of its EIR tools to simplify their calibration routines, improve overall long-term stability, and reduce monitoring costs. ***Semilab USA LLC***, *10770 N 46th St, Ste E700, Tampa, FL 33617, www.semilab.hu*

Epoxy for chip coating



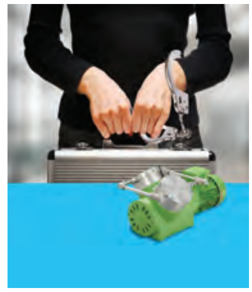
Featuring a combination of thermal conductivity and electrical insulation properties, Master Bond Supreme 3CCM-85 is a single-component epoxy for glob top and chip-coating applications. It can also be used for encapsulation and bonding. Supreme 3CCM-85 cures in 2–3 h at 80–85 °C, which is advantageous for use on heat-sensitive components and substrates. The toughened adhesive system has a thixotropic paste-like consistency and bonds well to various similar and dissimilar substrates. It has a volume resistivity of more than 10^{14} Ω-cm, a thermal conductivity of 0.72–1.44 $Wm^{-1}K^{-1}$, and is serviceable from −73 °C to 177 °C. Because Supreme 3CCM-85 is neither premixed nor frozen and remains usable for a long time at room temperature, it is more convenient to handle and store than typical two-component glob top systems. ***Master Bond Inc***, *154 Hobart St, Hackensack, NJ 07601-3922, www.masterbond.com*

Thin-film coating material

Indium Corporation has announced IndiOx (In_2O_3) for use in the manufacture of indium tin oxide (ITO) for thin-film coating. When doped with tin oxide, IndiOx—a stable, ceramic-like material—forms ITO, which is suitable for making transparent, conductive oxide layers in flat-panel displays and touch sensors for mobile devices. The ITO layer is deposited onto glass from a sputtering target manufactured from the ITO powder by sintering. IndiOx can also be used for glass coloring, gassing suppression in alkaline batteries, and as an anti-arcing additive in high-current electrical switches and contactors. It is available in three powder types, each with a different particle-size distribution range (D10–D90): Type A is crystalline, range 0.8–38 μm; Type B is fine, range 0.5–6 μm; and Type T is target grade, range 0.1–7.5 μm. ***Indium Corporation***, *34 Robinson Rd, Clinton, NY 13323, www.indium.com* PT

PHYSICS TODAY PRODUCT PICKS

Secure Transfer of Costly and Dangerous Gases



KNF leak-tight pumps are designed to transport and evacuate costly, high purity, and/or dangerous gases. Ultra-low leak rates of <6x10-6 mbar L/sec, plus a safety back-up diaphragm and other safeguards to prevent external contamination. Flow rates from 4.5 – 300 L/min. Options include inter-diaphragm monitoring, explosion-proof motors, and flow path material choices.

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DC205 ... $1995 (U.S. list)

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Stanford Research Systems
Tel: (408)744-9040 • www.thinkSRS.com

OBITUARIES

Zhores Ivanovich Alferov

Nobel laureate Zhores Ivanovich Alferov, whose work led to room-temperature semiconductor lasers and other groundbreaking devices, died on 1 March 2019 in Saint Petersburg, Russia.

Alferov was born on 15 March 1930 in Vitebsk, Belarus. He was 11 when the Nazis invaded the Soviet Union. His older brother, Marx, whom he adored, was killed in combat in 1944. After that traumatic experience, Alferov became a fighter for international understanding and peace.

Despite the chaos of the war and its aftermath, Alferov finished school in Minsk on time. He was accepted to the Leningrad Electrotechnical Institute and graduated with a physics degree in 1952. The next year Alferov went to the Physico-Technical (now Ioffe) Institute in Leningrad. Its founder, Abram Ioffe, had already begun systematic studies of semiconductors in the 1930s. Alferov was the institute's director from 1987 until 2003.

Alferov also took over another brainchild of Ioffe's. Convinced of the importance of educating teenagers in science, Ioffe established in the 1930s what became known as his "kindergarten." After the Soviet Union collapsed and many young people believed they should study economics for a better life, Alferov founded a lyceum in 1997 to teach science and foreign languages to 15- to 17-year-olds. In 2002, building on a core of young scientists, he started what is now the Saint Petersburg Academic University. He served as its rector until his death.

Russian president Dmitry Medvedev launched a modernization program in 2009. One initiative was the merging of current teaching and applied research in Skolkovo, a new science and technology district outside Moscow, and enabling the transfer of knowledge and technology to high-tech startups. From 2010 to his death, Alferov served as scientific advisory council cochair of the Skolkovo Foundation.

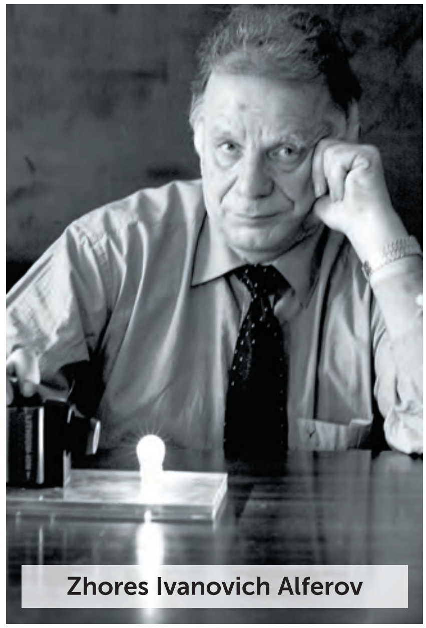
In 1960, 43 years after Albert Einstein predicted stimulated emission, Theodore Maiman demonstrated optical lasing in ruby. Within 18 months, lasing had been produced in other media, including semiconductor diodes based on gallium arsenide homojunctions. At that time, solid-state and gas lasers operated at room temperature, whereas semiconductor lasers operated only at 4 K. Researchers soon found numerous applications for 300 K lasers. Many recognized the importance of developing room-temperature semiconductor lasers.

In p–n homojunctions, the wide spread in space of the charge carriers leads to huge threshold current densities of roughly 10^5 A/cm^2. In 1963 Alferov and Rudolf Kazarinov applied for a Soviet patent; it proposed the confinement of carriers in a double heterostructure that would produce a higher carrier density by several orders of magnitude. Herbert Kroemer made a similar proposal in a publication shortly afterward. For their work, Alferov and Kroemer were awarded a share of the 2000 Nobel Prize in Physics.

Alferov pointed out in 1966 the advantages of double heterostructures, including efficient carrier injection, localization, and guidance of the emitted light, which exploits the larger steps in the index of refraction at interfaces. He and others first attempted to realize such structures by pairing semiconductors of indirect and direct bandgaps, such as gallium phosphide with gallium arsenide, but those early efforts failed.

The next year Alferov observed that aluminum gallium arsenide layers grown lattice-matched to gallium arsenide had great chemical stability. He used liquid-phase epitaxy to grow double heterostructures without any dislocations, made lasers from them, and in 1968 observed them operating at room temperature in pulsed mode. Two years later he published his results on such lasers operating at room temperature in continuous mode.

Semiconductor lasers are now omnipresent in daily life; they form the backbone of our optical communication systems and data centers. In 1988 Alferov and colleagues fabricated what was then the lowest-threshold laser diode with a gallium arsenide quantum well. One of



Zhores Ivanovich Alferov

SKOLKOVO FOUNDATION

us (Bimberg) and his team at the Technical University of Berlin realized in 1994 the first indium gallium arsenide quantum-dot injection lasers, which were based on molecular-beam epitaxy structures grown in Alferov's lab in Russia. They achieved the highest temperature stability and longest-ever wavelength for such lasers. Quantum-dot lasers are used today in large-scale applications in gallium nitride–based photonics and semiconductor single-photon sources.

Double heterostructures were the basis of many other new devices such as heterobipolar transistors and heterostructure solar cells. In 1986 the space station MIR was partially powered by solar cells developed by Alferov's lab at the Ioffe Institute.

Alferov had a brilliant, fascinating personality that sparkled with humor. He endured in pushing his ideas, no matter the obstacles. And he was faithful to his many friends around the world.

Dieter Bimberg
Changchun Institute of Optics, Fine Mechanics and Physics
Changchun, China

Technical University of Berlin
Berlin, Germany

Sergey Ivanov
Ioffe Institute
Saint Petersburg, Russia

Viktor Vekselberg
Skolkovo Foundation
Moscow, Russia

Charles Kittel

Solid-state physicist Charles Kittel, a professor emeritus at the University of California, Berkeley, passed away peacefully at his home in Berkeley on 15 May 2019, two months before his 103rd birthday.

Born in New York City on 18 July 1916, Charlie entered MIT in 1934. He moved to Cambridge University in 1936 and received his BA there two years later. He earned his PhD degree in 1941 from the University of Wisconsin–Madison, where his adviser was Gregory Breit. From 1940 to 1942, Charlie worked on problems in degaussing and magnetic mine warfare at the Naval Ordnance Laboratory. He served in the US Navy as a research physicist at a British Admiralty research establishment in Scotland and as a naval attaché at the US Embassy in London; he went on to work on antisubmarine warfare and operations research in Washington, DC, and London. In 1945 he returned to MIT, taking a position in the Research Laboratory of Electronics.

Charlie was a research physicist in the solid-state physics group at Bell Labs in Murray Hill, New Jersey, from 1947 to 1951. His work ranged over much of solid-state theory, including magnetism, ultrasonics, and thermal properties. His association with the physics department at Berkeley began in 1950 with a visiting associate professorship. He joined the faculty as a professor of physics the next year and became emeritus in 1978.

Among Charlie's many honors were the American Physical Society's Oliver E. Buckley Condensed Matter Physics Prize in 1957, the University of California Distinguished Teaching Award in 1970, and the Oersted Medal from the American Association of Physics Teachers in 1978.

Charlie is credited with building the solid-state (now condensed-matter) physics component of Berkeley's physics department. He played a central role in hiring new faculty, and he worked closely with experimentalists who conducted groundbreaking research on cyclotron resonance in semiconductors. Charlie assembled an outstanding theoretical group of faculty, postdoctoral researchers, and graduate students, and he established and developed undergraduate and graduate courses in condensed-matter, thermal, and introductory physics. His texts in those areas are classics. In particular, his *Introduction to Solid State Physics*, originally published in 1953, was not only the dominant text for teaching in the field, it was on the bookshelf of researchers in academia and industry throughout the world. In many ways, his choice of content defined solid-state physics.

For much of his career, Charlie focused his research on topics related to determining material properties. They included semiconductors, magnetic behavior, ferroelectrics, optical properties, electron-spin and nuclear magnetic resonance, and superconductivity. In 1946 he showed that technologically important fine-particle ferromagnets had high coercivity because the particles remained single domain when fine enough. Later in 1946 James Griffiths found that the ferromagnetic resonance frequency in thin films is proportional to the square root of the product of magnetic induction B and the external field strength H instead of to H alone, as is the case in nuclear and paramagnetic resonance. Three months after Griffiths's paper appeared, Charlie published his proof that the dependence arose from the demagnetizing field. That and Charlie's related early work substantially strengthened our theoretical understanding of ferro- and ferrimagnetism. He pointed out that glasses had low thermal conductivity because their structural disorder reduced the phonon mean free path to the atomic scale, an early recognition of the importance of strong disorder for transport.

In a classic paper on cyclotron resonance in p-type germanium, Charlie, Gene Dresselhaus, and Arthur Kip reported the first direct measurement of the kinematics of electrons in solids. They confirmed in quantitative detail the


Charles Kittel

DEPARTMENT OF PHYSICS, UNIVERSITY OF CALIFORNIA, BERKELEY

correctness of band theory and demonstrated the importance of including spin–orbit coupling. In private communication to one of us (Morrel), Enrico Fermi recognized the significance of their findings.

With Malvin Ruderman, Charlie initiated the development of a model for what today is known as the RKKY interaction, now understood to explain giant magnetoresistance in layered materials. With Kip, Paul Levy, and Alan Portis, Charlie carried out one of the earliest studies of electron-spin resonance in color centers. Such centers are now of interest for quantum computing.

Charlie will be remembered not only by his family but also by the colleagues whom he worked with and by the students and postdocs whom he mentored. Members of the physics community and readers of his texts will remember Charlie for his amazing ability to look at complex properties of matter and come up with simple models and accurate descriptions that defined the essence of the physics.

Marvin L. Cohen
University of California, Berkeley

Morrel H. Cohen
Rutgers University
New Brunswick, New Jersey
Princeton University
Princeton, New, Jersey

RECENTLY POSTED NOTICES AT
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Gottfried Jens Feder
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Edgar Pearlstein
3 March 1927 – 15 January 2019

James Donald Louck
13 December 1928 – 21 November 2018

Peter M. Levy
10 January 1936 – 20 November 2018

QUICK STUDY

Jeremy Munday is a professor in the department of electrical and computer engineering at the University of California, Davis.

A new twist on the quantum vacuum

Jeremy N. Munday

A subtle macroscopic effect in the space between two birefringent plates produces a measurable Casimir torque.

One usually imagines a vacuum as empty space devoid of any matter. That picture isn't quite accurate when quantum mechanics is taken into account. Emptiness turns out to be an illusion: The real vacuum is full of activity in the form of quantum fluctuations—sometimes thought of as virtual particles that appear and disappear so quickly that they don't violate Heisenberg's uncertainty principle. In this Quick Study, I discuss how electromagnetic fluctuations can give rise to forces and even torques between macroscopic objects without the need for any other interactions. Indeed, the quantum mechanics of a vacuum may prove to be an exciting tool for engineering nanoscale devices.

Forces from nothing

In the late 1940s while working at Philips Laboratory Eindhoven in the Netherlands, Dutch physicist Hendrik Casimir developed a theory to describe the interaction forces he observed in colloidal suspensions. Intrigued by the notion of quantum fluctuations of electromagnetic fields and by conversations with Niels Bohr, Casimir considered what would happen in a different scenario involving two parallel, uncharged, metallic plates.

In a classical vacuum, nothing happens. But in a quantum vacuum, he realized, the presence of the closely spaced plates—essentially an optical cavity—would influence the fluctuating fields (see, for example, the Reference Frame by Daniel Kleppner, Physics Today, October 1990, page 9, and Physics Today, November 2011, page 14). More specifically, conductive plates force the electric and magnetic fields to go to zero at the boundaries, and only a subset of the fluctuations can exist between the plates; the largest wavelengths are excluded simply because they do not fit.

The plates effectively reduce the energy density, often called the zero-point energy, associated with those quantum fluctuations. The closer the plates, the lower the zero-point energy. Because nature likes to minimize the energy of a system, the two plates should be attracted to each other—an interaction referred to as the Casimir effect.

Within 10 years of Casimir's prediction, an experiment by Dutch physicist Marcus Sparnaay confirmed the existence of the Casimir force between two parallel plates. In Sparnaay's own words, the experiments "do not contradict Casimir's theoretical prediction." That humble phrasing reflected the difficulty of measuring such small forces while keeping the plates parallel and in close proximity—typically below a micron—and removing electrostatic interactions and other artifacts.

Around the same time, 1956, Russian chemist Boris Derjaguin realized that replacing one of the plates with a sphere would simplify the measurement: Researchers would no longer need to worry about keeping the plates parallel. Although the sphere–plate geometry did improve detection, not until the 1990s did modern measurement techniques usher in a new wave of Casimir force experiments. (See the article by Steve Lamoreaux, Physics Today, February 2007, page 40, and Physics Today, February 2009, page 19.)

From forces to torques

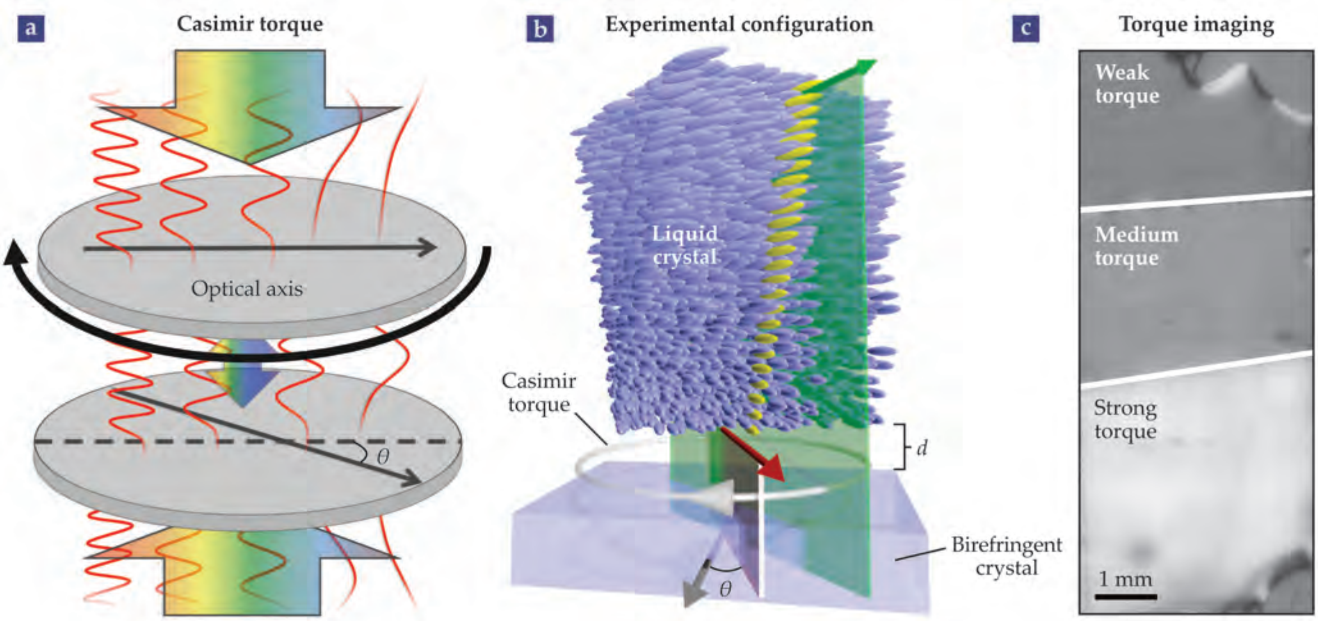
Casimir's theory describes the force between metal plates. But what happens when the plates are not perfect conductors? Theorists Igor Dzyaloshinskii, Evgeny Lifshitz, and Lev Pitaevskii answered that question in 1961 when they generalized Casimir's result to the case in which the plates are described by arbitrary, isotropic dielectric functions. Today their theory is used in comparisons to experiment; the optical properties of the actual metals used in the experiments are incorporated as variables into the theory.

In the 1970s a new configuration was considered: What if the optical properties of the plates are anisotropic—for example, when using birefringent crystals such as calcite? In that case, the total free energy of the system depends not only on the separation between the two parallel plates but also on the angle θ that defines their relative orientation. The system should exhibit a torque that causes the plates to rotate into a position of minimum energy—a Casimir torque.

Minimum energy is reached when the optical axes with the highest refractive index align. The theory for that idea was worked out by Adrian Parsegian and George Weiss and independently by Yuri Barash. For relatively small separations, generally less than a few tens of nanometers, they found that the torque has a $\sin 2\theta$ dependence and is inversely proportional to the separation squared.

As with the Casimir force, several technical issues complicate measuring the Casimir torque. Two relatively large-area plates need to be kept parallel and at submicron separations. One plate also needs to freely rotate relative to the other, and that rotation must be detectable above background noise and artifacts. A way to perform such an experiment is to suspend one birefringent plate above another using a torsion rod.

The twisting of the rod induced by the Casimir torque could be measured optically or electronically to determine the rotation angle. But parallelism, dust removal, and surface imperfections turn out to be difficult to control in that setup. Another possibility is to perform experiments in which one plate is levitated above another either using optical tweezers in vacuum



IMAGING THE TWIST FROM VACUUM. (a) When two optically anisotropic plates form a narrowly spaced optical cavity, the energy associated with quantum fluctuations between them depends on their orientation. To minimize the free energy of the system, the Casimir torque rotates one plate relative to the other until their optical axes align. **(b)** This configuration illustrates my group's recent experiment to measure the Casimir torque between a liquid crystal and a solid birefringent crystal. A thin isotropic layer of material separates the crystals by a variable distance *d*. The yellow rods illustrate the extent to which the liquid-crystal sample twists from top to bottom; the green and red arrows show the average direction of the liquid at the two endpoints. The dark gray arrow in the birefringent crystal depicts the crystal's optical axis. **(c)** Shining polarized light through the liquid and solid crystals offers a way to reveal the Casmir torque. A sample is prepared with three spacing-layer thicknesses that separate the liquid crystal from the solid birefringent crystal. Viewed between crossed polarizers, the image brightness is proportional to the strength of the torque. A thinner spacing layer *d* results in a stronger torque and hence a brighter image.

or using electrostatic or dispersion forces in a fluid. Unfortunately, those setups suffer from many of the same problems as experiments involving torsion rods.

To circumvent those problems, my group developed an alternative experiment that enabled the first quantitative measurement of the Casimir torque. The trick was to replace one of the birefringent plates with a liquid crystal, as shown in the figure. Liquid crystals contain birefringent molecules that can have local and long-range order. They behave much like solid birefringent crystals but can also wet another surface and rotate at the molecular level.

For our experiment, we used a solid birefringent crystal on which we deposited a thin—less than 30 nm—optically isotropic layer of aluminum oxide. That layer separates the solid crystal from the liquid crystal, much like the vacuum gap in Casimir-force experiments. Once the liquid crystal is placed atop the aluminum oxide, it wets the surface to form a three-layer stack: a solid birefringent crystal, aluminum oxide, and liquid crystal. The thickness of the spacer layer determines the distance between the solid and liquid crystals, and it can be varied by making multiple samples. The Casimir torque then rotates the liquid crystal so that its optical axis aligns with that of the solid crystal. We detected the rotation by measuring the polarization rotation of an incident light beam using an optical microscope.

The experiment, published in 2018, confirmed many of the predictions made by Parsegian, Weiss, and Barash. It showed that the torque decays with a power-law dependence on the separation and has a sin 2θ dependence on the angle. The optical properties of the crystal substrate and of the liquid crystal affect the magnitude of the torque and its sign (clockwise or counterclockwise rotation). My lab has measured torque densities as small as a few nanonewton meters per meter squared on surfaces separated by tens of nanometers.

Quantum effects in the real world

Beyond a confirmation of a quantum effect predicted decades ago, the measurement of the Casimir torque sets the stage for engineering vacuum fluctuations to modify how nanoscale and microscale devices work. In the world of microelectromechanical systems (MEMS), the Casimir force and the related van der Waals force are thought to have an important effect on surface-adhesion phenomena that cause devices to break. Reducing, eliminating, or even reversing the Casimir force among MEMS devices could ameliorate the problem.

Rather than being hindrances, the Casimir force and torque may perhaps give rise to more sensitive accelerometers and torsion sensors. What's more, the fact that the Casimir torque can affect liquid crystals—a staple of modern display technologies—suggests that liquid-crystal applications may also be on the horizon. Among the possibilities is ultralow-power switching that requires merely a tiny voltage to break the alignment of the liquid crystal and allow light to pass or be absorbed when the crystal is placed between crossed polarizers.

Additional resources

▶ V. A. Parsegian, *Van der Waals Forces: A Handbook for Biologists, Chemists, Engineers, and Physicists*, Cambridge U. Press (2005).

▶ D. Iannuzzi et al., "The design of long range quantum electrodynamical forces and torques between macroscopic bodies," *Solid State Commun.* **135**, 618 (2005).

▶ D. A. T. Somers et al., "Measurement of the Casimir torque," *Nature* **564**, 386 (2018).

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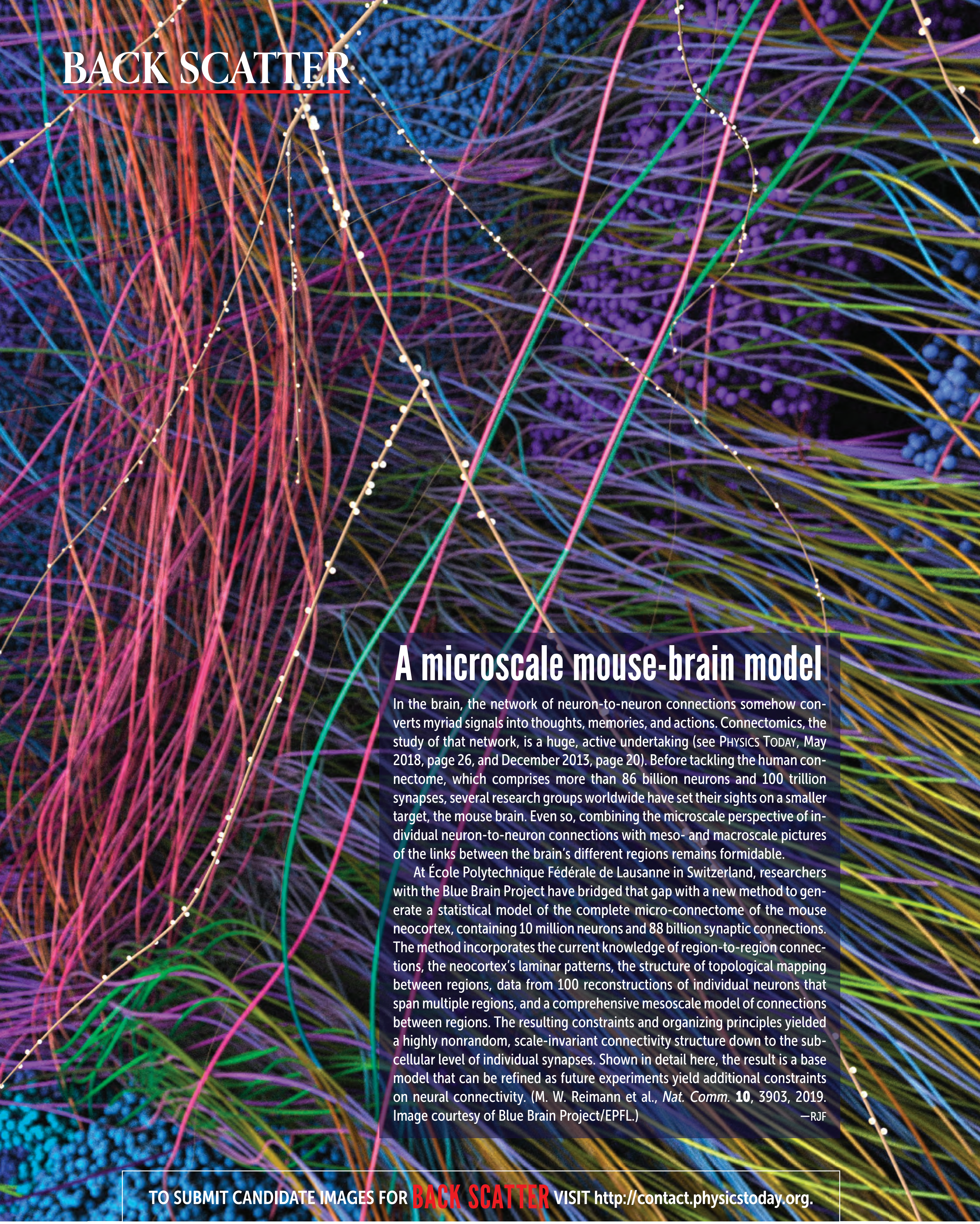
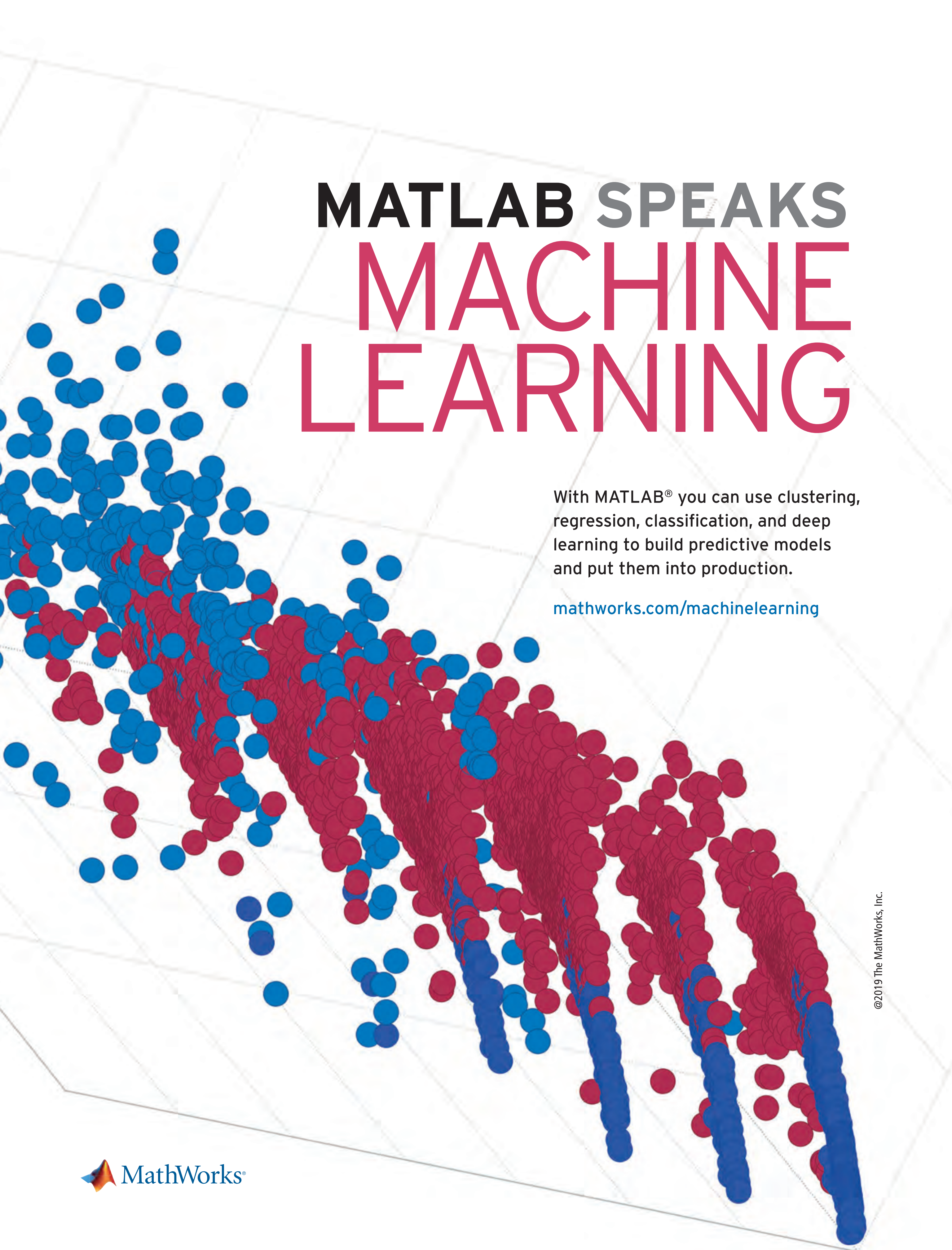


A microscale mouse-brain model

In the brain, the network of neuron-to-neuron connections somehow converts myriad signals into thoughts, memories, and actions. Connectomics, the study of that network, is a huge, active undertaking (see PHYSICS TODAY, May 2018, page 26, and December 2013, page 20). Before tackling the human connectome, which comprises more than 86 billion neurons and 100 trillion synapses, several research groups worldwide have set their sights on a smaller target, the mouse brain. Even so, combining the microscale perspective of individual neuron-to-neuron connections with meso- and macroscale pictures of the links between the brain's different regions remains formidable.

At École Polytechnique Fédérale de Lausanne in Switzerland, researchers with the Blue Brain Project have bridged that gap with a new method to generate a statistical model of the complete micro-connectome of the mouse neocortex, containing 10 million neurons and 88 billion synaptic connections. The method incorporates the current knowledge of region-to-region connections, the neocortex's laminar patterns, the structure of topological mapping between regions, data from 100 reconstructions of individual neurons that span multiple regions, and a comprehensive mesoscale model of connections between regions. The resulting constraints and organizing principles yielded a highly nonrandom, scale-invariant connectivity structure down to the subcellular level of individual synapses. Shown in detail here, the result is a base model that can be refined as future experiments yield additional constraints on neural connectivity. (M. W. Reimann et al., *Nat. Comm.* **10**, 3903, 2019. Image courtesy of Blue Brain Project/EPFL.) —RJF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