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February 2017 • volume 70, number 2

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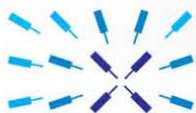
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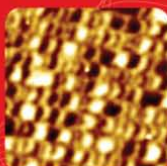
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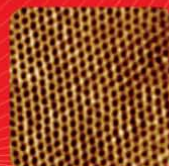
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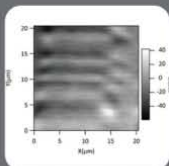


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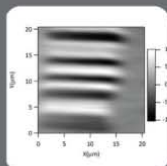
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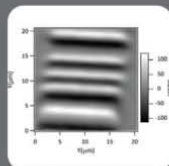
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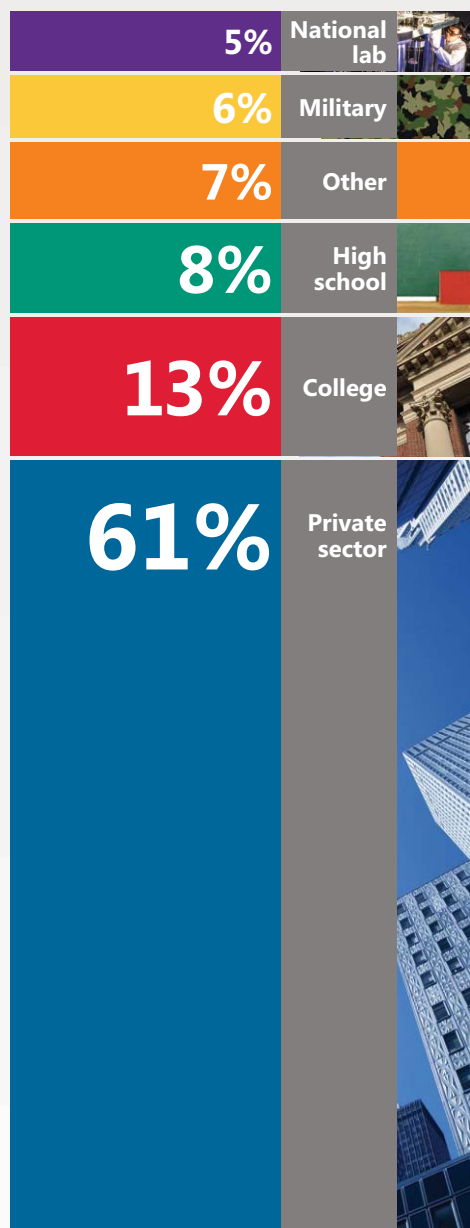
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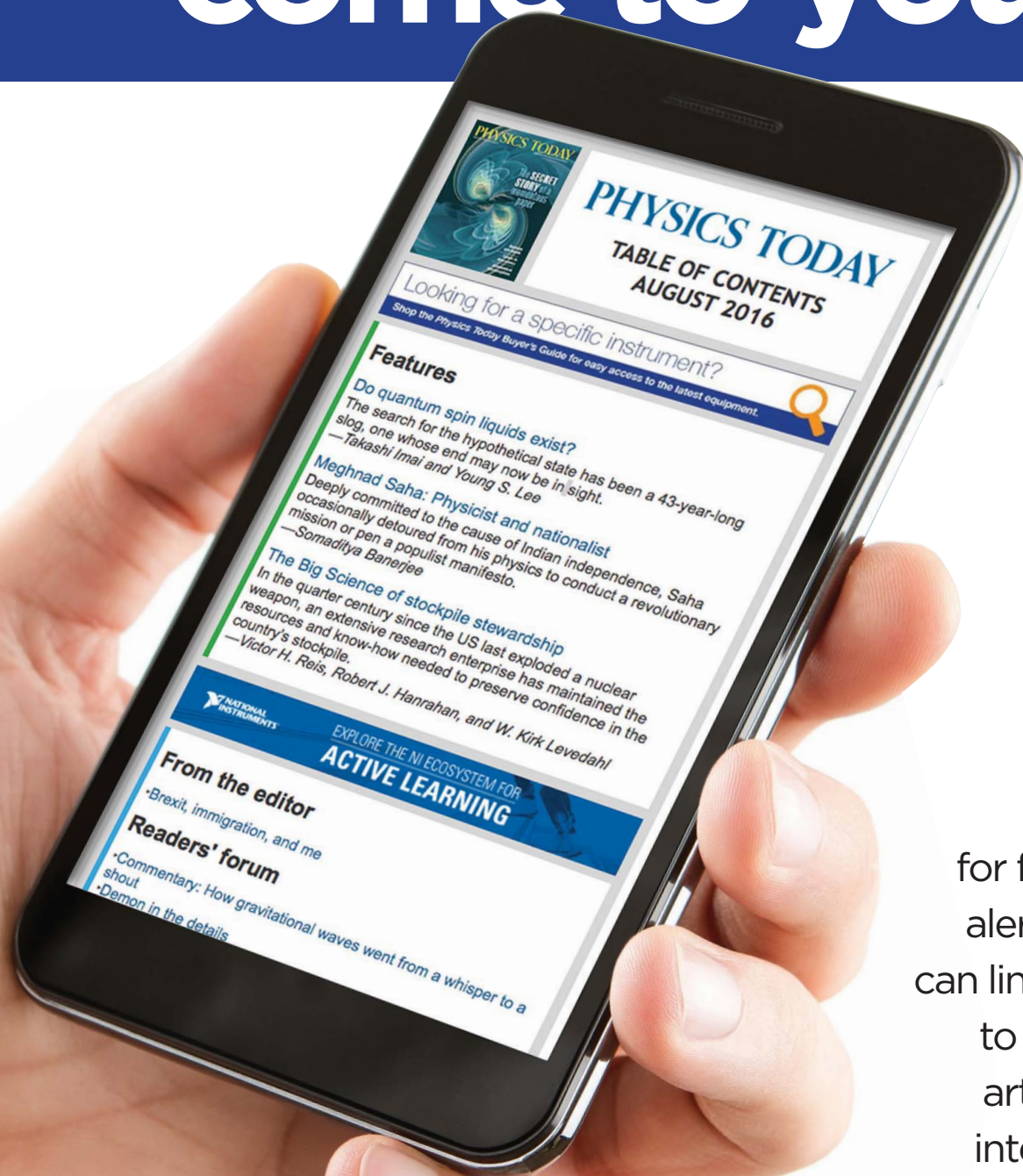
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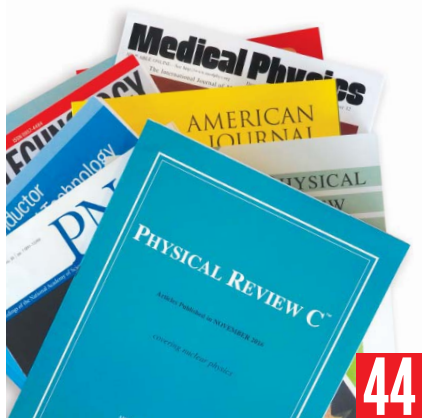
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Joseph P. Bassi

Boulder, Colorado, grew to become an important science center in part because nearby mountains provided an excellent spot for solar observation. But local scientists' connections to the Northeast establishment and some clever PR didn't hurt.

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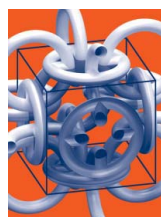
Melinda Baldwin

The imprimatur bestowed by peer review has a history that is both shorter and more complex than many scientists realize.

50 A bridge between undergraduate and doctoral degrees

Theodore Hodapp and Kathryn Sparks Woodle

Initiated in 2013, the American Physical Society Bridge Program has assisted more than a hundred underrepresented racial and ethnic minority students to pursue PhDs in physics.



ON THE COVER: Physics students learn that the Hall effect can be used to tell whether a material's mobile charge carriers are positively or negatively charged, but that test can be fooled. Shown here is the unit cell of a periodic metamaterial. When made out of an n-type semiconductor, the structure produces the Hall signature of a p-type semiconductor. To learn more about the metamaterial and how it works, turn to the story on **page 21**. (Image courtesy of Christian Kern.)

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► Impact factor

Elsevier's new CiteScore index is meant to challenge the journal impact factor, which was the brainchild of Eugene Garfield (above) in 1972. PHYSICS TODAY's Melinda Baldwin recaps the history of Garfield's controversial citation-based measure of academic journals.

TWENTIETH CENTURY FOX



► Hidden Figures

It's Oscar season, and one of 2016's most buzzworthy movies tells the story of black women who were "computers" at NASA. PHYSICS TODAY's Melinda Baldwin dives into the calculations that helped the US pull ahead in the space race.

AIP EMILIO SEGRÉ VISUAL ARCHIVES



► Vera Rubin in PT

The pioneering astronomer, whose research solidified the case for dark matter, died in December at age 88. PHYSICS TODAY's online editor Andrew Grant shares several insightful pieces that Rubin wrote for the magazine, including multiple letters standing up for women in science.

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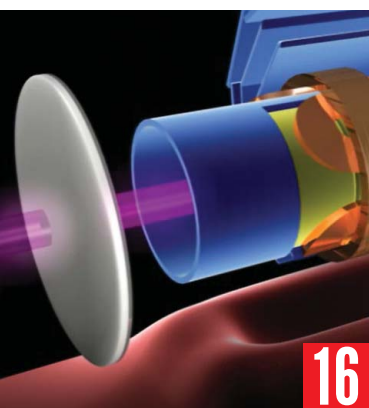


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FROM THE EDITOR

Olive spoons and terrapin forks

Charles Day

My wife and I live five blocks south of H Street, a revitalized commercial strip in northeast Washington, DC. The first signs of redevelopment took the form of new restaurants, bars, and apartment buildings. Next came a streetcar line. Soon H Street will boast a Whole Foods store.

As a keen cook, I look forward to the new grocery. Whenever I walk my dog past it, I check for progress. One dark early morning I spotted something unusual in the apron of flagstones outside Anthology, an oddly named new apartment building across from Whole Foods: white LED lights set between the stones.

At first I marveled at the twinkling decoration. Then a second, more sobering thought occurred to me. In 2014 the Royal Swedish Academy of Sciences awarded the Nobel Prize in Physics to Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura “for the invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources.” Yes, LEDs will save energy if they replace incandescent light-bulbs. But if the uses of LEDs proliferate beyond those of traditional incandescents, the savings could be lost.

A similar loss of savings could occur if carbon-based composites become cheap enough for widespread use in cars. Lighter cars use less fuel. But car companies could decide to exploit the new material to make cars bigger rather than more efficient.

The cancelling out of technological efficiency by commercial priorities has happened before. In 18th-century Britain, flatware was made from silver. Only the rich could afford to buy full sets of knives, forks, and spoons and to employ servants to keep them polished. By the mid 19th century, cutlery had figured out how to mass-produce silver-plated flatware from mild steel. Because the new flatware was cheaper, middle-class households could buy it. To boost profits, cutlery marketed new implements of befuddling variety, such as fish knives, cheese scoops, olive spoons, terrapin forks, oyster prongs, chocolate muddlers, gelatin knives—to borrow a list from Bill Bryson’s book



At Home: A Short History of Private Life (Doubleday, 2010).

What lessons do the olive spoon and terrapin fork have for us in the 21st century? First, they can prod us to examine the notion of technological progress. Advances in metallurgy led to advances in cutlery production, which led to super-specialized flatware. Is that progress? The so-called Internet of Things promises what benefits exactly? A “smart” milk carton that can alert your “smart” fridge, which can, in turn, alert your cell phone that the milk is about to sour?

A second lesson concerns economics. By selling bigger, more diverse sets of flatware, 19th-century cutlery firms could employ more people. Their customers bought the implements under no more persuasion than advertising wields. No doubt the owners of terrapin forks enjoyed showing them off at dinner parties. A triumph for capitalism!

I side with free-market economists on the matter of whether the government should tell companies what goods and services to sell to consumers. Except in times of national peril, it shouldn’t. Still, installing LED lights in sidewalks and manufacturing terrapin forks seems wasteful.

The extent to which humankind should husband Earth’s natural resources is debatable. Pessimistic ecologists point to shrinking rainforests and dwindling freshwater supplies. Optimistic economists point to market forces: If a resource becomes too scarce, its price shoots up, and cheaper substitutes will inevitably be found. Besides, precious resources such as erbium and the other rare earths don’t disappear when we use them to make electronic devices. Recycling them might be expensive, but they remain available.

Regardless of how the debate is resolved, I won’t be buying any olive spoons or terrapin forks.

PT



A SET OF 19TH-CENTURY TERRAPIN FORKS made by Gorham in its Egypt-inspired Isis pattern. (Image courtesy of Antique Cupboard, Big Bend, Wisconsin.)

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READERS' FORUM

Physics education research and student development

Thirty years ago, while teaching a physics class, I noticed that most of the students answered certain test questions incorrectly—in exactly the same way—because of a common misconception. I went back to my lecture notes and beefed them up, but I got the same results from the next class. Finally, I said the magic words, “This will be on the test; be sure you understand it.” On my subsequent tests, students gave me the answer I wanted. But in the next semester, those same students had reverted to their original viewpoints. That behavior was pointed out in the Quick Study by Andrej Favia, Neil Comins, and David Batuski (PHYSICS TODAY, August 2016, page 74).

Suppose a problem involves a package being dropped from a moving aircraft, with the package being initially at rest relative to the plane. If the student draws a diagram with a straight down or triangular trajectory, the mathematics that follows is correct, but the answer is wrong. Knowing that the trajectory is parabolic is crucial to the correct solution.

Unknown to me, other faculty members in the US were noticing the same phenomenon and began making lists of misconceptions, which have been presented at meetings of the American Association of Physics Teachers and in online forums. Beginning in the 1990s, the Force Concept Inventory—a test of those misconceptions—was formed,¹ and more than 12 000 students were tested, both with and without reformed instruction—which involves active student engagement during lecture and laboratory in various tested forms.

The key to correcting common errors is eliciting the misconception in preliminary questioning, confronting it with contrary hard evidence, and then guiding students in the formation of a new understanding.

The method worked. Testing before and after its use revealed significant gains in busting misconceptions—reform teaching was *substantially* better.¹ The reform effort fostered the Physics Education Research (PER) Group at multiple physics departments in the US.

“To successfully implement laboratory reform, the entire department has to agree on several components.”

Many converts came on board, but there were doubters. Academic freedom has allowed a mix of reform and nonreform classes to coexist in physics departments, and that coexistence has remained.

The optimal place to implement the new process is the laboratory. In traditional labs, students follow terse and often confusing cookbook instructions, have little understanding of what they are doing, and move one foot in front of the other. They then go home with reams of raw data in handwritten tables—to make graphs, draw conclusions, and answer final questions. Alone.

In the five venues where I have tried to reform the labs, only one department embraced the change. As I look back, the failure to adopt was related to the fact that faculty do not have academic freedom in laboratories; usually, the entire department uses the same materials. Diverse views about what are the crucial points cannot be accommodated easily. And so there develop factions, hard feelings, and sometimes sabotage of reform efforts.

To successfully implement laboratory reform, the entire department has to agree on several components:

- Eradicating misconceptions must be a major purpose of experiments. That includes guiding students to manipulate experiments and understand the

measurement process, learn by inquiry, replicate important equations, and apply the scientific method.

- Following one's intuition about best teaching practices does not trump what extensive PER research has found to be most effective.
- Attending one conference does not make a faculty member a PER expert. Multiple techniques must be tested in the local academic culture.
- Sending students home with huge tables of data to be analyzed—the way I was taught—should be abandoned.

My preferred method for laboratory work is to quickly take all-encompassing data by computer acquisition, perform automatic graphing, and have a summative small-group-guided interpretation period during the lab time. In my view, a student should meet 90% of the lab goals while still in the lab, not in take-home work.

Not attaining department agreement on the above items leads to failure. Few physics departments in the US have implemented laboratory reform and maintained it over several years. The University of Colorado, Washington University, and Dickinson College have continually provided leadership in developing techniques and resources for improving student outcomes.

Reference

1. R. Hake, *AAPT Announcer* 24(2), 55 (1994).

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Fracking and the future of fuels

The July 2016 issue of PHYSICS TODAY carries an article by Michael Marder, Tadeusz Patzek, and Scott Tinker entitled “Physics, fracking, fuel, and the future” (page 46). The article claims “to contend with the challenges of fueling modern society” and invites physicists to

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help. Unfortunately, although they describe fracking and its impact carefully, the authors don't mention the controversy now raging about wind, solar, and other alternative fuel technologies, including modern nuclear technology. If Marder and coauthors want to stimulate constructive progress for humanity, they should help readers to think about fuels that have real promise of outlasting oil and gas.

The article cannot be the end of the discussion. The world drastically needs to overhaul its energy production scheme to use truly sustainable, modern, and safe nuclear reactors, while utilizing the vast existing infrastructure of turbines and generators for electricity production. Despite media portrayals to the contrary, nuclear energy is the safest power system known to man.¹ In the late 1960s, the Sierra Club's motto was "Atoms, not dams," and Ansel Adams, who was on the club's board of directors for 37 years, said, "Nuclear energy is the only practical alternative that we have to destroying the environment with oil and coal."

Consider the following facts about molten-salt reactors (MSRs), which were demonstrated in 1965–70 at Oak Ridge National Laboratory.

- MSRs require no expensive containment since they operate close to atmospheric pressure.²
- MSRs can eliminate the need for Yucca Mountain storage by consuming existing nuclear wastes.
- MSRs consume close to 100% of their fuel, compared with 3% for older reactors with solid uranium fuel.
- Thorium fluoride molten fuel for MSRs is of no weapons value.
- Thorium fuel is more abundant and cheaper than uranium.

The time is now to replace the current infatuation with solar and wind, which are illusions at best. When the sun doesn't shine or the wind doesn't blow, the power generation stops, so they are not equal to the demand of modern society for energy availability 100% of the time. Germany is demonstrating that removal of nuclear energy in favor of wind and solar results in more carbon emissions, not less.³ Nor is energy storage even close to meeting the need when those alternatives fail. For this nation and the world to succeed without drowning itself in a flood of carbon diox-

ide in the next few decades, we need to follow the advice of Glenn Seaborg in 1962:

The overall objective of the [Atomic Energy] Commission's nuclear power program should be to foster and support the growing use of nuclear energy and . . . make possible the exploitation of the vast energy resources latent in the fertile materials, uranium-238 and thorium.⁴

I thank Alex Cannara for assistance in preparing this letter.

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3. B. Waterfield, *Telegraph*, "Germany is a cautionary tale of how energy policies can harm the economy," 16 January 2014.
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The article "Physics, fracking, fuel, and the future" had many crucial omissions and misleading statements and thus failed to give a clear idea of where we are and where we are headed with regard to fossil fuels in general, renewable energy, and energy technologies. For example, climate change, the main driver in the push to reduce fossil-fuel consumption, was not mentioned in the article.

Moreover, the authors do not seem to realize that the movement away from fossil fuels is already well under way. The Energiewende (Energy Transition), Germany's program to change to low-carbon, nonnuclear energy sources, is never mentioned, and that Germany, Spain, and Italy already obtain more than 20% of their electricity from renewable resources is ignored. The authors seem unaware of California's goal to generate, without nuclear power, 30% of its electricity from renewable resources by 2020 and 50% by 2030.

The authors attempt to discuss petroleum extraction modeling: Their figure 2 shows a plot of US crude-oil production and results from M. King Hubbert's model. Inexplicably, the strong decrease

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in US petroleum production in the past year is omitted. That decrease is not due to resource limits but rather to the unprofitability of shale-oil production at oil prices of about \$45 a barrel. Fracking has indeed opened up a significant new source of oil, but just like conventional oil it is a finite resource and production will peak based on economics and other factors.

Hubbert crafted an econometric model with political constraints.¹ The key role of economics is obvious: If oil is too expensive, demand and extraction will drop, as it did in 1973; if too cheap, companies will go bankrupt and supplies will drop, as they have in 2016. The role politics plays is less obvious than that of economics since regulations passed to restrict production and increase prices are unpopular and thus not widely debated. For example, in 1932 the US Congress established a tariff on oil imports to protect the US oil industry from cheaper foreign petroleum.

If US producers had been forced to compete with oil first from Venezuela

and then from the Middle East, US production would have peaked in the mid 1950s. Understanding how the oil market functions is crucial if oil production is to be modeled properly. Since 1973 the market has been divided between OPEC and non-OPEC producers, with OPEC adjusting production to obtain prices it deems appropriate based on economic and geopolitical considerations.²

In 2004 Exxon Mobil used that understanding and Hubbert's model to project a peak in non-OPEC conventional crude-oil production by about 2010, at which point OPEC would have complete control of the market. Based on that projection, Exxon Mobil declared that it would build no new oil refineries in the US³ since increased supplies of oil for them could not be guaranteed. In fact, non-OPEC conventional crude-oil production peaked in 2005, and OPEC raised prices rather than increase production.

Finally, the authors seem unable to imagine a world with much reduced fossil-fuel consumption (see the caption of the article's figure 1). My house in

Princeton, New Jersey, demonstrates that such reduced consumption is certainly possible. We insulate heavily, use high-efficiency windows, appliances, and lighting, and buy renewable wind electricity off the grid; a geothermal heat pump heats and cools our home; a heat-pump water heater supplies hot water; a photovoltaic array on our roof adds some renewable electricity to our grid. We also use an electric car for local travel.

Alternatives to fossil fuels and technologies, including energy efficiency and conservation, are actually widely available and affordable both in the developing and developed world, but may not be as cheap as fossil-fuel technologies. All of us should adopt the new (and old) high-efficiency technologies and work to inform the public that alternatives are available and that we can live quite comfortably without much fossil-fuel consumption at all.

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Alfred Cavallo

(cavallo-harper@verizon.net)

Princeton, New Jersey



In the July article by Michael Marder, Tadeusz Patzek, and Scott Tinker, I found no reference to greenhouse gases, global warming, fugitive methane emissions, drought, pollution, ocean acidification, coral bleaching, overpopulation, sea-level rise, energy efficiency, energy conservation, nonpolluting energy sources, overfishing, and other concerns that many scientists, technical people, politicians, and citizens are dealing with. There is a growing realization today that we may suffer a catastrophe if we use all the fossil fuels we are able to extract. How do the authors view my concerns?

Richard LaRosa

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South Hempstead, New York

[Editor's note: *PHYSICS TODAY* received several letters raising the same concerns as Richard LaRosa's.]

► **Marder, Patzek, and Tinker reply:**

David Cornell points out that we did not discuss wind, solar, and nuclear energy. Our purpose was to spur debate on the involvement of the physics community in research and education into energy by focusing on recent developments in hydrocarbon extraction, not to provide a comprehensive overview of potential solutions to the global energy problem. One of us (Tinker), through the Switch Energy Project (switchenergyproject.com), has provided a broad overview of advantages and disadvantages of various energy sources.

Alfred Cavallo brings up too many points for us to respond to all of them. He asks why we omitted the strong decrease in US petroleum production in the past year. According to the US Energy Information Administration, for the first nine months of each of the past six years US petroleum production has

been 1.5, 1.7, 1.9, 2.3, 2.5, and 2.4 million barrels. There has not been a strong decrease.

Cavallo also presents the virtues of energy-efficient homes. We note that one of us owns a home that runs off solar panels, has only electric appliances, uses only electricity for heating and cooling, and exports many megawatt hours of power each year to the electric grid. He also disconnected the city water supply and uses only rainwater gathered in three large tanks. Another of us invested heavily in home energy efficiency, including additional insulation, radiant barrier, water heaters, and beyond. The third reinsulated his home, gave up his parking permit, and has biked to work every day for more than 15 years. Such conservation measures are needed, but they cannot by themselves solve the problems we raised.

Richard LaRosa asks for our thoughts on the environmental dangers of using fossil fuels. His concerns are valid, and we share them. Yet to stop using fossil fuels precipitously and without a plan

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for replacement would undermine economies, curtail environmental investment, and produce a catastrophe more sudden and more certain than those he mentions. All sources of energy, at scale, have considerable environmental challenges.

Michael Marder

(marder@chaos.utexas.edu)

University of Texas at Austin

Tadeusz Patzek

King Abdullah University of Science and
Technology

Thuwal, Saudi Arabia

Scott W. Tinker

University of Texas at Austin

Book on Sakharov raises issues

We are disappointed that PHYSICS TODAY would publish an alleged book review (July 2016, page 61) by Alexei Kojevnikov of *Andrei Sakharov: The Conscience of Humanity*, which was edited by us and includes papers presented at a conference in December 2014. Kojevnikov's piece was not a review of the book at all, but an exposition of his own flawed personal interpretation of Sakharov's life and views. Worse, the reviewer slurs the book's essays by maintaining, falsely, that they use Sakharov's views on human rights to justify recent wars. Kojevnikov misrepresents both the essays and Sakharov's own ideas and the ways in which they continually evolved. He did not provide a single citation from the essays to support his description. The editors of PHYSICS TODAY were remiss in trusting—but not verifying—his outrageous claims.

An accurate statement of Sakharov's views can be gained by reading his own writing. One example is his "Open Letter to Anatoly Aleksandrov, President of the USSR Academy of Sciences," which reads in part,

I am convinced that the prevention of thermonuclear war is our most important problem and must take absolute priority over all other issues. The resolution of that problem involves politics, economics, the creation of interna-

tional trust among open societies, the unconditional observance of fundamental civil and political rights, and disarmament.

Disarmament, especially nuclear disarmament, is mankind's most important task.¹

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Sidney D. Drell

George P. Shultz

Hoover Institution

Stanford, California

[Editor's note: With sadness we inform our readers that Sidney Drell died on 21 December 2016.]



The July 2016 issue of PHYSICS TODAY contains Alexei Kojevnikov's review of the book *Andrei Sakharov: The Conscience of Humanity*, edited by Sidney Drell and George Shultz. The subject of the book and the editors are familiar to readers of PHYSICS TODAY, and therefore the review attracts attention. However, the reaction it evokes is mainly bewilderment and disappointment. Any review will contain its author's opinion, which can be positive or negative. However, the reader anticipates that a review will offer at least some information about the book's contents. In that respect, the "review" by Kojevnikov is anything but. The only thing that one finds out about the actual book is that it contains contributions from 11 authors.

We are not exaggerating. Kojevnikov's "review" is not a review at all. The entirety of the remaining text is filled by the reviewer's expounding on his own rather dubious concept of Sakharov's value system, and it ends with the criticism that the book does not reflect Kojevnikov's concept. His treatment of Sakharov's political and moral philosophy is highly questionable and, in our view, distorts Sakharov's position. It certainly fails to reflect the degree to which Sakharov's worldview continuously evolved.

We also believe Kojevnikov is wrong in trying to portray the morality and actions of the USSR during the Cold War as better, or at least not worse, than the

morality and actions of its Western adversaries.

Apart from the fact that Kojevnikov's writing does not belong in the Books section since it provides literally zero information about the actual book, we find it unfortunate and regrettable that PHYSICS TODAY has furnished publication space to such poor treatment of the philosophy espoused by one of the most respected and admired scientists and humanists of the 20th century.

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► **Kojevnikov replies:** My understandably disappointed respondents have not addressed the main criticism formulated in my review, namely that many contributors to *Andrei Sakharov: The Conscience of Humanity* cited Sakharov's moral authority only to advance ideas and agendas that fundamentally contradict his humanitarian values. Here are some examples from the book: Retired general Jim Mattis invoked Sakharov while extolling the morality of the US military's continuing engagement in the Middle East. Retired admiral James Ellis Jr, who commanded the 1999 NATO attack on Yugoslavia, used human rights as a justification for that and subsequent wars. He also suggested that a preemptive strike can "be viewed as an ethical imperative" against possible nuclear proliferation. Theranos CEO Elizabeth Holmes referred to Sakharov and human rights as the basis of her own work, which the media has since exposed as fraudulent corruption of science by commercialization.

In contrast, Sakharov stood up against the high-level scientific frauds, hawkish politicians, and trigger-happy generals of his time. He resolutely opposed warmongering and preventive strikes, championed human rights as the basis for peace and reconciliation of ideological tensions but not for war, and criticized as "flagrant crimes against humanity" the superpowers' military interventions in other countries, such as Vietnam and Afghanistan.

In today's world, the misuse of

human rights arguments for violent ends has become widespread, and I felt obliged to remind readers that it contradicts Sakharov's worldview. The letters call my summary "flawed," "dubious," and "questionable" but were not able to specify a single idea of Sakharov's that I got wrong. I trusted his own writings rather than wishful misinterpretations by some later biographers, and although there was no space for long quotations, I did indicate how Sakharov's ideas developed over time. The true legacy of the great humanist is absolutely incompatible with hawkish and neoconservative agendas and must not be used for such purposes.

Alexei Kojevnikov
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University of British Columbia
Vancouver, British Columbia, Canada

Society, politics, and the realm of physics

I was amazed to read the editorial about Brexit in the August 2016 issue of PHYSICS TODAY (page 8). I always feel uncomfortable when PHYSICS TODAY strays into the realm of politics. I understand that it is sometimes necessary, but UK immigration policy? I really don't care about the editor's opinion in this area. But I do object strongly to his assertion that Brexit was fueled by "ugly anti-immigration sentiment." I do not believe that is true. My reading is that the vote was motivated by the British people's dislike of the unelected, anti-democratic bureaucracy that runs the European Union.

I see nothing ugly about that. Moreover, I see nothing ugly about people wanting to control the immigration policy of the country of which they are citizens. So, Mr. Editor, stick to physics. We probably agree on that.

Robert S. Orr
(orr@physics.utoronto.ca)
Toronto, Ontario, Canada

► **Day replies:** Robert Orr's belief that immigration was not the biggest reason leave voters favored Brexit is supported by an opinion poll conducted soon after the referendum.¹ Almost half of leave

voters cited sovereignty as their main concern. But immigration came in second; it was the main concern of one-third of leave voters. What's more, the UK Home Office reported a surge in racially or religiously motivated hate crimes in the month after the vote.² Hate crimes also rose in the US after the election of Donald Trump as president.³

As for sticking to physics, this magazine has never done that. Our mission remains to report on physics, on the impact of physics on the wider world, and on the wider world's impact on physics. The Brexit vote will affect physicists, so PHYSICS TODAY covered it. (See "Brexit vote rattles UK and European scientists," June 2016, PHYSICS TODAY online.)

It's also part of PHYSICS TODAY's mission to serve as a forum for the exchange of ideas—which is why I welcome Orr's letter.

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Charles Day
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PHYSICS TODAY
College Park, Maryland

Making a name with Chinese characters

In the obituary for Moo-Young Han (PHYSICS TODAY, November 2016, page 70), we listed the transcription of his name into Chinese as 韓武樂, which is the common usage in Chinese scientific literature. In Korean and Japanese journals, however, it is transcribed as 韓茂榮.

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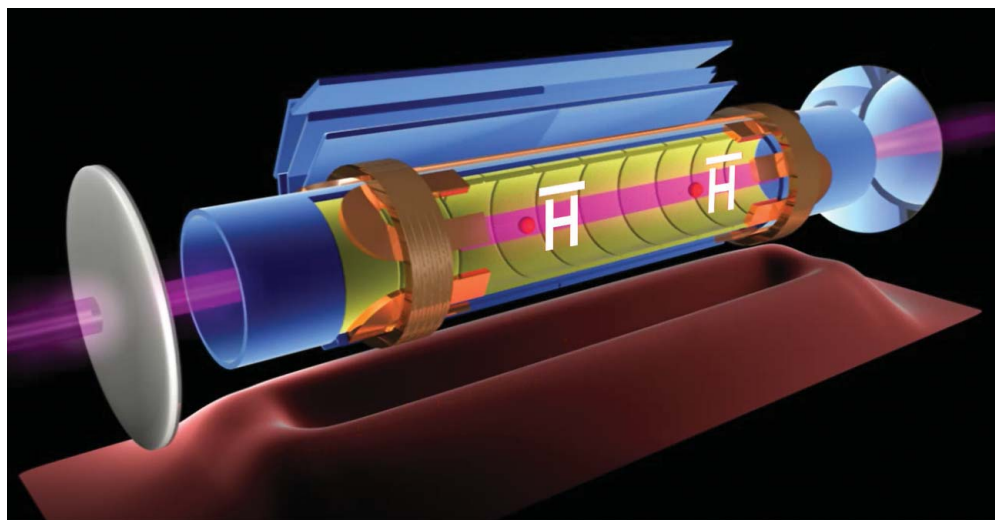
For the first time, researchers have probed the energy difference between two orbital states of an antimatter atom.

The observable universe contains almost no antimatter. Some naturally occurring radioactive isotopes decay via positron emission, and positrons and antiprotons are present in some high-energy environments, such as the particle showers produced by cosmic rays. But otherwise, matter is overwhelmingly dominant as the stuff of the natural world.

That's a puzzle. According to the laws of physics as we understand them, particles and their antiparticles should behave identically, except for a difference in sign for discrete properties such as charge. They should have been produced in identical numbers in the first moments after the Big Bang. The particle–antiparticle pairs should all have annihilated, and the universe should have been left with no matter or antimatter at all.

It wouldn't have taken much of a matter–antimatter imbalance in the primordial universe to produce the matter we see today. One extra proton per billion proton–antiproton pairs would have sufficed. But even that tiny excess is currently unexplainable. (See the article by Helen Quinn, *PHYSICS TODAY*, February 2003, page 30.)

The preponderance of matter over antimatter doesn't strictly require that matter and antimatter have some difference other than sign. But if laboratory experiments could detect such a difference, no matter how slight, it could be a crucial step in helping theorists to understand the asymmetry of the early universe. Toward that end, for the past 30 years several research groups at CERN have been working to trap and study atoms of antihydrogen. (See the Quick Study by Gerald Gabrielse, *PHYSICS TODAY*, March 2010, page 68.) A main goal of that research is to perform precision spectroscopic measurements to compare the atomic structure of antihydrogen with the known structure of hydrogen.



Now one of the CERN teams, the ALPHA collaboration, has achieved the first spectroscopic success: observing the transition between antihydrogen's 1s and 2s states.¹ Although the results reveal no difference yet between antihydrogen and hydrogen, the ALPHA researchers hope that their experimental precision, currently 200 parts per trillion, will greatly improve in the coming months.

Catching antiatoms

The standard technique for atomic spectroscopy—exciting atoms with a laser and detecting the photons they emit—is typically performed on samples of around 10^{12} atoms. For most ordinary matter, those samples are easy to come by. For example, more than 6×10^{22} hydrogen atoms can be extracted from a single milliliter of water.

Antimatter atoms are far more precious because of both the scarcity of their component particles and the difficulty of producing and handling them. CERN's Antiproton Decelerator, the source of all the facility's antihydrogen nuclei, produces just 3×10^7 antiprotons every 100 s. Those particles must be manipulated without the help of containers, tubes, nozzles, or cryostats made of matter.

The raw antiprotons, though decelerated, still travel at about 7% of the speed of light. To slow them further, the ALPHA team directs the antiparticle beam at a thin foil of aluminum. More

FIGURE 1. THE ALPHA-2 APPARATUS for trapping and spectroscopically probing atoms of antihydrogen. An array of coils and electrodes produces an inhomogeneous magnetic field that creates the potential-energy profile shown in dark red beneath the cylinder. The laser beam (pink), amplified by high-reflectivity mirrors, passes through the cylindrical trap. (Courtesy of Jeffrey Hangst.)

than 99% of the antiparticles are lost in the process, but those that survive annihilation and are scattered to a low enough energy can be combined with positrons collected from radioactive decay to produce antihydrogen. The procedure yields about 25 000 atoms per trial.

And that's the easy part. "Making cold antihydrogen, so we can trap it, is really hard," says Jeffrey Hangst, the ALPHA collaboration spokesperson. The atoms are charge neutral, so trapping them electromagnetically relies on their magnetic moment. In an inhomogeneous magnetic field, some of the atoms are drawn toward regions of lower field, so the team's magnetic trap, with low field in the middle and high field around the edges, serves to confine the atoms—provided their energies are lower than 0.5 K. In ALPHA's first successful trapping of antihydrogen in 2010, the researchers trapped just 38 atoms across 335 trials, and they held onto each trapped atom for a fraction of a second.² They've since

refined the experiment to trap an average of 14 atoms per trial and hold them for many minutes.

Small-sample spectroscopy

The 2010 experiment was focused on trapping, not spectroscopy. So in addition to improving their trapping rates, the ALPHA researchers had to rebuild their apparatus to accommodate a laser beam. The new setup, called ALPHA-2, is depicted in figure 1. To make the most of the small antihydrogen samples, the laser power is amplified by an optical cavity bounded by high-reflectivity mirrors placed outside the trapping region. About 1 W of laser power circulates through the region where the atoms are trapped.

The coils and electrodes of the magnetic trap leave no room for optical detectors, and a 14-atom sample wouldn't offer much of an optical-emission signal anyway. Happily, the trapped antihydrogen lends itself to an alternative spectroscopic method that works well for small numbers of atoms. When one of the atoms is excited by the laser, it doesn't always return directly to its original state. Sometimes it absorbs an additional photon and is ionized, and sometimes it returns to a spin-flipped version of the ground state. In either of those cases, the magnetic trap no longer confines it. The bare antiproton or spin-flipped atom drifts into the wall of the apparatus, is annihilated, and produces an easily detectable signal. At the end of the trial, the trap is turned off so the remaining atoms can also be counted.

The researchers probed the transition between antihydrogen's ground, or $1s$, state and its first excited state, $2s$. The excitation's long lifetime—about an eighth of a second—gives the excited-state atoms plenty of time to absorb another photon before decaying back to the ground state. The lifetime arises because the transition is forbidden for a single photon. So rather than tuning their laser to 121 nm, corresponding to the full energy of the transition, the researchers used a wavelength of 243 nm and relied on atoms absorbing two photons simultaneously to make the transition. The two-photon excitation has the added advantage of increasing the measurement's precision: When the two photons arrive from opposite directions, their Doppler

shifts nearly cancel, so the spectral line is not significantly broadened by atomic motion.

Figure 2 shows a simulation of the expected results, provided that antihydrogen is just like hydrogen. When the laser is tuned to exactly the right frequency (a detuning of 0), about half the atoms should be lost from the trap during each 10-minute trial. When the laser is detuned by a few kilohertz, a slightly smaller fraction should be lost. And when the laser is detuned by 100 kHz or more in either direction, few to no atoms should be excited, so nearly all of them should remain in the trap.

With their beam time running out for 2016, the ALPHA researchers tested just two laser frequencies: one on resonance and one detuned by -200 kHz, or a relative frequency difference of about 200 parts per trillion. The choice of 200 kHz was essentially arbitrary, Hangst explains, and isn't indicative of any limitation of the experimental method. "We wanted a detuning large enough that we could be sure of seeing nothing."

And nothing is what they saw. They observed 27 annihilation events during the off-resonance trials, but that number was consistent with the expected background from cosmic rays. On the other hand, the 11 on-resonance trials looked at a total of 146 atoms, 79 of which escaped the trap.

Key to unification?

The ALPHA experiment implies that if there's any fractional difference between the transition frequencies of hydrogen and antihydrogen, it's less than 2×10^{-10} . In a way, that null result is reassuring. The symmetry between particles and their antiparticles is underpinned by the theories of both quantum mechanics and general relativity, so any observed difference between matter and antimatter spectra would require major changes to most of what we think we know about the laws of physics.

The nature of those changes remains to be seen. "In the search for a new effect, it's useful to identify all possible types of signals, and indeed a general theory of all possible signals exists," says Alan Kostelecky of Indiana University Bloomington. "But until an effect is discovered, predictions from specific models shouldn't be taken too seriously."

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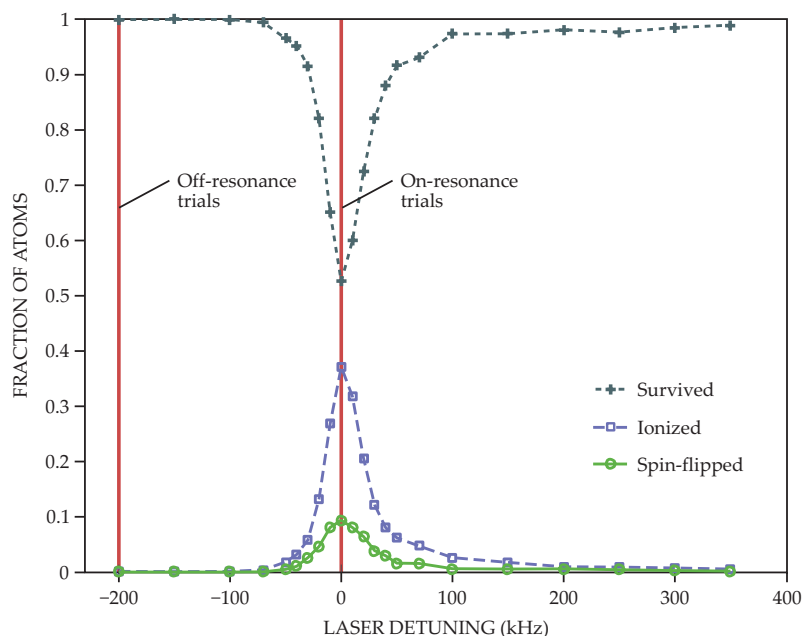


FIGURE 2. SIMULATED RESULTS of an antihydrogen spectroscopic experiment. Atoms that are excited by the laser may be ionized or spin-flipped and thus lost from the trap. So far, the ALPHA experiment has tested two values of the laser detuning, as marked by the red lines. The results for atoms remaining in and escaping from the trap are consistent with the simulation. (Adapted from ref. 1.)

Still, it's possible to make some educated guesses about what a matter-antimatter difference might look like. Because the revamping of quantum mechanics and general relativity could lead to unification of the two theories, one might expect the telltale spectroscopic difference to be on the natural size scale for unification effects: the ratio of the energy of elec-

troweak processes to the Planck energy, or somewhere between 10^{-17} and 10^{-23} .

It's conceivable that spectroscopic measurements could eventually chip away at that range. But that would require progress not just in antihydrogen spectroscopy but also in hydrogen spectroscopy. The latter's precision is currently around 10^{-15} .

The ALPHA experiment resumes in May, and the researchers have a lot on their agenda. They want to get a detailed measurement of the $1s-2s$ transition by checking many more values of the laser detuning. They plan to explore the single-proton transition $1s-2p$, which would open the door to laser cooling of antihydrogen. And they're building a new machine to study a different open question: In the gravitational field of a planet made of matter, do antimatter atoms fall up or down?

Johanna Miller

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Supercooled water survives in no-man's-land

A "stop-motion" crystallization experiment laid bare the liquid's behavior in a temperature range that was once considered inaccessible.

Water doesn't necessarily freeze at its freezing point. A skillful experimenter who maintains the liquid free of impurities can chill it well below 0°C , or 273 K , in a metastable, supercooled state. In the 1970s chemists Austen Angell and Robin Speedy, then both at Purdue University, set out to determine just how cool water could go.¹ What they observed remains one of the biggest mysteries in thermodynamics: As their sample dipped below 250 K , its isothermal compressibility and heat capacity began to soar, indications that its density and entropy were fluctuating wildly at the molecular scale. Water seemed on the verge of some never-before-seen trans-

formation. But before the drama could play out, the sample froze.

Unable to usher the liquid below 247 K , the researchers did the next best thing: They extrapolated their data. And they concluded that whatever the mystery transformation was, it happened at 228 K , where their power-law fits predicted a singularity.

In the decades since, several possible explanations have emerged—that the fluctuations were merely precursors to crystallization, for instance, or that they signaled the existence of a theretofore unknown liquid-liquid phase transition. (See the article by Pablo Debenedetti and Gene Stanley, *PHYSICS TODAY*, June 2003,

page 40.) Speedy himself conjectured that 228 K marked the temperature at which water reached a thermodynamic bound known as a spinodal, beyond which a metastable liquid phase does not exist.²

A correct explanation, if one can be found, would do more than settle a decades-old debate. It would deepen scientists' understanding of other unusual properties of water, including the anticorrelation of entropy and volume observed at temperatures below 277 K . But the theories have proven all but impossible to scrutinize in the lab. That's because at 232 K , the so-called homogeneous nucleation temperature T_H , even pristine water will freeze—and freeze quickly. Just below that temperature, a crystalline phase spontaneously emerges in just tens of microseconds, even if no impurities are present to seed its growth.

Greg Kimmel and Bruce Kay, who have been experimenting with water for nearly two decades at Pacific Northwest National Laboratory (PNNL), knew there was little—no, nothing—they could do to slow down water's crystallization below T_H . So instead they devised a com-

bination of techniques that allowed them to speed up their observation times. In a newly published paper, they and their PNNL colleagues report the fruits of that labor:³ the deepest experimental sortie yet into the no-man's-land of water's phase diagram below T_H . The results don't settle the mystery of water's fate in the supercooled regime, but they cull the contending theories.

Stop-motion crystallization

Chilling ordinary water is one way to create a supercooled liquid; melting ice is another. When liquid water is rapidly cooled to 136 K or colder at atmospheric pressure, it adopts a glassy form known as amorphous ice. In essence, its molecules freeze in place but maintain their liquid-like configuration. If the amorphous ice is then reheated past 136 K, the molecules jiggle free, and the water again behaves like a liquid.

For decades, researchers have been exploiting that roundabout path to the supercooled regime in order to experiment with water below T_H . At those extremely low temperatures, molecules diffuse sluggishly, so even though the thermodynamic driving force for crystallization is high, the kinetics are slow, and there's ample time to perform measure-

ments. As the melted amorphous ice warms, however, the kinetics speed up. At the so-called crystallization-onset temperature T_x —roughly 160 K at atmospheric pressure—an experimenter ends up in a familiar bind: The melt crystallizes almost instantaneously. The region between T_x and T_H therefore constitutes a sort of no-man's-land; absent confirmation of a continuous thermodynamic path across it, one can't be sure the melt is truly a liquid phase, much less one that could illuminate the strange happenings near 228 K.

The PNNL researchers accessed that no-man's-land by using a pulsed IR laser to melt amorphous ice for nanoseconds at a time. As illustrated in figure 1, they deposited a 25-monolayer amorphous-ice film atop a crystalline-ice film, which coated a platinum substrate held at 90 K. When irradiated by an IR pulse, the amorphous layer thaws, warms above T_x , and begins to crystallize at the amorphous-crystalline interface. (Because the temperature never exceeds water's melting point, 273 K, the underlying crystalline film remains frozen.) Then, just as crystallization in the amorphous layer is getting under way, the heat dissipates, crystallization halts, and the remaining amorphous melt cools

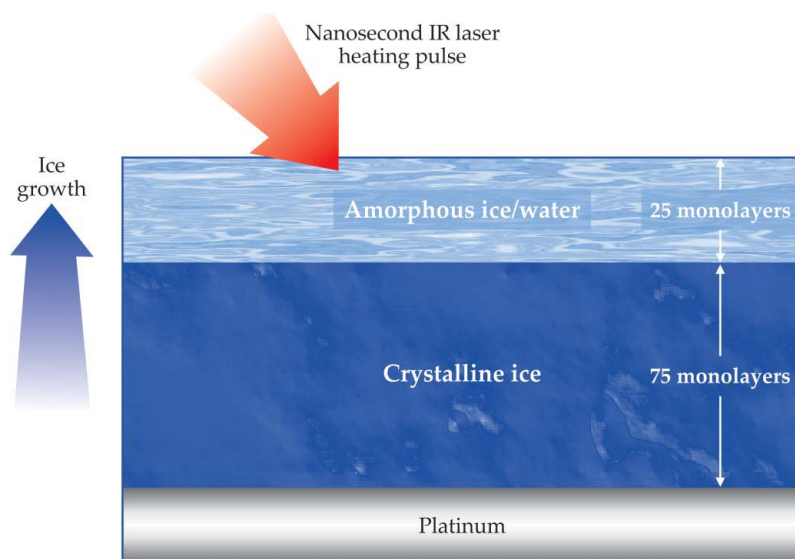


FIGURE 1. STOP-MOTION CRYSTALLIZATION. Researchers at Pacific Northwest National Laboratory observed the rapid crystallization of supercooled water using the 100-monolayer structure illustrated here. A 10 ns IR pulse melts the overlying amorphous-ice layer just long enough for it to partially crystallize at the interface with the underlying crystalline ice; the rest of the layer cools back to the amorphous-ice state. By repeating the pulses and monitoring the growth of new ice, the researchers could tease out crystallization rates and, by extension, dynamic properties of the liquid phase. (Adapted from ref. 3.)

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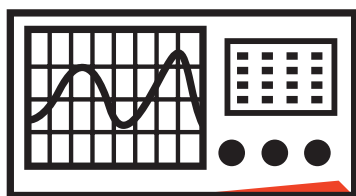


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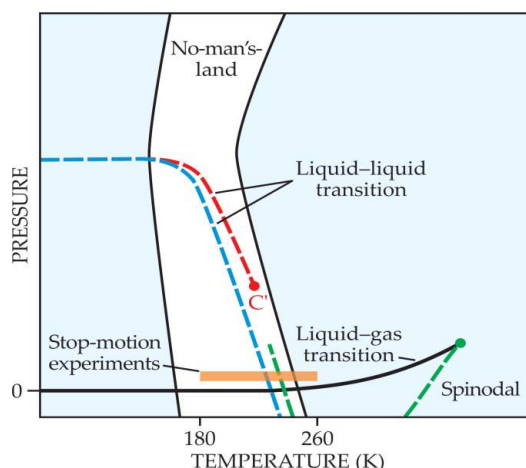


FIGURE 2. SEVERAL PHASE-DIAGRAM FEATURES have been hypothesized to explain supercooled water's behavior in an experimentally challenging "no-man's-land," including a liquid-liquid transition curve that terminates at a high-pressure critical point C' (red); a liquid-liquid transition curve that dips to negative pressures (blue); and a spinodal (green) that decreases, then rises, in pressure as temperature falls. New "stop-motion" experiments exploring no-man's-land at vacuum pressures (orange bar) find no evidence of a spinodal

or a liquid-liquid transition, but they don't rule out the possibility of a liquid-liquid transition with a high-pressure critical point.

back to the amorphous ice state. With each new pulse, the process repeats, and the amorphous-crystalline interface edges upward.

Kimmel likens the procedure to the stop-motion techniques Claymation directors used to make *Wallace and Gromit* and other films. "They make their clay figurines and then they take a picture. Then they move them a little bit and take another picture, and so forth. Then they make a movie out of it." Kimmel and his coworkers perform a similar trick with water, except instead of taking pictures, they use absorption spectroscopy to determine how much new crystalline ice forms after each thawing pulse. From that growth rate, the researchers can infer the liquid's diffusivity, which serves as a window into its thermodynamics.

In 2014 a collaboration led by Anders Nilsson of SLAC used femtosecond x-ray pulses to investigate water microdroplets cooled into no-man's-land,⁴ but only to temperatures near 228 K—not quite low enough to rule conclusively on Speedy's spinodal conjecture or competing theories. The PNNL team, by contrast, was able to measure diffusivities between 180 K and 260 K, nearly the full width of the elusive region.

The limiting factor below 180 K was the PNNL researchers' own patience. The number of IR pulses required to crystallize the film of amorphous ice grew sharply as the measurement temperature fell, explains Kay. "We could explore something like a million pulses in a 24-hour period. It took our postdoc Yuntao Xu three days to get the lowest data point." Once the team had measure-

ments down to 180 K, however, a smooth interpolation could be drawn to connect the diffusivity curve with one obtained by conventional means below 160 K.

A tale of two liquids?

The PNNL team found that water's diffusivity declines steeply but continuously as its temperature falls through no-man's-land. Even as the data pass through Speedy's hypothesized spinodal (the green curve in figure 2) there's no hint of a kink that would signal a thermodynamic singularity.

To David Limmer, a chemist at the University of California, Berkeley, the smoothness of the curve definitively rules out the spinodal conjecture—especially in light of Nilsson and company's results, which hinted at a similar conclusion. "The fact that you can have a smooth continuation of the high-temperature diffusion data to the lower-temperature data is certainly suggestive of a well-defined metastable liquid at temperatures lower than many people had expected."

But could there be two well-defined liquids? A popular explanation of the fluctuations in the Angell-Speedy experiment is that they stem from the existence of a first-order transition between a high-density liquid phase and a low-density one exhibiting a more ice-like molecular configuration. That theory would also neatly explain the sharp density jumps seen when amorphous ice is cycled above and below pressures of about 2 kbar. (See *PHYSICS TODAY*, December 2013, page 16.) But the PNNL experiments produced no hints of such a transition.

Even to many proponents of two-

liquid theories, that isn't terribly surprising. To precisely control the thickness and structure of their water films, the PNNL researchers performed their experiments under vacuum. Although some two-liquid theories predict a first-order phase transition at vacuum pressures (see the blue curve in figure 2), most predict that the liquid-liquid equilibrium curve extends down only to a critical point

located at several hundred times atmospheric pressure (red curve). To test those scenarios, the PNNL group would have to adapt its technique for high-pressure operation, a task that Kay says "would be tricky, but possibly doable."

For now, the researchers have set their eyes on a different experimental prize: measuring the homogeneous nucleation rate of water throughout no-man's-land—

data that would provide a coveted benchmark for numerical models.

Ashley G. Smart

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Semiconductor metamaterial fools the Hall effect

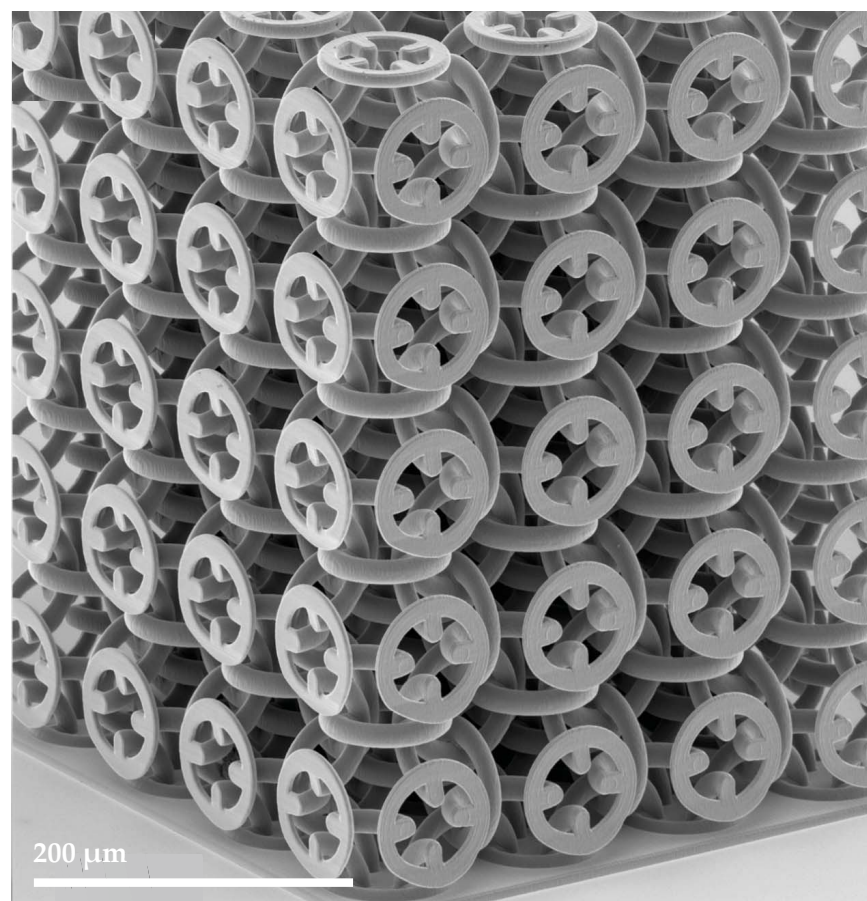
A structure made entirely out of an n-type semiconductor can mimic some properties of a p-type semiconductor.

Much to the confusion of many beginning physics students, electric current vectors are conventionally written as if they represented the flow of positive charge: The direction of the current is opposite to the direction in which electrons actually move. The convention has its origins in Benjamin Franklin's one-fluid theory of electricity. Lacking evidence to the contrary, Franklin assumed that the phenomena he observed resulted from the movement of a positive "electric fire." The theory was mostly serviceable: There's often little to distinguish a positive charge moving in one direction from a negative charge moving in the other.

One way to tell the difference is via the Hall effect, the appearance of a transverse voltage when an electric current passes through a magnetic field. Charge carriers are deflected in the direction that corresponds to the cross product of the (conventionally written) current and the field. If the charge carriers are positive, they produce a voltage gradient in the same direction. If they're negative, the gradient is in the opposite direction.

The Hall effect provides experimental evidence that currents in metals arise from the flow of negative charge. It also offers a way to distinguish between n-type semiconductors, whose charge carriers are also electrons, and p-type semiconductors, whose charge carriers are positively charged holes.

But the relationship between charge-carrier sign and Hall voltage is not always so simple, as Martin Wegener and his



colleagues at the Karlsruhe Institute of Technology in Germany have now experimentally shown.¹ Using an n-type semiconductor, the researchers crafted a microstructured metamaterial, shown in figure 1, that behaves like a p-type semiconductor—at least as far as the Hall effect is concerned.

Science mirrors art

The literature is full of examples of metamaterials with electromagnetic, acoustic, or mechanical properties that are qualitatively different from those of their

FIGURE 1. INSPIRED BY MEDIEVAL

ARMOR. The metamaterial shown in this electron micrograph is a periodic array of linked hollow rings. Made of n-type zinc oxide, it exhibits the Hall signature of a p-type material. (Adapted from ref. 1.)

constituents. For example, metamaterials can be designed to have both negative electric permittivity and negative magnetic permeability (or, more simply, a negative index of refraction), despite the fact that there are no such bulk materials in nature.

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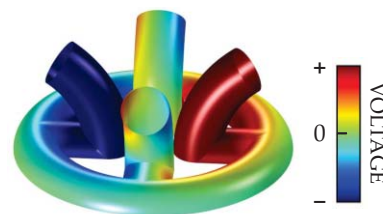
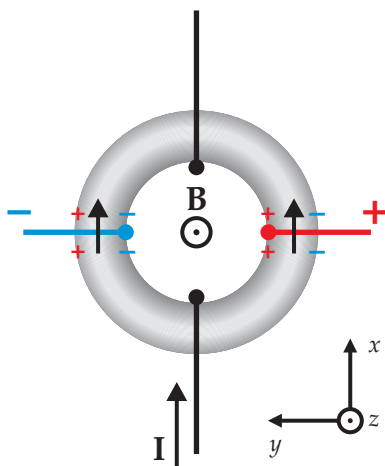


FIGURE 2. WHY THE HALL VOLTAGE FLIPS.

With the current I in the x direction and the magnetic field B in the z direction, as shown here, an n -type semiconductor produces a local Hall-voltage gradient in the $+y$ direction. But because of the way the rings are linked, the ring on the $+y$ side picks up a negative potential and the ring on the $-y$ side picks up a positive potential. The simulated potential map on the right shows the same region in more detail. (Adapted from refs. 1 and 3.)

That tunability of electromagnetic properties can be exploited to create an invisibility cloak: a metamaterial shell that bends electromagnetic waves in a way that leaves no trace of the cloak itself or any objects it conceals. (See *PHYSICS TODAY*, February 2007, page 19.) Unfortunately, the effect isn't quite as striking in real life as it is in the fictional *Star Trek* or *Harry Potter* universes. Cloaking metamaterials are made up of tiny resonators that function only over a limited frequency range. To reveal an invisibility cloak, all you need to do is illuminate it with a different color light. Most other curious metamaterial behaviors also arise from internal resonances, so they're also frequency dependent.

The Hall-effect inversion is different. Rather than relying on an oscillation of just the right frequency, it works with direct current. As pointed out by the University of Utah's Graeme Milton, one of the mathematicians who predicted the effect, the fact that an n -type metamaterial can so effectively mimic a p -type base material "shows some limitations on what information we can gain about what's really inside a three-dimensional body."

Milton and his collaborator Marc Briane came up with the idea of Hall-effect inversion while working with Vincenzo Nesi on a different but related problem: the effective conductivity of a composite material under a static nonzero electric field but no magnetic field. They rigorously proved that it was possible for certain properties of the conductivity to change sign in a 3D composite but not in a 2D composite. The same turned out to be true for the Hall voltage.

Milton and Briane were exploring the

electromagnetic properties of 2D arrays of interlocked rings resembling medieval chain-mail armor when they happened upon the website of a chain-mail artist named Dylan Whyte. Briane sought Whyte's permission to reproduce one of his artistic images in a paper. In his reply, Whyte suggested a 3D interlocking ring structure for the mathematicians to consider. "That turned out to be precisely what we needed!" says Milton. He and Briane showed theoretically in 2009 that a version of Whyte's structure, made entirely of n -type materials, had the Hall properties of a p -type semiconductor.²

Forging links

Briane and Milton's metamaterial required three distinct n -type materials: one for the rings themselves, one to form bridges between linked rings, and one background material in which the whole structure was embedded. Creating such a metamaterial in the lab—on the micron scale and with the necessary precision of all the material interfaces—would have been unreasonably demanding.

But two years ago, while tinkering with numerical simulations of Hall-effect inversions, Wegener's postdoc Muamer Kadic found that the structure could be simplified to require only one semiconducting material.³ (The unit cell of the simulated structure is shown on the cover of this issue.) That simplification brought fabrication within reach.

The fabrication effort, led by PhD student Christian Kern, began with 3D direct laser writing—a form of 3D printing—to make a scaffold structure out of a polymer material. The scaffold was then coated with a thin film of n -type

zinc oxide, a wide-bandgap semiconductor. Removing the scaffold was unnecessary: Because it's electrically insulating, it has no effect on the metamaterial's electrical properties. The interlocked rings were essentially hollow tubes rather than solid tori—but according to simulations, that geometry doesn't change the qualitative behavior.

Theory was borne out by experiment: The n-type ZnO metamaterial produced the Hall voltage of a p-type semiconductor. For a qualitative picture of what's going on, consider the sketch in figure 2. With the current in the $+x$ direction and the magnetic field in the $+z$ direction, the Hall effect in an n-type material normally produces a positive potential on the $+y$ side (toward the left in the figure) and a negative potential on the $-y$ side. Indeed, that's still the case locally for

small regions of material, such as the vicinities of the small black arrows. However, because the currents and voltages are passed from ring to ring via the rings' inner edges, the ring on the left picks up a negative potential and the ring on the right picks up a positive potential. Compounded across the 5-unit-cell width of the metamaterial, the effect gives a measurable inverted Hall voltage on the order of 50 μV from a current of 0.5 mA and a magnetic field of 0.83 T.

It's not yet clear what applications, if any, the Hall-effect inversion might have. Just because the metamaterial behaves like a p-type semiconductor doesn't mean it is one. "The charge carriers still carry negative charge," says Kern, so the metamaterial can't replace the p-type material in a semiconductor diode, for example. And even if it could, p-type semiconduc-

tors are readily available, so there'd be no obvious advantage to the replacement.

Still, Wegener and his group are pressing onward. They're working on the technical challenges of interfacing their metamaterial with a silicon chip, to study the effect in more detail and possibly exploit it in a magnetic field sensor. And they're looking into anisotropic metamaterials, which can produce a Hall-voltage gradient with a component parallel to the magnetic field—another effect not found in nature.

Johanna Miller

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PHYSICS UPDATE

These items, with supplementary material, first appeared at www.physicstoday.org.

SUPERLUMINOUS EVENT MAY LOSE SUPERNOVA STATUS

In June 2015 the All-Sky Automated Survey for Supernovae snagged a huge fish: an extremely luminous object, dubbed ASASSN-15lh, whose spectrum appeared consistent with that of a supernova. The object's luminosity peaked at about 2.2×10^{45} erg/s (2.2×10^{38} J/s), a factor of two higher than that of any other measured stellar

explosion (see PHYSICS TODAY, March 2016, page 14). Yet the ramifications of the supernova interpretation, including the sheer scale of nucleosynthesis necessary to generate so much energy, led scientists to consider alternative mechanisms.

Following a 10-month examination at multiple wavebands, one research team now argues that ASASSN-15lh is actually a star that got torn apart by the extreme tidal forces of its galaxy's supermassive black hole (SMBH). The scientists, led by Giorgos

Leloudas from the Weizmann Institute of Science in Israel and the University of Copenhagen in Denmark, found that ASASSN-15lh went through three distinct spectroscopic phases, including one with helium emission lines that have never been

The event took place at the center of a massive red galaxy whose star formation rate has all but petered out. Such galaxies harbor SMBHs but not the young blue stars whose lives end in supernovae. The researchers also observed a second peak in UV emissions about two months after ASASSN-15lh, which is consistent with the behavior of a previous transient that is thought to be a tidal disruption event.

In making their case, Leloudas and colleagues faced one major objection: The SMBH in question is so massive that it should swallow stars whole rather than shredding them first. The researchers circumvented that problem by proposing that the black hole is rapidly spinning (see artist's conception here), which can extend the range of strong tidal forces by nearly an order of magnitude. (G. Leloudas et al., *Nat. Astron.* **1**, 2, 2016.)

—AG

CONSTRAINING INTERPRETATIONS OF QUANTUM MECHANICS

John Stewart Bell's famous theorem is a statement about the nature of any theory whose predictions are compatible with those of quantum mechanics: If the theory is governed by hidden variables, unknown parameters that determine the results of measurements, it must also admit action at a distance. Now an international collaboration led by Adán Cabello has invoked a fundamental thermodynamics result, the Landauer erasure principle, to show that systems in hidden-variable theories must have an infinite memory to be compatible with quantum mechanics.

In quantum mechanics, measurements made at an experimenter's whim cause a system to change its state; for a two-state electron system, for example, that change can be from spin up in the z -direction to spin down in the x -direction. Because of those changes, a system with hidden variables has to have a memory so that it knows how to respond to a series of measurements; if that memory is finite, it can serve only for a limited time. As an experimenter keeps making observations, the system must eventually update its memory, and according to the Landauer principle, the erasure of information associated with that update generates heat. (See the article by Eric Lutz and Sergio

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detected in the brightest supernovae. Further support for the researchers' proposal comes from the location of ASASSN-15lh.

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Ciliberto, *PHYSICS TODAY*, September 2015, page 30.) In the electron example, if all spin measurements must be made along the x - or z -axis, each measurement dissipates a minimum amount of heat roughly equal to Boltzmann's constant times the temperature. Cabello and col-

leagues show, however, that if an experimenter is free to make spin measurements anywhere in the xz -plane, the heat generated per measurement is unbounded—obviously, an unphysical result.

Heat need not be produced in a hidden-variables theory if a system could store unlimited information. Such is the case, for example, for David Bohm's version of quantum mechanics, in which a continuous pilot wave serves as the information repository. And in formulations of quantum mechanics without hidden variables, such as in the Copenhagen interpretation, heat is not generated because there is no deterministic register to update. (A. Cabello et al., *Phys. Rev. A* **94**, 052127, 2016.) —SKB

THE SPACE WEATHER ON THE CLOSEST EARTH-LIKE EXOPLANET

In August 2016 hints were confirmed that an Earth-like planet orbits the Sun's nearest stellar neighbor, the red dwarf Proxima Centauri. The discovery excited astronomers. Proxima Centauri is close enough that the exoplanet, Proxima Centauri b, will be directly visible to the next generation of space telescopes and to the giant ground-based telescopes currently under construction. (The accompanying artist's impression depicts Proxima Centauri

as seen from the exoplanet surface.) Furthermore, the exoplanet's orbit lies within the star's habitable zone—that is, the volume of space within which a planetary surface can sustain liquid water given enough atmospheric pressure. Does the exoplanet have a thick atmosphere? To begin to address that question, Cecilia Garraffo of the Harvard-Smithsonian Center for Astrophysics and her colleagues modeled the hot wind of charged particles that emanates from Proxima Centauri. Because the precise values of the star's magnetic field and the exoplanet's orbital inclination and eccentricity are unknown, the researchers ran their magnetohydrodynamic model eight times with different sets of parameters. According to the model, Proxima Centauri's wind is roughly as



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strong as the Sun's, even though the red dwarf is smaller and dimmer. But because of Proxima Centauri's low luminosity, its habitable zone lies much closer to the star than the Sun's does. For all eight scenarios, the wind that buffets Proxima Centauri b is approximately 1000 times more powerful than solar wind is at Earth's orbit. Even though the exoplanet likely has a magnetic field, whatever atmosphere the exoplanet was endowed with was likely blown away long ago. (C. Garraffo, J. J. Drake, O. Cohen, *Astrophys. J. Lett.* **833**, L4, 2016.) —CD

PITCH SHARPENING IN WOODWINDS

Today's concert woodwinds feature as many as two dozen tone holes and a bevy of levers, called keys, that put the full chromatic scale over multiple octaves at a player's fingertips. Yet even on keyless instruments, like the recorder, bagpipe chanter, and the Japanese shakuhachi, a player can use so-called cross-fingering to fill in the chromatic gaps: Covering one or more tone holes below the first open hole usually lowers, or flattens, the pitch by a semitone. But in what's known as an intonation anomaly or pitch sharpening, cross-fingering can, in some circumstances, raise the pitch.

The flute is often presented as an example for understanding wave resonances: The open hole closest to the player's mouth sets the effective length, which in turn determines the resonant frequencies

and thus the notes produced. Although the actual pitch details aren't quite that simple, the behavior is for the most part well understood and amenable to numerical calculation. Yet pitch sharpening has gotten little attention. Now Seiji Adachi at the Fraunhofer Institute for Building Physics in Stuttgart, Germany, offers an explanation of the effect by modeling a minimal system—a flute with one open tone hole—as a system of coupled oscillators. Closed tone holes below the open hole essentially create a downstream pipe of adjustable length. The upper and lower flute sections will have their own resonant frequencies, but since the sections interact, the resonances shift—some higher, some lower.



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Moreover, some of the coupled modes are more easily excited than others. By extending his model to include an additional resonant mode in the upper bore, Adachi could quantitatively account for both pitch flattening and pitch sharpening in an actual recorder. (S. Adachi, *Acoust. Sci. Tech.* **38**, 14, 2017.) —RJF PT

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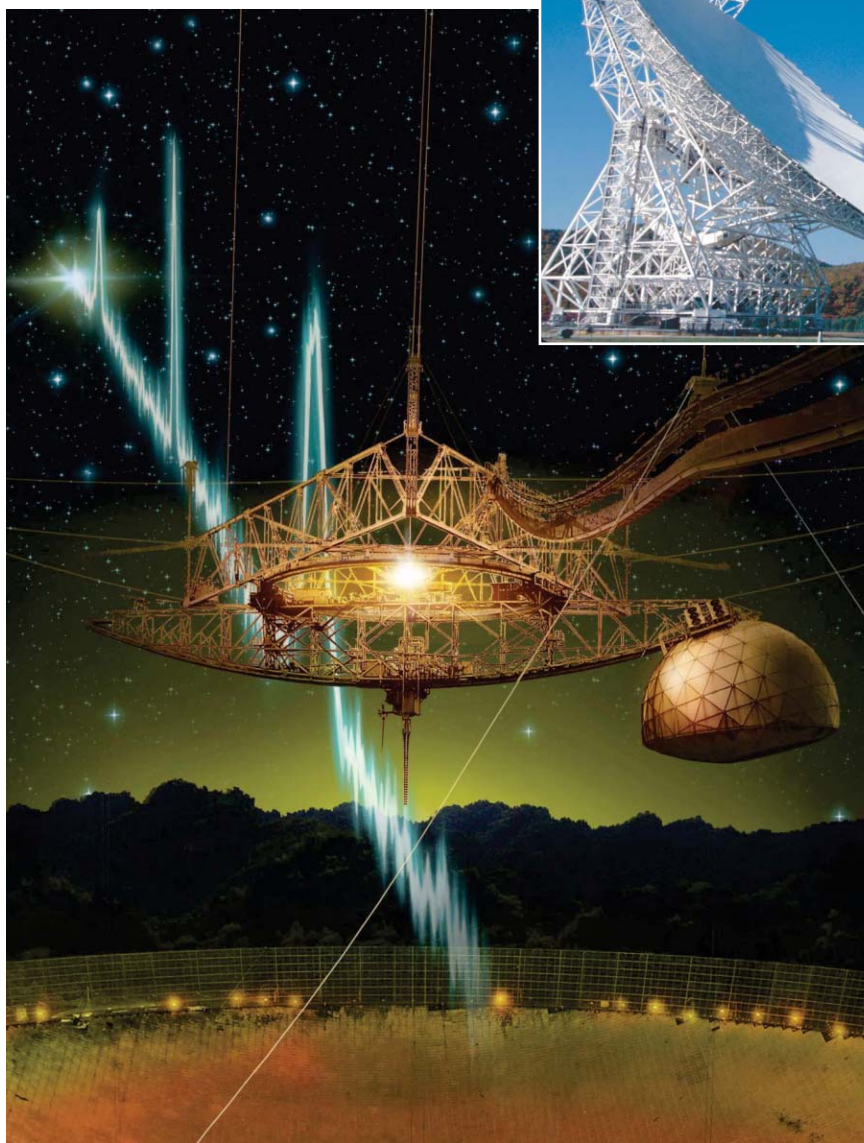
Fates of two big radio dishes hang in the balance

Although still productive, the facilities must find alternative funding to avoid being sacrificed for new cutting-edge telescopes.

Start up the Large Synoptic Survey Telescope (LSST). Invest in midscale telescopes and instrumentation. Join one of the extremely large telescopes. Increase funding for individual investigators. Those are some of the top recommendations for US ground-based astronomy from the 2010 decadal survey, *New Worlds, New Horizons*. They were made under assumptions of growing budgets. (See PHYSICS TODAY, October 2010, page 25.)

Soon after the survey, though, funding fell behind the optimistic projections, which had the budget of the NSF astronomical sciences division—the main US funder of ground-based astronomy—doubling by 2021. In its 2012 portfolio review, the division sketched out belt-tightening measures that included divesting from a handful of optical-IR, solar, and radio telescopes. Those telescopes, in order of priority to keep open, are the Nicholas U. Mayall Telescope, the Very Long Baseline Array (VLBA), the National Solar Observatory (NSO) Integrated Synoptic Program, the Robert C. Byrd Green Bank Telescope (GBT), WIYN, and the McMath-Pierce Solar Telescope. Also on the endangered list, but for future consideration, were Arecibo Observatory and the Southern Astrophysical Research Telescope (SOAR).

The cuts to existing facilities are intended to support the goals of keeping a “balance between current facilities and new endeavors, between large projects and small grants, and between risk and reward.” The review stresses that astronomy “is caught between budget realities and the transformative opportunities of new technologies.” Just how tightly caught is becoming increasingly clear. For several optical and radio telescopes, new partners and sources of funding are



TWO LARGE RADIO TELESCOPES are caught in the crosshairs of budget trimmers at NSF, as the foundation scrimps, saves, and shaves to stay at the frontiers of science. Arecibo Observatory (above) was used in an international collaboration that pinpointed the source of a fast radio burst in a host galaxy, and both it and the Green Bank Telescope (inset) in West Virginia are involved in the search for gravitational waves. Both need to find new funding streams to avoid closure. (Artist's conception courtesy of NAIC—Arecibo Observatory, an NSF facility.)

being found and new modes of operating are being implemented. But the future of others—notably two radio facilities, the GBT in West Virginia and Arecibo Observatory in Puerto Rico—remains uncertain. And if anything, the possibility of NSF joining one of the extremely large telescopes in the works—the Thirty Meter Telescope or the Giant

Magellan Telescope—has become more remote. (See PHYSICS TODAY, August 2015, page 24.)

The astronomical sciences budget has been nearly flat at around \$245 million throughout this decade. In recent years, about three-fifths has gone to operating facilities and two-fifths to research, education, and midscale innovations (projects

in the \$4 million to \$15 million range). But with new facilities coming on line, the budget is increasingly squeezed and the portion that goes to facilities could climb, says NSF's Jim Ulvestad, who was director of astronomical sciences until last month, when he became acting assistant director for mathematical and physical sciences. Even after the austerity measures, the numbers don't add up. (See the figure on page 28.)

The combined annual running costs of the main new facilities will be more than \$93 million. That's for the Atacama Large Millimeter/Submillimeter Array (ALMA), which started up in 2011 (see PHYSICS TODAY, December 2016, page 22); the Daniel K. Inouye Solar Telescope, for which first light is expected in 2018; and the LSST, which will follow in 2020. The divestitures outlined so far would save at most \$45 million a year.

"Just closing all existing facilities would not solve the problem of having money for the new ones," says the University of Arizona's Buell Jannuzi, chair of the Astronomy and Astrophysics Advisory Committee, which advises Congress and the Department of Energy, NASA, and NSF on how those agencies can coordinate US astronomy activities. The new facilities have been highly ranked by the astronomy community in past decadal reviews. But, notes Jannuzi, "most of the legacy facilities are still incredibly productive." Ulvestad calls having to fit the division's activities into a flat budget the "tyranny of arithmetic."

New partners, new purposes

Running ALMA costs NSF more than \$40 million a year. The astronomical sciences division has scrapped the money together by scrapping its university radio telescope program, ending its optical instrumentation program for university telescopes, cutting back on advanced technology instrumentation, reducing its grants program—which it was able to restore after a couple of years—and divesting from facilities to the tune of \$15 million.

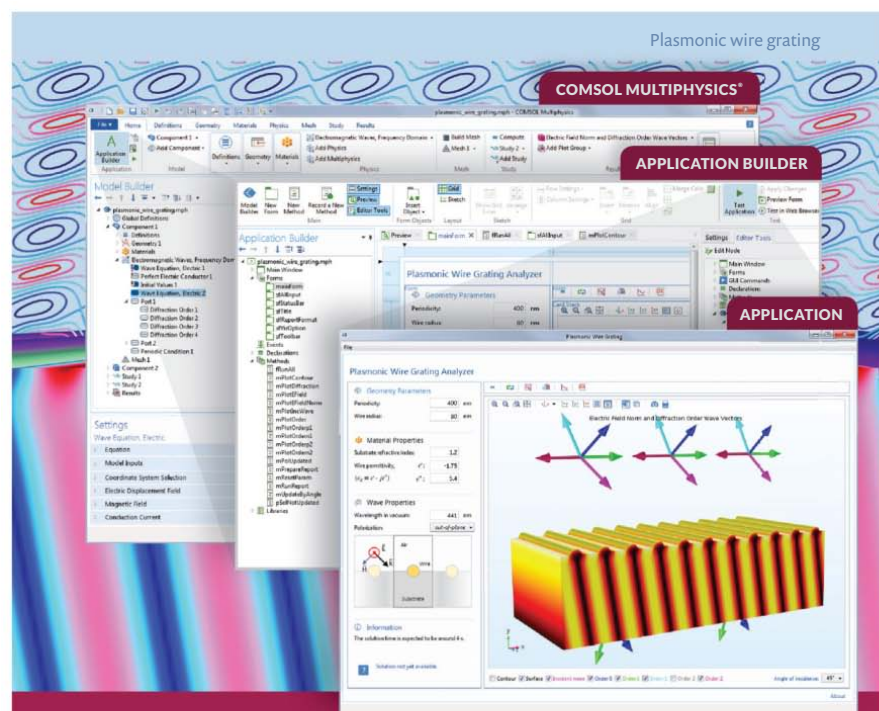
Some of that divesting is taking place at the National Optical Astronomy Observatory (NOAO) in Kitt Peak, Arizona. The DOE is turning the 4 m Mayall telescope into a dedicated galaxy mapper to characterize dark energy (see PHYSICS TODAY, October 2016, page 28). NASA is taking over the NOAO's NSF-funded

40% share of the 3.5 m WIYN to determine the masses of exoplanets. And for now NOAO's 2.1 m telescope is being operated under a three-year agreement by a consortium of universities.

Starting last October, the VLBA has been getting half its funding (about \$4 million) from—and giving half its time to—the US Naval Observatory (USNO), which uses it to measure Earth's orientation parameters. Such measurements have "always been an important part of civilian timekeeping and naviga-

tion," says Tony Beasley, director of the National Radio Astronomy Observatory (NRAO), but previously the USNO got less time, contributed much less money to the VLBA, and got some data free.

Such arrangements mean less—or, as with the Mayall, no—time is available for open proposals by astronomers. "Some of the communities dependent on them for their science are getting squeezed," says Beasley. "Losing 50% of observing time on the VLBA will have a huge impact on the science community. But it



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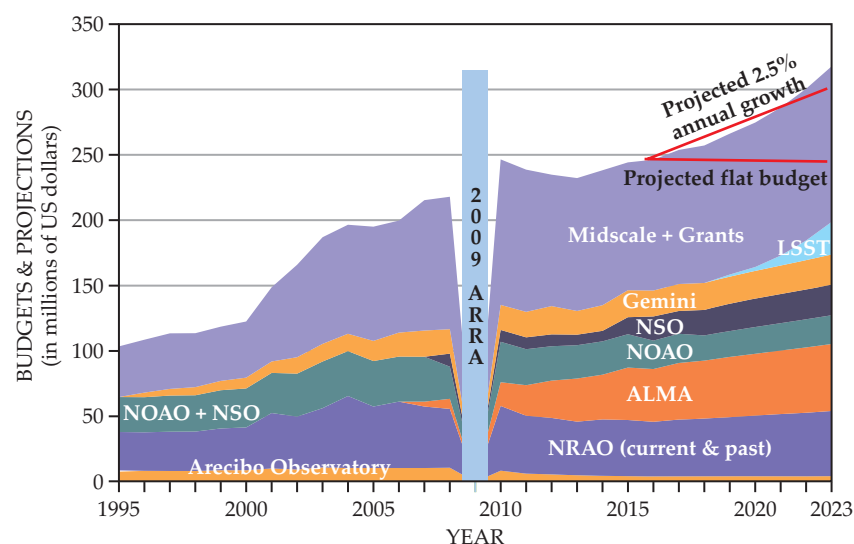
would be terrible if the facilities had to be closed.” And, he adds, “since someone wants to put money in, the science new partners fund is generally exciting.”

Radio troubles

The fingering of the GBT for divestment in the portfolio review surprised many radio astronomers. Not only is it, at 100 m diameter, the world’s largest steerable dish, but it is relatively new. The GBT was completed in 2001, and after commissioning and implementation of new instruments, it reached prime operating condition in 2012, says Green Bank Observatory director Karen O’Neil. It is in the National Radio Quiet Zone and sees 85% of the sky, she says. “There is no other telescope that can do what the GBT does.” For example, she says, “if you want to see how gas is distributed in a galaxy, you need an array for high-resolution detail, but you need a photon bucket to see how gas is distributed and to find the low-surface brightness features.”

The NSF astronomical sciences division is prepared to fund up to half of the tapped facilities’ operating costs, but if the facilities can’t come up with the difference, NSF will have a tough time staying involved. The total for the GBT is \$12 million a year. So far West Virginia University, the Breakthrough Initiative, and NANOGrav—a project that keeps tabs on pulsars to search for gravity waves and, ironically, gets its funding through NSF’s physics division—are together putting in about half the needed \$6 million a year. The Breakthrough Initiative is a good partner, says O’Neil. The initiative’s project involves listening for signs of extraterrestrial life. “They are willing to make their data public, and they are flexible so the astronomy community can get in urgent observations.”

Arecibo is used for radio astronomy and radar studies of Earth’s atmosphere, meteors, asteroids, and planets (see the article by Daniel Altschuler and Chris Salter, *PHYSICS TODAY*, November 2013, page 43). It is 52 years old and, at 305 m in diameter, still the world’s largest dish. (When China’s recently completed Five-Hundred-Meter Aperture Spherical Radio Telescope, or FAST, starts doing science, its strengths will be different, since it will operate at lower frequencies and without planetary or atmospheric radar instruments.) The NSF divisions of



SINCE THE SPIKE IN 2009 from the American Recovery and Reinvestment Act (ARRA), the budget for NSF’s division of astronomical sciences has been nearly flat. To cover the growing operating costs of new facilities as they ramp up and hold funding constant for individual grants and midscale projects requires 2.5% annual growth, as shown by the sloped red line—and even in that optimistic scenario many wished-for division activities would remain undone. The projections do not account for inflation. LSST, Large Synoptic Survey Telescope; NOAO, National Optical Astronomy Observatory; NSO, National Solar Observatory (includes Daniel K. Inouye Solar Telescope); ALMA, Atacama Large Millimeter/Submillimeter Array; NRAO, National Radio Astronomy Observatory (includes some non-NRAO radio astronomy facilities). (Figure adapted from one provided by NSF’s Jim Ulvestad.)

astronomical sciences and of atmospheric and geospace sciences each pay about \$4 million a year, as does NASA, which uses Arecibo for its congressionally mandated activities in tracking near-Earth objects. Another \$1 million comes from the facility’s visitor center and education activities.

The 2012 portfolio review considered two budget scenarios, and reality is closer to the more pessimistic one, says Ulvestad. The revision to the divestment stance on Arecibo came in late 2013, in an open letter NSF wrote to the astronomy community; the facility would need to find other funding. To make matters worse, in April 2016 a separate portfolio review recommended that NSF atmospheric and geospace sciences reduce its annual Arecibo contribution to \$1.1 million by 2020.

To keep Arecibo open, officials are considering everything from running zip lines for tourism to collaborating with the Breakthrough Initiative, says the observatory’s deputy director Joan Schmeltz. NANOGrav, already a big user, would like to help save the telescope and have more time on it, says project chair Xavier Siemens of the University of Wisconsin–Milwaukee. The project team has “approached private donors [for

grants] to buy time” on both Arecibo and the GBT, he says. So far, though, neither facility has come up with an alternative formula for survival.

Fates and frontiers

For radio pulsars, a single dish is perfect, says Ulvestad. But most of the science in the decadal survey requires imaging at arcsecond resolution or better. “You can’t do that with a single radio dish. Interferometers are king. Fundamentally, they have the capability to do more of the recommended science.”

So how can operations for the new facilities be paid for? The simple answer is more money. Building and operating facilities are funded separately at NSF. “When they agree to build something new, the estimate for operations is not rigidly budgeted into future costs,” says NRAO’s Beasley. “It’s hard to have life-cycle budgeting.” Not only that, he says, but new facilities cost 10 times as much to build and operate as the earlier generation. “No reasonable growth of the budget can absorb that.”

One of NSF’s most important roles, Ulvestad says, is driving innovation to stay at the cutting edge of science. “If we build big facilities and don’t give grants

to people to do science with them, that doesn't advance the frontier. Staying at the frontier as science evolves costs money. If the budget stays flat, we'll have to make more really tough choices."

NSF is conducting environmental impact studies at Arecibo, Green Bank, and NSO's Sacramento Peak in New Mexico. The possible recommendations are to continue running the facilities with no change, continue running with less NSF funding but with money from new collaborations, partially shut the facilities but keep open educational aspects,

mothball, or permanently shut down the observatories.

The studies look at social and economic factors in addition to financial and environmental ones. The Green Bank Observatory is the second-largest private employer in its county, notes O'Neil. And shuttering Arecibo would quash morale and be a big loss for education in already financially devastated Puerto Rico (see *PHYSICS TODAY*, January 2016, page 28). NSF says it will decide this summer about Arecibo and by early next year about Sacramento Peak and the GBT.

Toni Feder

Citizen observers chart Arctic change

Researchers are increasingly partnering with local residents to obtain climate and environmental data. But the endeavor calls for interpersonal savvy.

For the past decade, Joe Leavitt, an Inupiat subsistence hunter in the coastal Alaskan town of Utqiagvik (formerly Barrow), 500 km north of the Arctic Circle, has filled notebook after notebook with his observations of the sea: the buildup of *qinu*, or slush ice, before the fall freeze-up; the thrusting up of ice ridges by colliding floes; the fracturing and healing of the winter pack ice. Once a month he mails his notes to a team of geophysicists at the University of Alaska Fairbanks, who collect them, along with the dispatches of a dozen or so other observers scattered along the Alaskan coast, as part of a project known as the Seasonal Ice Zone Observing Network. The hope is that the observations, paired with the team's traditional fieldwork, can shed new light on Arctic sea-ice trends—trends that still aren't fully explained by climate models.

The NSF-funded project is one example of what's come to be known as community-based monitoring. The practice has proliferated in the Arctic, where local residents can often obtain information that would be impractical, if not impossible, to acquire by more conventional means. The Atlas of Community-Based Monitoring and Indigenous Knowledge in a Changing Arctic lists the Seasonal Ice Zone Observing Network as one of four dozen such projects under way throughout the region.

According to Henry Huntington, sci-

ence director of Arctic ocean projects at the Pew Charitable Trusts, the rise of community-based environmental monitoring has coincided with a sea change in scientists' attitudes toward the endeavor: "Twenty years ago it was, 'Hmm, that's an interesting little curiosity.' Now, even in the hard-science and glaciology worlds, they're beginning to see it as a serious line of inquiry."

Yet the pursuit isn't without its growing pains. Piecemeal funding has hampered efforts to establish sustained, large-scale projects, and some scientists still struggle to cultivate relationships in the Arctic's typically small, predominantly indigenous communities. But recent gestures by the US government—including a joint commitment with more than 20 other governments to expand scientific partnerships with the Arctic's indigenous communities—signal that the region's growing league of citizen observers may play a rising role in research.

Climate collaborators

Although the vast majority of global greenhouse gas emissions are released outside of the Arctic, communities inside the Arctic are bearing an outsized share of the consequences. In its 2016 Arctic Report Card, the National Oceanic and Atmospheric Administration noted that the region is warming at twice the rate of lower latitudes and is already 2 °C warmer than its 1981–2010 average. Last



Dr. Felix Rohde, Product Management

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September, Arctic sea-ice cover retreated to its second-lowest annual minimum on record. (More precisely, 2016's minimum tied with 2007's; the record low was in 2012.)

For Leavitt, who hunts whales and other marine mammals, the impacts of those changes are both tangible and ubiquitous. "Winter comes in one month later and it thaws out one month earlier," he says, noting that hunting on the thinning Arctic sea ice has become increasingly perilous. Leavitt recalls using seasonal ice roads to reach ice fishing ponds as early as September in decades past. "Now I can't even make it up there 'til November." In other locales, the combination of retreating ice cover and thawing permafrost have left communities vulnerable to coastal erosion.

Arctic dwellers' position on the front lines of climate change makes them natural partners for the scientists who study it. Not only do the communities have proximity in their favor, explains Andy Mahoney, a sea-ice scientist at the University of Alaska Fairbanks, "they've got the expertise to get out in what is quite a harsh environment, and they have a vested interest in that environment. They can get very locally specific information that's valuable to them but also valuable for understanding the Earth as a whole."

Mahoney collaborated with Shari Gearheard, of the National Snow and Ice Data Center in Boulder, Colorado, on the NSF-funded Siku-Inuit-Hila project, a 2006–13 sea-ice study that teamed scientists with members of Inuit communities in Utqiagvik; Clyde River, Nunavut, Canada; and Qaanaaq, Greenland. As part of the project, Mahoney and Gearheard provided inexpensive sea-ice monitoring stations to the local observers, who then collected ice-thickness data at significant locations off their respective coasts. The study revealed unexpectedly thin ice in the fjords off Qaanaaq, evidence that warm Atlantic waters were encroaching farther into northwest Greenland than previously thought.

Data like those obtained in the Siku-Inuit-Hila project can be difficult to collect by conventional means. Visiting scientists tend to flock to the Arctic during the summer but rarely stay long enough to make field measurements through the winter. Satellites can detect the areal extent of an ice sheet but not its thickness—and the resolution is often insufficient to



HAJO EICKEN, a University of Alaska Fairbanks geophysicist, helps run the Seasonal Ice Zone Observing Network, which partners with residents of coastal Alaskan towns to monitor local sea-ice phenomena.

MATTHEW DRUCKENMILLER

pick up on subtle changes in ice texture that can be relevant to coastal dynamics. "The coastal zone is a boundary for the Arctic Ocean," says Mahoney. "Unless you get the circulation and the ice properties correct there, you're not going to get the rest of the model right either."

Building ties

Peter Winsor, a physical oceanographer at the University of Alaska Fairbanks, is working with residents in communities along the coasts of the Gulf of Alaska and the Bering and Beaufort Seas to measure water-column properties in shallow areas that can't be reached by large research vessels. Although "there's an enormous amount of good science that can be done in the near-shore region," says Winsor, historically, "many of us scientists didn't go to the near shore."

But, he adds, "you can't just barge into a community and say, 'Hey guys, we want you to dip these instruments in the ocean.'" Winsor notes that he had established close ties with members of the communities he partners with long before launching a formal project. For him and other scientists who are collaborating with Arctic residents, successful projects are as much a product of relationship and trust building as of scientific savvy.

"You get there by really listening to what their needs are, so that you're not just addressing your own narrow scientific interests but also responding to their science needs," says Mahoney. Although those needs and interests are rarely identical, they often overlap. The same infor-

mation that's valuable for forecasting weather trends, oceanographic properties, and tundra conditions may help local residents to, for example, plan hunting and fishing seasons, chart safer travel, or better allocate natural resources. Mahoney thinks those kinds of opportunities for mutually beneficial research are too often overlooked. "I think there has been a history of people coming into communities just looking for labor—help lifting heavy boxes or guiding to get into certain areas—and not recognizing the contributions the community already makes to the actual science."

A rising profile

Although pilot projects have flourished, funding for sustained, Pan-Arctic networks of citizen observers remains scarce. As Winsor sees it, such networks—comprising geographically diverse communities making identical measurements, year after year—could potentially be a key to illuminating how regional changes in climate propagate from one part of the globe to another. His initial grant provided funds to work with three communities, but he's looking to grow that number to six. Ideally, he says, "we'll stick with those six and keep them going for decades and decades."

Recent indications of support from the US and other Arctic nations may justify Winsor's optimism. In 2013 the Interagency Arctic Research Policy Committee, a subcommittee of the US National Science and Technology Council, added community-based-monitoring and traditional-knowledge components

to its five-year Arctic Research Plan. Last March President Barack Obama and Canadian prime minister Justin Trudeau jointly pledged “to more broadly and respectfully include indigenous science and traditional knowledge” on several science and policy fronts, including “advancing our understanding of climate change.” And in September, at a White House ministerial meeting, the US, the European Union, and 23 other governments committed to expanding international collaboration on Arctic science—and to doing so in partnership with the Arctic’s indigenous peoples.

Martin Jeffries, executive director of the Interagency Arctic Research Policy Committee, points to several tangible gains that emerged from the ministerial gathering, including the planned expansion to Canada and Finland of the Environmental Protection Agency’s Local Environmental Observer Network, an online forum in which scientists and community members discuss unusual



THE SIKU-INUIT-HILA PROJECT was a 2006–13 collaborative study of sea ice that teamed scientists with members of Inuit communities in the US, Canada, and Greenland. Here, team members install an ice-thickness monitoring station. (Image courtesy of Shari Gearheard.)

environmental occurrences. Jeffries says the most important development, however, may have come before the meeting was gavelled in: “The day before, we had an afternoon listening session where about 40 senior leaders from the federal government sat down with about 40 leaders of Alaska native and international indigenous peoples organizations to listen to their concerns, their needs,

and how they’d like to be involved in Arctic science.”

That’s progress, says Pew’s Huntington. But he nevertheless sees a gap between the rhetoric and actual investment. “It’s terrific that it’s getting that high profile,” he says. “But it still feels at times like an uphill battle to get beyond the pilot project and workshop stages.”

Ashley G. Smart

Effort in asteroid defense under way despite funding constraints

A US interagency program is refining methods of deflecting asteroids as it works toward finding tens of thousands of undetected near-Earth objects.

In 2013 a meteor estimated to be 17 m in diameter exploded with the energy of a 450 kt nuclear weapon in the sky 23 km above the Russian city of Chelyabinsk. Although no lives were lost, more than 1600 people were injured, mostly from flying glass shattered by the shock wave. Regional hospitals were overwhelmed.

That was before Russia annexed the Crimea and relations with the US soured. Collaborations between US and Russian national laboratories dating to the immediate post-Cold War period were ongoing. It was natural for Russian lab directors to seek help from their US counterparts to mitigate a future asteroid strike, says Don Cook, who as the director of defense programs and deputy administrator of the Department of Energy’s National Nuclear Security Administration (NNSA) oversaw the US

nuclear weapons labs and arranged their participation in the bilateral research effort.

In seeking interagency approval for that effort, Cook met some resistance from staff at the National Security Council. The suspicion was that the NNSA labs might use such a program as a pretext to resume nuclear testing, in the event that an existing weapon couldn’t be used against an asteroid. Ultimately, the skeptics at the security council were mollified when the NNSA and NASA signed a memorandum of understanding to cooperate with each other on what has become known as planetary defense, with NASA designated the lead agency.

The program has grown even after collaborations with Russia were terminated in 2014. Today, scientists and engineers at NASA work on planetary defense with counterparts at the NNSA’s

Lawrence Livermore, Los Alamos, and Sandia National Laboratories.

NASA and its contractors continue to discover near-Earth objects (NEOs)—comets and asteroids that have perihelions of 1.3 astronomical units or less—at a rate of a few per day. As of January, approximately 15 000 asteroids and 107 comets have been uncovered and have had their orbits calculated, according to NASA’s near-Earth asteroid survey. Of those, around 1700 are considered potentially hazardous, meaning their orbits pass within 8 million km (1250 Earth radii) of Earth. (See PHYSICS TODAY, September 2015, page 22.)

The number of NEOs rises steeply with diminishing size. Although NASA long ago met a 1998 commitment to Congress to locate at least 90% of NEOs larger than 1 km, some 3500 NEOs of 300–1000 m diameter predicted to exist remain undetected, nearly as many as the 3855 that have been located. Approximately 14 500 asteroids of 140–300 m are undiscovered; just 2500 of those in that

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THE 17 M METEOR that exploded over Chelyabinsk, Russia, in 2013 spurred efforts to find near-Earth asteroids and defend against their hitting Earth.

size range have been cataloged, according to NASA's scorecard. Smaller objects are not as closely tracked; it is estimated that about 15% of objects of 140–300 m and less than 1% of objects 70 m or smaller have been found. Lindley Johnson, who heads the planetary defense coordinating office at NASA, says that "it is reasonable to say that there are well over 10 million in number between 70 and 20 meters in size." Johnson recalled that the Chelyabinsk object was even smaller than 20 m.

The meteor that exploded over Tunguska, Siberia, in 1908, flattening trees over a 2000 km² area, had an estimated diameter of 60 m. In planetary defense terms, Tunguska was considered a city killer; according to Cook, if such a blast occurred over a populated area, the number of casualties could reach 1 million. Larger objects would devastate an entire region, although the extent of destruction would depend on asteroid composition. The Barringer crater in eastern Arizona, for example, is believed to have been caused by the impact of a 50 m meteor about 50 000 years ago. A relatively rare nickel-iron asteroid, it devastated much of what is now the eastern half of the state.

The asteroid that wiped out the dinosaurs 65 million years ago was estimated to have been about 10 km in size. "When you talk about dinosaur killers, they're 50 million–60 million years apart," says Joseph Nuth, a scientist at NASA's Goddard Space Flight Center who spoke at the December meeting of the American Geophysical Union

(AGU). Calculations of the risk of significant NEO strikes change based on the numbers of objects that have been found, says Los Alamos scientist Galen Gisler, another speaker at the meeting. "Fortunately, those [probability] numbers have been going down the last couple decades." Adds Nuth, "you can do a lot of modeling, but you can be in the right place at the wrong time."

Johnson says asteroid detection and mitigation in the US currently is being performed by 250 people and has an annual budget of \$50 million. An NNSA spokesperson, who could not provide a specific value for the labs' contribution, said the activity is considered part of their programmatic work.

Although NASA's budget for asteroid mitigation has grown from \$10 million annually before the interagency program began, Johnson says the program

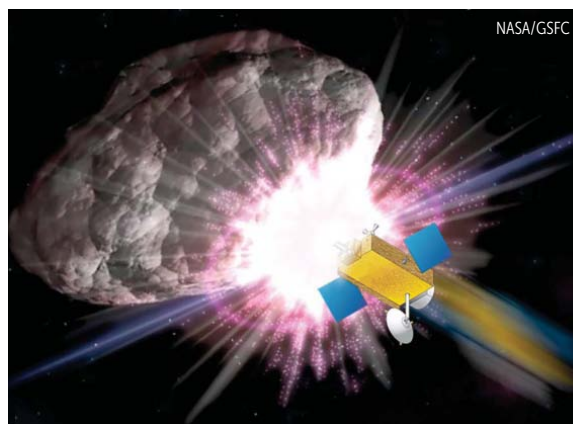
really needs around \$250 million a year. That would include \$150 million–\$200 million annually over five to six years to pay for a space-based IR observatory. At the current rate, ground-based telescopes will take three to four decades to locate all of the 100 m or larger NEOs.

The *Near-Earth Object Camera (NEOCam)* observatory proposed by NASA's Jet Propulsion Laboratory would have cut that "window of vulnerability" to as little as a decade, says Johnson. But *NEOCam* lost out to the two other missions—*Lucy* and *Psyche*—which were given the green light in early January to explore objects in the main asteroid belt.

Preventing catastrophe

As its name implies, planetary defense has to include some method of mitigating an impending strike. Two missions for demonstrating asteroid deflection technologies are already on the drawing board. NASA's *Asteroid Redirect Mission*, proposed for launch in 2020, has a planetary defense component known as gravity tractor. Its primary mission is to pick off a large boulder from an NEO and transport it to lunar orbit, where it would be examined by astronauts. For its secondary mission, the spacecraft would hover near the asteroid to exert a gravitational tug sufficient to alter the NEO's orbit.

Also proposed for a 2020 launch is NASA's *Double Asteroid Redirection Test*, which would evaluate the feasibility of using a kinetic impactor to nudge an asteroid's orbit away from Earth's and would cost about \$250 million, Johnson says. The probe would be



NASA/GSFC

AN ARTIST'S CONCEPTION of a kinetic impactor striking an asteroid at high velocity. The method is one of two main approaches being examined for altering the orbit of an asteroid that is threatening Earth.

directed to crash at 6 km/s into one of the members of the binary asteroid Didymos. The European Space Agency's (ESA's) *Asteroid Impact Mission* would observe the collision and its effect on the binary system. Estimated to cost €250 million (\$260 million), it was not approved by the ESA council of ministers in December. ESA director general Johann-Dietrich Woerner said in a blog post that he remains convinced of the need for the mission and will seek its reconsideration.

Neither NASA mission is currently funded, however. Development money for the redirect mission is included in the fiscal year 2017 budget, which Congress has yet to pass. Proposed in the wake of the Obama administration's decision not to send astronauts to the Moon, the redirect mission is controversial. The Trump administration could cancel it.

The planetary defense program is also weighing the use of a nuclear weapon as a potential last resort. For a kinetic impactor to alter an asteroid's trajectory, at least 10 years' warning of a potential impact would be needed to build the spacecraft and get it to the target. For an asteroid expected to hit Earth with less notice, a larger initial deflection, such as provided by a nuclear detonation, might be needed. Objects larger than 300 m also are likely to require a nuclear deflection, says Livermore physicist Megan Bruck Syal. Modeling shows that an existing nuclear weapon would be able to deflect an NEO of up to 1 km in size, she says. No one has proposed a nuclear demonstration.

In the vacuum of space, a nuclear device wouldn't produce the airblast that's mainly responsible for an explosion's destruction on Earth. For a targeted asteroid, radiation—primarily x rays—from the detonation will vaporize the surface and create a rocket-like blowoff that propels the asteroid in the opposite direction.

Whether the deflection is kinetic or nuclear, Goddard's Nuth said designing, building, and launching a highly reliable spacecraft to intercept an asteroid or comet is likely to take five years. "It's imperative that we reduce our reaction time to less than a year from high certainty of impact to launch," he told reporters at the AGU gathering. He urged that a spacecraft be built so it is available should a threat arise; he estimates the cost to be several hundred million dollars.

Johnson disagrees. He argues that such an interceptor would most likely never be used, would be costly to maintain, and would likely become obsolete as new mitigation technologies are developed in the future. He favors using the available resources to accelerate completion of the asteroid survey.

NNSA contribution

For its part, the NNSA is using its expertise and prodigious computing resources to predict the effects of devices on asteroids. Kevin Greenaugh, the NNSA's assistant deputy administrator for strategic partnership programs, says the modeling helps train young scientists to work on physics problems that are also relevant to the weapons program. Their results on the behavior of materials during impacts are being incorporated into weapons simulations, he says.

Speaking at the AGU meeting, Los Alamos scientist Catherine Plesko said that a kinetic or nuclear device would have to either speed up or slow down the threatening asteroid's orbit. Blowing it up would require more energy and create shrapnel that would have to be tracked. Bennu, a 500 m asteroid discovered in 1999, is the target of NASA's *Origins, Spectral Interpretation, Resource Identification, Security—Regolith Explorer*

(OSIRIS-REX) mission, which will reach the asteroid next year. It has about a 1 in 2000 chance of hitting Earth around 200 years from now, Plesko said. One of the mission's goals is to measure the Yarkovsky effect, the force caused by the emission of heat from the asteroid, which can alter its orbit over time.

Chelyabinsk is about 1600 km from the Kara Sea and 3200 km from the Arabian Sea. Although the meteor that crashed there opened eyes to the threat, an asteroid strike would be most likely to occur somewhere over the three-quarters of Earth that is ocean. Gisler's modeling results show that the wave created by a 300 m or smaller meteor hitting the ocean could reach several hundred meters. But unlike an earthquake-generated tsunami, that wave would dissipate relatively quickly.

Unless the NEO crashed near a coastal city, where its effects would be catastrophic, the most significant impact of an ocean strike would be the injection of huge quantities of water vapor into the stratosphere, where it would not quickly rain out and could affect climate, Gisler says. A Chelyabinsk-like airburst over the ocean would dissipate and have a much weaker impact than a marine strike.

David Kramer

High-energy-density science blooms at NIF

The weapons facility is exploring phenomena found in brown dwarfs, the cores of "super Earths," new phases of carbon, and other extreme environments.

Four years beyond the original deadline for reaching its goal, and more than seven years since it was commissioned, the National Ignition Facility (NIF) has yet to produce fusion energy greater than what's delivered to initiate the laser-driven reaction. But even as scientists at the \$3.5 billion Lawrence Livermore National Laboratory facility continue their quest for ignition, a small but growing band of academic researchers has been harnessing the unmatched compression and other diagnostic capabilities of the 1.8 MJ laser to explore fundamental questions in condensed matter,

astrophysics, planetary science, and other areas (see "NIF may never ignite, DOE admits," June 2016, PHYSICS TODAY online).

"We're trying to grow the community and get more basic science from NIF," says Bruce Remington, program leader for NIF discovery science. The number of shots at NIF devoted to academic research has increased almost fivefold in just two years, to 38 last year, and 8% of NIF's experimental time, some 18 days a year, was set aside for those experiments. Nine projects were selected from the 36 proposals received in last year's solicitation.

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John Browne, chair of NIF's Management Advisory Committee, says NIF opens "a broad space of parameters for the science community to look at temperatures and pressures they can't get any other way."

Raymond Jeanloz, a physicist at the University of California, Berkeley, and one of NIF's first academic users, says the facility offers "truly a new regime" for a high-energy-density science community that he estimates at about 200 experimentalists. NIF's energy range is 60 times as high as the University of Rochester's 30 kJ Omega, the next most energetic US laser, and can exert 10^{15} Pa of pressure on a 2-mm-diameter target. Even if poor coupling or other inefficiencies degrade that by a few orders of magnitude to 10 TPa, it's equivalent to the pressure at the center of Jupiter and far exceeds the 2.3 TPa of pressure that keeps the hydrogen atom from collapsing on itself, he says.

At such pressures, experimentalists might observe a new regime of chemistry, "keV chemistry," in contrast to the more typical eV energies of standard chemical bonding. "We think at these conditions the core electrons, the inner guts of atoms, actually get involved in chemical bonding. There is theoretical support for that prediction, but very little experimental work has been done in the area," Jeanloz says. Those conditions also can be found deep inside giant and supergiant planets, but also in the more extreme conditions that prevail in brown dwarfs.

NIF's productivity has risen dramatically, with the total number of shots, most of which are for the weapons program, more than doubling, from 191 in fiscal year 2014 to 417 in FY 2016. And the lab has been able to make greater use of the laser's full design energy, says NIF director Mark Herrmann, due to an improved understanding of optically induced damage to the laser's large lenses. That new knowledge has led to changes in the initial fabrication of optics, increased uniformity of beam intensity across their aperture, and a more automated optics recycling process.

The NIF academic research program also provides lab scientists who work in the classified weapons realm an opportunity to publish in the open literature.

A big challenge for scientists working on NIF is obtaining a fine-grained picture of phenomena that occur when NIF's 192 beams strike targets. The time



JAMES PRYATEL, LAWRENCE LIVERMORE NATIONAL LABORATORY

A TECHNICIAN REMOVES an image plate from the National Ignition Facility (NIF) dilation x-ray imager, said to be the world's fastest x-ray framing camera. The two-dimensional imager is one of 70 specialized diagnostics that have been developed for NIF.

and size scales are extremely small: Resolving what occurs inside hohlraums, the cylindrical containers that house peppercorn-sized capsules of fusion fuel, requires nanosecond-scale measurements at 50 μm resolution in a high-energy x-ray environment. Tracking implosions of the capsules requires measurements at the scale of a few microns in a high-neutron-flux environment, says General Atomics vice president Joseph Kilkenny, who's long been stationed at NIF.

More than 100 scientists and engineers at the lab and at other institutions have helped develop NIF's 70 separate diagnostics. Recent advances include hybridized CMOS detectors used to make movies through the entrance holes of hohlraums and a dilation x-ray imager, which stretches out photon signal pulses to provide 10 ps temporal resolution of capsule implosions. Conventional gated x-ray cameras achieve 100 ps resolution at best.

Some diagnostics are used for making measurements at Sandia National Laboratories' Z facility and at Omega, which also conduct experiments for the Department of Energy's inertial confinement fusion program.

Beyond diamond densities

Experiments just getting under way by one international collaboration will attempt to synthesize a new phase of carbon known as BC-8 that's predicted to occur at pressures around 1 TPa. Amy Lazicki Jenei, a Livermore researcher who's part of the eight-institution team,

says she and her collaborators also hope to see if BC-8 is metastable at ambient pressure and temperature. If so, it's possible that a new high-strength form of carbon could be grown the way synthetic diamonds are made today, using chemical vapor deposition. Other phases of carbon are predicted at the even higher pressures occurring in the interiors of carbon planets, a putative type of planet that forms from carbon-rich, oxygen-poor protoplanetary disks.

The group has already determined by using NIF's *in situ* x-ray diffraction diagnostic that diamond does not undergo a phase change at up to 800 GPa.

Other planetary science and astrophysics questions are being probed at NIF. In the hunt for exoplanets that could support life, a consideration is whether a planet has a solid iron core surrounded by a liquid iron outer core. That combination is what generates the dynamo and resulting magnetosphere that shields a planet's surface from the charged particles that stream from its parent star. Inner-core pressures in large exoplanets dubbed super Earths are predicted to range up to 3.5 TPa—10 times the pressure in Earth's center. A new NIF–university collaboration will subject small amounts of iron to pressures up to 2 TPa to see if the metal remains solid under those conditions.

An ongoing project begun in 2015 explores the dynamics of stellar birth in such clumpy dust clouds as the "pillars of creation" columns in the Eagle Nebula. When a new star lights up, its UV radiation sweeps away the dense cloud through radiative ablation. That mecha-

nism is also what drives implosions in NIF fusion experiments, where intense x rays cause the surfaces of fuel capsules to blow off at high velocity. The experiments involve zapping and vaporizing three or four hohlraums in sequence. The resulting relatively long-lived 60 ns radiation source is useful for studies that require a steady light source to re-create the relevant physics.

Other science experiments aim to discover the contribution of radiative shock in supernovae, the conditions inside brown dwarfs and stars, and whether collisionless shock is responsible for the generation and amplification of the magnetic fields that pervade the universe.

Ignition work continues

The knowledge gained from experiments at NIF is important whether or not ignition is achieved, Herrmann says. "If we get ignition, we will open up whole new vistas of things we can do. If we don't get ignition, figuring out why we can't get it and what's wrong with our simulations that predict we can is important for the [weapons] enterprise."

Browne says that simulations have now improved to the point that researchers can credibly predict what will occur during shots. The question is whether that predictive capability will extrapolate to the ignition scale.

While optimistic about ignition at NIF, Herrmann notes that other similar facilities are being built in China, France, and Russia, some of which could be larger than NIF. But ignition won't be easy even at double NIF's energy, he cautions. "We will have to learn more to make it work even with more energy."

Since the US stopped underground testing in 1992, the weapons labs' directors have certified the US stockpile of nuclear weapons every year, evidently without the need for NIF to achieve ignition. Still, says Browne, a former director of Los Alamos National Laboratory, ignition would give the labs "a way of looking at real honest-to-goodness weapons

problems that you might have seen if you had been doing nuclear testing" and would add confidence that the weapons simulations can predict those problems. (See the article by Victor Reis, Robert Hanrahan, and Kirk Levedahl, *PHYSICS TODAY*, August 2016, page 46.)

On top of refining the number and intensity of the nanoseconds-long laser pulses that constitute each shot, ignition scientists have been trying out capsule shells fashioned from diamond. The initial capsules were plastic; other candidate materials include beryllium. Researchers also have been trying to figure out how to minimize the hydrodynamic instabilities that arise from the presence of 30-nm-thick films that hold the capsules in place inside the hohlraums and reduce instabilities created by the fill tube through which cryogenic deuterium and tritium are fed into the capsules just prior to shots.

Experiments have also been conducted to determine the optimum density of helium gas used inside the hohlraum. Too much gas produces more laser-plasma instabilities; too little causes the walls to collapse before the implosion can occur.

The next step is to try out larger hohlraums. The farther the capsule is from the inner walls, the greater the opportunity for the x rays radiated by the hohlraum to smooth out and become uniformly deposited on the capsule. But there's a trade-off: If the hohlraum gets too big, the energy delivered to the capsule will be insufficient to drive the implosion.

Riccardo Betti, assistant director for academic affairs of the University of Rochester's Laboratory for Laser Energetics, says NIF now has three or four combinations of hohlraums, gas concentrations, and capsules to experiment with. "There is no silver bullet, but they have a better understanding and a choice of paths," says Betti, who reviewed NIF's progress toward ignition in a paper published in *Nature Physics* last year. The best NIF results date to 2014, when the lab

recorded a shot in which half of the fusion reactions came from alpha-particle heating in the fusion reaction, and half were caused by the implosion compression. Ignition, he notes, amounts to "run-away alpha heating."

Much of NIF's time since the initial ignition push ended in 2012 has been devoted to other nuclear weapons-related topics, including the behavior of plutonium under extreme pressures. In one technique, some of NIF's beams are used to squeeze plutonium and others create a bright x-ray source to probe the metal's atomic structure. Herrmann says those experiments have been able to reach previously unattainable pressures that are relevant to nuclear weapons. The exact pressures are classified, but Herrmann says they are "considerably higher" than those that diamond anvil cells can attain.

A large body of experiments in support of the nuclear weapons stockpile address hydrodynamic instabilities and radiation hydrodynamics in a high-energy-density regime. That research is also of fundamental scientific interest, and many of the experimental techniques can be used to characterize materials that aren't weapons-related.

Browne says those weapons experiments have increased confidence in the continuing reliability and safety of the aging weapons arsenal. "It's had a direct impact on how the weapons program has tried to understand actual things they face in certifying the stockpile," he notes.

Jeanloz sees an enormous amount of science in inertial confinement fusion to be done at NIF regardless of whether ignition is within its grasp. A lot more research will need to be done if ignition is achieved to make reaching it easier, more efficient, and reproducible. "The richness of the field is not whether or not you plant your flag on that mountaintop called ignition," he says, "but really the path toward there, and filling in a better understanding of material properties, and the dynamics, including hydrodynamic instabilities."

David Kramer **PT**



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How did a scientific Siberia



Joe Bassi is an assistant professor in the department of social sciences and economics at Embry–Riddle Aeronautical University, Worldwide campus. This article is based on his book *A Scientific Peak: How Boulder Became a World Center for Space and Atmospheric Science* (American Meteorological Society, 2015).



turn into AstroBoulder?

Joseph P. Bassi

Boulder, Colorado, grew to become an important science center in part because nearby mountains provided an excellent spot for solar observation. But local scientists' connections to the Northeast establishment and some clever PR didn't hurt.

The rise of Boulder as a city of knowledge was sudden and in many ways unexpected. In the 1940s and 1950s, a small Colorado city little known for scientific or intellectual accomplishment became a world-recognized science center as entrepreneurs and members of the local community, including state university representatives, exploited opportunities to advance Sun–Earth connection science. They created what French astrophysicist Jean-Claude Pecker was to call AstroBoulder, and they did it without centralized planning.

The early Cold War presented US physical scientists with not just new opportunities for funding but also new rationales for doing science. With the advent of ballistic missiles, defense officials realized that the upper atmosphere and space were becoming a medium that needed to be better understood; Sun–Earth connection science had an immediate relevance to perceived national needs. Also, the complexities of defense-related research almost demanded the creation of more research establishments.

As evidenced by the development of Boulder, scientists and others did not merely seize the numerous opportunities that the early Cold War–era context presented; they participated in creating and shaping those opportunities in what was then the rapidly evolving world of US science policy. Indeed, *PHYSICS TODAY* declared in its July 1950 issue (page 35) that “the springtime of Big Physics has ar-

rived.” It certainly had in Boulder by the late 1940s.

Harvard astronomy heads west

The development of Boulder is also part of the story of how, in the early and mid 20th century, US science migrated west from the northeastern scientific establishment. In the late 1930s Harvard University astronomer Donald Menzel wanted to find an optimal location for the first coronagraph in the Western Hemisphere. The device had been invented by French astronomer Bernard Lyot a few years before, and Menzel and his graduate student Walter Orr Roberts wanted to get one operational for their solar studies (see figure 1). As Menzel hailed from Leadville, Colorado, he understood that his native state was a suitable place to locate the instrument. Fremont Pass, at 3450 m in elevation, provided a confluence of good observing conditions, passable



COURTESY OF THE UCAR ARCHIVES

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roads, and a willing sponsor: Max Schott, president of Climax Molybdenum Co. Menzel made the easy decision to place the coronagraph at the company's site near Leadville, mere miles from his hometown. Roberts and his wife Janet, with coronagraph in tow, soon set out for the great American West to work at the Climax solar observatory, officially known as the Fremont Pass station of the Harvard College Observatory (HCO).

The sudden onset of American involvement in World War II changed the fortunes of the tiny station and the course of science in Colorado. As Menzel predicted to various sponsors over the years, the arcane coronagraph data had important practical uses. Roberts made a significant discovery at the end of 1941 that linked Sun–Earth studies to military operations. “In late 1941,” he observed in an American Institute of Physics career survey, “I first noted from my own data, a connection of strong green-coronal line emission to the short-wave radio reception quality.” Allied scientists feared that the Germans might have similar interests with respect to radio prediction. Menzel seized the opportunity and asked the National Bureau of Standards (NBS, the predecessor of NIST) to have the Climax observatory declared a national defense project. The close bond between the observatory and the NBS Interservice Radio Propagation Laboratory (IRPL) would grow even stronger through Alan Shapley, shown in figure 2. Shapley, son of astrophysicist Harlow Shapley, Roberts’s mentor, joined the IRPL’s successor organization in 1947. The Colorado–Washington, DC, relationship he was to facilitate would profoundly influence the development of science in Boulder during the following decade.

As World War II came to a close in September 1945, the IRPL contracted with the Climax observatory to continue providing solar data (figure 3 shows the image quality obtainable at that time). That agreement gave some measure of security for continued operations, but not nearly enough to expand the site’s modest facilities and research agenda as Roberts and Menzel hoped to do. As with many Americans facing the uncertainty of the postwar world, Menzel and Roberts had to wonder what the immediate future held—in their case, for Harvard’s Fremont Pass station and solar science. The answer pointed them to the city of Boulder and the University of Colorado.

An innovative arrangement

Scholars often describe the post–World War II years as a period of institution building in the evolving discipline of solar physics. Having seen the benefits of the government’s large-scale science support during the war, Menzel and others wanted to continue the government–scientist relationship. Choosing to exploit new sources of government grants rather than relying on the research and funding decisions of, for example, a lone observatory director, they quickly began to exercise their own authority. That new approach is essential to understanding the progress of Sun–Earth connection science and postwar developments in Boulder. For one thing, it enabled astronomers to expand their discipline beyond its traditional emphasis on stellar and galactic research. Solar research therefore underwent a period of significant expansion in the postwar years, and Boulder benefited from that growth. Roberts moved there in 1946 to help create one of the institutions enabled by the shifting patronage patterns. It was to be a new type of corporation, one made of associated universities and dedicated to solar science.

The idea to transform the HCO station at Climax into a joint

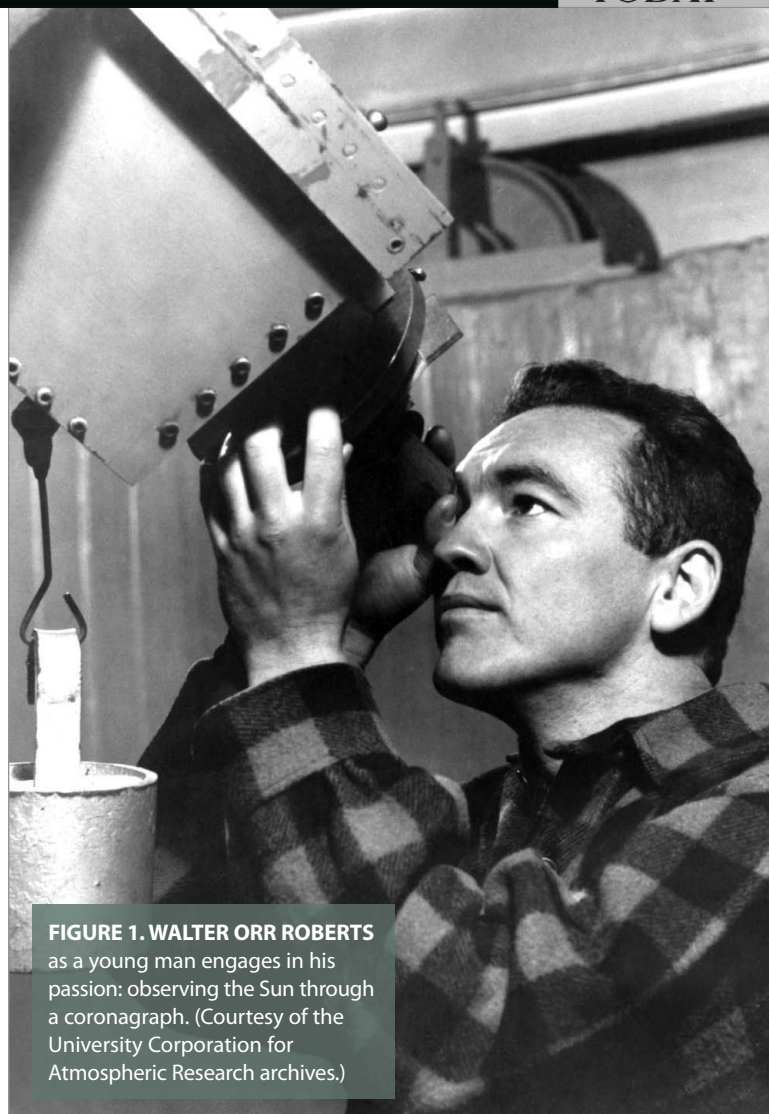


FIGURE 1. WALTER ORR ROBERTS
as a young man engages in his
passion: observing the Sun through
a coronagraph. (Courtesy of the
University Corporation for
Atmospheric Research archives.)

Harvard–University of Colorado endeavor originated in Menzel’s desire to have stronger ties to the state of Colorado so as to enhance his possibilities for local fundraising. Apparently, HCO director Harlow Shapley resurrected the idea of a joint project in October 1944 and proposed the University of Colorado Boulder as a candidate partner. Shapley volunteered that he could help Menzel “very carefully and cautiously feel out the situation” with Robert Stearns, president of the University of Colorado. Stearns liked the idea of a joint project because the partnership would associate his university with the Climax observatory, already a noted astronomical research facility, and thus forge a research link with the prestigious Harvard.

In September 1945 Denver attorney J. Churchill Owen wrote to Stearns that Harvard and the University of Colorado should form a nonprofit corporation with a governing board of trustees. Development of the observatory proceeded quickly. The new joint Harvard–Colorado solar observatory began life as the High Altitude Observatory (HAO) of Harvard University and the University of Colorado on 12 April 1946. It was in the first wave of a new type of scientific research organization: a corporation for science. Perhaps reflecting a natural Coloradan tendency for the use of wildlife metaphors, founding board member William Jackson, a member of the Colorado Supreme Court, recalled his initial thought that the HAO was a “strange beast.” Another board member asked, “Have you ever seen an animal like this before?”

After the Robertses’ period of relative isolation at Fremont

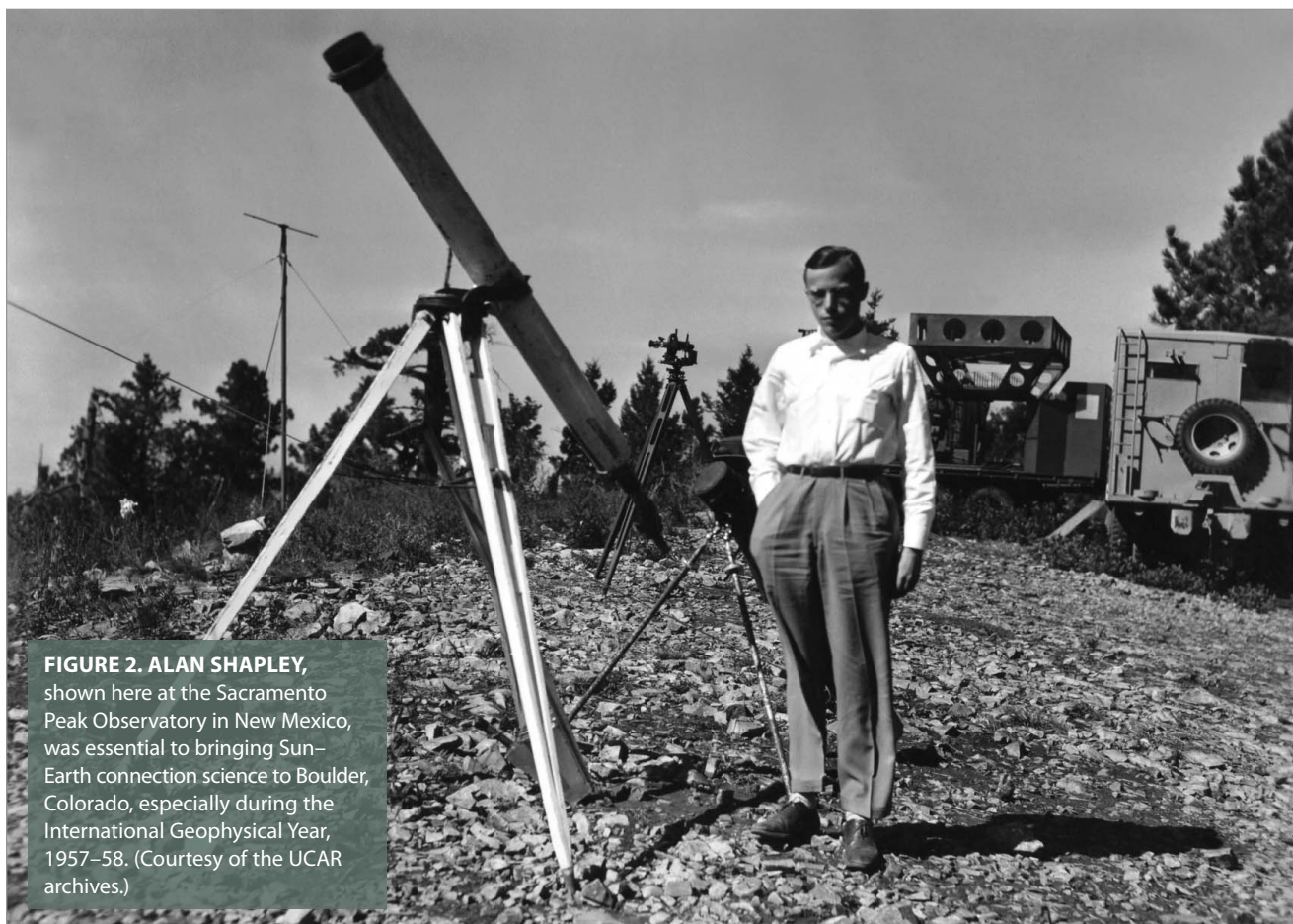


FIGURE 2. ALAN SHAPLEY, shown here at the Sacramento Peak Observatory in New Mexico, was essential to bringing Sun–Earth connection science to Boulder, Colorado, especially during the International Geophysical Year, 1957–58. (Courtesy of the UCAR archives.)

Pass (see figure 4), Walter needed new outlets for both his scientific curiosity and his personal ambitions. The University of Colorado was not Harvard, nor was Boulder Cambridge, Massachusetts. But the university was good enough for Menzel and Roberts's short-term goal to bring solar astronomy and Sun–Earth connection science west. After six long years, Walter and Janet came down from the mountain to Boulder, where Walter worked at the HAO offices. Hired observers ran daily operations at the Climax station.

On the chopping block

Boulder's development as a place for Sun–Earth connection science was almost stillborn. There was a move in the summer of 1947 to shift the Harvard solar observing operation to a new site in New Mexico. Menzel, no doubt stimulated by his wartime activities and the success of creating the HAO, sought to expand his astronomical activities after the US Air Force offered support for the second of what Menzel would eventually refer to as his western solar stations.

Physicist Marcus O'Day and his group at the Air Force Cambridge Research Laboratories had found themselves leading the air force's effort to use captured V-2 rockets for upper-atmosphere research. O'Day suggested to Menzel that the air force might fund solar research to augment the V-2 studies. American V-2 research centered at the White Sands Proving Ground, and a key requirement was that the new observatory's site offer total surveillance of V-2 flight paths so that personnel could couple solar observations and rocket flights. That criterion restricted the new observatory to a location somewhere in the Sacramento Mountains, to the east of White Sands. Roberts initially supported Menzel's plan and stated to Harlow Shapley

that "the establishment of a south station now looks to me like a very desirable thing."

However, some astronomers at the HCO in Massachusetts began to question the wisdom of having a growing number of HCO research stations out west. Events, and the possibility of large amounts of government funding for the newer, bigger site in New Mexico, put what Shapley had previously called "our lovely Colorado project" on the chopping block.

Roberts was shocked by the possibility of losing his new Colorado operation to New Mexico. His response to Shapley kept Boulder's nascent scientific community viable and thus established the foundation for many future developments in the city with respect to Sun–Earth connection science. "I do not think this will be a feasible thing," he wrote on 26 August, referring to Shapley's proposal to slowly dissolve HAO work and shift operations to New Mexico. As reasons for his opposition he cited the isolation of the proposed site as compared with Boulder, the "extreme unpleasantness" of temperatures in Alamogordo, uncertainty about site observing conditions, the lack of "a campus atmosphere," and "the undesirability of a very close relationship with the Army or military in these research programs." He also wrote that "it would be of utmost difficulty to keep our [spouses] in a state of happiness" if they had to move to the new Sacramento Peak Observatory.

To handle the threat to the HAO's continued existence in Colorado, Roberts suggested a compromise. To avoid a head-to-head competition with the observatory in New Mexico, he suggested each site have a suite of instruments that complemented the other's. Personnel at Boulder and Sacramento Peak could then work as a team and not as rivals.

The US Department of Defense approved the Sacramento

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Peak site in April 1948. Roberts and others were important guiding hands in constructing the New Mexico observatory while they also enlarged the HAO site at Climax (see the image on page 36). Roberts's compromise saved the HAO from being terminated. With it, he ensured that solar research and Sun–Earth connection research stayed in Boulder, a *sine qua non* for the city's future development as a center for science.

“Our minds were already made up”

The Central Radio Propagation Laboratory (CRPL), founded in 1946 as the successor to the IRPL, was the US hub for predicting radio propagation. As such, it stood at the center of Sun–Earth connection research. Within a couple of years, US government officials began to think about moving the CRPL facility from its location in the Washington, DC, area. At the time, relates CRPL scientific administrator Alan Shapley, the northeastern-based scientific establishment viewed Boulder as a “scientific Siberia,” because it was “west of the Hudson River.”

Several factors contributed to Boulder's becoming the location of the new CRPL facility despite the attitudes of the scientific establishment. Contrary to popular wisdom, those factors do not include that Mamie Eisenhower hailed from Colorado. Rather, a combination of early Cold War defense policies and, perhaps, political machination brought the CRPL to the foothills of the Rockies.

Most renditions of the move to Boulder begin with the account of NBS director and noted physicist Edward Condon. Head of the NBS from 1945 to 1951, Condon wrote in a letter to his wife that the government wanted to build the new lab facility outside Washington for generic “military strategic considerations” and that Boulder would make a good “summer capitol [*sic*]” for him. Condon composed that letter in the summer of 1949, after Menzel and Roberts invited him to tour Colorado following a conference on cosmic rays, held in Idaho Springs. Documentary evidence suggests at least one other genesis of the idea for the CRPL's relocation to Colorado. In this alternate version, Condon was forced to head west, and the long-distance journey had little to do with national security concerns. The prime mover in the alternate understanding is powerful Colorado senator Edwin “Big Ed” Johnson.

“It has been rumored that Dr. Condon brought the Central Radio Propagation Laboratory to Boulder,” wrote the retired Johnson to Francis Reich of the Boulder Chamber of Commerce in 1967. He added, “The truth is that this tremendously famous Laboratory brought Dr. Condon to Boulder.” Historical consensus is that Condon, prompted by Johnson, did have strong pro-Colorado sentiments. Even so, a major \$4.5 million relocation effort by the US government needed strong justification to the public and other politicians. Officials formed a four-person site selection committee. Although Alan Shapley was not an official member, he served as an unofficial secretary. He was in continuous communication with Roberts, ostensibly because of the professional and scientific links between the HAO and the CRPL.

Events proceeded quickly after Condon's summer sojourn to Colorado. The existing air force–sponsored activities at the University of Colorado and the military-funded HAO paled in comparison with the prospect of a multimillion-dollar federal government research center in the heart of Boulder. Roberts, Stearns, and the Boulder community rallied around making the enticing possibility a reality. The Boulder Chamber of Commerce took immediate action. President John Allardice and secretary Reich “are in touch with Colorado's members of Congress,” reported a Boulder newspaper. Allardice and Reich communicated not only with Colorado's elected officials but also with Roberts and others. As the campaign intensified, Roberts served as an important link connecting the NBS's site selection committee and the Boulder Chamber of Commerce. His position in the world of Sun–Earth connection physics and his interest in the establishment of the new lab made him ideally suited to serve in that intermediary role.

The NBS created a formal site selection procedure. Though Boulder advocates needed to navigate that process, there was little doubt as to what the final result would be. The selection criteria ensured that Boulder would be a front-runner in the competition. And, as Alan Shapley confessed years later in an interview about a site selection committee trip, “If the truth be known, our minds were already made up before we reached Boulder.” Nonetheless, 28 university towns made the first cut. A second round reduced the list to three: Palo Alto, California; Charlottesville, Virginia; and Boulder.

Before the final decision was to be made, Shapley wrote to Roberts about land. “The way these things work,” he commented, “the *free availability* of land may become an important factor in the selection of a site.” A land offer made it easier for the committee to justify and sell the decision that they had in effect already made. “Of the three primary locations under consideration,” wrote the NBS board in its final report to Condon on 13 December, “only one, Boulder, has formally offered a suitable tract of land, comprising 210 acres, to the Federal Government.” Later that month, on the basis of the NBS report, Secretary of Commerce Charles Sawyer made the decision to move the CRPL to Colorado.

Prosperity insurance

After helping to get Boulder selected as the site for the CRPL and other new NBS labs, the Chamber of Commerce needed to deliver the land it had promised. To do so required collecting \$70 000, the estimated purchase price for the land pledged to the government. But where would they find the funds?

“Boulder citizens to be asked for nearly \$70,000 to purchase

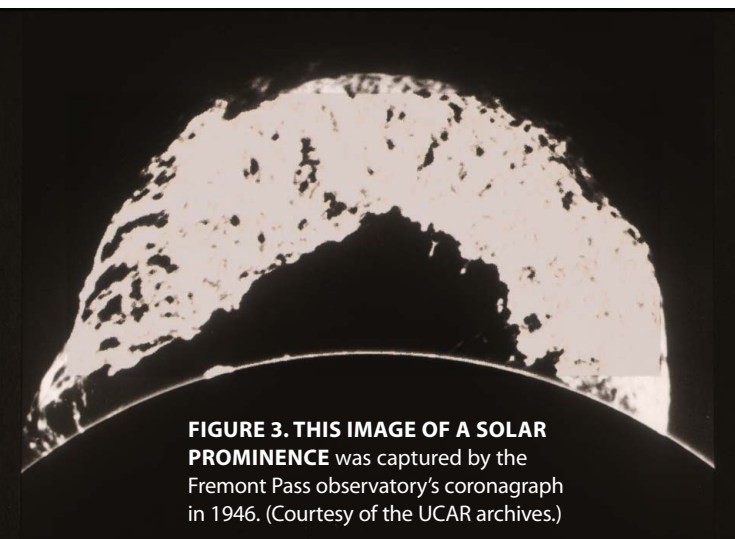


FIGURE 3. THIS IMAGE OF A SOLAR PROMINENCE was captured by the Fremont Pass observatory's coronagraph in 1946. (Courtesy of the UCAR archives.)



FIGURE 4. WALTER AND JANET ROBERTS enjoy some recreational time outside the Fremont Pass observatory in the Colorado mountains. The couple lived for many years in isolation there before moving to Boulder. (Courtesy of the UCAR archives.)

laboratory site” read a subheading to a 27 February 1950 *Daily Camera* article about the Chamber of Commerce’s fundraising campaign. The chamber decided on 11 April as the kickoff day to begin the drive. The Rotary Club and local unions were among the first to make pledges, a mix that indicates the diversity of support for the drive among Boulder’s citizenry.

A major part of the solicitation effort included the pitch that a donation was a type of insurance. “You probably now have health, accident and life insurance,” ran a full-page ad in the *Daily Camera*, “but how about your business? Will you have the customers and clients next year you have now?” It also asked, “Don’t you wish you knew?” Bringing the CRPL to Boulder, the argument went, should bring a \$2 million per year payroll “dividend” to the city for the \$70 000 “premium” needed for the site. The page spread ended enthusiastically and optimistically with “Pay your share of the premium—TODAY!” and “Collect your share of the dividends—TOMORROW!” The drive, an overwhelming success, yielded more than enough money for the land.

Dwight Eisenhower, the first incumbent US president ever to visit Boulder, dedicated the NBS labs on 14 September 1954 (see figure 5). He spoke of the labs as representing a “new type of frontier . . . of greater romantic value and greater material value than some of the discoveries of those earlier days.”

The International Geophysical Year

The greatest East–West collaboration of the Cold War era may well have been the International Geophysical Year (IGY), a 67-nation project that gestated in the 1950s and officially ran from July 1957 to the end of 1958. (See the article by Fae L. Korsmo, *PHYSICS TODAY*, July 2007, page 38.) From the beginning, many IGY researchers saw Boulder as a potential, if not obvious, candidate for IGY activities, both for the scientists who had migrated to the city and for the institutions that had developed there.

Roberts and Alan Shapley, because of their particular scientific interests and positions as administrators and scientific entrepreneurs, played particularly important roles in the IGY almost from its formal beginning at an international meeting held in 1953. Roberts and Shapley’s research agendas aligned with many of the broad goals of the IGY. But they also aligned with the research interests of IGY spark plug Sydney Chapman. A renowned space physicist, Chapman had formed and maintained close working relationships with both the HAO and the CRPL and routinely traveled to Boulder.

The CRPL’s mission to understand “the nature of the media through which radio waves transmitted” was also highly compatible with core IGY investigations. Shapley, keenly aware of the unique circumstance presented by a major international effort devoted to geophysics, wrote to NBS head Allen Astin in early 1954 that “the IGY provides the Central Radio Lab with an unparalleled opportunity” and that “a large fraction of CRPL current activities have objectives quite similar to those of IGY.” He could have written the same sentence about Boulder.

By the mid 1950s, all the parts were in place to make Boulder a centerpiece of IGY research activity—an infrastructure based on Sun–Earth connection science and the personal associations that connected Boulder to national and international IGY science. The relative ease by which Boulder transformed into a major site for IGY science is therefore not difficult to explain. Of the 12 technical panels the US National Committee for the IGY had formed by 1958, Boulder-based groups had research activities related to seven of them. The scientific links between Boulder and the IGY, strong from the start, only intensified.

As Shapley noted, the CRPL served as something of a mini-IGY by its very nature. One example of the laboratory’s close relation to the IGY began when Boulder scientists designed and constructed the latest version of an ionosonde, an instrument

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FIGURE 5. PRESIDENT DWIGHT EISENHOWER dedicated Boulder's new National Bureau of Standards laboratories on 14 September 1954. The labs contributed significantly to the city's being a center of scientific activity during the International Geophysical Year, 1957–58. (Courtesy of NIST archives.)

used to examine the ionosphere. Those activities dovetailed naturally with the HAO's solar work and observations, as the ionosphere was often the physical realm where HAO and CRPL interests connected. Thus an important part of the Sun–Earth connection science of the IGY was well represented by Boulder science. In turn, the IGY stimulated the burgeoning astrophysical work that began in Boulder in the late 1940s and early 1950s.

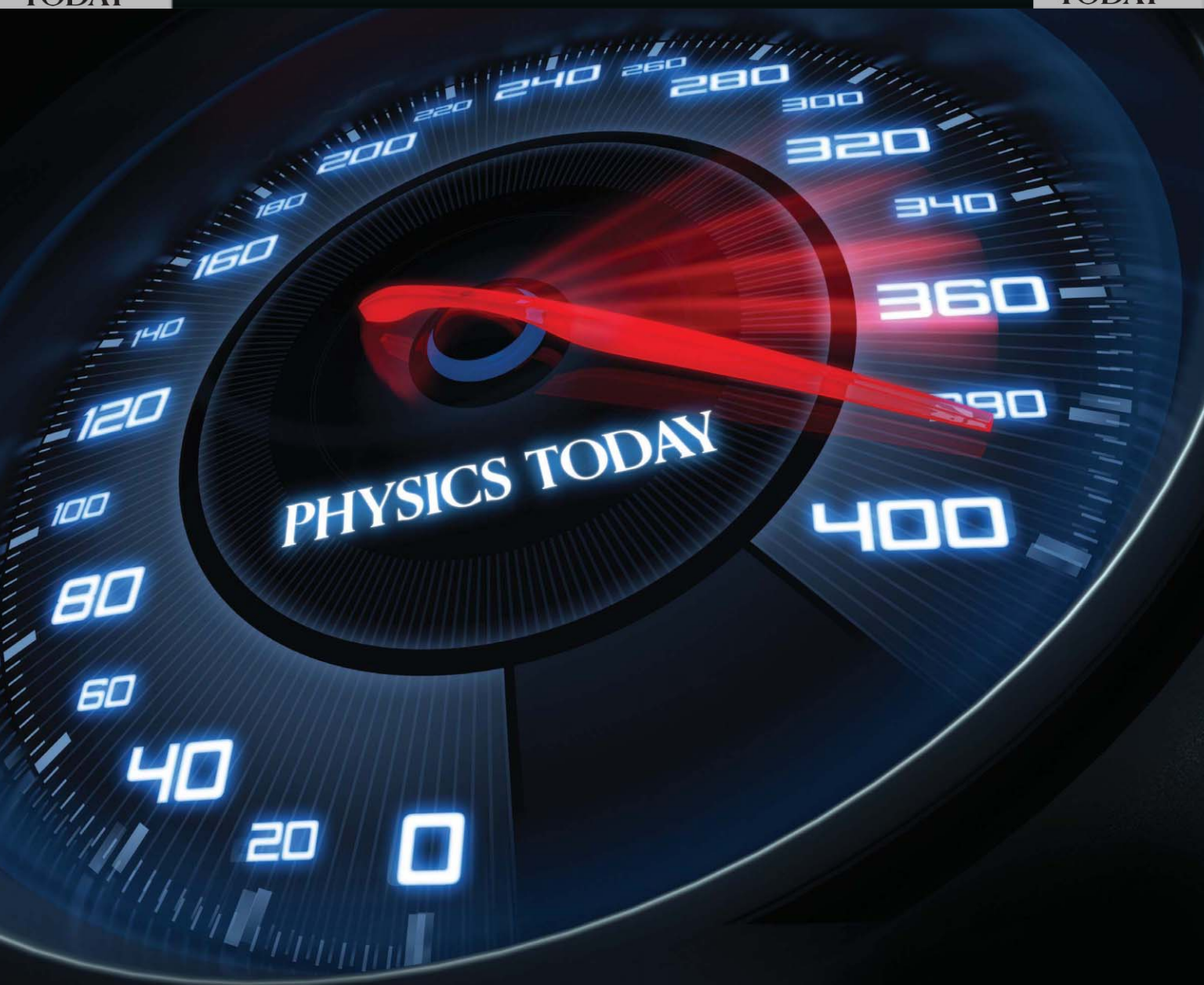
Boulder also distinguished itself as a data handling center. On the one hand, it had organizations that could coordinate IGY activities by alerting collaborating groups to geophysically significant events. On the other, it provided repositories from which researchers could obtain the IGY's globally collected disparate data sets, even years in the future.

Only the Washington, DC, area housed more of those important data repositories than Boulder. Given that less than a decade before, Boulder had the reputation of a “scientific Siberia,” the award of those highly visible IGY data centers served as an important indication of the city's rapid rise to prominence as a place for scientific research. As the city's reputation as a science hub grew, so did its possibilities. Soon, major research centers arose in Boulder—for example, the National Center for Atmospheric Research and the Joint (NBS–University of Colorado) Institute for Laboratory Astrophysics. By the early 1960s, Boulder had become a place for Big Science in America. The city had benefited from a confluence of shifting science patterns in the Cold War, shrewd politics, ambitious scientists and politicians, and fortunate timing. Those factors, coupled with the simple fact that Donald Menzel hailed from Leadville, Colorado, made AstroBoulder and set the stage for the city of science that Boulder is today.

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CYNTHIA CUMMINGS

IN REFEREES WE TRUST?

Melinda Baldwin

The imprimatur bestowed by peer review has a history that is both shorter and more complex than many scientists realize.

Melinda Baldwin is PHYSICS TODAY's Books editor and the author of *Making "Nature": The History of a Scientific Journal* (University of Chicago Press, 2015).



In the early summer of 1936, Albert Einstein and his assistant Nathan Rosen submitted a paper on gravitational waves to *Physical Review*. In it they argued that gravitational waves did not exist—a controversial claim that went against the prevailing scientific consensus. Six weeks after the paper's submission, *Physical Review* editor-in-chief John Torrence Tate wrote back to Einstein with a copy of a critical referee report and asked for a response to the reviewer's comments.

So far, this story will sound familiar to most PHYSICS TODAY readers. Modern scientists expect that their submissions to journals will be read and criticized and will require revision before they are admitted into the corpus of published scientific literature. Einstein, however, did not share those expectations. In fact, he was surprised and offended by the idea that his paper had been sent out for external review. (See the article by Daniel Kennefick, PHYSICS TODAY, September 2005, page 43.) In his riposte to Tate, Einstein said that he and Rosen

had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the—in any case erroneous—comments of your anonymous expert. On the basis of this incident I prefer to publish the paper elsewhere.

Einstein kept his word. He would never again submit a research article for publication in *Physical Review*.

It might be tempting to view Einstein's reaction as a show of ego by a senior physicist who thought his fame would allow him to skip the peer review process. However, digging deeper into the history of peer review uncovers a more complicated picture. In 1936 refereeing was not a universal practice at the world's top scientific journals. It was not even a universal practice at *Physical Review*. Einstein's previous submission to that journal, the famous 1936 Einstein-Podolsky-Rosen (EPR) paper, was not sent out for referee reports despite its provocative anti-quantum conclusions.

So Einstein's bafflement at receiving an anonymous report criticizing his paper was hardly inexplicable. But 80 years later, peer review is an expected and established part of publishing for scientists and scholars in almost every academic discipline.

How did this process become so ingrained in scientific life?

The origins of journal refereeing

Many academic and popular articles about peer review assign it the same origin story. In 1665 the Royal Society gave its secretary Henry Oldenburg permission to compile *Philosophical Transactions of the Royal Society of London*, generally regarded as the world's first scientific journal. Oldenburg immediately thought it wise to gather expert opinions on the pa-

pers he wanted to publish. Thus peer review was born and was ever after a consistent part of scientific publishing.

Or was it?

That origin story appears to have its roots in a famous 1971 sociology article—Harriet Zuckerman and Robert Merton's "Patterns of evaluation in science: Institutionalization, structure and functions of the referee system."¹ Zuckerman and Merton's article, based on an analysis of referee decisions at *Physical Review*, remains a foundational study of the sociology of peer review. It was so groundbreaking that PHYSICS TODAY printed a condensed version in its July 1971 issue (page 28). In crediting Oldenburg with the invention of peer review, Zuckerman and Merton implied that peer review's form and function had changed little since the 17th century.

More recent historical work, however, has called Zuckerman and Merton's history into question. In reality, Oldenburg rarely consulted outside opinions on what should be published in *Philosophical Transactions*, and he held such close control over the journal's contents that he occasionally referred to himself as its "author." There was not even a formal submission process. Oldenburg would simply print what interested him and what he thought might be of value to his readers, including not only experimental papers but secondhand accounts of others' experiments, discussions of recent books, and even his own personal correspondence.²

Although Oldenburg was indeed a pivotal figure in the history of science publishing, he was not peer review's inventor. That honor arguably belongs to William Whewell, a Cambridge University polymath who also coined the terms "physicist" and "scientist." In 1831 Whewell suggested that the Royal Society should commission written reports on papers submitted for publication in *Philosophical Transactions*. He thought those

REFEREES

reports should then be published in the Society's new journal, *Proceedings of the Royal Society of London*, thereby fulfilling the dual purpose of fostering rich scientific discussions and providing material for the new publication.³

The Royal Society adopted Whewell's suggestion of soliciting reports but shifted quickly away from his vision of printing them for public discussion. A handful of reports did appear in *Proceedings*, but by the mid 1830s that practice had ceased. Instead, the society decided that referee opinions were mainly useful for helping it avoid printing anything embarrassing in its publications. By the mid 19th century, refereeing for *Philosophical Transactions* was almost entirely run by two secretaries, one in the physical sciences and one in the biological sciences.

The secretaries were eminent members of the society, and they each worked with an assistant secretary to arrange refereeing for the papers submitted to *Philosophical Transactions*. The referee reports came to be seen as confidential documents for the internal use of the society. For many years, they were not made available to the authors of accepted or rejected papers.

Because authors did not see the reports, there was no real equivalent to today's common "revise and resubmit" decision. Submissions to *Philosophical Transactions* were either accepted or rejected. However, the secretaries did occasionally encourage authors of *Philosophical Transactions* papers to revise their articles before they went to print. Physicist George Gabriel Stokes, who served as the society's physical sciences secretary for more than 30 years, often suggested changes to authors via personal correspondence. Stokes would paraphrase useful comments from the *Philosophical Transactions* referees, and if Stokes himself had refereed the paper, he would often send the author a copy of his full, signed report.⁴

Refereeing in the early 20th century

At the end of the 19th century, an important shift began to take place in the scientific community's view of referees. With concerns growing about the overall quality of the scientific literature, the referee was no longer simply helping protect the reputation of a scientific society or journal. Instead, the referee was increasingly seen as someone whose work was to protect the reputation and trustworthiness of the entire scientific literature, to staunch a flood of "veritable sewage thrown into the pure stream of science," as physiologist and Member of Parliament Michael Foster put it.⁵

By the early 20th century, refereeing procedures had spread

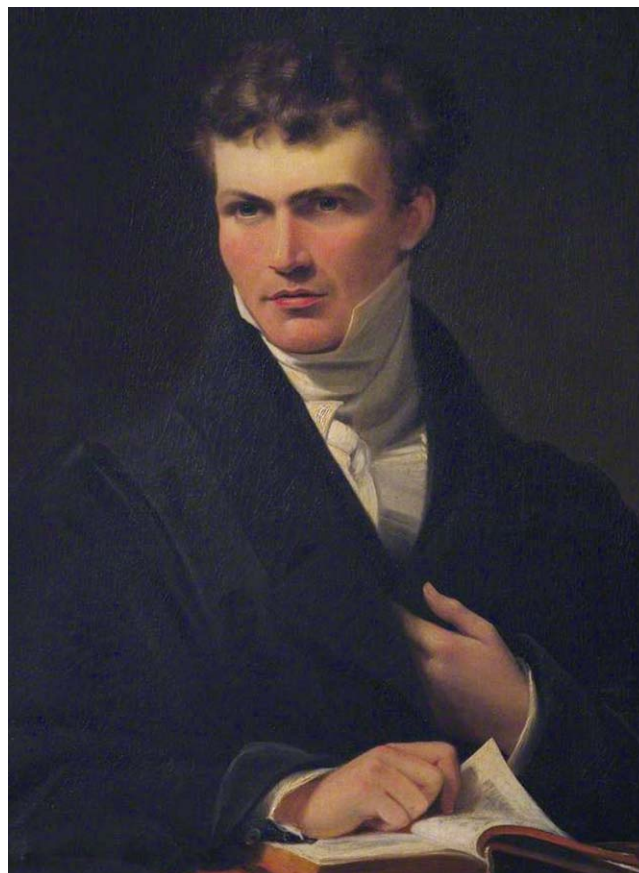


FIGURE 1. THE ENGLISH POLYMATH WILLIAM WHEWELL (1794–1866) proposed in 1831 that the Royal Society should collect and publish reports on *Philosophical Transactions* papers.

systematic refereeing for all papers become an official policy.⁶

Commercial journals printed by for-profit publishers were even less likely to employ systematic refereeing before the Cold War. Indeed, publications like the *Philosophical Magazine* or *Nature* would continue to keep editorial deliberations in-house well into the 20th century. Those periodicals placed a high value on printing issues quickly, and many were run by ambitious editors who saw little reason to consult anyone outside a small circle of trusted advisers to decide whether or not a paper was good.

Likewise, many prominent journals outside the English-speaking world relied heavily on the judgment of their editors to select content. Such journals often counted some of the country's most respected scientists among their editorial staff. For instance, Max Planck was a longtime member of the editorial board at the revered physics journal *Annalen der Physik*. Few physicists would have questioned Planck's ability to decide, with or without any outside opinions, which papers belonged in *Annalen*.

The story of external refereeing at grant organizations is similar to the story for journal refereeing. Private grant organizations such as the Rockefeller Foundation generally left funding decisions in the hands of trusted middle managers long after World War I.⁷ Grant organizations associated with governments or scientific societies were more likely to use external refereeing, although the practice was by no means universal.

When the US government formed the National Institutes of Health in 1948, NIH's division of research grants initially evaluated grant applications with little or no consultation with outside referees. Instead, small "study sections" composed of NIH-affiliated scientific experts were the first to review proposals.

to most scientific societies in the English-speaking world. In theory the procedures were wide-ranging, but in practice the referees themselves tended to belong to small networks of elite scientists.⁵ Early-20th-century refereeing procedures were less formal than the ones we now associate with scientific journals, and authors usually did not see referee reports.

At *Physical Review*, for example, referees knew that the editor would paraphrase their comments for authors and often submitted brief, casual, and occasionally sarcastic reports. Frequent referee Howard P. Robertson (1903–61) once suggested that a paper could be improved "if it were written in invisible ink." It was not until 1935 that *Physical Review* offered referees a standard questionnaire about papers. And not until the 1960s did

Final authority over funding decisions rested with institute directors—the heads of NIH's constituent institutions, such as the National Cancer Institute.

The National Science Foundation, established by federal law in 1950, was more reliant than NIH was on outside experts for opinions on proposals. Some proposals were sent out ad hoc for mail review: Copies of the proposal were mailed to scientists who submitted their comments by return mail. Other proposals were evaluated by special panels of experts assembled in Washington, DC.

As was the case with NIH, however, decisions about funding at NSF were largely in the hands of NSF employees. Directors were responsible for deciding which proposals to fund, and referee opinions were seen as only one piece of their decision—an important piece, but not the determining factor for whether NSF would award or withhold funding. Furthermore, at both NSF and NIH, referee reports were not shared with grant applicants. Scientists who submitted proposals would receive only a short summary prepared by a government employee that stated the major reasons for acceptance or rejection.

Before the Cold War, journals or grant organizations that eschewed refereeing or placed significant power in the hands of editors and directors were not seen as less reliable or less scientific than ones that depended on referees. And the story of Einstein's clash with *Physical Review* shows that researchers who were accustomed to editors or foundation directors making decisions did not necessarily see external refereeing as a superior system. Why, after all, should an author trust the word of an anonymous referee rather than a respected editor or program director who was willing to sign his name to his remarks?

Public trust and peer review

The term “peer review” first began to appear in the scientific press in the 1960s. Interestingly, the term does not seem to have originated at journals. Instead, “peer review” was originally used to describe review committees at grant organizations—most often NIH—and in the medical community.

“Peer review means different things to different people,” physician and researcher Irvine H. Page explained in a 1973 editorial for the *Journal of the American Medical Association*. He continued:

To most American physicians it means PSRO [the Professional Standards Review Organization, which reviewed compliance with American Medicare laws], to the British House of Lords it means Peers examining other Peers for moral turpitude, and to the scientific community, it means Study Sections and Councils that determine a grantee's financial and possibly research future.⁸



FIGURE 2. DEMOCRATIC SENATOR WILLIAM PROXMIRE

(1915–2005) was a vocal critic of NSF in the 1970s and a master of the acerbic press release. (Image reproduced by permission of the Wisconsin Historical Society.)

Significantly, journal refereeing was not one of the definitions Page offered, although scientists and editors slowly adopted the term for that purpose over the course of the 1970s.

One episode that brought the term into more common use was a 1975 controversy about funding at NSF—a controversy that would both highlight and solidify peer review's increasing importance to the research community.

Scientists in the US, particularly physicists, entered the Cold War riding on the success of the Manhattan Project. By 1953 US government spending on science had increased by a factor of 25 from its prewar numbers—and science's public profile only increased after the Soviet Union beat the US into space with the launch of *Sputnik* in 1957.⁹

The US enthusiasm for science funding proved finite, however. As early as 1966, a study by the Department of Defense concluded that DoD spending on basic research had not yielded significant progress on the department's goals, such as new weapons. The study was published in a document called the Project Hindsight report, whose findings caused some legislators and commentators to begin questioning scientific spending more broadly. Project Hindsight was an early hint that the social and financial status scientists had acquired in the early Cold War might be at risk.

By 1975 the Cold War had entered a relatively calm period of official détente between the two superpowers. The goal of keeping up with the USSR seemed less crucial. Furthermore, the US was suffering from an economic crisis. Oil and gas supplies shrank when several major oil-producing countries refused to sell oil to the US in retaliation for the country's support for Israel in the 1973 Arab–Israeli war. Economic growth stalled. Inflation and unemployment soared. With Congress under pressure to trim expenditures from dwindling tax revenues, a handful of lawmakers set their sights on NSF.

The most prominent NSF opponent was Senator William

REFEREES

Proxmire, a colorful Wisconsin Democrat with a knack for publicity. In March 1975 Proxmire began issuing his famous Golden Fleece Award, which he gave to the government project that he deemed the month's worst use of taxpayer money. The first two Golden Fleece Awards went to NSF projects: a University of Wisconsin sociological study about interpersonal attraction and psychologist Ronald Hutchinson's work on why humans, rats, and monkeys clench their jaws in moments of stress. Proxmire called on NSF to "get out of the love racket" and declared that Hutchinson's "nonsense" had "made a monkey out of the American taxpayer."

Meanwhile, an ambitious Republican congressman named John Conlan began criticizing NSF's spending on its education programs, particularly Man: A Course of Study (MACOS) and the Individualized Science Instructional System (ISIS). MACOS was a social sciences curriculum that had been controversial since the early 1970s in Conlan's home state of Arizona, where critics claimed that it promoted moral relativism. ISIS, a program aimed at fourth-graders, was accused of being too explicit about reproductive education.

In his quest to discover why MACOS and ISIS had received government funding, Conlan came into conflict with NSF leadership, including the foundation's director, H. Guyford Stever. Conlan requested full copies of NSF's referee reports, along with the names of the reviewers. Stever replied that referees submitted their reports under an "implied promise of confidentiality" and that releasing the text of the reports or the names of the reviewers would violate NSF policy. Conlan, however, was not persuaded.

I would again remind you that I am a Member of Congress on a Committee charged with the oversight of the National Science Foundation. . . . Consequently, I do again demand that you make available the peer reviewer comments originally demanded by me—in their original and complete form, not paraphrased.¹⁰

The public debate and private exchanges over NSF grants led to the National Science Foundation Peer Review Special Oversight Hearings, held before the House subcommittee on science, research, and technology in July 1975. Over the course of six days, Congressional questioners and witnesses discussed NSF's peer review process at length.

In his testimony, Conlan argued that NSF's system placed too much decision-making power in the hands of NSF directors, and did not give enough weight to referee reports. He claimed that the only way to hold the foundation accountable was to make referee reports public, along with the names of the referees.

The NSF team came to the hearing prepared to make changes in response to the criticisms. Director Stever announced that as of 1 January 1976, applicants would be given full copies of their referee reports instead of just the summaries. However, Stever insisted that referees must remain anonymous to ensure their candor. NSF leaders also indicated that in the future, a new audit office would ensure that directors were placing appropriate weight on positive and negative referee reports—in

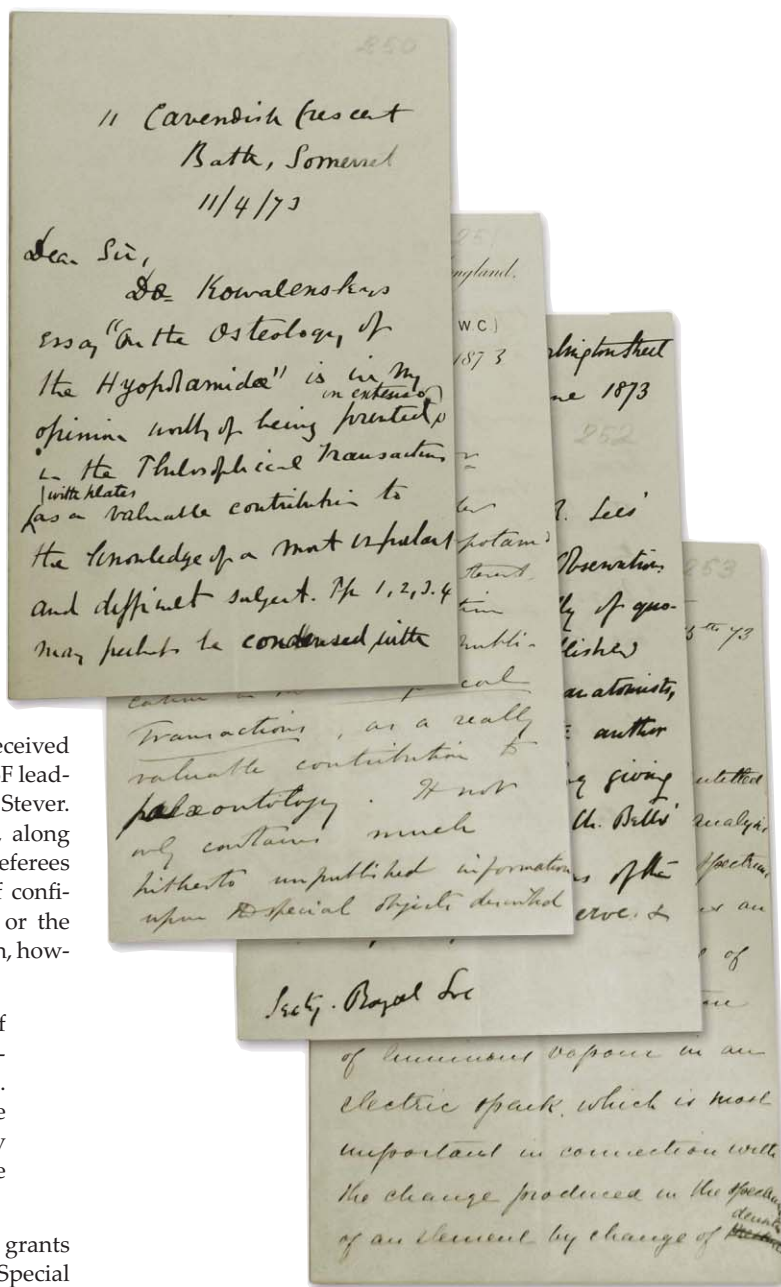


FIGURE 3. SEVERAL SHORT, HANDWRITTEN REFEE REPORTS submitted to the Royal Society in 1873. It was common for referees to simply recommend publication or rejection with only a few explanatory comments. These reports would not have been seen by the paper's author. (Image reproduced by permission of the Royal Society Library and Archives, item RR_7_176.)

other words, placing more decision-making power in the hands of referees.

Following the hearings, NSF's education programs were significantly downsized, and funding for MACOS and ISIS was almost entirely eliminated. However, NSF's peer review reforms quieted the fiercest criticisms, at least temporarily, and the controversy soon faded from public view. Proxmire, meanwhile, became embroiled in a lawsuit when Golden Fleece

awardee Hutchinson sued him for libel. Proxmire eventually made a public apology to the psychologist and omitted individual names from future Golden Fleece press releases.

Although most of the criticisms were leveled at the social sciences, scientists from across disciplines followed the controversy. PHYSICS TODAY reported closely on the hearings and on NSF's policy changes. Editor-in-chief Harold Davis argued in an editorial that the hearings demonstrated "that peer review is by far the best means we have for deciding how funding should be distributed in a given area." (See PHYSICS TODAY, September 1975, page 96.) In the same editorial, Davis went on to announce that PHYSICS TODAY would be sending complimentary issues to every member of Congress to illuminate the inner workings of the scientific community. As Davis put it, "In an age in which the issues of society cannot avoid being ever more closely involved with science and technology we are going to need more peer review, not less."

The 1960s and 1970s seem to have been a crucial period of transition for ideas about peer review. In the mid 20th century, external refereeing was simply one of several methods a journal or grant-issuing organization could use to choose which submissions to accept or reject. By the end of the Cold War, peer review was a prerequisite for scientific respectability.

The NSF controversy strongly suggests that one reason for the increased emphasis on peer review, at least in the US, was a shifting relationship between scientists and the public during the Cold War. Spending on both basic and applied research had increased dramatically in the 1950s and 1960s—but when doubts began to creep in about the public value of the work that money had funded, scientists were faced with the prospect of losing both public trust and access to research funding. Legislators wanted publicly funded science to be accountable; scientists wanted decisions about science to be left in expert hands. Trusting peer review to ensure that only the best and most essential science received funding seemed a way to split the difference.

Peer review in crisis?

Today peer review is an expected part of publishing any scientific article or obtaining grants. However, few would argue that it is a perfect process. Many observers have lamented that fraudulent or flawed results still reach the pages of peer-reviewed journals. Others complain that the peer review system favors established ideas and institutions and stifles scientific innovation.

In 2014 Michael Eisen, a cofounder of the publisher Public Library of Science (PLOS), told the *Wall Street Journal* that scientists and nonscientists need to discard the notion "that peer review of any kind at any journal means that a work of science is correct. What it means is that a few (1–4) people read it over and didn't see any major problems."¹¹

Another drawback with the current peer review system is that the work reviewers put in generally does not count toward tenure or promotion. Overburdened scientists face little incentive to write long, careful, and detailed reports that go beyond discharging their minimum duty as good scientific citizens.

The shift to online publication and reading seems to suggest alternative methods for vetting articles, such as allowing scientists to post comments about those they read. Physicists have long relied on the non-peer-reviewed [arXiv.org](http://arxiv.org) to find the lat-

est publications in their field, although readers may regard a paper posted to the arXiv but never published in a journal as somewhat questionable.

Other journals have been experimenting with slightly altered peer review systems. *PLOS One*, a well-known open access journal, instructs its referees to judge only the quality of the science in the paper, not the work's perceived importance or impact. The reasoning behind *PLOS One*'s policy is that working scientists will determine which papers are most important after publication. Another journal, *eLife*, puts referees and editors in communication with each other to arrive at a single joint decision on a paper's future, rather than sending authors multiple reports that might disagree wildly with one another.

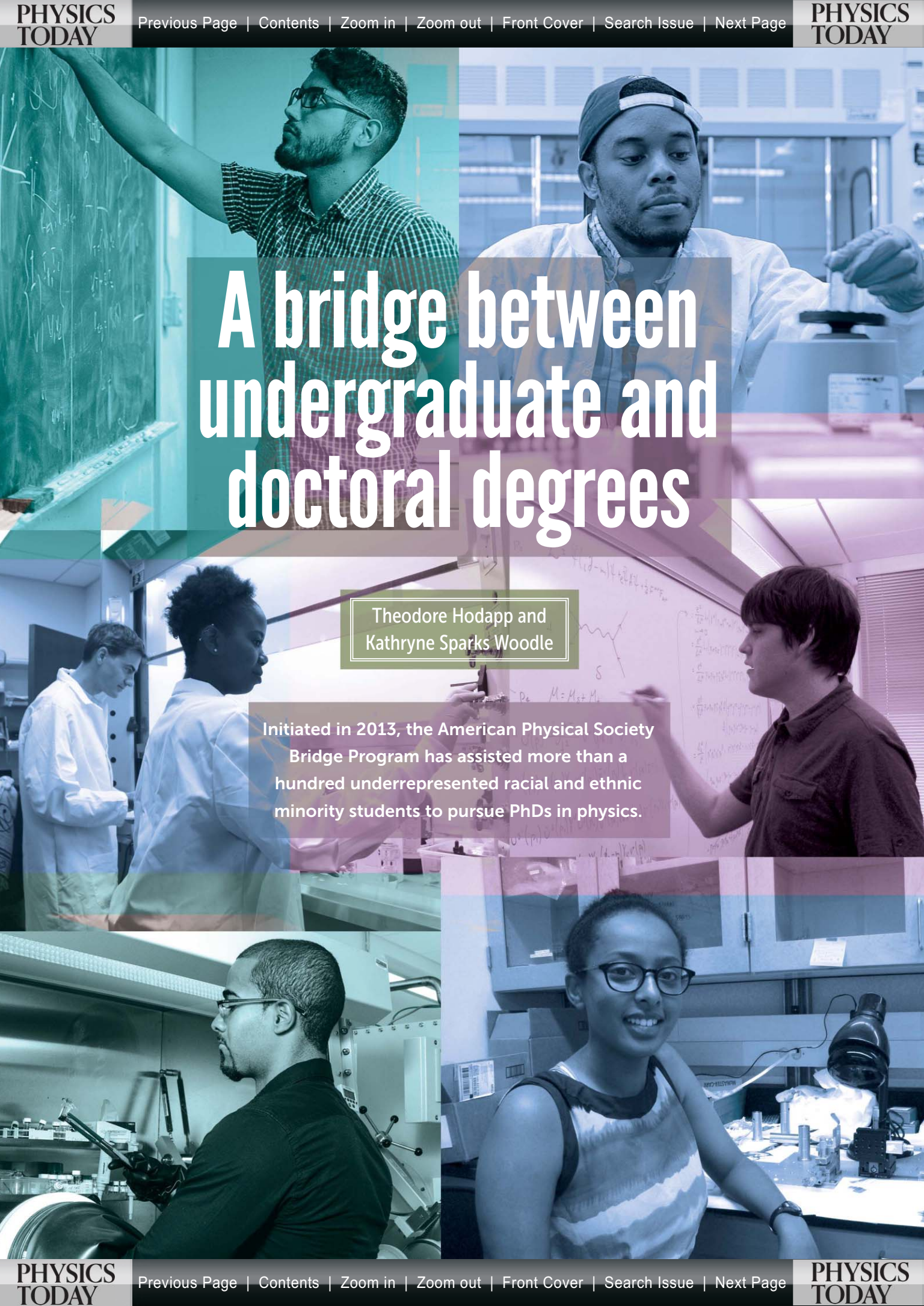
As the scientific community considers peer review's future, it may be instructive to consider its past. We often speak of refereeing as something that has been a stable and unchanging part of science ever since the age of Isaac Newton, but peer review's story is both shorter and more complex than we often assume. It is also littered with criticism. As early as 1845, the scientific referee was described as "full of envy, hatred, malice, and all uncharitableness."³ Complaints about reviewer uselessness and bias, in other words, are hardly new.

It also seems significant that refereeing procedures were not initially developed to detect fraud or to ensure the accuracy of scientific claims. Whewell thought referee reports would spur scientific discussion, and scientific societies adopted refereeing to ensure that nothing obviously embarrassing reached print. Authors, not referees, were responsible for the contents of their papers. It was not until the 20th century that anyone thought a referee should be responsible for the quality of the scientific literature, and not until the Cold War that something had to be peer-reviewed to be seen as scientifically legitimate.

Peer review's role in the scientific community has never been static. Its form and purpose have been shaped and reshaped according to what scientists needed from the practice—whether it was credibility for a scientific society, improvements in the scientific literature, or assurances to public funders that their money was being spent responsibly. If scientists are to transform peer review's future, they must consider what purpose they want it to serve—and whether that purpose can indeed be fulfilled by reports from two or more referees.

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A bridge between undergraduate and doctoral degrees

Theodore Hodapp and
Kathryne Sparks Woodle

Initiated in 2013, the American Physical Society Bridge Program has assisted more than a hundred underrepresented racial and ethnic minority students to pursue PhDs in physics.

Ted Hodapp directs project development for the American Physical Society (APS) in College Park, Maryland, and advises its department of education and diversity. **Kathryne Woodle** manages education and diversity programs for APS.



Physics is unflinchingly objective, intellectually difficult, and at times downright confusing. It also stimulates creativity and helps us understand pretty much everything—at least at some levels. None of those traits, or others you might think of as descriptive of a natural science, are intrinsically biased for or against African Americans, Hispanic Americans, or Native Americans. So why do such underrepresented racial and ethnic minorities (URMs) collectively earn a paltry 11% of undergraduate physics degrees in the US and only 6% of its doctoral degrees, as shown in figure 1?

Factors such as stereotype threat—a well-documented effect in which individuals underperform at challenging tasks when they feel they might conform to a stereotype of their group¹—and unconscious bias² contribute to the problem. But unknown to many in the physics community are the difficulties that are endemic to a student's background and to the culture of society at large.

All students struggle—that seems to be the nature of graduate work and independent research. But are those struggles primarily associated with understanding the science or with situations that tear one away from a focus on academics and sap creative energies? The latter often come after the loss of a loved one, a breakup, or some other personal crisis that undermines the ability to perform at one's peak. Now imagine what it is like to deal with those kinds of challenges, in addition to racial profiling and other issues. Imagine working at the lab late at night and having a security guard question whether you belong there. For some students, disruptions like those are everyday reality.

In 2008 the American Physical Society (APS) brought together leaders from minority communities to strategize what specific programs might be considered to address inequities. After a year of discussions, conversations with lots of people around the country, and a look at some distinctive, existing programs that showed promise in addressing underrepresentation, APS settled on trying to eliminate the disparity between URM students' participation at undergraduate and doctoral levels. The percentage of physics degrees awarded to URM students at both levels has remained stagnant for the past couple of decades (see figure 1b). A significant gap also remains between

the fractions of bachelor's and doctoral degrees awarded to URM students—a loss of URM physicists.

Increasing the number of URM PhDs by about 30 each year would be enough to close the gap between the number of bachelor's and PhD degrees that are earned, on average, by URM students. Thirty PhDs seemed like an achievable goal to those of us in the education and diversity department at the APS. Using knowledge gained through our discussions, we adapted existing program elements and developed new ones to create a

“bridge” program designed to help motivated and talented URM students gain acceptance into graduate programs and receive support to enable them to succeed.

In 2013 the first students matriculated into graduate schools through the APS Bridge Program (see figure 2). Although they have yet to earn doctorates, we expect the number of students now in the program to close the gap in percentage of URM degree recipients once they graduate. This article describes the APS program and explains why we think we now understand something about a system that is stacked against students who are talented and motivated but who often have to deal with cultural attitudes, poverty, or just bad advice that keeps them from experiencing the joy of going down the intellectually stimulating road we call physics.

A starting assumption

Our early discussions made us realize that some students, though capable and driven to complete PhD-level work, are, for various reasons, unable to gain admission to a graduate program or, once there, fail to obtain their degree. To counter both problems, we established three significant components of the Bridge Program:

1. Recruit, disseminate, and track applications from students who have not been admitted to graduate studies.
2. Establish “bridge sites”—universities willing to help students make the transition into and ultimately complete graduate studies.
3. Conduct research into underlying factors that contribute to the success or failure of students in attaining doctoral degrees in physics.

APS BRIDGE PROGRAM

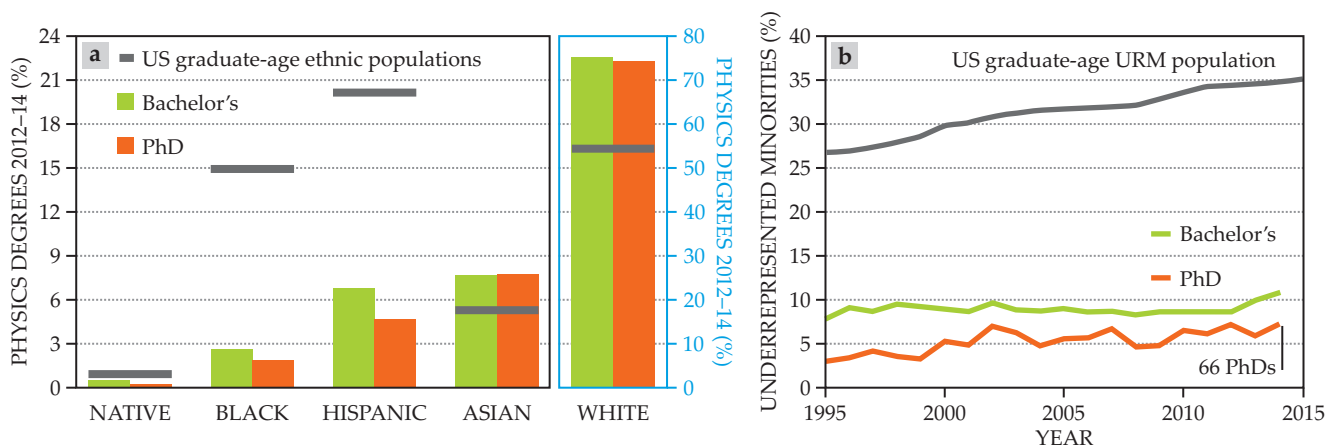


FIGURE 1. UNDERREPRESENTED RACIAL AND ETHNIC MINORITIES (URMs) in US physics programs include Native Americans, African Americans, and Hispanic Americans, whose fractional representation as bachelor's (green) or PhD (orange) degree recipients is disproportionately less than each group's representation in the total university-age population (gray bars). **(a)** For example, Hispanic Americans represent 20% of the US population but earn less than 5% of the PhDs awarded to US citizens or permanent residents. White and Asian Americans, by contrast, are overrepresented as degree earners in a similar analysis. The percentage of bachelor's degrees attained by those two racial/ethnic groups is also roughly the same as their percentage of PhDs. **(b)** By contrast, an achievement gap of about 5% exists between the percentage of URM students who received bachelor's degrees and the percentage who received PhDs. The gap has persisted for more than two decades.

Since beginning our program, we have found that about two-thirds of all applicants to the program were turned down at every graduate school to which they had applied, and the remaining third never even applied. A chief explanation we hear from the latter group is either a low score on the physics graduate record exam (GRE) or grades. This reason is particularly common to URM students, as the GRE has documented differentiation in scores based on gender and URM status. When broken down by race and gender, the distribution of GRE scores is, on average, lower for minorities and women.³

One result of a low score is that students often don't even bother to apply to graduate school, believing that they would be wasting their money trying to gain admission—a process that can set them back roughly \$1500 in applying to 8–10 schools. To increase the number of URM students transitioning into physics PhD programs, we connect these students with programs that are willing to look beyond GRE scores and that recognize (and foster) potential rather than just accomplishment. A permanent solution will require departments and faculty to consider systemic changes to admissions and other longstanding practices—a longer-term goal of the project.

National recruiting

While enabling URM students to succeed is at the heart of bridge programs, finding these can be a frustrating and time-consuming occupation for a physics department. Fortunately, APS is in a unique position in the physics community. We can do what most universities cannot: advocate for everyone. We can ask every department to nominate students they think would be successful if given the right opportunity. We can ask graduate departments to identify applicants to whom their own programs are unable to extend an offer and then to encourage those students to apply to the APS Bridge Program. We also do not let departments review applications until after 15 April, the standard deadline for students to accept graduate program offers, as we do not want to move students between programs. We want

to make sure students who did not receive an offer but have the potential to complete a PhD get that opportunity.

The APS-facilitated process offers several advantages. First, for each student we effectively “apply” to dozens of universities, including lesser-known ones of which most are unaware. (The US has about 185 PhD-granting and 60 MS-granting departments.) Second, our process is free for students—we do not require application fees, official transcripts, or their official GRE score.

The response to this recruiting effort has far exceeded our original expectations (see figure 2). In 2016 we received applications from 90 students—far more than our bridge sites, described below, could accept (they took 24 this year). Our solution was to vet additional “partnership” institutions willing to embody the principles behind the Bridge Program. With the help of the APS Committee on Minorities in Physics, we have now recognized 27 such departments, with the number rising by about 10 each year. The committee review process provides important feedback to each physics department and gives us confidence that an institution is committed to establishing conditions needed for URM students to succeed.

To date, we have placed 106 students into bridge sites, partnership institutions, and several other affiliated programs. Figure 3 shows the geographic distribution of sites hosting bridge students (red, blue, and green dots) and institutions that support the ideals of the APS Bridge Program (black dots). Ultimately, we intend to limit applications to vetted departments to ensure a supportive environment for all students coming through the APS process.

Figure 2 shows the increasing numbers of students entering graduate studies through the APS Bridge Program, along with those who have since left, resulting in a retention rate of 92% (the national physics graduate student retention rate is 59%).⁴ Many more students have been accepted than can be directly supported through project funding. The fact that the remainder are directly funded by institutions demonstrates a route to sustaining this effort into the future.

Creating supportive environments

Bridge programs have existed for many years at all levels of higher education. Today, numerous programs help high school students transition to college or college students get into medical school, but few exist to aid undergraduates progressing to graduate school. In 2009, after we realized that the gap between undergraduate and graduate participation among URM students was potentially fixable, we set out to visit existing physics bridge programs. The best known was (and still is) the Fisk–Vanderbilt Master’s-to-PhD Bridge Program.⁵ Enabled by the close proximity of the two institutes’ campuses, this highly successful program inducts students into Fisk University, a small master’s degree-granting HBCU (historically black college or university), and helps them transition into the PhD program at Vanderbilt. We also visited Columbia University’s Bridge to the PhD Program; the Imes-Moore Fellows Program at the University of Michigan; the Meyerhoff Scholars Program at the University of Maryland, Baltimore County; and others. All those programs are taking thoughtful approaches to improving diversity and can offer lessons that impact diversity and improve education for all students.

Following in the footsteps of those programs and with funding from NSF, APS established six bridge sites: at the Ohio State University, the University of South Florida, Florida State University, California State University Long Beach, Indiana University, and the University of Central Florida (the red dots in figure 3). Those institutions typically use the first year to help students make the transition (“bridge”) to graduate studies with undergraduate or graduate coursework as needed and provide mentoring and close attention.

During the second year, students are often well into their graduate coursework, with financial support provided by the university. At that point, they are in good shape to apply for admission into a PhD program. Of the 22 students accepted at bridge sites as members of the classes starting in 2013 and 2014, 15 are progressing toward a PhD, 11 at their original bridge sites.

Retention of students is a focal point of bridge programs, including ours. The tremendous effort to recruit and attract students into graduate school is wasted if they leave for reasons that can fairly easily be remedied. Key components of all bridge programs include financial support, induction, mentoring, and progress monitoring.

Financial support

Many students entering bridge programs cannot afford to self-finance their graduate studies, and most physics doctoral programs do not expect that of their students. The reality, however, is that URM students are more likely⁶ than majority students to begin their graduate education in a master’s program. And many such programs offer considerably lower financial support for their students than doctoral programs do, a reflection of the decreasing amount of state support for higher education at many institutions.⁷ For some students, especially those struggling academically, the distraction of working a part-time job often dooms their academic studies.

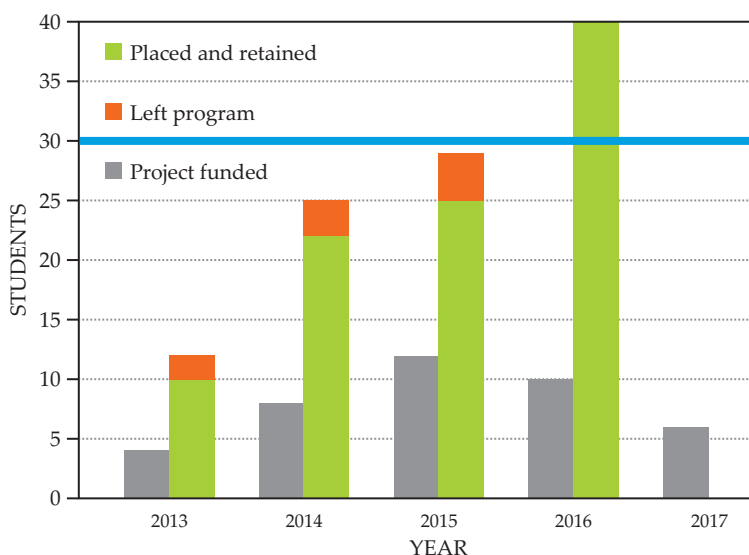


FIGURE 2. STUDENTS being placed into graduate programs (green) and leaving without a PhD (orange) from the American Physical Society Bridge Program for each year of the project. Gray bars indicate the number of students supported by APS project funding. To date, 210 students have applied to the program, 106 have been admitted, and 9 are no longer in it. The blue line represents the number of PhDs needed to equalize the percentages of doctoral and bachelor’s degrees awarded to underrepresented ethnic and racial minority students.

One student in our program represents a case in point. She reported that she was unable to gain admission to graduate school because of a low undergraduate grade-point average. But once fully supported in a PhD program through an application to the APS Bridge Program, she excelled at coursework. Although she had received Bs or lower in her core undergraduate physics courses, she earned As in the graduate-level versions of the same courses. What accounts for the difference? She had to work several jobs as an undergraduate to put herself through college and lacked the time to properly study. She has now passed her qualifying exams and is on the way to a PhD.

The timeliness of financial support is important as well. Some students are unable to afford moving expenses, rental deposits, or their first month’s rent. Starting the first semester of graduate school while already in financial straits makes it even more difficult, and stipends are often paid only at the end of the first month. To remove that hardship, APS advances funds to students before they arrive on campus. Some bridge sites also provide financial guidance because students who are unaccustomed to receiving a regular stipend are occasionally not familiar with how to effectively manage money. The guidance helps ensure that students are not handicapped by choices they made before beginning their studies. The problems are easy to solve, but for some students, they can spell the difference between success and failure.

Induction

The first few weeks of a student’s experience in graduate school can be traumatic: a new location with little or no support

APS BRIDGE PROGRAM

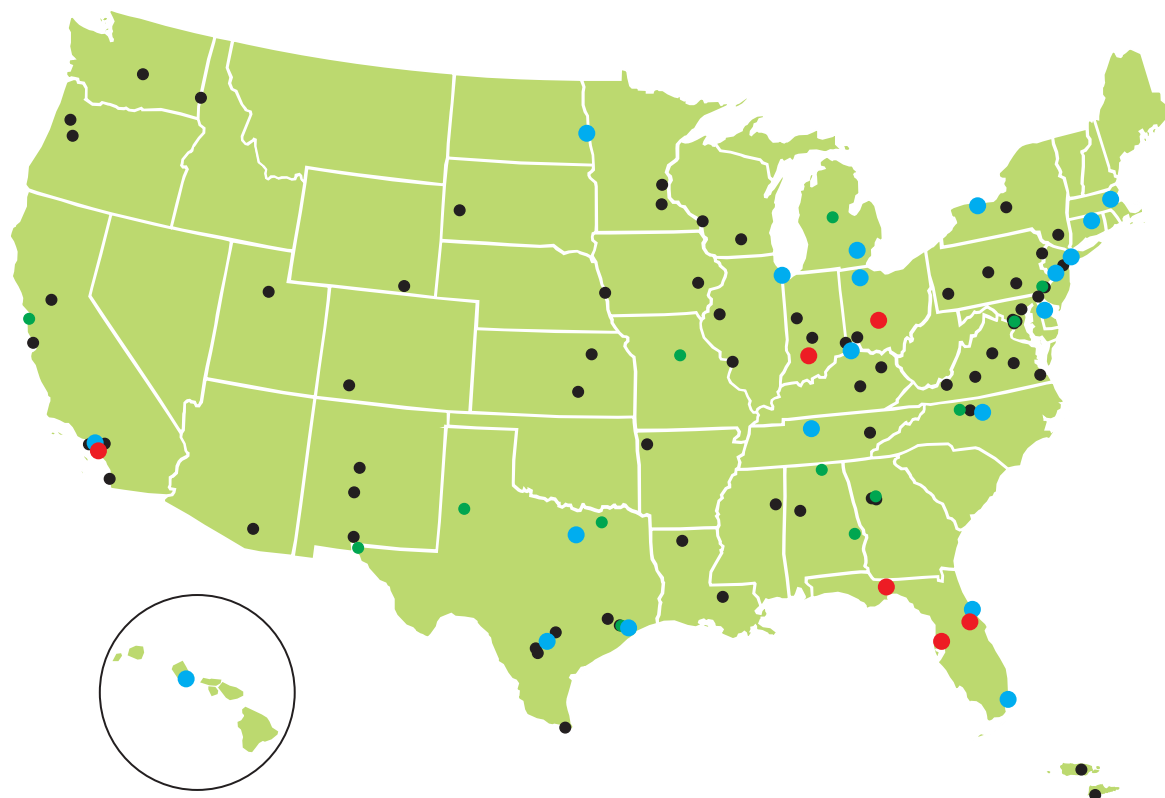


FIGURE 3. THE AMERICAN PHYSICAL SOCIETY BRIDGE PROGRAM currently comprises more than 100 participating institutions (all dots)—universities that support the APS's program ideals. They include six bridge sites selected by APS (red); "partnership" institutions, which have been vetted and officially endorsed by the society (blue); and "affiliated" institutions, which have not yet been vetted, but have accepted students (green).

networks, new living situations, and coursework at a level significantly above undergraduate courses. Those changes can be more daunting if English is not the students' first language or if their undergraduate coursework did not prepare them for the next level. Bridge programs address these issues in several ways, often beginning with diagnostic exams to probe a student's preparation. Although it is not always possible to convince students of their readiness for graduate E&M, scheduling undergraduate and graduate sections of the course at the same time gives students the option to switch a level, either up or down, a few weeks into the term, if that's necessary.

Social adjustments can be just as important as academic ones. One bridge site has its new students begin their first month on campus rooming with more senior graduate students. They learn about good housing options, limit their initial financial exposure, and begin to form friendships. Supporting many of those activities are physics graduate student associations, which are relatively low-cost organizations, now established at nearly every bridge site, in which students can forge social and professional networks (see box 1).

Mentoring

Students are more likely to thrive if they have different sources of support within easy reach when problems arise. Such support might include a trusted staff member in the departmental office, a student's research adviser, or a favorite instructor. This multiple-mentor model, sometimes referred to as constellation mentoring,⁸ encompasses several team mentors who can approach problems from different perspectives and spot trouble more rapidly than a single individual can. To be effective, such a team of mentors must also be educated about mental-health

professionals, housing services, and other campus resources. The mentors must also understand their responsibility to be aware of a student's progress or lack thereof. We recommend that the team meet regularly and that it poll the instructors of a student's core courses to gauge his or her involvement in class—for example, attendance, use of office hours, active engagement in discussions, and homework quality. Using this distributed mentoring model, bridge sites have been able to intervene quickly when difficulties arise (for a specific example, see box 2), locate resources, and solve simple problems that otherwise might derail a student.

In one example of effective mentoring, a bridge student left a large and vibrant Hispanic community, where he had enjoyed broad personal support, for a small college town. Once there, the site leaders spent time making sure he felt a part of the new community, and he is now progressing well toward a PhD. However, the availability of resources is not always enough. Students need to be reminded of them regularly, and special care should be taken when interpersonal issues underlie difficulties students are experiencing.

Progress monitoring

This last component is really just an extension of mentoring, but it is important enough that we call it out separately. At its

core, progress monitoring is another example of basic attention paid to graduate students. We ask all sites to check on their students regularly, especially in the first year. Evaluating their progress around week two of the first semester is extremely important: Are they attending and attentive in class? Handing in homework? Are they working in isolation or forming study groups with others? If red flags are raised, there is time to quickly step in and work to solve the problem. Maybe they are in the wrong-level course, or an outside influence may be a distraction. If so, the problems can often be resolved using resources of which they are unaware.

Week two is a great time to fix problems, because waiting until midterm essentially dooms a student. The time is well spent—especially if the correction is simple and its application reinforces and builds students' confidence while keeping them on track toward a degree. For example, one student at an APS bridge site had failing grades in the first semester, but not because he was incapable of the work. It turned out he was sick and did not know how to seek medical attention. English was not his first language and the culture in the locale of the bridge site was a significant change from where he had spent his entire life. The Bridge Program site leader discovered he was having trouble navigating the campus healthcare system and arranged for him to seek treatment.

He has now completed his courses and is on his way to a PhD—he just needed a little more attention than students are sometimes offered. The Bridge Program does not coddle students, but it is designed to head off easily fixed problems that many physicists, often from well-supported backgrounds or positions of privilege, may not encounter or even notice. Failing to see class distinctions associated with finances, race,

gender, and other factors can result in biases working against students.

What did we learn?

Establishing the APS Bridge Program was motivated by a glaring gap in educational attainment for underrepresented racial and ethnic minority students and by the knowledge that a small-scale solution had been successfully implemented at a few universities. There was a clear place for a professional society to provide the community with a service that would address the gap and bring the solution to scale. We did not anticipate the degree to which physics departments across the country would step up to the challenge of supporting bridge students. Sustaining those efforts is key to a long-term solution, we believe.

Central to the success of all bridge programs, and ultimately of any student who may need help in the transition into graduate school, is a rethinking of admissions and student support. Through our many discussions with students and faculty mentors, and more recently by gathering data from graduate programs across the US, we have come to a clearer understanding of the limitations of the physics GRE and other measures used in the admissions process. Many faculty already implicitly understand the limitations of these measures, but that knowledge is neither ubiquitous nor backed by peer-reviewed data to help influence the actions of cautious admissions committees. We realized early on that there was substantial demand for a more thorough investigation into discovering what application data are really telling graduate admissions committees.

To address that demand, we gathered data on a large fraction of physics graduate students and found that many of the

BOX 1. PHYSICS GRADUATE STUDENT ASSOCIATIONS

If your department is looking for a great way to help retain students, consider what is perhaps the most powerful concept we have seen—a physics graduate student association (PGSA). Analogous to undergraduate physics student clubs, such associations are more prevalent at PhD-granting institutions than at universities whose terminal physics degree is a master's. Nonetheless, PGSA's can work in all settings. They are inexpensive for a department to support, provide advice that entering students trust and understand, and build bonds that help students adjust to new and intellectually challenging environments.

To ensure sustained leadership and yet allow student leaders to maintain focus on their research, PGSA's such as the one shown here at Ohio State often have a rotating chair line, where students cycle through positions in successive years, avoiding burnout and building leadership skills. At almost every university where we have visited and discussed the concept,



students have overwhelmingly been in favor of a PGSA, and they quickly start one if none existed beforehand. In addition to providing peer mentoring and social functions for graduate students, PGSA's can

provide students' perspectives to faculty committees. Representation at that level can go a long way toward helping students advance professionally. (Photo courtesy of Michael Poirier.)

APS BRIDGE PROGRAM

BOX 2. AN ADMISSIONS AND MENTORING CASE STUDY

Admission difficulties

Fernand Eliud Torres Dávila, pictured here with one of his mentors, Ahlam Al-Rawi, is driven to get a physics PhD. While an undergraduate, he carried out research both in Puerto Rico and at the University of Nebraska–Lincoln, where he demonstrated a firm grasp of the concepts and his dedication to research. Despite that success, Torres Dávila received no offers of admission to PhD programs when he applied. However, faculty leaders at the University of Central Florida (UCF) saw promise and accepted him into their bridge program in 2015.

Early struggles

It became clear that Torres Dávila needed to take a few undergraduate courses on his arrival at UCF. But even in those courses he was not ready to proceed unassisted. Poor performance on the first homework set was flagged by UCF mentors. His problem was time management and an inability to effectively interact with course instructors. From then on he met with a mentor on a weekly basis to ensure that he remained on track, sought help from course instructors when needed, and kept up with the rest of the class. With a little supervision and hard work on his part, he was able to focus and receive passing grades.

**Success!**

Early intervention by UCF mentors helped Torres Dávila adjust to graduate school. He is now doing well as an MS student and ready to move on to a PhD program. He completed the 2015–16 academic year with two graduate-level core courses and four upper-division undergraduate courses to his credit and will complete all graduate core courses next spring. During his first year in the Bridge Program, he also carried

out research in an interdisciplinary materials-research group, made a poster presentation, and was a coauthor on a manuscript submitted for publication.

UCF site leader Talat Rahman says, “Without the Bridge Program, he might not have made it. At this point Fernand is self-assured, engaged in helping others, and moving on with his own goals. He has been very helpful to new bridge students.” (Photo by Talat Rahman.)

numeric measures used in admissions, including undergraduate grade point average (GPA) and GRE scores, are not always reliable predictors of success. If used, they should be considered carefully alongside other indicators, but never as a cutoff. The object lesson is that while the way our community practices admissions may yield qualified candidates, it is also inadvertently introducing bias—obscuring a number of individuals who could be successful. Since departments are less likely to admit these students using traditional admissions rubrics, an unseen bias is introduced into the process. This idea is one significant reason why NSF no longer requires the GRE for its prestigious Graduate Research Fellowships.

If we, as a community, want to make sure there are opportunities for everyone, then we need to recognize that some of the problems we must overcome are found outside J. D. Jackson’s *Classical Electrodynamics*. Some problems affect students in ways that we probably cannot immediately perceive. Fortunately, once we are made aware of them, many of these issues can be overcome relatively easily using resources and providing attention to students. Supporting students who didn’t get the same encouragement that many of us did and adopting a more nuanced approach during admissions, looking at potential rather than just accomplishments, are practices that will benefit everyone. URM students may not immediately see themselves as a part of our community, but with a little tweaking of our practices, they can join us in this exciting pursuit we call physics.

The APS Bridge Program is one way to do this, and hopefully it can reveal some of the ways we can make that path better for all students to come.

This article is based on work supported by NSF. We would like to thank the many faculty throughout the country who have dedicated so many hours to ensuring the success of bridge students, and who are working collectively to improve diversity within the physics community.

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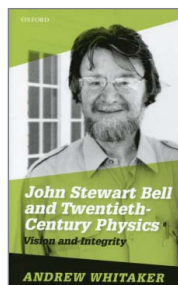
BOOKS

John Stewart Bell and
Twentieth-Century Physics

Vision and Integrity

Andrew Whitaker

Oxford U. Press, 2016. \$44.95 (460 pp.). ISBN 978-0-19-874299-9



John Stewart Bell, best known for his groundbreaking contributions to the foundations of quantum mechanics, was one of the most esteemed physicists of the 20th century. It was only a matter of time before he received a full biography, and historians and physicists interested in his life and work will welcome *John Stewart Bell and Twentieth-Century Physics: Vision and Integrity*.

After his undergraduate studies at Queen's University Belfast, Bell moved to Harwell National Laboratory and the University of Birmingham, where he worked with Rudolf Peierls and later earned his PhD. He went on to work in the theoretical division at CERN, where he stayed for the rest of his career and became known for his work on accelerator design and on particles and fields.

In the mid 1960s Bell brought a major innovation to another field, foundations of quantum mechanics. After exposing flaws in John von Neumann's proof against the possibility of modifying quantum mechanics via the introduction of additional "hidden" variables, Bell reexamined the famous Einstein-Podolsky-Rosen thought experiment suggested by Albert Einstein and his collaborators in 1935. Bell was able to prove that no theory complying with the assumptions of realism and locality could reproduce all quantum mechanics results—a proof that we now call Bell's theorem.

John Clauser and Abner Shimony were among the first to explore Bell's theorem experimentally, and experiments with the theorem continue to this day. The most recent ones involve massive particles, detectors separated by 140 km or so, and photons coming from distant stars in the galaxy. So far the experiments have confirmed quantum predictions, led to the establishment of entanglement as a quantum signature, and contributed to the blossoming of quantum information research.

Although Bell's current prominence

derives mostly from his work on quantum foundations, biographer Andrew Whitaker rightly notes that during his lifetime, Bell's reputation arose largely from his more conventional work on particles, fields, and accelerators. When Bell was elected as a Fellow of the Royal Society of London in 1972, the citation was almost entirely dedicated to nuclear and elementary-particle physics.

John Stewart Bell and Twentieth-Century Physics presents a vivid description of Bell's life and covers his diverse scientific accomplishments in detail. Occasionally, there is too much detail—certain passages risk overwhelming the reader. Despite that flaw, the book is invaluable for readers seeking a better understanding of quantum mechanics. It is also useful for readers interested in the history of 20th-century physics, particularly those who want to know more about particle physics and the history of CERN.

Whitaker was well placed to write this book. A physicist himself, he works on foundational issues of quantum mechanics, has interests in the history of science, and has already published books presenting the conceptual subtleties of quantum mechanics. He also currently teaches at Bell's alma mater, Queen's University Belfast. Thus he is very familiar with Bell's work and background.

Although thoroughly researched, the book would have benefitted from a deeper plunge into the literature about the stigma that haunted research in foundations of quantum mechanics throughout most of the second half of the 20th century. Bell was keenly aware of that professional bias, as Whitaker notes, and it could have been more thoroughly presented. Talented physicists such as Clauser, Heinz-Dieter Zeh, and Klaus Tausk found their careers obstructed because of their interest in foundations. For example, when Clauser was looking for a job in the summer of 1972, the chair of the physics department at San Jose

State University asked physicist Bernard d'Espagnat if Clauser's work was "real physics."

Bell himself received a letter from Léon Rosenfeld in December 1966 just after the publication of the paper deriving the theorem that now carries his name. Rosenfeld told Bell that he considered "hunting hidden parameters as a waste of your talent," adding: "I don't know, either, whether you should be glad or sorry for that." Nowadays the prejudice against foundational research is a thing of the past; quantum information theory is a blossoming field that draws directly from once-maligned work. However, for the sake of the current and future good health of physics, the full history should not be forgotten.

Bell's biography reminds us of the obstacles encountered in the making of physics. Whitaker's book, with its vivid biographical depiction and wealth of technical detail, fills a lacuna felt by many historians, philosophers, and physicists.

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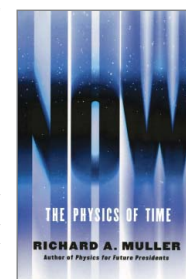
Now

The Physics of Time

Richard A. Muller

W. W. Norton, 2016. \$27.95 (368 pp.).
ISBN 978-0393285239

Richard Muller's *Now: The Physics of Time* is an ambitious undertaking that begins much like a popular account of relativity and quantum physics, but culminates by proposing a new theory of time. As in his acclaimed *Physics for Future Presidents: The Science Behind the Headlines* (Norton, 2007), based on a course he offers for nonscience majors at the University of California, Berkeley, the writing is entertaining and at times refreshingly idiosyncratic. Muller has a way of keeping a reader's attention with provocative ideas or claims. Examples include sections entitled "Actually, There Are No Black Holes" and "Feynman Reverses Time" and an extended discussion on the entropic arrow of time. Skeptical



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readers can be assured that he wraps up his mysteries with sober resolutions, but intriguing lessons remain.

Other popular accounts have already covered much of what *Now* discusses, but the book stands apart because Muller, a professor at the University of California, Berkeley, is a leading experimental cosmologist. Although Muller's lucid discussions of the behind-the-scenes difficulties of cosmological experiments make up only a small fraction of the text, they present important new insights to a general audience. It would not hurt if the Antaeus parable, which warns of the perils of losing touch with the ground, were declared required reading for any theoretical physicist.

The first parts of the book aim to introduce the basic physics of spacetime. Some crucial passages, however, may be hard to follow for a novice, as the treatment of relativity relies perhaps too much on difficult discussions of frames. For instance, someone not already familiar with local inertial frames is not likely to get much out of the statement, "If you are accelerating, handle the equations by imagining that your acceleration is essentially a continuous jumping of your proper frame from one reference frame to another one that is moving slightly faster." It is also unfortunate that the book eschews spacetime diagrams on the grounds that they could undermine Muller's new view of time by giving the impression of a spacetime without a dynamical flow.

Muller advises readers to be clear about frames of reference, but he does not always follow that important counsel. When he asks, "How far is it from the outside to the surface of the black hole?" he replies, "The answer is infinite." He seems to be integrating the line element at fixed time, varying only the radial Schwarzschild coordinate, but that trajectory is not the worldline followed by the "falling surface" alluded to in his statement.

The main purpose of these introductory discussions is to set the stage for a new theory of time. In an attempt to avoid spoilers, I'll let the brief quote "the explosion of the universe continually creates not only new space but also new time" suffice to indicate the main idea. Muller is open about the proposal's weaknesses, such as the possibility of violations of general covariance. As the

quote suggests, his proposal incorporates an incremental progress of time, which has been envisioned in some discrete theories of quantum gravity. Proponents of such theories are still struggling with the immense difficulties of making their proposals consistent with covariance.

Muller's proposal is original and intriguing, and it has implications beyond physics. He dares to think in broad categories, connecting a physical theory about the universe with climate change and such unwieldy topics as free will. Potential observational tests of Muller's new theory, however, receive rather short treatment. Some statements might be held against the theory if taken as specific predictions; for example, in chapter 22, Muller draws connections between entropy, empathy, and the electorate, and asserts that "the US voter does not

want to elect a sociopath." In addition, it sometimes seems that Muller is too quick to push aside competing theories. For instance, he argues that the immense entropy contained in black holes cannot matter for Arthur Eddington's explanation regarding the arrow of time, because black holes are so far away from us. There may be much to criticize about Eddington's proposal, but such quick dismissal is not entirely persuasive.

Nevertheless, Richard Muller's new theory deserves a serious look, and his book presents important lessons in physics and beyond. Most readers will find intriguing new insights in *Now: The Physics of Time*. The book might even be useful to the future presidents in the title of Muller's previous opus.

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Cavity Optomechanics

Nano- and Micromechanical Resonators Interacting with Light

Edited by Markus Aspelmeyer, Tobias J. Kippenberg, and Florian Marquardt
Springer, 2014. \$179.00 (357 pp.). ISBN 978-3-642-55311-0

Quantum Optomechanics

Warwick P. Bowen and Gerard J. Milburn
CRC Press, 2016. \$99.95 (358 pp.). ISBN 978-1-4822-5915-5

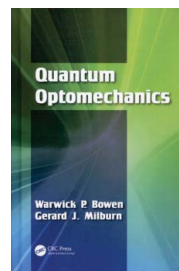
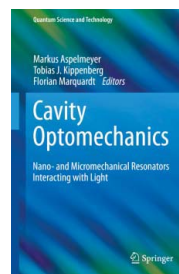
Optomechanics, the study of the mechanical effects of light on massive objects, has a long and distinguished history. It took off nearly 50 years ago, when Arthur Ashkin demonstrated that small dielectric balls can be accelerated and trapped using the radiation-pressure forces associated with focused laser beams. That led to the development of optical tweezers, a tool with wide-ranging applications in biological science.

A parallel development, investigations into the strong enhancement of mechanical effects created by resonant light scattering, led to the laser cooling of ions and neutral atoms. That was followed by the realization of atomic Bose-Einstein condensates in 1995 and the subsequent explosion in the study of quantum degenerate atomic systems. Critical break-

throughs can also be traced back to work on optical gravitational-wave antennas that started in the 1970s and 1980s. It is in that context that researchers understood the role of fundamental quantum optical effects in mechanical position measurements and the resulting standard quantum limit and advanced the idea of back-action evading measurements.

Quantum optomechanics, the field that evolved from those developments, promises to provide motion and force detection near the fundamental limits imposed by quantum mechanics. The field provides the basis for the quantum state control of truly macroscopic objects and for experiments that may lead to a more profound understanding of quantum mechanics.

Light can interact with matter either resonantly or nonresonantly, and both interactions



present challenges. Resonance can result in a large enhancement of an interaction, but it is limited to a narrow range of wavelengths. Nonresonant interactions, on the other hand, present the considerable advantage of being largely wavelength independent, but they produce a smaller effect. Cavity optomechanics combines the best of both worlds through the use of carefully engineered resonant structures.

The two books under review offer complementary views of those developments. *Quantum Optomechanics* is co-authored by experimentalist Warwick Bowen and theorist Gerard Milburn, major contributors to the field. It is a graduate-level text that focuses largely on the quantum theory of optomechanical systems and has little to say about experiments, except in very general terms. *Cavity Optomechanics: Nano- and Micro-mechanical Resonators Interacting with Light* is a collection of 12 invited articles by leading experts from both sides of the Atlantic. It is edited by Markus Aspelmeyer, Tobias Kippenberg, and Florian Marquardt, researchers who have achieved some of the field's most significant recent discoveries. It covers both classical and quantum aspects of optomechanics, with a good balance between theory and experiment.

Quantum Optomechanics assumes a high level of theoretical sophistication and is a challenging text, even for theoretically oriented students. That is most evident in the authors' inclusion of advanced concepts not typically covered in a graduate curriculum. An introductory discussion of the basic physics of optomechanical systems, perhaps in classical terms, would have helped reduce the steepness of the learning curve for newcomers. Furthermore, the exercises mostly fill gaps in derivations, and they will primarily be of interest to theory-inclined students. The book will therefore be most useful to readers who are already well versed in the basic physics of optomechanics and want to dig deeply into the quantum theory of detection, noise, quantum coherent control, and related topics.

Those theory-minded readers will find much to admire in the book. *Quantum Optomechanics* skillfully reviews a wealth of important results on those topics. For example, the book's clear and authoritative discussions cover the various

troublesome noises, including measurement and back action, typical of quantum measurements. It also nicely treats the consequent standard quantum limit of mechanical position measurements. Advanced topics such as single-photon optomechanics receive their due, and the authors include a useful introduction to hybrid quantum systems—although perhaps a too brief one in view of the growing importance of the topic. The last chapter, on gravitational decoherence, gives a hint at one of the directions that

might be opened up by the availability of quantum optomechanical sensors.

Cavity Optomechanics is more user-friendly. Although not a textbook, many of its chapters would be useful in a graduate course or could serve as a valuable introduction for newcomers. The book opens with some brief remarks by the editors, followed by a concise introduction to the theory of cavity optomechanics, with a simple classical description and a clear discussion of basic quantum aspects. The next chapters give an

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BOOKS

overview of significant advances in the field through 2014. They cover various topics from both theoretical and experimental points of view, including cavity systems with suspended mirrors, optomechanical crystal devices, LC circuits, ultracold ensembles of thousands of atoms, visible light, microwaves, and more. A final chapter on hybrid systems nicely complements the corresponding chapter in *Quantum Optomechanics*.

The chapters on hybrid systems are not the only point at which readers will find value in consulting both *Quantum Optomechanics* and *Cavity Optomechanics*. Together, the two books make for an authoritative introduction to optomechanics that will serve the needs of graduate students and more experienced researchers interested in moving into the fast-growing field. *Cavity Optomechanics* provides an introduction to many of the most interesting experimental systems, and *Quantum Optomechanics* brings readers up to speed on the state of the art of the theory. Students and researchers concentrating on experimental physics may find that *Cavity Optomechanics* is often sufficient. Theorists would be well advised to dig deep into *Quantum Optomechanics* as well.

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Ridge, New York*

American Luthier

Carleen Hutchins—the Art and Science of the Violin

Quincy Whitney

ForeEdge, 2016. \$35.00 (312 pp.).
ISBN 978-1-61168-592-3

I became interested in the musical acoustics of string instruments late in my career and missed meeting Carleen Hutchins. As I got to know the field, however, it became clear that for most of the second half of the 20th century, she was a dominant force in violin acoustics. Hutchins's enormous effort, accompanying struggles, and eventual triumph is captured in great detail by journalist and biographer Quincy Whitney in her book *American Luthier: Carleen Hutchins—the Art and Science of the Violin*.

Hutchins's life was, by any

measure, remarkable. A Cornell-educated biology teacher and amateur violinist, she took up lutherie (the building and repairing of string instruments) in 1947 at age 36 to occupy herself while expecting her first child. She carved the scroll of her first attempt, a viola, in the maternity ward. Later, juggling motherhood and lutherie, she would use a three-hole poacher in which she cooked eggs for her toddlers in two holes and warmed her glue pot in the third. Anyone who has used animal glue will probably cringe at the thought.

While being treated for breast cancer in 1956, Hutchins met Virginia Apgar, the doctor who developed the famous Apgar test administered to all newborn babies, and struck up a lifelong friendship with the fellow amateur violinist. When the pair spotted a hospital telephone booth containing a piece of curly maple shelving that they fancied for a viola back, they planned and pulled off a now-famous heist to secure the desired wood. They replaced the shelf at dead of night with an equally attractive but acoustically useless piece of maple that Hutchins fashioned for the purpose and then cut to size on a toilet seat in the nearby ladies' room. Such was Hutchins's no-nonsense, get-on-with-it manner.

It was when Hutchins met retired Harvard physicist Frederick Saunders in 1949 that she set forth on her life's work. Saunders had been conducting acoustics experiments on whole violins. Hutchins suggested that to make any progress, Saunders would have to work with the individual plates, and that she could make those plates. In the absence of a useful mathematical model of the violin sound box (an absence that persists to this day, although fluid-structure coupled finite-element analysis is coming close), the only way to move forward was to build hundreds of instruments with variations in a dozen or so parameters. Needless to say, that was a Herculean task.

Over the next five decades, Hutchins built more than 300 musical instruments, mostly by herself, and concurrently learned their physics. Her aim was to bring the violin's power and clarity to the viola, cello, and bass, instruments whose lower strings are often hard to hear in ensemble playing. The

result was a new "violin octet," which consisted of eight newly designed instruments whose string tuning collectively covered five octaves and brought an even "violin tone" to the whole playing range.

Apgar and Saunders were just two of many talented people who bonded with Hutchins. She plainly had an ease with the accomplished, and after a while she no longer had to seek them out: They beat a path to her door—literally, as she operated out of her own house. She counted fellow luthiers, physicists, and world-renowned musicians such as Yo-Yo Ma and Leopold Stokowski among her friends and admirers.

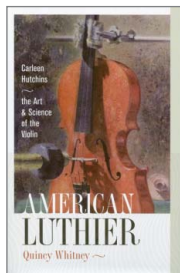
While researching *American Luthier*, Whitney interviewed dozens of people in the US and Europe. She intersperses the story with vignettes on historical topics that set the scene for Hutchins's acoustics work. Whitney also peers into the world of luthiers and violin dealers—upon which Hutchins did so much to shine the light of day—and discusses the still-vexed issue of the relative quality of old Italian violins versus fine modern instruments, which can differ considerably in cost.

I have some quibbles with the book, mostly points that should have been caught by an editor. First, although the book is intended for a nonexpert audience, occasionally terms and phrases like "Helmholtz mode" or "JASA," the abbreviation for the *Journal of the Acoustical Society of America*, pop up out of nowhere unexplained. Second, some of the physics explanations would confuse a layperson. For example, Whitney says "the rush of air exiting through the f-holes amounts to a ten mile per hour wind." I know what she means, but a person expecting to place a hand over a violin f-hole and feel a draft would be disappointed.

Since her death, Hutchins's fame seems to have faded somewhat, at least in part because of the failure of the conservative musical community to embrace her new instruments. Hutchins's work, however, was always going to be a tough sell to traditionalists. Thus *American Luthier* is a timely work, and I recommend it to anyone interested in musical acoustics or in Hutchins's extraordinary life.

Chris Waltham

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NEW BOOKS

Biological and medical physics

Molecular and Cellular Mechanobiology. S. Chien, A. J. Engler, P. Y. Wang, eds. American Physiological Society and Springer, 2016. \$189.00 (302 pp.). ISBN 978-1-4939-5615-9

The Origin and Nature of Life on Earth: The Emergence of the Fourth Geosphere. E. Smith, H. J. Morowitz. Cambridge U. Press, 2016. \$49.99 (677 pp.). ISBN 978-1-107-12188-1

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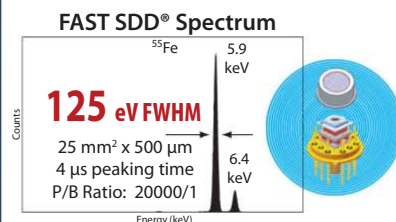
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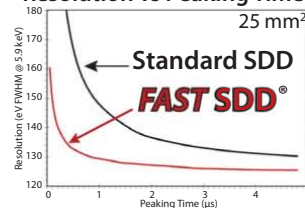
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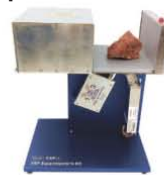
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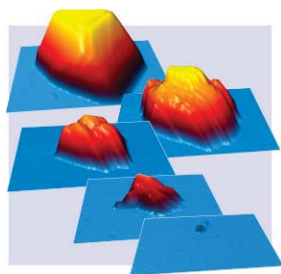
Focus on analytical equipment, sensors, and detectors

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 Rnanna@aip.org.

Andreas Mandelis

Electrochemical cell for atomic force microscopy

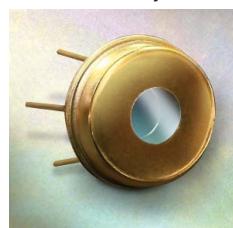
Electrochemistry capabilities are now available on the Oxford Instruments Asylum Research Cypher ES atomic force microscope. The company has introduced an electrochemical cell that lets users study EC reactions *in situ* in processes such as deposition, oxidation,



corrosion, and the mass transfer of metals and other materials at the nanoscale. The cell allows for simultaneous electrochemistry and heating and cooling for EC thermodynamics studies. It supports a wide range of working electrode materials and sizes for many experimental conditions and is compatible with most conventional and cutting-edge electrolytes. It is robust, is easy to assemble and clean, and can work with a user's choice of potentiostat and in glove boxes. Applications include materials research in electrochemistry, electrodeposition, and energy storage; bioscience; and atomic force and scanning probe microscopy research. **Oxford Instruments Asylum Research Inc**, 6310 Hollister Ave, Santa Barbara, CA 93117, www.oxford-instruments.com

Low-noise extreme UV photodetector

A new photodetector has joined Opto Diode's family of SXUV photodiodes.



The SXUV20C is an extreme UV (EUV) photodetector for measuring UV light and monitoring the power of EUV lasers. According

to the company, it has superior responsiveness in the 1–200 nm wavelength region and is designed to be stable over long periods of time when exposed to high-intensity EUV energy. The photodetector can easily be integrated into most UV laser systems; the 20 mm² circular active area provides a substantial surface for easy alignment to the laser. The SXUV20C offers superior hardness in extreme UV environments while providing lower noise than the previously released SXUV20HS1. The new instrument features high photon flux robustness, minimum shunt resistance of 50 MΩ, typical reverse breakdown voltage of 10 V, and typical capacitance of 3 nF. Operating and storage temperatures range from –20 °C to 80 °C and from –20 °C to 100 °C, respectively. **Opto Diode Corporation**, 1260 Calle Suerte, Camarillo, CA 93012, www.optodiode.com

Mass spectrometer for gas phase analysis



Hidden has launched its HPR-40 DSA mass spectrometer system for the measurement of gases and vapors in aqueous media. A fine membrane separates the aqueous media from the sample intake and allows permeation by selected gaseous species other than water vapor. Interface types include insertion probes for direct immersion in the liquid media, flow-through patterns for gas type identification, cuvette styles for photosensitive biofuel studies, and differential electrochemical mass spectrometry cells for monitoring electrochemical reactions. The HPR-40 DSA is equipped with automated inlet isolation to protect it from overpressure in case of membrane malfunction. Product development is application driven, with ongoing introduction of new media interface styles to address new user requirements. Application examples include fermentation processing, photosynthesis, electrochemical reaction studies, water quality, and enzyme kinetics analysis. **Hidden Analytical Inc**, 37699 Schoolcraft Rd, Livonia, MI 48150, <http://hiddeninc.com>

Multielement analyzer



According to Agilent Technologies, its 4210 microwave plasma–atomic emission spectrometer has high sensitivity, has detection limits down to ppb levels, and is faster than flame atomic absorption for a typical multielement analysis. Since it runs on air rather than flammable gas, it is safe and economical to operate. To extend the 4210's analytical performance, sample throughput, and ease of use, Agilent included an advanced valve system, an inert torch, a humidifier, a temperature-controlled spray chamber, a multimode sample introduction system, and enhanced diagnostics software. Automation software enables remote analysis and allows for applications such as onsite process stream sampling and environmental monitoring—for example, of remote river water. The spectrometer can also be used in laboratories in the food, agriculture, petrochemical, environmental, and mining industries. **Agilent Technologies**, 5301 Stevens Creek Blvd, Santa Clara, CA 95051, www.agilent.com

NEW PRODUCTS

Ultralow-noise x-ray camera



Princeton Instruments engineered its Sophia-XO:2048 high-speed, ultralow-noise vacuum UV and direct x-ray detection camera to address demanding, very low flux scientific applications. It features a 2048×2048 , $15 \mu\text{m}^2$ pixel CCD and has greater than 3 fps with 16 MHz readout speed at full resolution, 100% fill factor, and a 16-bit digitization rate. Using only air assist, proprietary ArcTec technology minimizes dark noise by thermoelectrically cooling the CCD to less than -90°C . Because the back-illuminated CCD has no antireflective coating, it can directly detect a wide range of x rays between about 10 eV and 30 keV. A 6-inch rotatable ConFlat flange with a high-vacuum seal design makes it convenient to interface with UHV instrumentation. The Sophia-XO is suitable for applications such as x-ray spectroscopy, microscopy, plasma diagnostics, and extreme UV lithography in research and OEM environments. **Princeton Instruments**, 3660 Quakerbridge Rd, Trenton, NJ 08619, www.princetoninstruments.com

UV and LED curing radiometer



Gigahertz-Optik has made available a horizontally constructed photodetector assembly with a wand probe that keeps the detector out of the hot zone of light sources used in UV processes such as curing of inks, coatings, and adhesives. The X1-1-RCH-116-4 UV and blue-light LED curing radiometer can maintain stability in high-temperature and intense UV flood and spot curing environments. The remotely controllable, four-channel X1-1 meter features auto-ranging, continuous-wave, dose, run/stop, offset, and peak hold functions; selectable integration time; a USB interface; and a backlit LCD. The wand-style detector consists of a radiation integrator coupled to a stainless-steel rigid tube that houses a quartz light guide. The guide pipes the light signal to a capsule housing the photosensor and filter assembly. The assembly is protected from direct irradiation, so the RCH detector can operate in temperatures up to 100°C . **Gigahertz-Optik Inc**, 5 Perry Way, Newburyport, MA 01950, www.gigahertz-optik.com

X-ray diffraction analyzer



PANalytical has developed Aeris, an x-ray powder diffraction (XRD) benchtop instrument that provides fast, precise phase information about the materials analyzed. Requiring only a single-phase power outlet and neither cooling water nor compressed air, Aeris offers ease of use and economical operation. According to the company, because the instrument incorporates technologies found on PANalytical's high-end systems, its performance can exceed that of typical benchtop x-ray diffractometers. PANalytical claims that Aeris is the first fully automatable benchtop XRD system and can easily be incorporated into industrial production control. Editions of Aeris are tailored to the specific needs of materials analysis in the cement, mining, and metals industries. The research edition is designed for quick XRD scans in any laboratory and is accessible for students. With its novel 2D option, it is suitable for teaching XRD. **PANalytical BV**, Lelyweg 1, 7602 EA Almelo, the Netherlands, www.panalytical.com

Inductively coupled plasma spectrometer

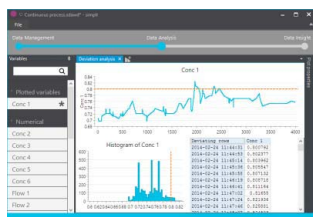


Spectro Analytical Instruments has unveiled the latest version of its Spectroblue inductively coupled plasma optical emission spectrometer. Improvements include software that meets new US Environmental Protection Agency requirements and a laterally diffused metal oxide semiconductor generator that delivers up to 1700 W of power. According to the company, it brings a high level of performance to laboratory analysis in industrial and environmental applications. Benefits include a faster warm-up time and excellent matrix compatibility: High power gives the instrument agility when dealing with rapidly changing plasma loads. Highly diluted samples can be detected and analyzed. The new generator saves users time and expense because none of its parts are subject to wear. The instrument uses state-of-the-art UV-Plus gas purification technology, and the company's OPI-Air interface avoids costly, complicated external water cooling. **Spectro Analytical Instruments GmbH**, Boschstr 10, 47533 Kleve, Germany, www.spectro.com

Compact scanning electron microscope

JEOL has expanded its InTouchScope series of scanning electron microscopes (SEMs) with a model that comes standard with a field emission gun and low-vacuum capabilities. Based on the company's JSM-IT300 tungsten SEM, the versatile JSM-IT300HR has a small footprint equivalent to that of a conventional general-purpose SEM. Even under analytical conditions—a working distance of 10 mm and a probe current of 1 nA—it provides a sharp image at a high magnification of $\times 50\,000$ to $\times 100\,000$. High-quality image observation is also possible in low-voltage and low-vacuum mode imaging. A beam-sensitive specimen can be studied with reduced thermal damage, and fine structures of an insulating material can be readily examined. A large stage accommodates various sizes and types of specimens. The graphical user interface integrates image observation and element analysis, and touch-panel, automatic, and recipe functions enable intuitive operation. **JEOL USA Inc**, 11 Dearborn Rd, Peabody, MA 01960, www.jeolusa.com





Data analysis software

MKS Instruments has announced Easy Analytics, part of its Umetrics Suite of Data Analytics Solutions. Designed for simplicity of use and clarity of results, Easy Analytics im-

ports, organizes, and analyzes process and quality data. The software allows users to import data to standardized or customized reports of quality and process status with one click, which minimizes the risk of errors and facilitates process status communication. A toolbox containing Western Electric Rules and capability analysis is also being released. It enables excellent data visualization and deviation quantification, so process engineers and development scientists can identify unexpected trends in data. Easy Analytics can be directly connected to the company's SIMCA multivariate data analysis software to more deeply analyze identified issues. **MKS Instruments Inc**, 100 Highpower Rd, Rochester, NY 14623, www.mksinst.com

Multifunction IR sensors

The CaliPile sensor family from Excelitas Technologies represents intelligent IR sensors capable of multiple sensing applications. Each sensor includes a highly sensitive thermopile detector and onboard electronics that allow it to perform in three distinct function modes: motion sensing, presence detection, and temperature measurement. Selectable frequency filters and levels let users set the product into one of the three operation modes, and each mode can be set into individual-use cases to achieve custom operation. Because the internal circuit combines data storage with calibration data and digital filters, the individual functions can be enabled from a single unit. The compact, flexible CaliPile series offers various form factors to meet a wide range of integration requirements. Applications include short-range presence detection with no additional lens requirements, noncontact temperature measurement, and overheating protection. **Excelitas Technologies Corporation**, 200 West St, Waltham, MA 02451, www.excelitas.com



Multipixel photon counter

Hamamatsu has released the latest series of its multipixel photon counter (MPPC), a type of silicon photomultiplier. By generating large gain within the device, which is composed of a dense matrix of thousands of microcells, the MPPC can detect very low levels of light, down to single photons. The microcells cumulatively produce an analog signal proportional to the number of incident photons. The S13361 series uses a through-hole electrode called through-silicon via, which allows wiring on the photosensitive area to be eliminated. The result is an enlarged photosensitive area that has little dead space and enables efficient coupling with scintillators and the like, so the device is suitable for use as a positron emission tomography detector. The MPPC features low cross talk, low afterpulsing, and low-voltage operation. Single-channel detectors and multichannel arrays are available. **Hamamatsu Corporation**, 360 Foothill Rd, Bridgewater, NJ 08807, www.hamamatsu.com **PT**

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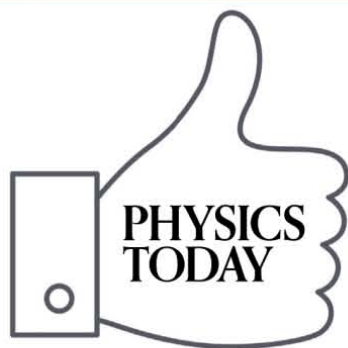
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Ralph J. Cicerone

Ralph J. Cicerone, born in New Castle, Pennsylvania, on 2 May 1943, was the first of his family to attend college and became a trailblazer in researching global environmental change. He died on 5 November 2016 at his home in Short Hills, New Jersey, in the company of his family.

After completing his BS in electrical engineering at MIT in 1965, Cicerone received his MS in 1967 and PhD in 1970, both from the University of Illinois at Urbana-Champaign. His thesis, on ionospheric photoelectrons, was done under Sid Bowhill.

Cicerone came of age scientifically in the 1970s, a heady but turbulent era for atmospheric science. A new class of synthetic chemicals called chlorofluorocarbons (CFCs) provided more efficient, nontoxic chemicals for refrigerants, spray-can propellants, foam blowing, and medical applications. But scientists recognized that chlorine atoms could destroy stratospheric ozone; that CFCs could deliver chlorine to the stratosphere; and that the current use of CFCs would lead to their accumulation in the atmosphere over the coming century.

The specters of global ozone depletion and predicted cancers from increased UV sunlight created a Jekyll and Hyde-like conflict with the myriad new technologies being sold under the guise of improving our daily lives. The CFC-ozone connection was the first example of a society-initiated atmospheric change that could cause global environmental damage. The resulting contentious interactions of Cicerone and the other early scientific explorers with the chemical industry has been dubbed the ozone wars.

One of the hardest ideas to get across to the public and policymakers was how CFCs would reach the stratosphere, build up chlorine atoms, and destroy the ozone layer. Cicerone and others who recognized the CFC problem—including Paul Crutzen, Chuck Kolb, Michael McElroy, Mario Molina, Sherry Rowland, Steve Wofsy, and one of us (Stolarski, then his colleague at the University of Michigan)—led the charge; they

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Ralph J. Cicerone

communicated not merely through scientific journals but also directly to the public. Cicerone pushed the science from the local to the national level, and he was responsible for the 1974 Ann Arbor City Council ban on CFC use in spray cans. That was followed by other local bans on CFCs, proposed amendments to the US Clean Air Act in 1977, and eventually the US and Nordic bans on such spray cans.

The ozone wars were long and brutal, but they were finally resolved by international scientific ozone assessments, detection of the Antarctic ozone hole and ozone depletion globally, and the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. The scientific accomplishments of those early explorers were recognized with the awarding of the 1995 Nobel Prize in Chemistry to Crutzen, Molina, and Rowland.

Cicerone's career shows lessons learned from the ozone wars: Scientific integrity is tantamount, facts must not be subjugated to political favor, collegiality among scientists is key, and global environmental and societal change is the story of the coming century.

Cicerone is best known in the scientific community for his leadership in ushering in the modern era of atmospheric chemistry and biogeochemical cy-

cles of the Earth system and for coupling that knowledge to societal effects of ozone depletion and climate change. His research led to new ways of understanding global atmospheric changes and identifying the causal chain that implicated humans. When most scientists involved in atmospheric chemistry were not interested in the biosphere, Cicerone studied methane and the complex systems that produce it, consume it, and sometimes release it to the atmosphere. His investigation of methane emissions from rice paddies was one of the first biogeochemical research projects; he studied the natural biogeochemistry of a human-made compound to better understand its environmental threat. The new information was critical for assessing the damage to the ozone and climate from agricultural chemicals and influenced the national debate on regulating them.

Beyond his scientific accomplishments, Cicerone was unique in organizing and energizing scientists. As director of the atmospheric chemistry division at the National Center for Atmospheric Research in 1981–89, he influenced a generation of scientists. In 1990, working with Rowland at the University of California, Irvine, he founded the new Earth system science (ESS) department—the first at a university to focus primarily on global change. Cicerone became Irvine's dean of physical sciences in 1994 and chancellor in 1998. Throughout his career, he maintained the perspective that the best science is accomplished by the best scientists working together as a community.

In 2005 Cicerone was elected president of the National Academy of Sciences (NAS), from which he just retired this past summer. As NAS president, he emphasized objective scientific studies in support of public policy. Among them are ones on climate change impacts, past temperature reconstructions, active remote sensing, and solar observations. In the face of an administration and Congress that doubted climate change, Cicerone used NAS funds to organize an independent review of the Intergovernmental Panel on Climate Change's 2001 assessment; it affirmed the IPCC's findings. When the IPCC became involved in another major controversy, Cicerone organized the international group of national science academies, and the resulting review helped save the international climate

OBITUARIES

assessments and maintain the pressure to act on climate change.

Cicerone's natural leadership was evident in the scientific problems he pursued or convinced others to pursue. Recognizing societal aspects was a hallmark of his work. His intellect, insight, kindness, and collegiality made him a pleasure to work with. Cicerone's vision of biogeochemistry and global change has altered graduate education internationally and influenced the way many of us approach global-change research. We will miss his regular questions and curiosity about the planet.

Michael Prather

University of California, Irvine

Richard Stolarski

Johns Hopkins University

Baltimore, Maryland



David Ritz Finkelstein

Theoretical physicist David Ritz Finkelstein, professor emeritus at Georgia Tech, died at home in Atlanta on 24 January 2016.

Finkelstein was born in New York City on 19 July 1929. He graduated from City College of New York with honors in both physics and mathematics, and in 1953 he received a physics PhD at MIT, for a thesis supervised by Felix Villars. He worked at Stevens Institute of Technology from 1953 to 1960, at Yeshiva University until 1976, and then at Georgia Tech until his death.

In a 1955 paper, Finkelstein addressed the question of whether an anomalous spin- $\frac{1}{2}$ state had been overlooked for the gravitational field. His discovery of the topological origin of such anomalous spins and a speculation that all physical variables may be topological in origin was the thread that led him in the 1950s and 1960s to kinks, the unidirectional membrane, and anyons, antecedents of anomalous quantum numbers in the fractional Hall effect and in high-temperature superconductivity.

A 1957 seminar Finkelstein gave on extending Schwarzschild's metric—a basic ingredient of the current understanding of black holes—was a revelation to Roger Penrose. Afterward, Penrose explained to Finkelstein his spin networks, and for years thereafter the two men exchanged their research subjects. Finkelstein saw quantum spins as a possible route into the quantum nature of reality

and took such ideas to unusual depths.

In 1958 Finkelstein was the first to describe what is now known as a black hole—his “unidirectional membrane.” The work influenced Lev Landau, Penrose, and eventually John Wheeler, and it was instrumental in bringing general relativity into mainstream physics. Although today it is considered his key contribution, for Finkelstein it was only a step in his overarching program to bring topology into quantum physics. He, together with Charles Misner in 1959 and Julio Rubinstein in 1962, discovered kinks—particles extended over a finite volume rather than concentrated at a point—topological charges, and topological spin-statistics theorems.

Finkelstein was among the earliest scientists to understand the role of quantum vacua, and he wrote some of the earliest papers on solitons in quantum theories. His 1962–63 papers with Josef Jauch, Samuel Schiminovich, and David Speiser were the first to formulate a unified $SU(2)$ gauge theory of massive vector bosons and light and thus introduced electroweak unification before Sheldon Glashow, Abdus Salam, and Steven Weinberg. Or, as Finkelstein put it, “I’m afraid I’m another one of the infinite number of people who did the Higgs field before Higgs.”

Even while making such seminal contributions to theory, from 1955 to 1971 Finkelstein pursued a parallel career as a plasma physicist. He is remembered as an exquisite experimentalist and was proud of the theory he developed with

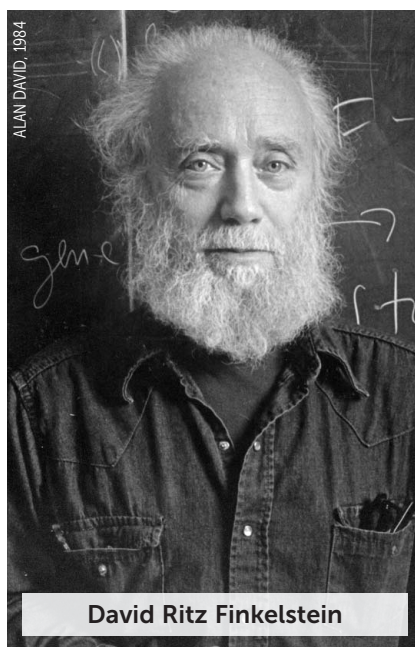
Rubinstein and James Powell for ball lightning.

During the summer of 1965, at the height of the civil rights movement, Finkelstein took his family to Mississippi after receiving a temporary NSF–American Physical Society appointment as a visiting scientist with the physics department of Tougaloo College, a historically black school. His efforts as acting department head included expanding the physics program and helping found Public Radio Organization, whose goal was to offer African Americans in central Mississippi unbiased news reporting and a community forum. The courage of the people he worked with in Mississippi influenced him profoundly.

In 1979 Finkelstein became the chair of Georgia Tech's school of physics, with the goal of raising the department to the level of its MIT sister department. When he failed to submit a budget, he was deposed by senior faculty. He soon realized that his failure as an administrator freed him to pursue his dream, so he started his second life, in which he dedicated himself to formulating a universal physical theory consistent with both quantum theory and gravity.

A charismatic mentor, Finkelstein involved numerous dedicated students in his efforts to quantize geometry. In 1946 he'd already realized that while classical logic was commutative, quantum physics was not. Hence, before a correct quantum spacetime theory could be formulated, the foundations of mathematics and logic itself had to be replaced by quantum logic. (For a full exposition, see his *Quantum Relativity: A Synthesis of the Ideas of Einstein and Heisenberg*, Springer, 1996.) A decade ago he reminisced, “When I began my own research I took it for granted that it had three stages: I would first find a theory in which I could at least potentially believe, then compute its consequences, test it against experimental data, and return to stage 1 for an improved version. After about forty years I could not help noticing that I was still in the first stage.”

In Sidney Coleman's words, Finkelstein “was a brilliant scientist with a passion for long shots. This meant that nine times out of ten he devoted his talents to ideas that do not pay off, but, one time out of ten, they *do* pay off. When this happened, Finkelstein's work was found to be of a great significance, extraordinary penetration, and ten years ahead of everyone else's, as was the case when



David Ritz Finkelstein

topological conservation laws entered the mainstream of quantum field theory.”

A few days before his death from idiopathic pulmonary fibrosis, Finkelstein had his laptop in his bed and was still working. He was a man who truly loved life.

Predrag Cvitanović

*Georgia Institute of Technology
Atlanta*

Leonard Susskind

*Stanford University
Stanford, California*



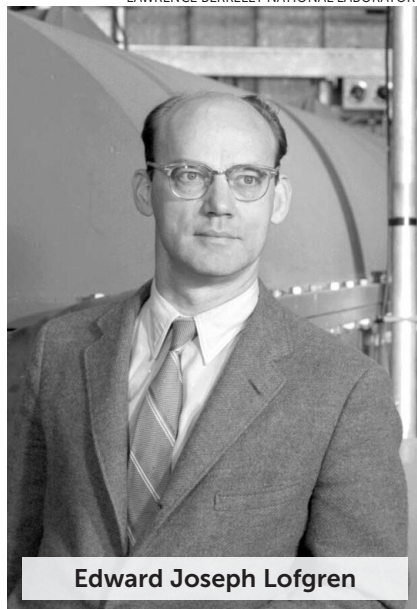
Edward Joseph Lofgren

Edward Joseph Lofgren, an innovative builder of particle accelerators, passed away in his residence at Piedmont Gardens in Oakland, California, on 6 September 2016 at age 102. He had outlived the entire first generation of scientists at Ernest Lawrence’s Radiation Laboratory (now Lawrence Berkeley National Laboratory). Lofgren will be remembered for his incredible skills in transforming ideas into practical hardware, his close association with Lawrence, and his uncanny intuition about the talents and potential of his Berkeley staff.

Lofgren was born in Chicago to Swedish immigrants on 18 January 1914. He moved with his family in 1927 to Los Angeles, where he grew up during the depths of the Depression. Although he had been admitted to Caltech, Lofgren didn’t have enough money to enroll there. By working on various bench jobs, he was able to complete two years at Los Angeles Junior College but still could not afford Caltech. Instead, to complete his education, he transferred in 1936 to the University of California (UC), Berkeley, where a scant five years earlier the first cyclotron had been operated at Lawrence’s Radiation Laboratory.

During 1938–40 Lofgren was a research assistant to Lawrence, who saw him as a talented physicist able to transform bold ideas into hardware. Lofgren’s first task was to improve uranium hexafluoride ion sources for the calutron, a mass spectrometer that Lawrence had transformed from the 37-inch cyclotron, to separate ^{235}U from ^{238}U . As a result of that work, Lofgren interrupted his graduate studies to contribute to the Manhattan Project efforts of the Berkeley team, first at Oak Ridge to help with the development of the calutron farms and then at Los Alamos to work on detonators in Luis

LAWRENCE BERKELEY NATIONAL LABORATORY



Edward Joseph Lofgren

Alvarez’s group. Lofgren’s research on ion sources, conducted under Lawrence’s supervision, became the basis of his thesis for his 1946 PhD from UC Berkeley.

With the initiation of the multi-GeV Bevatron project in 1949, Lawrence invited Lofgren to return to Berkeley Lab. Lofgren was able to demonstrate the phase-stability principle of Edwin McMillan and Vladimir Veksler by changing the RF frequency to match the cyclotron frequency of the particles as they accelerated to relativistic speeds in the 37-inch cyclotron; Lofgren thus made the machine the first synchrocyclotron. Soon after, Lawrence appointed Lofgren as the chief physicist on the project of building the synchrotron. His appointment marked the beginning of the “Berkeley approach” of managing accelerator projects as a partnership between a chief physicist and a chief engineer, who for the synchrotron was William Brobeck.

From 1950 through 1952, most of the laboratory’s efforts were diverted to building the ill-conceived Materials Testing Accelerator at the Livermore Laboratory. But with its impending termination, progress on the Bevatron quickly advanced. By the time the Bevatron began operation in early 1954, Lofgren was the leader of both a particle-physics research group, which competed with Owen Chamberlain and Emilio Segrè’s group to discover the antiproton, and the accelerator group that was charged with commissioning and operating the Bevatron. Although Lofgren’s group lost the antiproton race, it did discover the antineutrino in 1956.

Lofgren kept the Bevatron competitive for particle-physics research by initiating a modernization campaign in 1960. It included adding an extraction system that brought the beam to a newly constructed experimental hall. However, by 1970 the machine was nearing the end of its utility for particle physics; the last such experiment ended in January 1971.

To renew the scientific viability of the Bevatron—rechristened the Bevalac—Lofgren and Hermann Gruner headed a project to bring heavy ions 45 meters downhill from the SuperHILAC linear accelerator to the synchrotron, where they would be injected. The new configuration enabled groundbreaking research in relativistic heavy-ion nuclear physics and extensive studies in radiation biology and ion-based cancer therapy for deep-seated tumors.

In 1973 Andrew Sessler appointed Lofgren to be associate director for accelerators at the Lawrence Berkeley Lab. He was responsible for the newly formed accelerator division, which operated the Bevalac and concentrated on high-energy and heavy-ion physics research and advanced accelerator R&D. Lofgren served in that role until his retirement in 1979. It was fitting that Lofgren’s final official act at the lab was ceremonially turning off the Bevatron for the last time in February 1993.

Lofgren’s many projects included the 200 BeV design study conducted at Berkeley Lab; the study’s report formed the basis for the cost estimate and site selection for a new proton synchrotron. To the disappointment of Lofgren and his Berkeley colleagues, their proposal to build the machine near Sacramento was declined in favor of a competing proposal to build the accelerator—with a rather different design—in Illinois at what is now Fermilab.

Understanding how the physical world works was at the core of Lofgren’s being. He never grew tired of hearing about new discoveries in physics or explaining physical phenomena, such as how the fog forms in San Francisco, to his neighbors at Piedmont Gardens.

William Barletta

*Fermi National Accelerator Laboratory
Batavia, Illinois*

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Confirmed Invited Speakers:

Anthony Atala (Wake Forest Institute for Regenerative Medicine, Winston Salem, NC, USA)

Karen Burg (College of Veterinary Medicine, University of Georgia, Athens, GA, USA)

Shaochen Chen (Biomaterials and Tissue Engineering Center, University of California, San Diego, CA, USA)

Douglas Chrisey (Department of Physics, Tulane University, New Orleans, LA, USA)

Paulo Da Silva Bartolo (School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK)

Tal Dvir (Department of Molecular Microbiology and Biotechnology and the Center for Nanoscience and Nanotechnology, Tel Aviv University, Tel Aviv, Israel)

John Fisher (Department of Bioengineering, University of Maryland, College Park, MD, USA)

Jürgen Groll (Department for Functional Materials in Medicine and Dentistry, University of Würzburg, Würzburg, Germany)

Richard Hague (EPSRC Centre for Additive Manufacturing, University of Nottingham, Nottingham, UK)

Yong Huang (UF Center for Manufacturing Innovation, University of Florida, Gainesville, FL, USA)

Jos Malda (Department of Orthopaedics, Regenerative Medicine & Stem Cells Program, University Medical Center Utrecht, Utrecht, Netherlands)

Roger Narayan (Department of Biomedical Engineering, North Carolina State University, Raleigh, NC, USA)

Bradley R. Ringeisen (Bioenergy and Biofabrication Section, U.S. Naval Research Laboratory, Washington DC, USA)

Iain S. Whitaker (Department of Plastic and Reconstructive Surgery, Reconstructive Surgery & Regenerative Medicine Research Group, Swansea University Medical School, Swansea, Wales, UK)

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Professor, Department of Biomedical Engineering,
North Carolina State University
Associate Editor, *Applied Physics Reviews*

Anthony Atala

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Faculty Position

Institute of Physics, National Chiao Tung University, Taiwan

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D, or equivalent degree, in Physics, Aerospace Engineering, Electrical Engineering, Computer Science or a related field at the time of application. Additional qualifications required by start date: • Postdoctoral experience in collection, calibration or analysis of data from scientific instrumentation in space or relevant environments. • Experience with upper atmosphere or space physics satellite data. • Strong data analysis and programming skills. • Enjoy working in a collaborative environment with a diverse group of researchers and engineers to solve hard problems in spacecraft science operations and data processing. Preferred qualifications: • Experience with upper atmosphere and ionosphere numerical models. • Experience in software development and deployment in scientific data analysis pipelines. Appointment: • This position reports to the ICON PI and will work under his supervision and guidance. • The initial appointment will be at 100% time for 12 months with the expectation of extension based on satisfactory performance and availability of funding. • Salary will be commensurate with experience; benefits are included. • The expected start date of this position will be **March 2017**. To apply: To apply please go to the following link: <https://aprecruit.berkeley.edu/apply/JPF01088>. Applicants should submit the following materials: (i) an updated curriculum vitae, including a list of publications (required), (ii) a cover letter (optional), (iii) a statement of research interests (required), and (iv) names and contact information for 3 individuals who have agreed to provide a reference for this specific position (required). This position will remain open until filled. If you have any questions please contact **Dr. Thomas Immel** (immet@ssl.berkeley.edu) or **Tamiko George** (tamiko@berkeley.edu). Letters of recommendation will only be requested of finalists. All letters will be treated as confidential per University of California Policy and California State law. Please refer potential referees, including when letters are provided via a third party (i.e., dossier service or career center), to the UC Berkeley statement of confidentiality: (<http://apo.berkeley.edu/evalltr.html>) prior to submitting their letters. *The Space Sciences Laboratory is interested in candidates who will contribute to diversity and equal opportunity in higher education through their work. Women and minorities are particularly encouraged to apply. The University of California is an Equal Opportunity/Affirmative Action Employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability, age or protected veteran status. For the complete University of California nondiscrimination and affirmative action policy see: <http://policy.ucop.edu/doc/4000376/NondiscrimAffirmAct>.*

Faculty Positions The Kavli Institute for Theoretical Sciences, University of Chinese Academy of Sciences

The Kavli Institute for Theoretical Sciences (KITS) at the University of Chinese Academy of Sciences, Beijing, invites highly qualified individuals to apply for multiple tenure-track or tenured faculty positions in all areas of theoretical physics and related computational or interdisciplinary studies. Candidates for the positions are required to have a Ph.D. or equivalent degree and have demonstrated ability to conduct outstanding researches. Successful candidates are expected to do independent, innovative researches and encouraged to develop new interdisciplinary research directions. We offer competitive start-up resources and benefits. The KITS is one of the twenty network members of the Kavli Institutes worldwide. The previous name of the KITS is Kavli Institute for Theoretical Physics, China (KITPC). The newly reformulated institute is undergoing a rapid expansion in its faculty and is seeking outstanding candidates with the potential for exceptional research and excellence in teaching. Candidates should submit: 1) a curriculum vitae including a list of publications, 2) a summary of research accomplishments, 3) a statement of research interests and research plan, 4) three to five representative publications, and 5) at least three letters of recommendation sent directly by referees. All application materials should be submitted electronically as PDF files to **Ms. Tracy Jin** at kits@ucas.ac.cn. Review of applications will begin on **Jan. 1st 2017**, and continue until the positions are filled. *University of Chinese Academy of Sciences shall provide equal access to and opportunity in its programs, facilities, and employment without regard to race, color, creed, religion, national origin, gender, age, marital status, disability, public assistance status, veteran status, sexual orientation, gender identity, or gender expression.*



Chair and Professor, Department of Physics - Boston College

The Department of Physics at Boston College seeks a dynamic and creative leader for the position of Department Chair. The position will be at the rank of Full Professor with tenure. The successful candidate will be expected to lead and build upon the Department's core strengths in condensed matter and materials physics, and physics at the interface with other sciences and engineering, while maintaining her or his own distinguished and internationally-recognized scholarly research. Boston College Physics faculty presently includes 17 tenure-track and research faculty and a graduate program with more than 40 Ph.D. students. See www.bc.edu/physics. The Department is expected to grow in the coming years, and the Chair will oversee the recruitment of several additional faculty members. Boston College has been investing heavily in its science programs for the last 2 decades, and the university is poised to launch a major interdisciplinary and applied science initiative, through a new Institute for Integrated Science and Society. As such, the Department seeks candidates possessing excellent communication skills, interdisciplinary vision, and ambition, who will play a leading role in the Department's contribution to that initiative. Working with departmental committees, the Department Chair oversees the educational mission of the Department, including the integration of teaching and research activities, as well as the graduate program. Prospective candidates should submit a cover letter, curriculum vitae and leadership vision statement to https://apply.interfolio.com/40134. The position will remain open until filled. *Boston College is an Affirmative Action/Equal Opportunity Employer, committed to the policies, principles and practices of equal opportunity, affirmative action and nondiscrimination in all of its activities, including, but not limited to, employment. Boston College commits itself to maintaining a welcoming environment for all people and extends its welcome in particular to those who may be vulnerable to discrimination on the basis of their race, ethnic or national origin, religion, color, age, gender, marital or parental status, sexual orientation, veteran status or disabilities.*

Post Doc in Nanobiotechnology University of Notre Dame

Seeking a Ph.D, preferably in physics, electrical engineering, or a closely related discipline, to support research in nanobiotechnologies related to single molecule spectroscopy with scanned force microscopy and/or optical tweezers and/or nanopores. Experience in a subset of the following disciplines is mandatory: atomic force/scanned probe microscopy; free-space laser optics; transmission electron microscopy; microfluidics; molecular biology; semiconductor processing; lock-in measurements; and coding in MATLAB, LABVIEW, and Igor. FYI: refer to the web site: <http://www3.nd.edu/~gtimp/>. Applicants should send a CV via email to **Prof. Gregory Timp** (gtimp@nd.edu) at the University of Notre Dame.

Assistant/Associate Professor (Acoustics) Tenure Track Naval Postgraduate School,

Graduate School of Engineering and Applied Sciences, Depart

The Physics Department of the Naval Postgraduate School invites applications for a tenure track faculty position at the Assistant/Associate Professor level with expertise in one or several areas of acoustics that include acoustic sensor design for material characterization, acoustic spectroscopy, sonar transducer design and testing, and ocean acoustics. Exceptional candidates may be considered for appointment at a more senior level. A PhD is required, and degrees in physics or applied physics are preferred for breadth of teaching within the department. Applicants must show excellent research potential, are expected to develop an externally funded research program, and must have a strong commitment to graduate teaching. The Physics Department is part of the Graduate School of Engineering and Applied Sciences and has a long history of excellence in the areas of conventional weapons, electro-optic sensors, and acoustics. The department is comprised of approximately 15 tenure-track professors, 8 research professors, three senior lecturers, and one chaired faculty. The Physics Department has active research programs in physical acoustics, acoustic vector sensors, transducer design, ocean acoustic propagation, and acoustic communications. In addition, the department has several autonomous, ocean-going systems with acoustic sensing and communications capabilities available for research. Minimum qualifications: • Requires an earned doctoral degree in Physics, Applied Physics, Engineering Physics or acoustics-related engineering field; • Must be able to support a breadth of the department's instructional needs; • Excellent teaching ability or aptitude; • A sustained publications record; • Evidence of potential to advise student theses and dissertations based on comparable experience or aptitude; • Must currently hold or be eligible for a Secret clearance; • U.S. citizenship required. A letter of application including CV, statements of teaching and research interests, and the names and addresses of three or more references should be sent to: **Faculty Search Committee Department of Physics Naval Postgraduate School Monterey, CA 93943**. Email: juscombe@nps.edu. Salary is commensurate with qualifications and experience. Relocation package, including recruitment/relocation incentive may be authorized. The position will remain open until filled. *The Naval Postgraduate School is an equal opportunity employer.* For additional information about NPS, please refer to the website at <http://www.nps.edu>.

Tenure-track Assistant Professor in Experimental Physics University of Michigan-Flint

The University of Michigan-Flint invites applications for appointment as a tenure-track Assistant Professor in Experimental Physics beginning Fall 2017. *"UM-Flint is committed to building a culturally diverse faculty and staff and strongly encourages applications from women, minorities, individuals with disabilities, and veterans. The University of Michigan is an equal opportunity/affirmative action employer."* For more information visit <https://umflint.edu/csepe>.

The Research Centre for Gas Innovation (RCGI), hosted at the **University of São Paulo**, is seeking postdoctoral and PhD candidates to work within the team of researchers in the fields of Engineering, Physics & Chemistry and Energy Policy and Economics. The positions available involve activities related to the development and solution of relevant problems related to the Natural Gas, Biogas, Hydrogen and CO₂ abatement in a sustainable World in the generations to come. The RCGI has got a team of leading experts on their respective areas of knowledge in order to offer innovative solutions to the technological problems related to gas as well as providing support for the improvement of energy policies in Brazil and worldwide. For registration and more information, visit <http://www.rcgi.poli.usp.br/opportunities>.

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For more information and applications write to:

**Prof. B. Di Bartolo, Department of Physics,
Boston College, Chestnut Hill, MA 02467, USA;
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The Faculty of Sciences invites applications for a

1. W3 Professorship for Experimental Astroparticle Physics

(Tenure Track Heisenberg Professorship)

at the Department of Physics, Erlangen Centre for Astroparticle Physics (ECAP), to be filled by the earliest possible starting date.

The successful candidate is expected to represent the field adequately in teaching and research. The position is associated with the research focus *Physics and Mathematics of the Cosmos* of the Faculty of Sciences at FAU and will be part of the Erlangen Centre for Astroparticle Physics (ECAP), where the key research activities in astroparticle physics are currently in gamma ray and neutrino astronomy. The successful candidate is expected to have outstanding international qualifications and shall establish research at ECAP in a field of astroparticle physics that is preferentially not yet represented at FAU. The *ECAP Laboratory*, a research facility which recently received approval, will provide excellent infrastructure for experimental work from 2022 onwards. The successful candidate will collaborate with working groups for astrophysics, astronomy, theory, and detector technology.

The professorship is to be created as part of the Heisenberg programme of the Deutsche Forschungsgemeinschaft (DFG). The establishment of the professorship and the appointment are contingent on the candidate's successful application for a Heisenberg professorship with DFG. According to DFG regulations, the W3 position shall be initially limited to three years. A permanent position may be granted after a positive evaluation by DFG and the university three years after the initial appointment. If the position is to be continued after this three-year period, no new appointment procedure need be carried out.

For further information and the application guideline please see <https://www.fau.eu/university/careers-at-fau/professorships/>.

2. W3 Professorship for Theoretical Physics

at the Institute of Theoretical Physics, Department of Physics, to be filled at the earliest possible starting date.

The successful candidate is expected to represent the field adequately in teaching and research. We are looking for a scientist with an outstanding track record in the field of quantum theory. The main research subject of the successful candidate should be in the fields of light-matter interaction, many-body quantum physics or quantum optics. Future scientific collaborations with the Department of Physics, the Max Planck Institute for the Science of Light and research networks in Erlangen are desirable.

For further information and the application guideline please see <https://www.fau.eu/university/careers-at-fau/professorships/>.

Please submit your complete application documents (CV, list of publications excluding reprints, list of lectures and courses taught, copies of certificates and degrees, list of third-party funding) to the Dean of the Faculty of Sciences, FAU Erlangen-Nürnberg: Prof. Dr. Frank Duzaar, Universitätsstr. 40, D-91054 Erlangen by **15.4.2017**. Please also send an electronic version to nat-dekanat@fau.de.

www.fau.de



Molecular Beam Epitaxy Engineer: Station Q Purdue

As part of Microsoft's team to pursue topological quantum computing, Station Q Purdue is focused on development of new hybrid semiconductor-superconductor platforms. We seek a molecular beam epitaxy engineer to join our growing effort. A successful candidate will operate, maintain, and develop new growth protocols in a multi-chamber molecular beam epitaxy (MBE) system that combines arsenide- and antimony-based III-V semiconductor growth with in-situ superconductor deposition. This system was specifically designed to develop new physical platforms for topological quantum computation.

Requirements:

- A minimum experience of 5 years of MBE growth of antimony and arsenide materials is required.
- Familiarity with structural characterization techniques including atomic force microscopy, high resolution x-ray diffraction, and electron microscopy is desired.
- An advanced degree (MS, MEng, or PhD) in materials science, physics, electrical engineering or allied discipline is required.
- Successful candidates must demonstrate meticulous attention to detail combined with creativity, and a willingness to work in a dynamic team environment.

Microsoft is an equal opportunity employer. All qualified applicants will receive consideration for employment without regard to race, color, sex, sexual orientation, gender identity or expression, religion, national origin or ancestry, age, disability, marital status, pregnancy, protected veteran status, protected genetic information, political affiliation, or any other characteristics protected by local laws, regulations, or ordinances.

To apply directly please visit:

<https://careers.microsoft.com/jobdetails.aspx?ss=&pg=0&so=&rw=1&jid=270367&jlang=EN&pp=SS>

For additional information, please contact **Prof. Michael Manfra, Director Station Q Purdue**, mmanfra@purdue.edu.

Cryogenic Electrical Characterization Engineer: Station Q Purdue

As part of Microsoft's team in quantum computing, Station Q Purdue is seeking a Cryogenic Electrical Characterization Engineer. Station Q Purdue is focused on development hybrid semiconductor-superconductor systems for topological quantum computing. Engineering responsibilities include, but are not limited to: mobility and density measurements of two-dimensional electron gases at T=4K and below, operation and maintenance of both wet and dry cryogenic refrigeration systems including systems operating at T=0.3K and T=20mK, electronics trouble-shooting, and computer-controlled data collection. Requirements: 3 years of experience with low temperature electrical measurements, demonstrated ability to interface computers with electrical measurement hardware, previous experience with the operation of a dilution refrigerator is highly desired. A minimum of a bachelor's degree in Physics or Electrical Engineering or allied field is required. Applicants need to demonstrate basic understanding of electron transport in semiconductors. A successful applicant will demonstrate the ability to work productively within a goal-oriented team.

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For more information please contact **Prof. Michael Manfra, Director Station Q Purdue**, mmanfra@purdue.edu.

Semiconductor Processing Engineer: Station Q Purdue

As part of Microsoft's team to pursue topological quantum computing, Station Q Purdue is focused on development of new hybrid semiconductor-superconductor platforms. Station Q Purdue seeks a processing engineer to fabricate devices composed of III-V semiconductor-superconductor-magnetic insulator hybrid structures. 3-5 years of experience in processing III-V semiconductors is required. Experience with optical lithography, electron beam lithography, wet chemical and dry etching, metals deposition, and ohmic contact formation is required. Responsibilities will include optimization of processing of InSb-based devices, and development of processing recipes for new combinations of semiconductors and superconductors. Meticulous attention to detail and the ability to formulate diagnostic tests to optimize processes is required. A minimum of a bachelor's degree in Physics, Materials Engineering, or Electrical Engineering or allied field is required.

Microsoft is an equal opportunity employer. All qualified applicants will receive consideration for employment without regard to race, color, sex, sexual orientation, gender identity or expression, religion, national origin or ancestry, age, disability, marital status, pregnancy, protected veteran status, protected genetic information, political affiliation, or any other characteristics protected by local laws, regulations, or ordinances.

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For additional information, please contact **Prof. Michael Manfra, Director Station Q Purdue**, mmanfra@purdue.edu.

Visiting Assistant Professor of Physics, Goucher College, Baltimore, MD

The Center for Natural Sciences at Goucher College invites applications for a one-year visiting position in physics at the Assistant Professor level beginning in Fall 2017. The successful applicant must have a Ph.D. in physics or a related field, be able to teach across the undergraduate physics curriculum, and have the necessary background and interest to teach introductory astronomy for non-majors and general relativity and astrophysics for majors. We seek applicants dedicated to applying principles of equity and inclusion in all areas of the campus community. Please visit <http://goucher.interviewexchange.com> for application instructions. Review of applications will begin on **February 15, 2017** and will continue until the position is filled. *Goucher College is an Equal Opportunity Employer.*

Postdoctoral Scholar Position in Coherent X-ray Diffractive Imaging & Atomic Electron Tomography

The Department of Physics & Astronomy and California NanoSystems Institute (CNSI) at UCLA are seeking candidates for a Postdoctoral Scholar working in coherent diffraction imaging (CDI) and/or atomic electron tomography. This position is funded by an NSF science and technology grant (see www.universityofcalifornia.edu/news/uc-campuses-partner-24-million-imaging-science-center). The successful candidate will have the opportunity to use 3rd generation synchrotrons, X-ray free electron lasers and state-of-the-art electron microscopes. Experience in CDI, computational methods, phase retrieval, X-ray imaging/diffraction, materials preparation and characterization or STEM is preferred, but candidates with a strong background in other areas will be equally considered. Applicants should send a CV and a list of publications to **Prof. John Miao** (miao@physics.ucla.edu). For more information, please visit www.physics.ucla.edu/research/imaging.

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HEAD AND PROFESSOR

Department of Nuclear, Plasma, & Radiological Engineering

College of Engineering University of Illinois at Urbana-Champaign

INTERNATIONAL SEARCH

The College of Engineering at the University of Illinois at Urbana-Champaign invites applications and nominations for the position of Head of the Department of Nuclear, Plasma, & Radiological Engineering (NPRE). The NPRE Department has a long history, now more than 55 years, of excellence in education, research, and service in the field of nuclear engineering. The NPRE faculty offers comprehensive research and education programs centered on three theme areas: (1) nuclear power engineering, (2) fusion and plasma science and engineering, and (3) radiological engineering and medical physics. Specific research and academic strategic directions include: Radiological imaging, risk and reliability analysis, nuclear non-proliferation, radiation detection, neutronics, thermal-hydraulics, fuel cycle, nuclear materials, radiation damage, plasma nanosynthesis and fusion plasma-material interaction. The Department Head serves as the chief executive officer, responsible for all administrative, budgetary, hiring, and promotion decisions in the Department. The incumbent has significant discretion and authority for leading the faculty in their missions of research, teaching, and public service. The search committee seeks candidates with a distinguished record of scholarly achievement and internationally recognized in their field for research excellence, leadership, and scholarship.

The desired start date for this position is August 16, 2017, or as soon as possible thereafter. Complete applications should be received by March 1, 2017 for full consideration, but applications will be accepted until the position is filled. Please visit <http://jobs.illinois.edu> to view the complete position announcement and application instructions.



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As a distinguished scientist and recognized leader in his/her field the incumbent will be called upon to brief DoD senior officials regarding Laboratory research efforts in the above areas, to serve as liaison between NRL, the Navy and other national and international organizations, and to consult on important scientific and programmatic issues.

Applicants should be recognized as national/international authorities in the above areas of research, and should have demonstrated the scientific vision and organizational skills necessary to market new research proposals to obtain funding and bring long term, multi-faceted research programs to successful completion. NRL is the Navy's corporate lab and operates under the Navy Working Capital Fund (NWCf).

You must apply online by logging in to USAJOBS at www.usajobs.gov and searching for the vacancy announcement number **NW713XX-00-1743284K94372325**. Please carefully read the announcement and follow the instructions when applying. Please contact **Tara Bright** at tara.bright@nrl.navy.mil for more information. Vacancy announcement closes on **28 February 2017**.

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Postdoctoral Fellowship Positions in Medical Physics and Engineering

Multiple postdoctoral positions are immediately available in the Division of Physics and Engineering, Department of Radiation Oncology at the University of Texas Southwestern Medical Center for individuals who are interested in cancer in medical physics. The research topics are the development of proton- or heavy charged particle-based cancer radiotherapy techniques, cancer dose calculation, and treatment plan optimization. A Ph.D. in physics or a related field is required. Strong programming skills are essential. Knowledge of Monte Carlo simulation is desired. Interested candidates should e-mail a CV and a list of references to: Sarah.Sandhu@UTSouthwestern.edu. UT Southwestern Medical Center is an Affirmative Action/Equal Opportunity Employer. Women, minorities, and individuals with disabilities are encouraged to apply.

FEATURED Job

Laboratory Manager/Researcher

Tufts University
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Requirements:

- Ph.D. in the area related to material science and engineering or a related field (MS degree could be considered in exceptional cases)
- Experience of working with the microscopy mentioned in this advertisement

Please apply online at jobs.tufts.edu and search job # 1500. Questions: Lorin.Palidoro@tufts.edu

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Instrumentation Specialist

Willamette University

Willamette University is accepting applications for an Instrumentation Specialist to perform and coordinate maintenance and repair of scientific equipment used in molecular-level analysis across the College of Science and Forestry, and provides support of instructional and research equipment. This is a full-time, exempt, year round position that is eligible for tenure. Salary dependent on experience and education. To review the position description and to apply online, please visit <http://jobs.willamette.edu>. Deadline: Open until finalists are selected. Willamette University is an Equal Opportunity Employer.

Computational/Theoretical Scientist

Laboratory for Laser Energetics

The Laboratory for Laser Energetics is seeking a Computational/Theoretical Scientist to join the team. The position involves the development of computer models for the simulation of laser-plasma interactions. The candidate should have a Ph.D. in physics or a related field, and experience in the development of computer models for laser-plasma interactions. The position is full-time and exempt. Salary is commensurate with experience and education. To apply, please visit <http://jobs.ller.ccny.cuny.edu>. The position is open until the position is filled.



香港中文大學 The Chinese University of Hong Kong

Applications are invited for:-

Department of Physics Research Assistant Professor (Ref. 160001PW)

The Department invites applications for a Research Assistant Professorship in experimental quantum physics/materials.

Applicants should have (i) a PhD degree in physics, chemistry or materials science; and (ii) experimental research experience in at least one of the following fields:

- quantum sensing
- microscopy and manipulation of nano-objects
- magnetic resonance spectroscopy
- optical spectroscopy of nanomaterials

The appointee will (a) work closely with faculty members in research on quantum sensing based on diamond and related materials using optically detected magnetic resonance; (b) demonstrate a strong record of research accomplishments, potential for establishing externally funded research programmes; and (c) undertake light teaching duties at undergraduate and postgraduate levels. Information about relevant research in the Department is available at: <http://www.phy.cuhk.edu.hk>.

Appointment will initially be made on contract basis for up to three years commencing as soon as possible, renewable subject to mutual agreement.

Applications will be accepted until the post is filled.

Application Procedure

Applicants should upload a full resume, a brief research statement (not longer than three pages), copies of academic credentials, a publication list and/or abstracts of selected published papers when submitting an application for the post.

The University only accepts and considers applications submitted online for the post above. For more information and to apply online, please visit <http://career.cuhk.edu.hk>.

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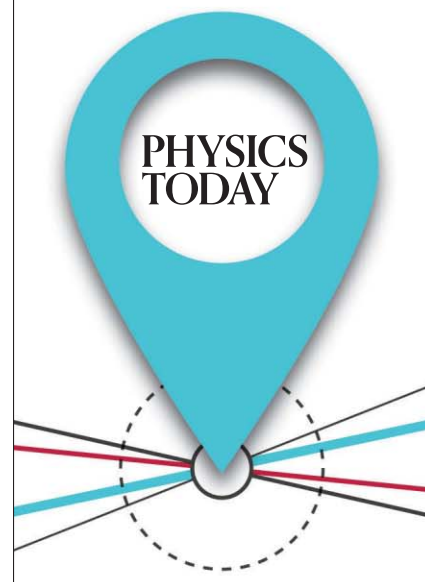
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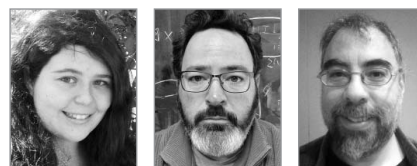
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QUICK STUDY

Andrea Welsh is a PhD student in physics, **Edwin Greco** is a faculty member in the physics department, and **Flavio Fenton** is an associate professor of physics and Welsh's thesis adviser at the Georgia Institute of Technology in Atlanta.



Dynamics of a human spiral wave

Andrea J. Welsh, Edwin F. Greco, and Flavio H. Fenton

With a few simple instructions, participants at the Atlanta Science Festival mimicked a phenomenon that can have fatal consequences in biological systems.

Spiral waves, which travel along expanding circular paths, are a feature of many physical, biological, and chemical systems. Some of their most dramatic manifestations are in the human body. For example, spiral waves can occur on the tongue in migratory glossitis, a condition in which the papillae—the bumps that cover the upper part of the tongue and house the taste buds—are missing due to inflammation of the mucous membrane, and the patterns of smooth patches can propagate as spirals. They also occur in the cortex of the brain, where they can lead to epilepsy.

The most dangerous spiral waves occur in the heart (see the PHYSICS TODAY articles by Leon Glass, August 1996, page 40, and Alain Karma and Robert Gilmour, March 2007, page 51). There, spiral waves of electrical activity (see figure 1) can induce tachycardia, an anomalously high resting heart rate, as the spiral propagation drives the heart to contract more frequently. When spirals break into multiple spiral waves, the heart is in a state of fibrillation, a condition of rapid unsynchronized contraction that fails to pump oxygenated blood to the body. Without intervention, fibrillation is deadly; in the US alone, it claims some 300 000 lives annually.

Excitable crowds

Just as cells in biological systems can exhibit complex collective behavior, groups of people also can display emergent behavior at larger scales. That's what happens in mosh pits, where music fans' dancing behavior is like flocking patterns, and in sports stadiums where fans form the propagating Mexican wave, so called because it became popular internationally after being broadcast during the 1986 FIFA World Cup in Mexico. In those cases the crowd is acting like a so-called excitable medium, a group whose individual entities—or "cells," be they biological cells or human spectators—have a well-defined resting state; a threshold state that, when reached, triggers the cell to become excited for a period of time; and a refractory period, following the excitation, during which the cell cannot be excited.

In Mexican-wave behavior, individuals start in the resting state: with arms down by their sides. The threshold is triggered in a person who sees a nearest neighbor to the left or right lift their hands over their head; the individual then becomes excited by raising their own hands for a specified time. After that activation, the individual lowers their arms and is in the refractory state until their arms are all the way down.

Atlantans make waves

Mexican waves propagating through large groups of people are commonplace. We wanted to see if a spiral wave could also be formed by a large group of people, a feat that had not been reported in the literature. In the process, we hoped to teach the Atlanta, Georgia, community about the deadly effect of cardiac spiral waves.

In 2014 and 2015, we performed an experiment during the city's annual Atlanta Science Festival. In each of the two events, 500–600 people were organized into approximately square grids. All the participants were provided with the rules for forming the Mexican wave, with one crucial change: For the spiral wave, any of the four nearest neighbors can trigger individual participants to raise their hands.

A spiral wave could propagate in either the clockwise or counterclockwise direction, and nothing in the rules we provided determines one possibility instead of the other. To break the symmetry and realize a particular propagation direction, we had to set up specific initial conditions. As shown in figure 2a, we started with a line of excited elements extending from about the center of the crowd to the midpoint of one boundary. We required that the people to the right of the excited elements be refractory for a brief period of time, which ensured that they would not be activated by their neighbors at the start, though they could be activated later on. By changing which side of the initially excited line was made refractory, we could change the clockwise or counterclockwise chirality of the spiral wave.

Once the initial condition was set, participants were asked to follow the rules

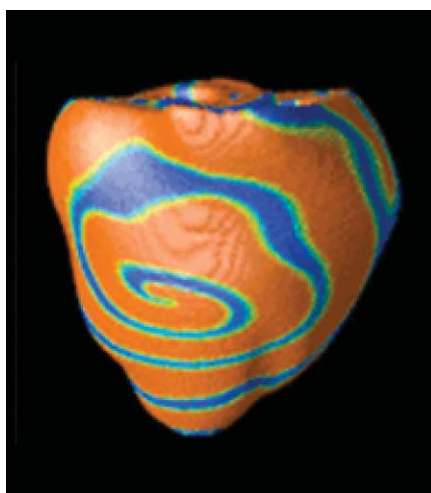


FIGURE 1. IN THE HEART, spiral waves of peak electrical activity (orange in the dramatized simulation pictured here) can lead to high heart rates or, if they break up, to fatal uncoordinated contractions.

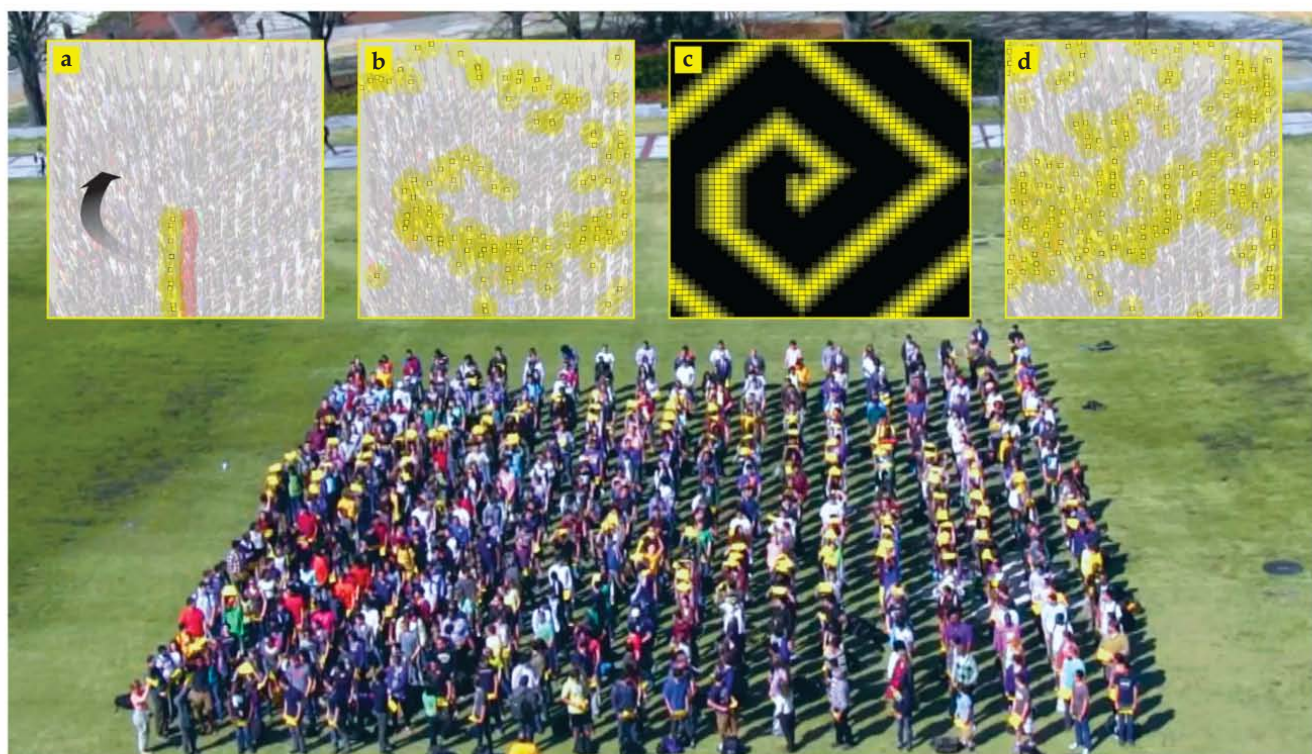


FIGURE 2. AT AN ATLANTA SCIENCE FESTIVAL outreach activity (background photo), people formed a spiral wave. **(a)** To ensure clockwise propagation of the wave, a line of volunteers (holding up square sheets and highlighted in yellow) began the exercise in the excited state with arms raised while their neighbors to the right (pink) were in the refractory state—unable to be excited for a specified period. **(b)** The people holding up sheets (yellow) display the characteristic shape of a spiral wave. **(c)** When a computer simulation rigorously follows the rules given to festival participants, the resulting wave (yellow) is much sharper. **(d)** Some human spiral waves persist, but others become disordered as indicated by the highlighted individuals with raised sheets.

we had distributed; we recorded a video of the group dynamics from the roof of a nearby seven-story building. We were not sure if the exercise would really work. It's significantly more difficult to follow four nearest neighbors than it is to observe one in the direction from which a Mexican wave is propagating. People do not react and follow rules identically, and various glitches could prevent the formation and propagation of the spiral wave. However, as shown in figure 2b and the videos available with the online version of this Quick Study, spiral waves formed quite readily. In many cases, they survived for several rotations.

Analysis of the experiments showed that the waves had a width of seven people, an average propagation speed of the wavefront of about three people per second, and a rotation period averaging 4.5 seconds.

We were able to reproduce those values in a computer simulation in which the time step was 0.25 seconds and the cells were excited for 2 seconds and refractory for 1.5 seconds. A striking difference emerged between experiments and simulations. The computer simulations produce spiral waves that follow a diamond shape, as shown in figure 2c, instead of the curved spiral waves formed in a crowd of real people. The smoothness of the human-generated waves arises because people have small differences in their reaction times and because they actually respond to more than just their four nearest neighbors.

Spatiotemporal disorder

Many systems that exhibit spiral waves eventually manifest complex spatiotemporal dynamics when the spirals break into multiple spiral waves. In our experiments with crowds, we were

pleasantly surprised to sometimes observe that phenomenon (see figure 2d). Breakup of the original spiral wave was driven by small variations in reaction times between participants, who sometimes excited themselves too early and sometimes too late. In addition, a few participants excited themselves without any close neighbor being excited.

The demonstration at the Atlanta Science Festival serves as an excellent example of how aggregations of a simple element—a person armed with a few rules—can generate new, emergent behavior whose spatial and temporal dynamics is much more complex than is realized in a single exemplar. Collections of real people following the rules can form not only simple waves such as the Mexican wave but also spiral waves. They can also develop complex spatiotemporal disorder. Furthermore, our outreach exercise shows that a few single elements suffice to destabilize a spiral wave and create irregular dynamics, which underscores the ease with which small system changes can lead to fibrillation in the heart and similar if less grave behavior in other systems.

We are grateful to NSF for support of this research.

Additional resources

- E. M. Cherry, F. H. Fenton, "Visualization of spiral and scroll waves in simulated and experimental cardiac tissue," *New. J. Phys.* **10**, 125016 (2008).
- J. L. Silverberg et al., "Collective motion of humans in mosh and circle pits at heavy metal concerts," *Phys. Rev. Lett.* **110**, 228701 (2013).

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BACK SCATTER

Diamonds from the deep

The oxidation state of Earth's silicate-rich mantle has had a profound effect on our planet's evolution, including core–mantle differentiation, mineral formation, and the distribution and availability of carbon, hydrogen, and oxygen. Most measurements derive from the highly oxidized upper mantle, yet theory and experiments suggest that the deep mantle should include chemically reduced regions and metallic iron alloys. Now Evan Smith of the Gemological Institute of America and colleagues report that a certain class of large gem-quality diamonds—including the 3106-carat Cullinan, the largest ever found—provides direct verification of those predictions: metallic

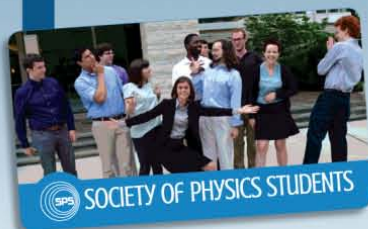
inclusions of a solidified mixture of iron, nickel, carbon, and sulfur.

The inclusions, like this 0.3 mm one from a 5-carat diamond, are silvery in appearance, have black graphitic cracks extending from them, and sometimes are surrounded by a thin layer of methane or hydrogen. They indicate that the diamonds precipitated from pockets of metallic liquid, a sign of reducing conditions. Other mineral inclusions place those pockets at depths of 360–750 km, a range that spans the transition region between the upper and lower mantle and is much deeper than where most other gem-quality diamonds form. (E. M. Smith et al., *Science* **354**, 1403, 2016.)

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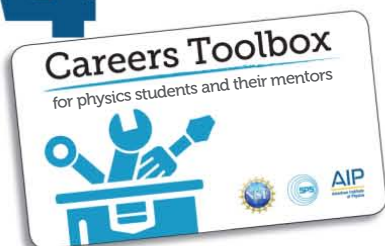
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