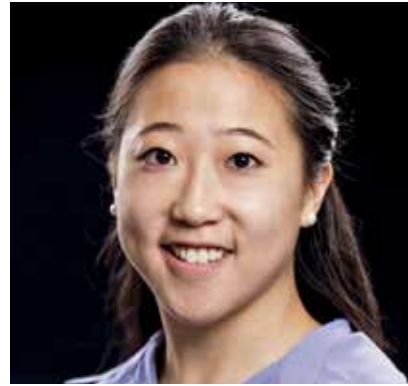


# PHYSICS

Harvard University Department of Physics Newsletter

FALL/WINTER 2018



WOMEN IN PHYSICS AT HARVARD AND BEYOND

## Conversations with the Department's PhDs



HARVARD UNIVERSITY  
Department of Physics



Harvard Physics Faculty: then (1980, top) and now (September 25, 2018, photo by Paul Horowitz).  
For names of faculty members on both photographs, please see our website: <https://www.physics.harvard.edu/about>.

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## ON THE COVER:

Clockwise from top left: Lisa Randall (photo by Eduard Pastor), Elizabeth West, Alyssa Goodman (photo by Kris Snibbe, Harvard Staff Photographer), Christie Chiu, Elizabeth Simmons (Creative Commons Attribution license), Janet Conrad (photo by Kayana Szymczak), and Emily Russell.

Middle row: Ann Nelson and Sally Dawson.

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# Letter from the Chair



Dear friends of Harvard Physics,

I'm delighted to introduce the fifth issue of the Harvard Physics Newsletter—and my first as the Chair of the department. It was a busy year, with somber and exciting events. We have lost two faculty members and friends, Nicolaas Bloembergen and Richard Wilson; please read the warm tributes to them in this newsletter.

Three distinguished members of our community have retired during this last year, Bertrand Halperin, Gary Feldman, and Sheldon Glashow (the latter from Boston University; Prof. Glashow retired from Harvard in 2000). Profs. Halperin and Feldman remain an active presence in the department, and we look forward to their continued contributions for many more years. A new faculty member, a condensed matter experimentalist, Julia Mundy, is putting the finishing touches on her new lab in the Laboratory for Integrate Science and Engineering. Julia is a familiar face in our department: she graduated from Harvard College in 2006, earned her PhD at Cornell, and has now returned to her *alma mater* as an Assistant Professor of Physics.

For our cover story, we asked Caitlin McDermott-Murphy, a colleague in the Department of Chemistry and Chemical Biology, to talk with several female Harvard Physics PhDs about their experiences as

physicists and as women in the field. We were interested to know more about the paths that led them to the discipline and to our program. Caitlin is also looking at some of the national statistics concerning women in physics, and the unique challenges they face along their career trajectories.

In the spring, a Harvard Presidential Task Force on Inclusion and Belonging issued a very thoughtful report on “Pursuing Excellence on a Foundation of Inclusion.” We formed a departmental committee to implement its recommendations, and I am most grateful to Profs. Jenny Hoffman and John Huth for leading this effort. Our meetings have made clear that we have much to learn, and I trust this will lead to a more inclusive environment in the department.

We have a tradition of focusing on our history in every issue. For this edition's historical focus article, we describe a special panel event held on February 12 of this year, in which our department celebrated the 100th anniversary of the birth of Julian Schwinger. Schwinger, the 1965 Nobel Laureate in Physics, was a member of the Harvard Physics department and one of the most accomplished physicists of the last century. The article includes excerpts from the speeches of the four panelists—Walter Gilbert, Sheldon Glashow, Roy Glauber, and Daniel Kleitman—in which they offer their fun and fond reminiscences of being Schwinger's students and colleagues.

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I hope you will enjoy the stories about the experimental labs of Professors Jenny Hoffman (by Steve Nadis) and Kang-Kuen Ni (by two graduate students in the Ni Lab, Lee Liu and Yu Liu). The Hoffman Lab is focused on creating novel materials that exhibit unusual properties, such as high temperature superconductivity. The Ni Lab has recently combined two atoms into a dipolar molecule, under conditions that could lead to new platforms for quantum computing.

Of particular interest to me is the article on “Active Learning” by Logan McCarty, the GSAS Director of Science Education. Active Learning is a fairly new concept in physics education, pioneered by Professor Eric Mazur and several other prominent science educators. It replaces the traditional formula of classroom instruction (a lecturer at the blackboard in front of a class) with a more participatory model in which students get more deeply engaged in their own learning, as well as learning from the professor and each other. This semester, I am working with Louis Deslauriers—an early adopter and expert on this mode of teaching who is profiled in Logan’s article—to redesign Physics 143a, Quantum Mechanics I, to follow the precepts

of Active Learning. This has been an eye-opening experience for me, and I am learning a great deal from Louis on how to improve on the conventional blackboard style of lecturing.

I am looking forward to another exciting year in the department, with new scientific discoveries, involving our very talented graduate and undergraduate students, postdoctoral fellows, and faculty.

Please enjoy the Newsletter and let us know what you think. If you happen to be in the area, please stop by to say hello, join us for our Monday Tea, or attend a Colloquium, Loeb Lecture, or any of the other numerous events held here. Please consult the back cover for more information and instructions on how to get on our mailing list.

We look forward to staying in close contact and welcome your comments and questions.

Best wishes,

**Subir Sachdev**  
Chair and Herchel Smith  
Professor of Physics

## THE DEPARTMENT TODAY:

**186**  
Undergraduate concentrators

**234**  
Graduate students

**93**  
Postdoctoral fellows

**200**  
Other research scholars

**11**  
Non-ladder faculty members

**6**  
Tenure-track faculty members

**45**  
Tenured faculty members

**35**  
Staff members

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# Retirements

Announcing the retirement of three distinguished faculty members



## Gary Feldman

Gary Feldman earned his BA in Physics from the University of Chicago in 1964 and his PhD in Physics from Harvard in 1971. He then held research and teaching positions at the Stanford Linear Accelerator Center at Stanford University before returning to Harvard as a Physics Professor in 1990. He was named a Frank B. Baird Jr. Professor of Science in 1992 and served as chair of the Harvard Physics Department from 1994 to 1997. Feldman's early research focused on the physics of electron-positron annihilation at high energies. He co-authored papers relating to the discoveries of the  $J/\psi$  meson and the tau lepton. Feldman's later research shifted to neutrino oscillations. His Harvard group designed and built front-end electronics for Fermilab's MINOS and NOvA neutrino experiments. Feldman was also a co-spokesperson for the NOvA neutrino experiment for 11 years and is continuing active participation in it. He is a fellow of the American Physical Society and American Academy of Arts and Sciences.



## Sheldon Glashow

Sheldon Glashow came to Harvard in 1954 after getting a BA from Cornell. He earned his PhD in 1959 under the supervision of Julian Schwinger, a Nobel Prize-winning physicist. Glashow then taught at Stanford and the University of California, Berkeley, before joining Harvard's faculty as a Physics Professor in 1966. He was named the Higgins Professor of Physics in 1979, a position he held until 2000. In 1979, Glashow was awarded the Nobel Prize in Physics—along with Steven Weinberg and Abdus Salam—for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including their prediction of the weak neutral current. Glashow and James Bjorken predicted the existence of the charm quark about a decade before its discovery in 1974. In 1973, Glashow and Howard Georgi proposed the first grand unified theory. Glashow became an emeritus professor at Harvard in 2000, the same year he became the Arthur G.B. Metcalf Professor of Mathematics and Science at Boston University. He retired from Boston University this year and is now Professor Emeritus both there and at Harvard.



## Bertrand Halperin

Bertrand Halperin got his BA from Harvard in 1961 and returned in 1976 as a professor after getting a PhD from the University of California, Berkeley, in 1965 and working at Bell Laboratories for 10 years. A specialist in theoretical condensed matter physics, he has been on Harvard's Physics faculty for the past 42 years. Halperin just received the 2019 American Physical Society Medal for Exceptional Achievement in Research, given for "his many contributions to the understanding of the dynamics of phase transitions, of low-dimensional quantum phenomena, of the quantum Hall effect, and his pioneering work on the role of topology in both classical and quantum systems." Halperin had previously won the 1982 Oliver E. Buckley Condensed Matter Physics Prize, the 2001 Lars Onsager Prize, and the 2003 Wolf Prize in Physics. In recent work, he has continued to study the quantum Hall effect in various settings—including in graphene and strongly-correlated electron systems—while also investigating hybrid semiconductor-superconductor devices.

## New faculty



### Julia Mundy: Crafting New Materials with Exquisite Precision

by Steve Nadis

For Julia Mundy, joining the Physics Department faculty earlier this summer felt a bit like coming home, as she had received her Bachelor's from Harvard in chemistry and physics a dozen years earlier. "It was an exciting place to be an undergraduate, and it's now an exciting place to be a faculty member," Mundy says. "There's a rich culture and tradition here of focusing on the biggest, most important questions in order to push the science forward in completely new ways. You can feel a creative spirit running through this department that I'm glad to be part of."

Mundy is not the first member of her family to teach at an Ivy League university. Her grandmother, a plant biologist, taught at Yale and the University of Connecticut; her great aunt is an emeritus math professor at Columbia. Mundy's own interest in science was sparked, in part, by seeing her grandmother's work when she was just a small child. As she grew older, she started to read the papers and a book her grandmother wrote. Later, while in graduate school, she connected with former members of her grandmother's research team. "I was not only inspired by her scientific legacy but also by hearing about her strong dedication to mentoring young scientists," Mundy says.

She graduated from Harvard in 2006 with highest honors in Chemistry and Physics, while also earning an AM in Chemistry during her fourth year. Before going to graduate school in applied physics at Cornell, she spent two years teaching high school students in Baton Rouge (shortly after Hurricane Katrina) and in New Haven,

Connecticut, through the Teach for America program. "I've always been committed not only to my research but also to helping others access high-quality educational opportunities," says Mundy. She found the experience rewarding and looks forward to continuing to teach—this time to college students.

Now that she has her own lab, Mundy will pursue the line of work she began at Cornell and continued during her postdoctoral fellowship at the University of California, Berkeley—"synthesizing new materials, imaging them at the smallest length scales, and developing new techniques to understand their properties." She's especially eager to apply these methods toward answering new physical questions. Her research is extremely collaborative in nature, and Mundy enjoys "active interactions with people from all kinds of disciplines."

With the Molecular Beam Epitaxy (MBE) equipment in her lab, she's making materials that can't be created in other ways, "laying them down, atom by atom, tweaking the location of those atoms to the picometer scale in order to control their interactions and to elicit specific electronic, magnetic, and optical properties." Mundy will also make use of the new Transmission Electron Microscope (TEM) at the Center for Nanoscale Systems to study the materials she's assembled.

"While my research is mainly driven by fundamental physics," she notes, "you might think about translating some of the materials we discover to an applied setting and eventually utilize their properties in a device." What's most exciting to Mundy is that, with the resources and collaborations available to her at Harvard, she and her fellow lab-mates are "well positioned to address so many different problems and questions."

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## IN MEMORIAM



Based on a piece originally written for *Optics & Photonics News*, November 2017

### Nicolaas Bloembergen

by Eric Mazur

Nicolaas Bloembergen, a long-time member of the faculty at Harvard and a giant in the world of optical science, passed away on 5 September 2017 in Tucson, Ariz., at the age of 97. He was a major intellectual force in the explosion of science and applications related to the interplay of matter and radiation. He pioneered the development of nuclear magnetic resonance (NMR), made important contributions to the development of masers and lasers, and is the father of nonlinear optics.

Nico, as he liked to be called, was my mentor, postdoctoral advisor, and friend since the 1980s. Even though he received the Nobel Prize, the top honor in physics, for his work in nonlinear optics and spectroscopy, he always remained one of the humblest people I have ever known. To him, what was important was not winning the Nobel Prize. He considered the success of the people around him his biggest accomplishment.

Nico grew up in Dordrecht, Netherlands, the second of six children. His passion for science was encouraged early by his father, a chemical engineer and an executive at a chemical fertilizer company. Nico enrolled at the University of Utrecht, graduating just before the Nazis closed the university. After spending the remainder of the war in hiding, he left the Netherlands to pursue his graduate degree with Ed Purcell at Harvard.

During his graduate studies, Nico developed the first NMR machine and wrote one of the seminal papers on nuclear magnetic resonance—colloquially known as the BPP paper, for Bloembergen, Purcell and Pound. His interest in NMR led to the development of masers and made him a player in the nascent field of lasers in the early 1960s.

Shortly after the construction of the first laser, Peter Franken and co-workers at the University of Michigan observed second-harmonic generation. This discovery led Nico and his group to develop the theoretical basis for this and many other nonlinear processes in his monograph, *Nonlinear Optics*.

Nico remained active at Harvard well into his 70s, when he decided to retire and move with his wife, Deli, to Tucson. There, he joined the faculty at the University of Arizona, where he continued to come to work once or twice a week well into his 90s.

I have already mentioned Nico's humility earlier. Simplicity and frugality were guiding principles throughout his life and career. I remember my surprise when I first joined his lab at Harvard in 1982; it was an eye-opener to see that Nobel Prize-winning optical work could be done on home-built wooden benches with optical mounts machined by graduate students.

Nico assigned me to a project that involved taking Raman measurements with an old ruby laser. Unfortunately, the doubling crystal of the laser was so badly damaged that its efficiency was reduced to 0.1 percent. I clearly needed a new doubling crystal. When I went to see Nico with my request, he looked disturbed.

"First you get a signal," he said. "And then we buy a new crystal."

Although I couldn't quite follow the logic, his tone made it clear that any discussion was futile. A few weeks later, I came up with ideas to get a much larger signal with whatever little energy the crystal could generate—and I learned that in research, ingenuity matters much more than resources. It was a lesson worth learning.

Nico, we will miss your friendship and wisdom.



## IN MEMORIAM



## Richard Wilson

by Elaine Wilson

Richard “Dick” Wilson, Mallinckrodt Professor of Physics Emeritus at Harvard University, died on May 19 in Needham, Mass.

Wilson will be remembered for his scientific work, student mentorship, principled humanitarian and environmental stands, and interdisciplinary connections across the globe. He was also a railway enthusiast, Morris dancer, concertina player, world traveler, and hiker.

Born on April 29, 1926, in Putney, England, Wilson studied at London’s Colet Court and St. Paul’s schools, evacuating to Crowthorne by bicycle during World War II. He earned his BA and DPhil at Christ Church, Oxford. He was a Guggenheim Fellow for postdoctoral work in the U.S. at Rochester University and then Stanford University with Wolfgang “Pief” Panofsky. While at Stanford, Wilson met Andrée Désirée DuMond, marrying her after a brief courtship.

In 1952, the couple moved to Oxford University for Wilson’s research lecturer position and in 1955 to Cambridge, Mass., for a faculty position at Harvard.

Wilson specialized in experimental particle physics, studying the nature of the smallest particles that constitute matter as they collide at very high velocities. He led the upgrade of Harvard’s proton cyclotron to 160 MeV in order to study nucleon-nucleon interactions. With Harvard and MIT colleagues, Wilson designed, constructed, and used the Cambridge Electron Accelerator 6 GeV synchrotron, which, from 1962 on, further probed nucleonic structure.

Wilson was involved in constructing and using the new Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill., frequently “commuting” there from Harvard, to maintain close contact with students and research. At Fermilab, Wilson continued the study of nucleonic structure with high-energy muon beams. When Harvard’s cyclotron became obsolete for particle research, Wilson helped adapt it for the treatment of cancerous tumors. He also studied electron-positron interactions with the CLEO collaboration at the Cornell Electron Storage Ring. Finally, Wilson joined a research group using the intense polarized beam of the new Continuous Electron Beam Accelerator Facility in Virginia.

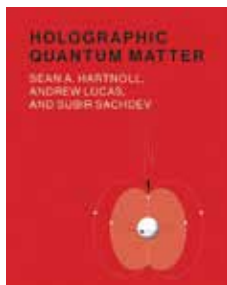
Wilson often visited the USSR and, later, Russia, believing that direct cultural and scientific contact was essential to prevent war. After the exile of dissident Soviet physicists, he boycotted USSR conferences and was an early and visible supporter of Andrei Sakharov.

Wilson studied nuclear power safety and environmental carcinogens, such as asbestos. He visited Chernobyl after the nuclear accident, taking a PBS film crew with him. He also did extensive studies into the presence of arsenic in water in Southeast Asia, and he raised funds to provide safe drinking water in many villages, especially in Bangladesh, which he visited every year.

Wilson authored 935 scholarly papers and eight books.

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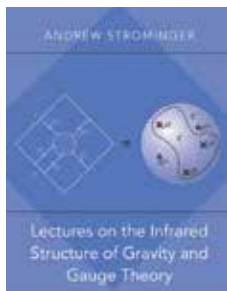
# Books by Faculty



## Holographic Quantum Matter

Sean A. Hartnoll, Andrew Lucas, and Subir Sachdev, MIT, 2018

This book, written by pioneers in the field, offers a comprehensive overview of holographic methods in quantum matter. It covers influential developments in theoretical physics, making the key concepts accessible to researchers and students in both high energy and condensed matter physics. The book provides a unique combination of theoretical and historical context, technical results, extensive references to the literature, and exercises. It will give readers the ability to understand the important problems in the field, both those that have been solved and those that remain unsolved, and will enable them to engage directly with the current literature.

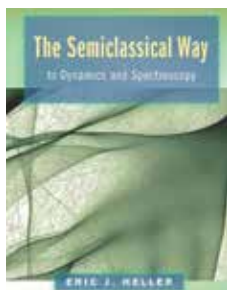


## Lectures on the Infrared Structure of Gravity and Gauge Theory

Andrew Strominger, Princeton, 2018

The book presents an accessible, graduate-level synthesis of a frontier research area in theoretical physics. Based on a popular Harvard University course taught by Prof. Strominger, it gives a concise introduction to recent discoveries concerning the structure of gravity and gauge theory at very long distances. These discoveries unite three disparate but well-developed subjects in physics.

Uniquely connective and cutting-edge, *Lectures on the Infrared Structure of Gravity and Gauge Theory* takes students and scholars to the forefront of new developments in the discipline.



## The Semiclassical Way to Dynamics and Spectroscopy

Eric J. Heller, Princeton, 2018

Physical systems have been traditionally described in terms of either classical or quantum mechanics. But in recent years, semiclassical methods have developed rapidly, providing deep physical insight and computational tools for quantum dynamics and spectroscopy. In this book, Eric Heller introduces and develops this subject, demonstrating its power with many examples.



## The Green-Eyed Dragons and Other Mathematical Monsters

David Morin, 2018

This book is a collection of 57 very challenging math problems with detailed solutions. It is written for anyone who enjoys pondering difficult problems for great lengths of time. The problems are mostly classics that have been around for ages. They are divided into four categories: General, Geometry, Probability, and Foundational, with the Probability section constituting roughly half the book. Many of the solutions contain extensions/ variations of the given problems. In addition to the full solution, each problem comes with a hint. Are you eager to tackle the Birthday Problem, Simpson's Paradox, the Game-Show Problem, the Boy/Girl Problem, the Hotel Problem, and of course the Green-Eyed Dragons? If so, this book is for you!

# Faculty Prizes, Awards, and Acknowledgments\*

Clarivate Analytics (formerly Thomson-Reuters) Highly Cited Researcher 2017:

**PROF. EUGENE DEMLER**

Scientist of the Year,  
The Harvard Foundation:

**PROF. CORA DVORKIN**

2018-2019 Fellow at the Radcliffe  
Institute for Advanced Study:

**PROF. CORA DVORKIN**

Star Family Challenge for Promising  
Scientific Research Award:

**PROF. CORA DVORKIN**

Abraham Pais Prize for History  
of Physics (APS):

**PROF. PETER GALISON**

APS Fellowship:

**PROF. MARKUS GREINER**

APS 2019 Medal for Exceptional  
Achievement in Research:

**PROF. BERTRAND HALPERIN**

Harvard Graduate Women in Science and  
Engineering Mentor of the Year Award:

**PROF. JENNY HOFFMAN**

Distinguished Visiting Professor,  
Academy of Mathematics and  
Systems Science of the Chinese  
Academy of Sciences:

**PROF. ARTHUR JAFFE**

2019 New Horizons In Physics Prize:

**PROF. DANIEL JAFFERIS**

Clarivate Analytics Highly Cited  
Researcher 2017:

**PROF. PHILIP KIM**

2018 Tomassoni-Chisesi Prize:

**PROF. PHILIP KIM**

Clarivate Analytics Highly Cited  
Researcher 2017:

**PROF. MIKHAIL LUKIN**

National Academy of Sciences:

**PROF. MIKHAIL LUKIN**

APS George E. Valley, Jr. Prize:

**PROF. JULIA MUNDY**

Moore Fellow in Materials Synthesis:

**PROF. JULIA MUNDY**

2019 George E. Valley, Jr. Prize:

**PROF. JULIA MUNDY**

Camille Dreyfus Teacher-Scholar Award:

**PROF. KANG-KUEN NI**

2019 I.I. Rabi Prize in Atomic,  
Molecular, and Optical Physics:

**PROF. KANG-KUEN NI**

Guggenheim Fellowship:

**PROF. LISA RANDALL**

2019 J. J. Sakurai Prize for  
Theoretical Particle Physics:

**PROF. LISA RANDALL**

2018 ICTP Dirac Medal:

**PROF. SUBIR SACHDEV**

Lars Onsager Prize:

**PROF. SUBIR SACHDEV**

Clarivate Analytics Highly Cited  
Researcher 2017:

**PROF. ASHVIN VISHWANATH**

Clarivate Analytics Highly Cited  
Researcher 2017:

**PROF. AMIR YACOBY**

APS Fellowship:

**PROF. SUSANNE YELIN**

2019 Breakthrough Prize In  
Life Sciences:

**PROF. XIAOWEI ZHUANG**

Clarivate Analytics Highly Cited  
Researcher 2017:

**PROF. XIAOWEI ZHUANG**

The Royal Netherlands Academy of  
Arts and Sciences Heineken Prize for  
Biochemistry and Biophysics:

**PROF. XIAOWEI ZHUANG**

\*Includes awards received since the publication of last year's newsletter.

WOMEN IN PHYSICS AT HARVARD AND BEYOND

# Conversations with the Department's PhDs

by Caitlin McDermott-Murphy



## Many Roads to Physics

We have all been asked the question: What do you want to do with your life? We listen to—or tune out—our parents’ and teachers’ advice, search for role models, and talk to friends and strangers. Many of us feel an impulsive attraction to something—be it jazz, plants, baseball, or algorithms. And, for some, physics promises a vast universe filled with both possibilities and mysteries.

**Ann Nelson** [PhD 1984; Advisor: Howard Georgi] always wanted to be a scientist, but her path was not always as clear as her passion. During her middle and high school years, most students and teachers balked at the idea of a female physicist. Undeterred, Nelson focused on her studies. By the end of high school, she was attending physics classes at the nearby University of California, where she blended into the sea of students.

In 2018, Nelson earned the prestigious American Physical Society’s J.J. Sakurai Prize for Theoretical Physics, along with Michael Dine (UC Santa Cruz), for “groundbreaking explorations of physics beyond the standard model of particle physics.”

Astronomy fascinated **Emily Russell** [PhD: 2014; Advisor: David A. Weitz] from an early age, starting around ten. She read *Sky and Telescope* and *Astronomy* magazines and asked for a telescope for her 12th birthday. She got one. Then, in early high school, she realized that “in order to describe all the cool stuff that happened in astronomical systems, you had to turn to physics,” she says. “The more I learned about [physics], the more I came to love it. It explains everything, the whole world, the whole universe.”

Russell, one of only two girls in her Advanced Placement physics class, was not intimidated by the gender imbalance. She excelled, and her physics teachers soon encouraged her to take the exam to apply for the United States Physics Team. In fact, it wasn’t until graduate school that she noticed any gender bias in her field.

After receiving her PhD, Russell joined Google. Now, she works on the local search quality of the company’s search engines, Google and Google Maps. “When people search for real places in the real world (such as ‘the Eiffel Tower’ or ‘coffee near me’),” she explains, “it’s my team’s job to figure out what places to show.” During her PhD program, Russell frequently worked with enormous quantities of

microscopy images of colloidal systems, trying to synthesize and make sense of the data. As a software engineer, she feels she’s engaged in very similar types of research, albeit with different data and different goals in mind. “It’s great. I love trying to understand complex systems,” she says.

For **Elizabeth (Petrik) West** [PhD 2017; Advisor: John Doyle], physics promised answers to the world’s most intricate puzzles. As a Catholic, she aspires to translate “at least a few pages of the finest story ever written, by the Creator Himself.” The difficulty West encounters in physics is an inspiration to her. “In music, the most beautiful pieces are often the most difficult to play,” she says. “In sports, great feats of athleticism require great effort. By analogy, I felt sure that a subject as challenging (for me) as physics must be worth learning.” Now, West works as a postdoctoral researcher at the University of California, Los Angeles, in Eric Hudson’s lab, developing a general approach to interrogating the internal quantum state of trapped, ultracold molecular ions.

**Janet Conrad** [PhD: 1993; Advisor: Francis Pipkin] also hesitated to pursue physics at first owing to her initial dream of becoming an astronomer. For her, stars provided an observable beauty while physics seemed more abstract. What changed her mind? “I discovered, by working at the observatory at Swarthmore, that it is cold and dark at 4 a.m.,” she said. “I learned very early on that it’s experimental physics that I love.”<sup>1</sup>

At the time of Conrad’s graduation, most particle physicists were preoccupied with finding the top quark. It was the thing to do. Instead, Conrad decided to go after the lightest known matter particles, neutrinos, which were showing unexpected properties. People warned her the decision would ruin her career. Instead, the field took off, and she was a pioneer. Now a Professor of Physics at the Massachusetts Institute of Technology, Conrad is a member of several collaborations, including IceCube, an experiment at the South Pole that uses the atmospheric neutrino flux to search for new physics, and MicroBooNE, a liquid argon-based detector running on the Fermilab Booster Neutrino Beamline.

Clockwise from top left: Lisa Randall (photo by Eduard Pastor), Elizabeth West, Alyssa Goodman (photo by Kris Snibbe, Harvard Staff Photographer), Christie Chiu, Elizabeth Simmons (Creative Commons Attribution license), Janet Conrad (photo by Kayana Szymczak), and Emily Russell. Middle row: Ann Nelson and Sally Dawson.

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“It’s not always true that the thing you fall in love with ends up being the thing you’re good at,” Conrad said. But she—along with Nelson, Russell, West, and many others—has made it true.

**Christie Chiu**, a current graduate student in the Greiner Lab, didn’t immediately choose physics either. Faced with a cornucopia of choices, she wanted to study all fields of science: physics, of course, but also mathematics, computer science, programming, and more. In the end, she couldn’t resist the fundamental, invisible power of physics. Like West, she is now an experimental physicist in atomic, molecular, and optical physics. She gains inspiration from all of her original interests, and she gets to build and see the invisible.

Last spring, Chiu was one of eight exceptional graduate researchers to be named a 2018 Harvard Horizons Scholar. At the program’s symposium in April, she delivered a talk, “Engineering an Analog Quantum Computer,” to a packed audience at Sanders Theatre. “Physics allows us to engineer our world,” she began. “Sometimes the physics is intuitive to us because we all experience it so much—like how sound travels in a room—and ... sometimes the physics isn’t intuitive.”

As an experimental physicist, Chiu works with her hands. She likes that. Even when the physics isn’t intuitive, she can still build models by manipulating individual atoms and image them to gain a greater understanding of quantum states. This knowledge could lead her and her teammates to invent new materials for high-efficiency electronics—materials that don’t lose as much energy through heating. What’s more, her model captures the complexity of quantum mechanics in an entirely new way. Someday it might lead to answers to questions that haven’t been asked yet.

## Advising the Future

Advisors and mentors can greatly influence students’ enthusiasm for physics and have a lasting impact on their careers.

During her undergraduate years at MIT, Chiu worked in Conrad’s lab, and Conrad served as her bachelor’s thesis advisor. “I definitely credit much of my love for physics and research to her,” Chiu said. “She was an absolutely excellent mentor—honest, inspiring, and truly all-around supportive of me.”

Conrad’s own advisor, Francis Pipkin, gave her ample freedom to explore, fail, try again, and succeed. He “let me explore the limits of what I believed I could do,” she said. Sadly, Pipkin passed away during Conrad’s studies. Yet, when faced with challenges in her research and lab management, she still imagines what advice he might offer to guide her toward an answer.

Russell attributes her success, in part, to Thomas Tombrello, a professor at the California Institute of Technology. During her freshman and sophomore years, she worked in his selective Physics 11 Research Tutorial, recalling “the absolute delight he clearly took in physics and the absolute confidence and encouragement he expressed toward his students.”

West credits a high school teacher, who taught her “an appreciation for the subject’s transparency—its simple, logical rules, as well as its depth, and the complex and exquisite phenomena that arise from the application of those rules.” She is also grateful for the support of her graduate advisor, John Doyle, and the welcoming scientific community she encountered in the Harvard/MIT Center for Ultracold Atoms (CUA).

According to Nelson, her advisor Professor Georgi achieved, and achieves, singular success in advising female graduates. “He treats everyone the same,” she said. “I don’t think he favors women, particularly, but ... he presumes competence, and he presumes ability, in everybody.”

**Elizabeth Simmons** [PhD 1985], another Georgi group graduate, also experienced harmful, if perhaps unintentional, attitudes, including “incredulity, of the ‘you don’t look like a physicist’ variety.” At the same time, she had numerous research mentors and role models such as the late Walter Brown at Bell Labs, Professor Georgi, Chris Quigg at Fermilab, and Bernice Durand from the University of Wisconsin.

Now, advisors themselves, Nelson, Conrad, and Simmons all recognize the need to bolster the numbers of other underrepresented minority groups in physics. In a May 2017 issue of *Physics Today*, Nelson published a commentary that addressed the lack of women, African-Americans, Native Americans, and Hispanic Americans in physics departments across the United States.<sup>2</sup> For her part, Nelson, now a Professor of Physics at the University of Washington, advocates for heightened awareness of underrepresentation in general, more resources to support minority physicists, and a more objective hiring process.

Simmons also hopes to expand the standard image of a physicist. “Other STEM fields are doing a lot better in this regard than physics,” she said. “A lot of work remains to be done.”

In August 2017, Simmons was appointed the Executive Vice Chancellor for Academic Affairs at the University of California San Diego. In this influential role, one of her top priorities—along with intellectual reach and educational creativity—is to build an inclusive campus climate. “Elizabeth has been a tireless advocate of diversity in science, working on behalf of underrepresented groups for years,” said Marcela Carena, a physicist and director of International Relations



Harvard Graduate Women in Physics, Fall 2017.

at Fermi National Accelerator Laboratory, who has known Simmons for more than 25 years. “Her dedication to this cause, in addition to her intense research and scholarship, is nothing short of amazing.”

Conrad, too, sees diversity—of race, thought, gender, sexual identity, etc.—as essential to innovation. She has, more often than not, chosen the divergent path, like her rebellious neutrino. Now she encourages her own students to pursue creative research avenues, to disagree when warranted, and to test their limits whenever possible.

For a long time, particle physicists kept tackling problems with bigger and bigger accelerators and detectors. Conrad wants to change that pattern. In fact, her MIT colleague Lindley Winslow has already built a detector that fits in the palm of a hand. It “looks like a ruby,” Conrad said. “I love beautiful experiments.”

Conrad continues to investigate neutrinos for more unexpected, beyond-the-Standard-Model, behavior. Most recently, she has been featured in *Quanta Magazine*, *Newsweek*, on NPR, and other media outlets, where she’s discussed a possible addition to the neutrino family, the sterile neutrino. Although more research needs to be done to verify its existence, this new elementary particle could revolutionize physics.

## The Role of Role Models

“I often get asked, ‘Why are there so few women in physics?’” wrote Nelson in 2017. “I may not be able to fully answer the question, but I can tell you why there are women like me in physics. Because we love

math and nature. Because we like doing computations and figuring things out, step by systematic step. We love the flashes of insight and the excitement of revelations from new data. We revel in breathtaking moments of awe. And we had support, mentors, encouragement, opportunities, and colleagues who gave us a positive view of ourselves as physicists.”<sup>2</sup>

As a prospective student at Harvard, Nelson witnessed an unusual interaction between Professor Howard Georgi and a senior graduate student in his group, **Sally Dawson** [PhD 1981, now Senior Scientist at the Brookhaven National Laboratory]. They disagreed on an aspect of her work; Sally told him he was wrong. Surprised, Nelson thought, “Wow, you can do that? That’s cool.”

Apart from Dawson, Nelson had few role models early in her career, a time when female PhD physicists were sparse. Harvard’s Physics Department, for example, didn’t hire its first female Senior Research Associate in Physics, Margaret Law, until 1971. And it wasn’t until 1992 that Harvard first awarded tenure to a female faculty member, Melissa Franklin.

In a 1976 interview, Law reminisced about having edited a report “that a group of local women scientists brought out about the status of women in science and what one could do to improve it, and the whole thing that kept coming [up] over and over again was role models, role models; we need more role models in schools and universities.”<sup>3</sup>

Now, we have them. The women included here represent just a small cohort of successful physicists who happen to be women. There are, of course, many, many more.

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## ALUMNAE, NOW HARVARD FACULTY

### LISA RANDALL

Frank B. Baird, Jr., Professor of Science, Harvard Department of Physics. PhD 1987; Advisor: Howard Georgi.

Randall consistently surpasses limits. In 2007, *Time Magazine* named her one of their “100 Most Influential People.” Her name populates numerous “most accomplished” lists and membership rosters for the most prominent scientific academies and societies. A well-known public persona and scientific heavyweight, Randall wins awards as a physicist, an author, and even an artist. She wrote a libretto for an opera that debuted in Paris, and she co-curated an art exhibit.

In an interview with the American Physical Society, Randall said she pursued physics in part because “one of the nice things about math and science is it’s obvious; you get the answer or you don’t get the answer.” So far, Randall has published four books that explain these answers to the general public. These books have earned widespread accolades and continue to add to Randall’s award count. Two of them—*Warped Passages: Unraveling the Mysteries of the Universe’s Hidden Dimensions* and *Knocking on Heaven’s Door: How Physics and Scientific Thinking Illuminate the Universe and the Modern World*—made the New York Times list of 100 Notable Books of the Year.

### ALYSSA GOODMAN

Robert Wheeler Willson Professor of Applied Astronomy; co-Director for Science at the Radcliffe Institute for Advanced Study. PhD 1989; Advisor: Irwin I. Shapiro.

Goodman investigates how interstellar gas arranges itself to form new stars. She co-founded Harvard’s Initiative in Innovative Computing, which combines computing and science to create new tools to accelerate research, learning, medical advances, and progress in other areas as well.

In childhood, Goodman received nothing but encouragement from her parents. As a professor, she tries to give back this unflinching support to her students. In a 2015 *Harvard Gazette* article, titled “An Inspiration to Students,” then undergraduate Jasmine Chia said Goodman taught her that “the world of science is accessible to all who are willing to put in the hard work and passion. There are no limits.”<sup>4</sup>

The department’s female PhDs have gone on to careers in academia, financial consulting, industry, patent law, software engineering, data science, and even marketing. They work at Apple, Stanford University, CERN, SpaceX, Middlebury College, Amazon, the National Institute of Standards and Technology, and Lyft, among other places of employment.

A few trends emerge. These women share similarities in their paths to physics. They had at least one inspirational teacher. They either ignored opposition or rebelled against it. And almost all agree that physics is a challenge for everyone, irrespective of demographic factors.

## Ongoing Challenges

We live in an asymmetric world. In physics, for example, men have always outnumbered women. Along with computer science and music composition, physics maintains some of the lowest percentages of female PhDs across the country. In 1966, women in the United

States earned only 2% of the PhDs in physics. In 2015, this number rose to a still modest 20%.

What accounts for the gap? Recent studies explore various factors, including gender bias and discrimination, lack of opportunities and resources, inadequate advisors and mentors, department culture, and family obligations.

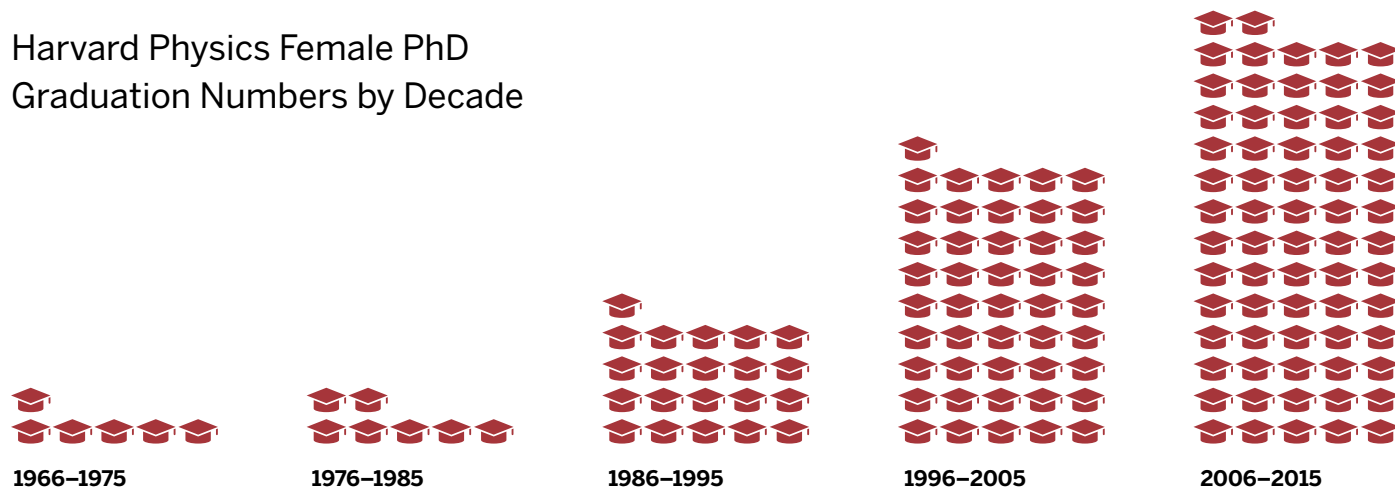
One 2018 meta-study, for example, examined the ratio of female to male authors across 10 million science, medicine, and technology journals worldwide.<sup>5</sup> Physics ranked third to last. Only computer science and quantitative finance had larger disparities. The paper, which relied on data from 2016, predicts that physics will not achieve gender parity in authorship until almost one hundred years from now.

Harvard, for its part, does better than the national averages. In 2018, women accounted for one-third of the department’s PhD students. Still, as one department staff member put it, “one third is a success only in comparison.”

Currently, the department has nine female faculty members, representing 17.6% of the faculty body. By comparison, women make



## Harvard Physics Female PhD Graduation Numbers by Decade



up 11% of faculty at the average Physics PhD-granting institution in the United States. For the average undergraduate institution, where women occupy a larger proportion, they still comprise only 16% of the total.<sup>6</sup>

Although the numbers show progress, the advances have been painfully slow. Still, a discussion of gender disparity deserves more than bare statistics. The issue, complex and variant, cannot be distilled into any single measure, according to the American Institute of Physics. Researchers should—and will—continue to examine what factors contribute to the gender gap. And, while investigation is ongoing, it's important to recognize female physicists for their scientific accomplishments.

## The Way Forward

In a 2013 study,<sup>7</sup> Philip Sadler, a professor in Harvard's Center for Astrophysics, investigated five common factors that influence a female student's decision to pursue a career in the physical sciences: single-sex classes, female teachers, female scientist guest speakers, discussion of female scientists in class, and discussion of the underrepresentation of women. Which had the greatest effect on female retention? Direct conversations about underrepresentation.

The Harvard physics department has held such conversations and plans to continue them. Professors Jenny Hoffman and John Huth now head a new Equity and Inclusion Committee in Physics. With input from the community, the Committee will determine how the department can make Harvard Physics a place where everyone can thrive. They launched the effort with an open town hall in June 2018.

On the student side, the Harvard Women in Physics group offers workshops and social events for all undergraduate, graduate, and postdoctoral women and men. Recently, they organized an American Physical Society (APS) Conference for Undergraduate Women in

Physics, volunteered at the MIT Museum's Girls' Day, convened a panel to discuss how to prepare for graduate school, and held open lab tours for undergraduates.

The graph above shows the numbers of female PhD graduates from Harvard over the last 50 years. The progress has been slow, as stated, but seems to be gaining momentum, finally. And many people within this department, and throughout the university at large, are eager to see that trend continue.

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FOCUS

## Julian Schwinger: A Centennial Celebration at Harvard

by Steve Nadis

“Prodigies don’t always pan out. Julian Schwinger did.” Thus proclaimed an October 1996 article in *Physics Today*. “He had fastened onto physics for his life’s work while still in his early teens when he got to the letter ‘P’ in a systematic odyssey through *Encyclopedia Britannica*.” Schwinger was born in New York City on February 12, 1918, the son of Polish-Jewish émigrés whose families were in the garment industry, and on February 12, 2018, exactly 100 years after his birth (and 14 years after his death), his career and extraordinary accomplishments were celebrated at Harvard’s Jefferson Laboratory.

There was indeed a lot to celebrate. Schwinger published a physics paper in a professional journal when he was just 16 years old—the first of more than 200 publications that followed. He enrolled in the City College of New York (CCNY) at the same age but came close to flunking out due to the large number of courses he was required to

take outside of physics that were of little interest to him. Luckily, Schwinger crossed paths with Columbia physicist Isidor Rabi who immediately recognized the teenager’s preternatural abilities. Schwinger then transferred to Columbia where he had the freedom to indulge his passion for physics. There, under Rabi’s supervision, he earned a Bachelor’s degree and PhD by the age of 21. Schwinger then worked for two years at Berkeley as J. Robert Oppenheimer’s postdoctoral assistant before taking a lectureship at Purdue, interspersed with work at MIT’s “Rad Lab” to help advance the nation’s radar capabilities during World War II.

From 1945 to 1972, Schwinger served as a full-time member of the Harvard Physics faculty. In the course of an incredibly diverse career, he made important contributions to broad areas of physics including nuclear, atomic, particle and condensed matter physics, statistical mechanics, classical electromagnetism, synchrotron radiation,

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waveguide theory, general relativity, and quantum field theory. But he is best known, by far, for providing an essentially complete theory of quantum electrodynamics (QED), which combines quantum mechanics and special relativity to describe the interactions between light, matter, and the electromagnetic field. Schwinger unveiled his reformulation of QED in high profile lectures in 1948, as well as in a series of papers published in 1948 and 1949 in *Physical Review*, while continuing to expand upon these ideas in the 1950s. He shared the 1965 Nobel Prize for this work with Richard Feynman and Sin-Itiro Tomonaga, other key framers of QED theory. In 1951, Schwinger became (with Kurt Gödel) the first winner of the Albert Einstein Award; he earned the National Medal of Science in 1964.

It was this legacy that drew a standing-room-only crowd of more than two hundred attendees—including current physics students, faculty, and research scholars, plus former Schwinger students and other interested parties—to Jefferson Lab 250 in February of this year. People had come to pay tribute and learn about a man widely regarded as one of the 20th century's greatest physicists. Physics Professor Howard Georgi (BA '67) delivered the opening remarks for the proceedings called "Memories of Julian." He was joined onstage by three former Schwinger students—Sheldon Glashow (PhD '59), an emeritus professor of physics at Boston University and Harvard; Roy Glauber (BA '46, PhD '49), an emeritus professor of physics at Harvard; and Daniel Kleitman (PhD '58), an emeritus professor of applied mathematics at MIT—and a former assistant, Walter Gilbert, who previously served as a Harvard professor of molecular and cell biology. All told, Schwinger supervised 73 PhD recipients, making him one of the most prolific graduate advisors in physics anywhere. Like their mentor, Gilbert, Glashow, and Glauber each won a Nobel Prize, as did two other Schwinger students, Walter Kohn (PhD '48) and Benjamin Roy Mottleson (PhD '50).

Georgi kicked off the Special Colloquium by introducing himself as a "Schwinger grand-student," given that he did his PhD work at Yale under Schwinger student Charles Sommerfield (PhD '57). In his junior year as a Harvard undergraduate, Georgi took Schwinger's 253 (quantum field theory) course. "It was amazing," Georgi recalled. "He was a magisterial lecturer. He just had total control, not just of the material but of the total class... The blackboard was spectacular. Every mark was clearly planned, and he always ended at the right-hand side of the blackboard in Jefferson 356 so that at the end of class he could scoot out. I always assumed he was escaping from his graduate students. But I'm looking forward to finding out what was actually going on with this mysterious character."



Image courtesy of AIP Emilio Segrè Visual Archives, Weber Collection.

Georgi, fortunately, had some expert help with that inquiry, as his remarks were followed by those of the four highly credentialed panelists—Glauber, Gilbert, Kleitman, and Glashow—people who knew Schwinger well.

Some insights into Schwinger's character were also volunteered during the question-and-answer session by a former student, Fred Cooper (PhD '69), as he described the scene in Stockholm at the 1965 Nobel Prize award ceremony. "In a room full of people, including a large number of reporters," Cooper recounted, "Schwinger humbly told the audience: 'I woke up this morning, and the problems I couldn't solve yesterday, I can't solve today.'" Maybe the speedy exits from the lecture hall that Georgi alluded to were designed to avoid student questions so that Schwinger could attend, instead, to the questions bubbling within his own fertile mind, coupled with an urge to resume work on the intransigent problems he was still determined to solve.

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**Roy Glauber (excerpted remarks).**

I thought I'd make a few observations about the history of the times we lived in. First, let me remind you that even the atomic nucleus is a relative newcomer on the scene. It dates from the turn of the last century, and very little was known about it for a long time. Many of the things that were found out about the nucleus were found out by one particular man, I. I. Rabi of Columbia. And he [Rabi] did one more thing: He found a shy CCNY "refugee" among the students at Columbia, and that was Julian Schwinger. Julian had a difficult time at CCNY; he went uptown to sit in on lectures at Columbia, and Rabi noticed him and acted as a kind of godfather. He, in fact, was responsible for giving Schwinger his PhD at Columbia and sending him to California to work with Oppenheimer. Schwinger spent most of the war years at MIT. I was at Los Alamos then, a bit underage I might add.

The time I want to focus on now is the end of the war when people were devoted to peacetime thoughts. How were we going to investigate the physics of these nuclei? The energies available were really quite low. Well at Los Alamos we had a lecture by a visitor in either September or October of 1945. It was a lecture on a new accelerator designed by Julian Schwinger, whoever he was. Bill Rarita happened to work in an office opposite mine and introduced me to this Schwinger chap who turned out to be rather short of stature and wore his hair with a bit of a pompadour up in front, which gained him about an inch in height. He was a rather shy guy, but he did give a lecture on a kind of particle accelerator he had designed, a proton accelerator. It was quite a clever and very simple device.

The extraordinary thing was the lecture. It lasted about an hour and a half and, I have to say, was one of the best lectures I ever heard. It was extraordinary because he had worked out every last detail of this device. I found it unbelievably impressive, especially compared to a great many of the lectures I heard at Los Alamos. No such lecture ever had the smoothness or the continuity or obvious cogency of this particular lecture.

At that stage, I still had two undergraduate courses in fields other than science that I had not yet taken, so I had no degree and felt I had little choice but to come back here [to Harvard]. Meanwhile, I had been figuring that I would go to work for my boss at Los Alamos, Hans Bethe, who was in his way enormously impressive and a real father figure. I have to say that hearing this single lecture from Schwinger and given the knowledge that he had just received an appointment at Harvard, I was seriously shaken in my determination to go back with Hans Bethe when he returned to Cornell, and in fact

I didn't. I came back here, absolutely delighted that Schwinger was going to be at Harvard from that point on.

**Walter Gilbert (excerpted remarks):**

I had a postdoctoral fellowship at Harvard [starting in 1957], and the year after that Harvard made me Julian's assistant. Julian and I constantly talked about doing something together and then never did. Our entire experience was actually going to Julian's lectures.

[The students and I] sat entranced as he covered the blackboard from one top corner to the lower further corner and copied everything down, thinking that at least by writing it down we would be able to catch some of the mystery and some of the magic of it. In those years he was lecturing on his conception of quantum mechanics, which he called measurement theory, and it was wonderfully obscure. I never could do anything with it.

The physics world centered around Julian in a curious way. Almost all of us were doing other things in physics and talking to him off and on. I remember spending a long afternoon standing outside the building here, leaning on the cars with Julian, discussing the Hungarian uprising and the world situation. It was probably the only serious conversation I had with him throughout that entire period. And I carried it in my memory. After every lecture, we would go down to the restaurant in Harvard where we could have a 99 cent lunch. It had to be under a dollar for tax reasons.

**Daniel Kleitman (excerpted remarks):**

Sheldon Glashow and I graduated from Cornell University in 1954 and enrolled as graduate students in the physics department at Harvard. We both enrolled in Professor Schwinger's course, among others, and continued to take his courses for the next two years. He started from the very beginning with his formulation of quantum mechanics and proceeded to develop quantum field theory and much more.

The class consisted of about 30 students assembled at exactly five minutes after the hour. Schwinger would arrive at the door and immediately begin his lecture. He spoke without notes and talked in a quiet voice in a manner so crystal clear and persuasive that it was hypnotic. Nobody dared to ask a question. Aside from his voice and the sound of his chalk, there was absolute silence in the room aside from occasional burps from a classmate who had a digestive disorder. At exactly five minutes before the hour, he would be positioned close to the door, would put down his chalk and exit, often moving rapidly toward his sports car with which he would travel home. The lectures were as well organized and informative as any I have ever experienced. Every one of them.



Left to right: Walter Gilbert, Sheldon Glashow, Daniel Kleitman, and Roy Glauber. Photograph by Paul Horowitz.

As an adviser, he was always friendly and helpful. My problem was I thought that the time to talk with him was when I made significant progress. Much later I learned that the time for a student to talk to his adviser was when he was stuck. Fortunately, I was able to develop a working relation with this gentleman here, Professor Roy Glauber, and with his aid and comfort and the kindness of Julian Schwinger, I graduated and went out into the world.

Julian Schwinger's lectures were wonderful and inspiring. They inspired us to do something similar—to produce out of one's own mind a reformulation of an important subject that will solve important problems. I never found the opportunity to do that in the world of physics. Fortunately for me, I was lucky enough to do such things at a much, much smaller scale in mathematics, and so I became a mathematician.

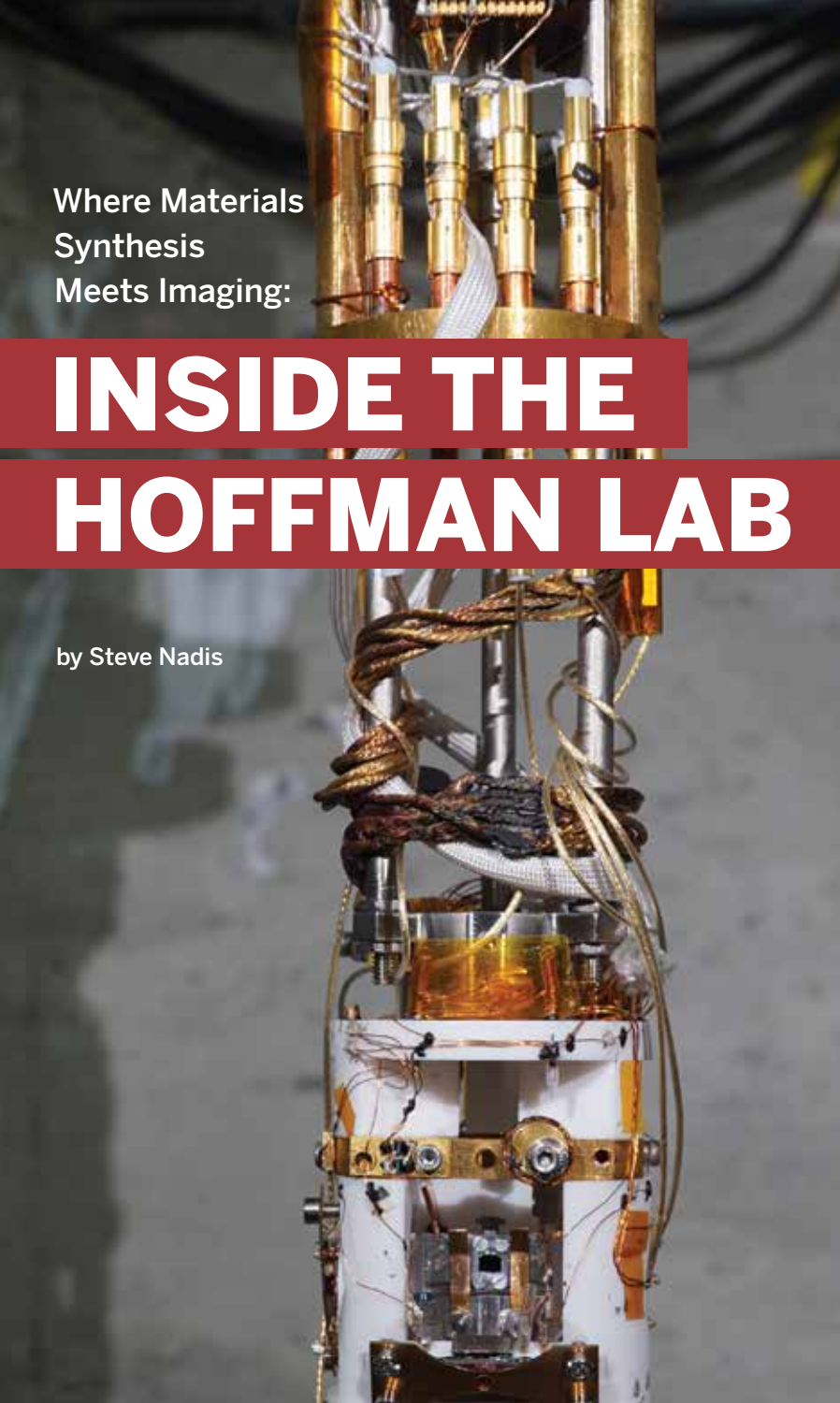
### **Sheldon Glashow (excerpted remarks):**

I was at Cornell [as an undergraduate] because I was rejected at Harvard. But Harvard accepted me [for graduate school]. I guess we were in our second year that [Schwinger] had that famous interview with about ten of us: Danny [Kleitman] and me, Marshall Baker, Charlie Sommerfield, Ray Sawyer, and three guys whose name begins with "W," and maybe somebody else. By the time Schwinger got to me, he had run out of problems that made any sense, so he developed a remark that he had published earlier. He said that there are these things called Yang-Mills theories and they might be useful. "Why don't you think about that?" he asked. Anyway, I'd like to say right now that Schwinger was indeed the first person to invoke Yang-Mills theories, gauge theories, as we call them today, to unify weak and

electromagnetic interactions. I found no such allegation anywhere in the literature aside from in his 1956 paper. So he sent me off and said do it. Of course I had no idea of how to do it.

Let me jump ahead. My PhD examination committee consisted of Paul Martin from here, recently sadly deceased, Julian Schwinger, a physicist named Sacks (a good friend of Julian's who was chairman of the department at Wisconsin at the time), and Frank Yang of Yang-Lee [and Yang-Mills fame]. I started to explain what I had done, which wasn't all that much, but I started by explaining how the electron neutrino and muon neutrino are very likely different from one another—different particles and that had to be built into the model. At that point Yang said, "Stop. Mr. Glashow, what do you mean the electron neutrino and muon neutrino are different from one another? There's no way to establish such a fact." And Julian said, "Shelly, quiet down. Let me answer Yang." So at that point my exam was more or less over, and Schwinger explained in great detail what such an experiment would be like. It would be the experiment that would be done later by Schwartz and Lederman and Steinberger. He described how such an experiment could prove that electron neutrinos were different from muon neutrinos, and he, Schwinger, had very peculiar reasons, correct ultimately, that the neutrinos had to be different from one another.

But I got my degree. And it was wonderful working with Julian. The one regret that we had, which we expressed to one another much later, was that we never got around to writing that paper on the electroweak theory that we should have written.



Where Materials  
Synthesis  
Meets Imaging:

# INSIDE THE HOFFMAN LAB

by Steve Nadis

Late one night in June, Physics Professor Jenny Hoffman found a curious message in her email inbox under the subject: “Progress from your 3D Atomic Printing Shop.” The body of the message read as follows: “This is a status update for your recent order with us. The shape of the letter ‘H’ has been straightened out this afternoon and will be refined in the coming days. Yours, 3D-ATOM-SuperPRINT.”

Above: Scanning tunneling microscope in Hoffman Lab.

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The email was actually sent by Physics postdoc Christian Matt as a humorous way of announcing a new advance achieved in the lab. Hoffman was amused by the message, as well as elated, noting that this was the smallest ‘H’ she had ever seen, consisting of just seven atoms. “And it demonstrates a growing theme in our lab,” she says, “namely that we can use our scanning probe microscopes not only for microscopy but also for manipulating materials, including single atoms, as well as for manipulating single vortices [quanta of magnetic flux] in superconductors and spin domains in hard magnets.”

Matt created his atomic-scale rendering of the alphabet’s eighth letter using a technique devised by Harris Pirie, a Physics graduate student who’s also based in the Hoffman lab. Matt started with a thin sample of cerium antimony that was atomically flat and clean, save for random atoms that sometimes land on the surface to which they’re loosely bonded. By taking the scanning tunneling microscope (STM) tip, which is like the point of a super-sharp pen, and bringing it close to the stray atom while applying a negative voltage, he explains, you can pick up the atom and move it where you want it to go. You then lower the tip and release the atom by applying a positive voltage. Matt repeated the process six more times to create the “H,” which could stand for “Harvard” or “Hoffman” or “Harris” or any and all of the above, he says. Although he had hoped to make the letter even bigger, by laying down more atoms, the tip had become blunt and a bit dirty, so he had to settle for a seven-atom depiction.

This was not the first time individual atoms had been moved to make a letter or word. In 1989, Don Eigler and a team at IBM spelled out “IBM” by arranging 35 xenon atoms on a metal surface. But it was the first time, so far as anyone in the lab knows, that such “printing” had been accomplished on cerium antimony. That’s a highly “correlated” material—wherein strong interactions between electrons can give rise to interesting new physics—in contrast to conventional metals where electrons barely interact at all. A main focus of the Hoffman lab is to use its high-resolution imaging tools to improve our understanding and control of exotic materials like this, which contain new phases of matter and hold the potential for significant practical uses.

To that end, the lab has designed and built three customized STMs. A sign on the door in which the equipment is housed, located in the basement of

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the Laboratory for Integrated Science and Engineering (LISE) building, says, “PLEASE OPEN SLOWLY—BE CALM,” for even the slightest vibrations can disrupt the STM measurements. “If you push the door too quickly,” Pirie explains, “you can create a pressure wave that creates a vibration that is way bigger than the effect we’re trying to measure.” The three microscopes are all located in the sub-basement, three floors underground, to shield them from outside disturbances. Each STM floats on a 30-ton concrete base that is suspended on air springs. “The room itself is floating, and we independently float the table on which the microscope stands,” Pirie says. On top of that, the walls are soundproofed, all in an effort to minimize the effects of noise and vibrations.

In addition to the imaging and manipulation of existing materials, the Hoffman lab is equally focused on making new materials. The group uses a technique called molecular beam epitaxy (MBE) to create novel films or layered “heterostructures” that combine two or more materials. Lab researchers might start, for example, with a base or substrate of strontium titanate ( $\text{SrTiO}_3$ ), and heat it to more than  $1000^\circ\text{C}$  to boil off impurities. They might then separately heat and vaporize sources of iron and selenide, spraying the two beams at the same time onto the strontium titanate substrate where they adhere to the surface, forming iron selenide ( $\text{FeSe}$ ), one molecular layer thick. In this way, surfaces can be built up a single ultra-thin layer (or film) at a time. The scientists are eager to see how the different layers interact and how the characteristics of one substance may change due to the close proximity of another.

The MBE is kept at an ultra-high vacuum so that no dust, dirt, or other unwanted substances can contaminate the materials being grown. This device is also attached, without breaking the vacuum seal, to the STM, explains Pirie, “which is used to analyze the newly created materials and find out how to grow them better.” Unlike extra-galactic astronomy and sub-atomic particle physics, which are focused on observing and understanding the world as it is, the Hoffman lab closes the loop through both observation and synthesis in order to understand the world as it could be—the objectives being to generate new physics and optimize the properties of materials that never existed before.

Scanning probe microscopy is somewhat like running your finger over a surface to figure out how rough or smooth it is—albeit doing so with picoscale precision. The basic approach is to apply a voltage to the sample and then move the STM tip closer to the sample until a so-called “quantum tunneling current” is established. Moving the tip toward or away from the sample is therefore like tuning the dial on a variable resistor: As the tip gets closer to the sample, the current steadily increases and the resistance declines. As the tip is moved over an uneven surface, the STM automatically adjusts its distance to maintain a constant current. The surface topography can thereby be determined to sub-picometer ( $10^{-12}$  meter) accuracy.

Iron selenide, which was mentioned before, is of particular interest to the Hoffman group owing to the mysterious role it plays in superconductivity—the resistance-free flow of electrical current. On its own, iron selenide is only superconducting at or below the critical temperature of 8 degrees Kelvin. However, when a single atomic layer of iron selenide is deposited onto a base of strontium titanate, the critical temperature for superconductivity goes up to 110K. That astonishing effect was first observed in China in 2012, but there’s no consensus yet as to what’s behind the phenomenon. “We’re trying to use the STM to see where the enhancement comes from,” says Jason Hoffman, a research associate in the Hoffman lab (who is not related to the lab head). “And we’re experimenting more generally with combining two materials with low superconducting transition temperatures in an attempt to boost the transition temperature at the interface.”

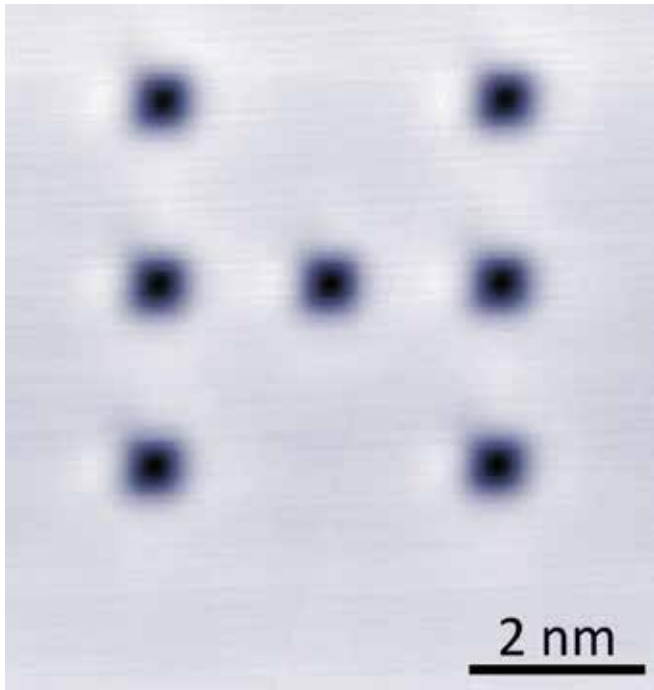
If we can figure out how this enhancement works and reproduce it on a copper oxide substrate that already has a critical temperature above 130K, adds Pirie, “then we might come close to the ultimate goal—a superconductor that works at room temperature.”

The Hoffman lab was recently awarded a grant from the Office of Naval Research with Prineha Narang, Assistant Professor of Computational Materials Science (SEAS), to do a high-throughput search for more such “oxide-chalcogenide” interfaces that show enhanced superconducting temperatures. Narang will run a computer search of possible material combinations, while Hoffman and her colleagues will try to grow the most promising of these materials and see if they match predictions—again in keeping with the general theme of closed-loop physics.

Meanwhile, there’s a parallel and sometimes overlapping effort underway to explore topological insulators, which conduct electricity only on the surface, not in the interior. “You can’t get rid of the conducting surface,” notes Pirie, whose research lies in this area. “If you peel off the outer layer, the material below becomes the new conducting surface.” These materials, he adds, are somewhat like bar magnets. When you cut a bar magnet in half, you get two bar magnets. Similarly, when you cut a topological insulator in half, you get two topological insulators.

Coupling a superconductor and a topological insulator can lead to intriguing results, Jenny Hoffman says. “The two materials influence each other’s properties.” Electrons at the boundary move back and forth, forming a new kind of superconductor whose spins are aligned (unlike a typical superconductor where electrons of opposite spins are paired). In some configurations, the topological superconductor can trap excitations called Majorana fermions—recently discovered particles (first proposed in 1937) that serve as their own antiparticles.

Majorana fermions are fascinating in their own right but could also play a big role in quantum computing, which Hoffman and her team members plan to investigate with their new Harvard colleague,



Seven atoms arranged on cerium antimony. (Image courtesy: Hoffman Lab)

Assistant Professor of Physics Julia Mundy (see Mundy's profile on page 5).

Meanwhile, the group is also focusing on atomic scale 3D printing, which draws upon the combination of MBE and scanning probe microscopy to assemble never-before-seen quantum materials and heterostructures. The "H" created in the spring of 2018 (see the image, left) was a fun exercise that demonstrated some of the relevant technology, though important applications can surely follow. "If we can manipulate atoms and arrange them in specific positions on the surface of a material, we can create structures where there's interesting physics going on related to superconductivity, magnetism, and other phenomena," Jason Hoffman notes. "And there are practically endless possibilities for computing or making electronic devices such as switches, gates, and complicated circuits."

That, says Jenny Hoffman, sums up the motivation behind much of the research in the lab. "I want to make new materials. I want to put material A and material B together and see what's happening at the interface—the goal being to discover a new state of matter that never existed before and then look at it in real time with atomic resolution." She and her coworkers are making steady, though incremental, progress toward that goal—atom by atom and layer by layer—as they strive to "close the loop" through physics that can make a palpable difference in the world.

## Jenny Hoffman's Lifelong Dream

Jenny Hoffman is a driven experimentalist who's been known to stay up all night to solve a physics-related problem. Despite having an extremely productive research career, Hoffman doesn't focus on physics alone because, she says, "I always do better with at least two things going on." She has a hobby that can also keep her up all night—24-hour endurance running. On top of that, she and her husband, Harvard physicist Daniel Larson, are parents to three active children (ages 6, 9, and 12), and child rearing has been known to contribute to some sleepless nights as well. But Hoffman likes to keep busy, moving around as much possible—tendencies, she claims, that helped guide her onto her current career (and athletic) path.

When Hoffman was nine years old, she told her father, a Harvard Business School alum, that she wanted to be a Harvard math professor when she grew up. "Then I discovered that I don't sit still too well, so math was out." She later considered a career in theoretical physics but realized that might also bring up the same sitting issue. She eventually settled on experimental physics, which seems to fit well with both her temperament and intellect.

Her first foray into this area occurred in the summer of 1996, just after she graduated from high school, when she interned in the laboratory of Harvard physicist Eric Mazur, whom Hoffman calls "an

amazing mentor." She was charged with automating a liquid nitrogen transfer system and really enjoyed the hands-on, concrete nature of the project.

She didn't have much time to pursue research as an undergraduate at Harvard because she was on the Radcliffe varsity crew team. During her sophomore year, she met Larson, who was then a Harvard senior, and they've been together ever since. Larson was accepted to a graduate physics program at Berkeley, but he decided to defer for a year to wait for Hoffman to go to Berkeley too. Hoffman, in turn, had to graduate in three years rather than the usual four, which meant she would miss out on her opportunity to be captain of the crew team and the possibility of trying out for the U.S. Olympic team. But she ran her first marathon as a college junior and loved it, which helped her see that there might be life after rowing.

Upon entering Berkeley as a graduate student, Hoffman assumed that she would go into high-energy particle physics but balked when she considered there were only a handful of particle accelerators around the world, so she would likely be spending a lot of time sitting on airplanes. She was instead drawn to low-temperature experiments that could be pursued at practically any major university. At Berkeley, she built her first scanning tunneling microscope, which



she used to image the electronic structure of superconducting materials.

During her first five years at Harvard, Hoffman focused on atomic-resolution imaging of the electronic structure of quantum materials. The overriding purpose of her research was to understand why materials behave the way they do—to understand their macroscopic properties in relation to their microscopic electronic structure so that one might develop new materials with optimized properties that could enable new technologies.

Hoffman enjoyed collaborations with scientists growing interesting materials all over the world, but by 2010, she decided she no longer wanted to wait for others to discover and send her their materials to study. “I wanted to create new materials myself.” She brought the idea to fruition during a fellowship at the Radcliffe Institute for Advanced Study in 2013. Since then, she has been synthesizing hybrid materials through the process of molecular beam epitaxy (MBE), which involves “spraying” volatile elements, one atomic layer at a time, onto a solid substrate. Materials of particular interest to her include high-temperature superconductors, vanadates (vanadium oxides), and “topological insulators”—insulators wrapped within conductors that have potential applications in spintronics and quantum computing.

Of course, it’s never all work and no play for Hoffman, who believes it’s healthy, and indeed essential, to have an outside activity or two. “It helps clear my head, making me more effective as a physicist,” she explains.

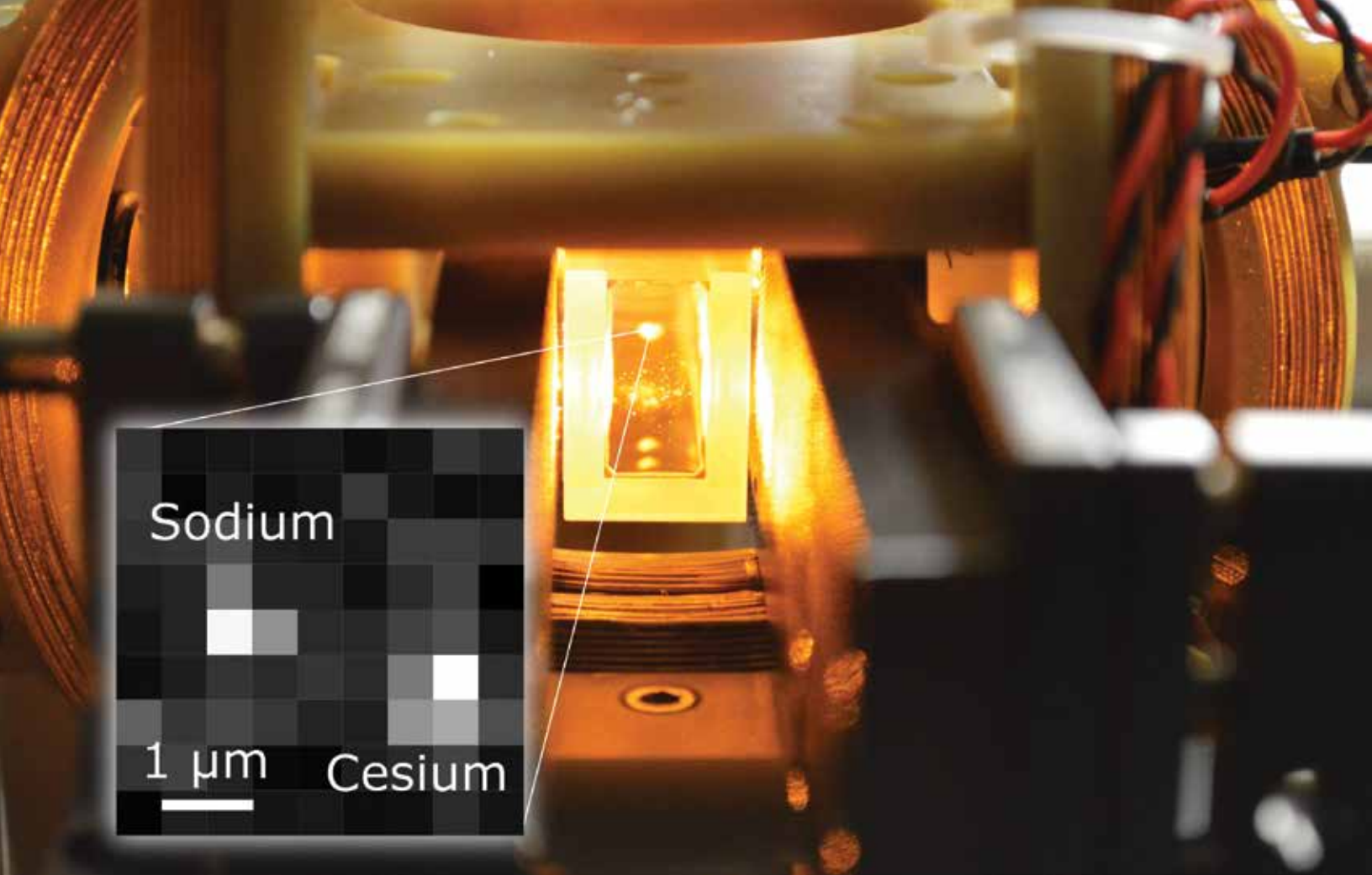
On New Year’s Eve 2005–2006, at the end of her first year at Harvard, Hoffman ran her first 24-hour race, which was held in Arizona. She won that event, qualifying for the U.S. National Team, but felt sick afterwards and discovered she was pregnant. She went on to have three kids—and nine straight years of pregnancy and breastfeeding—which kept her from racing competitively.

She gave it another try in the fall of 2014, entering the National Championship 24-hour race in Cleveland, Ohio. After winning that contest, she maintained a three-year streak as National Champion from 2014 to 2016. While preparing for the 2016 race, which was also held in Cleveland, Hoffman met with her former Radcliffe crew coach, Amy Baltzell, who is now a professor of sports psychology at Boston University. Baltzell told Hoffman that when you push yourself to your limits, you need a mantra. Baltzell helped her come up with the phrase, “This is my lifelong dream,” which Hoffman repeated to herself hundreds of times as she circled the 0.9 mile course for 24 hours over a total distance of 142 miles. Along the way, she captured her third National Championship win, along with USA Track & Field Athlete of the Week honors. She also became a member of the U.S. National Team, which won the gold medal last summer at the 24-Hour World Championships in Belfast.



Winning the USA National Championship 24-hour run in Cleveland, Ohio, September, 2016.

Since then, Hoffman has run a bit less (for her, though still more than just about anyone else), competing in some local races in the spring of 2018, including a first-place finish in a 50-mile race around Lake Waramaug, Connecticut, and a 7th-place finish in a 100-mile race around New York City. Meanwhile, she is contemplating some new challenges. A longstanding goal in the academic realm is to invent a novel material that turns out to be extraordinarily useful. On the physical exertion front, she and her husband plan to hike the entire 2200-mile-long Appalachian Trail with their three kids, sometime in the next few years. Hoffman also meets occasionally with Baltzell to discuss the next big project that she’ll personally take on. One item occupying a special place on her list is to run from coast to coast across the continental United States. “I don’t know when that will happen,” she says, “but you’ve got to have dreams.”



by Lee Liu and Yu Liu

Above: view of laser-cooled and trapped cloud of a million sodium atoms suspended inside the glass cell vacuum apparatus. Inset: Microscope view of fluorescence from a single sodium and single cesium atom trapped side-by-side.

## **THE NI LAB: QUANTUM CONTROL AND THE STUDY OF CHEMICAL REACTIONS**

For centuries, physicists have relied on scattering measurements to probe the inaccessible. In 1801, Thomas Young's double slit experiment revealed the wave nature of light. A century later, Rutherford's gold foil experiments established that an atom's volume is mostly empty space. A century after that, the Higgs boson was discovered at the LHC. The ideas underlying the humble (and not so humble) scattering experiments are as timeless as they are powerful.

Quantum scattering also underlies chemical reactions. The relationship may not be obvious at first: on the one hand, quantum scattering involves sending a probe (light, alpha particles) at a target (double slit aperture, gold atoms) and seeing what comes out. On the other hand, a chemical reaction involves the breaking and forming of chemical bonds via the rearrangement of electrons and nuclei. How the rearrangement proceeds depends on the electrostatic and exchange forces generated by the electronic and nuclear configurations at every instant in time. The situation is complicated by the fact that the behavior of one electron or nucleus influences (and is in turn influenced by) all its neighbors. Understanding this process is one of the grand goals of chemistry.

There is an intuitive picture that enables us to recast this complex situation into the language of quantum scattering. The chemical reaction can be thought of as a ball rolling along a landscape of hills and valleys. The elevation represents the potential energy of the system, and the coordinates of the ball represent the nuclear (and consequently, electronic) configurations. Thus, all the complexity of chemical reaction dynamics is encoded in the topography of the landscape called a “potential energy surface” (PES).

Just as a gold atom redirects alpha particles into different scattering angles, the PES “redirects” incoming reactants into different products and product states. The PES, therefore, completely describes the dynamics of that particular chemical reaction (Fig. 1). In general, however, it is impossible to calculate details of the reaction accurately from scratch. Experiments that reproduce the “ideal” chemical reaction are needed to impose some constraints on the theory.

What constitutes an ideal chemical reaction? Let’s look at quantum scattering for guidance:

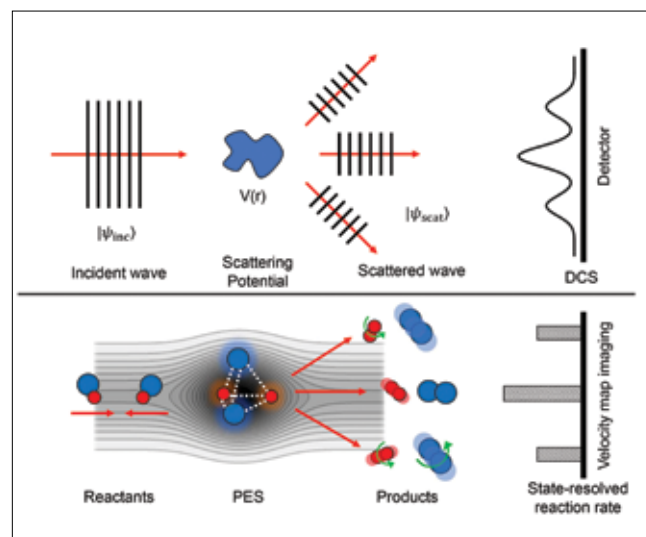
QUANTUM SCATTERING	CHEMICAL REACTION
Prepare a known incoming state $\Psi_{in}$ .	Prepare reactants in a pure quantum state (internal and colliding).
Measure the differential cross section.	Measure the products with single quantum state resolution.
Extract the shape of the scattering target $V(\mathbf{r})$ .	Extract the PES.

As experimentalists, we concern ourselves primarily with the first two entries on this chart, though that is easier said than done. Under conditions where chemistry normally takes place (such as in a car engine or laboratory beaker), the reactants are simply too hot. For example, at room temperature, typically hundreds of colliding states and hundreds of internal states may be occupied! The total number of quantum states involved is therefore in the tens to hundreds of thousands. The solution is to go into the “ultracold” regime: At less than one millionth of a degree above absolute zero, all but a single entrance channel among the many possible states are frozen out.

However, even getting to such frigid temperatures is not sufficient. In bulk, collisions occur at random, meaning other processes can compete with the desired reaction. To probe just a single reaction channel, we need to use a beaker so small that it contains only the precise number of particles needed for the reaction and no more.

Finally, exothermic chemical reactions can release enormous amounts of energy, meaning that, even if one were to prepare a single entrance channel, the outgoing products may still occupy a vast multitude of states.

Fig. 2 (page 27) depicts an idealized situation with a single reactant channel on the left (i.e., well-defined internal states, colliding states, and particle number) and a reasonable number of product channels on the right. Such a system would afford us the clearest possible picture of the mechanisms underlying the reaction. In our lab, we are working towards exactly these systems. Furthermore, with precise knowledge and control of chemical reactions, we will work to build designer molecules<sup>1</sup> and harness their rich and coherent quantum degrees of freedom for the purposes of quantum engineering.<sup>2</sup>



Above right: Fig. 1. In a typical quantum scattering experiment, a known incoming state  $\Psi_{in}$  (e.g., a plane wave) is incident on a scattering target,  $V(\mathbf{r})$ . The output is a scattered wave  $\Psi_{out}$ . The problem of finding the shape of the unknown  $V(\mathbf{r})$  then becomes that of measuring the differential cross section (DCS). Knowledge of  $V(\mathbf{r})$  then allows us to predict the outgoing fragments for a given  $\Psi_{in}$ . [Bottom] In a chemical reaction, in direct analogy to quantum scattering, measuring the state-resolved reaction rate allows us to determine the PES, and thereby obtain a complete mechanistic understanding of the chemical reaction.

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## Our Platform

In the Ni lab, we are engineering two different chemical systems: a quantum degenerate gas of KRb molecules and single ultracold NaCs molecules in optical tweezers. Both systems can produce a few types of chemical reactions that we can study in a quantum state-resolved fashion. Our current focuses are the double displacement  $K Rb + K Rb \rightarrow K_2 + Rb_2$  reaction for the KRb system, and the photoassociative  $Na + Cs \rightarrow NaCs$  reaction for the NaCs system.

### Preparing the Reactant State: Ultracold Atoms and Molecules

The 1997 Nobel prize in physics was awarded for laser cooling dilute gases of alkali atoms to a millionth of a degree above absolute zero. Over the last decade, scientists have learned to assemble those same atoms into ultracold molecules.<sup>3,4</sup> We highlight the key steps towards creating ultracold KRb and NaCs below.

#### Laser Cooling

Both experiments begin by cooling constituent atoms (K and Rb, or Na and Cs) using the workhorse of atomic physics experiments, laser cooling. With a judicious combination of magnetic field gradients and laser beams tuned near the atomic resonance, the light-induced forces can be arranged to slow and push atoms—initially at room temperature and traveling at hundreds of meters per second—into a central spot. There they condense into a dilute cloud at a temperature of 1 millikelvin. This is usually followed by a stage called “optical molasses” to get to tens of microkelvin or less. From this starting point, the atoms are cooled even further.

#### Quantum Degenerate Gas of KRb

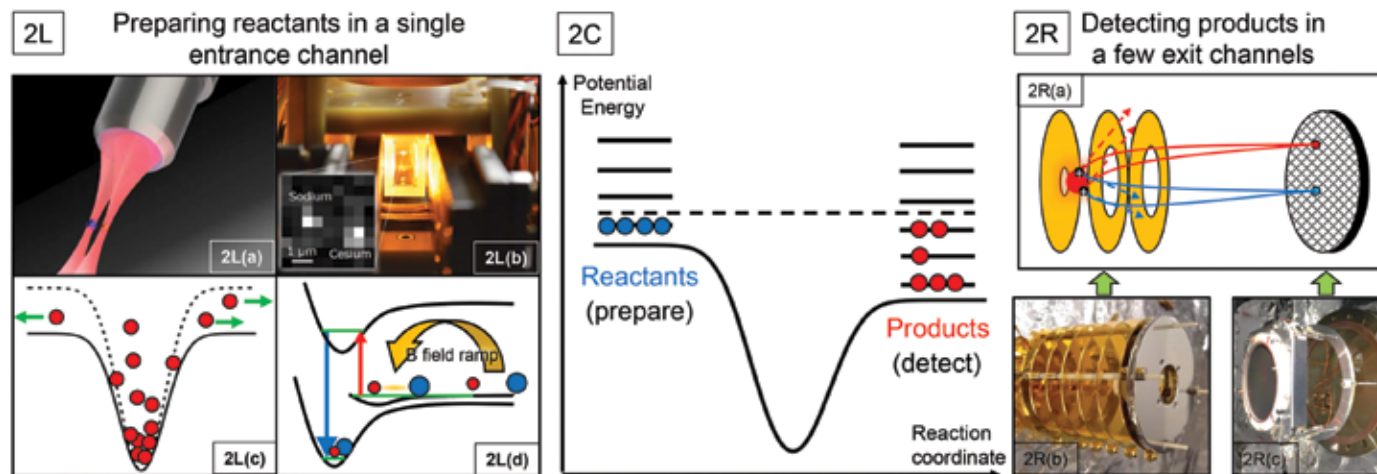
After the atoms reach a few tens of microkelvin, we load them into “traps” formed by either magnetic or optical fields. To cool the atoms inside these traps, we control the shape of the trap so that the hottest atoms in the thermal ensemble spill out, allowing the rest of the atoms in the trap to thermalize to a colder temperature (see Figure 2L(c)). This technique is appropriately named evaporative cooling.<sup>5</sup> Doing so repeatedly allows us to cool the gas of atoms below

1 microkelvin. As the temperature drops, the density of the gas increases. At a cold enough temperature ( $<1\mu\text{K}$ ) and a high enough density ( $>10^{14}\text{cm}^{-3}$ ), the de Broglie wavelength of the atoms starts to exceed their distances from each other, and they form a so-called quantum degenerate gas. This is a favorable condition for creating molecules out of these atoms.

Even in the quantum degenerate gas, the typical atomic separation is a few tenths of a micron. The typical separation between two atoms in a bond molecule is one thousand times less. To bridge this enormous length gap, we immerse the free atoms in a uniform magnetic field and slowly ramp the field across a Feshbach resonance, driving them into a very weakly bound molecular state. Then we use a pair of carefully timed laser pulses to drive a Raman transition from the weakly bound into the deeply bound molecular state (see Fig. 2L(d)). By tuning the frequency and polarization of the two pulses, we can completely control the quantum state that the KRb molecules are prepared in. Being fully coherent, this technique preserves the sub-microkelvin temperature of the sample.<sup>3</sup> This brings us to the desired starting point of the reaction.

#### Single Ultracold NaCs

In a parallel, related effort, we load single Na and Cs atoms from the optical molasses into separate optical tweezers.<sup>1</sup> Tight optical tweezers have already proven to be a versatile tool for manipulating individual neutral atoms,<sup>6</sup> enabling us to add atoms to an optical “beaker,” one by one (see Fig. 2L(a)).



**Fig. 2.** 2C: A schematic, one-dimensional view of the potential energy surface. Internal energy levels are denoted schematically by a ladder of horizontal lines. The reaction is exothermic, such that a single incoming channel may produce many output channels. Due to energy conservation, the products can be distributed among internal states only up to the initial total energy (dashed line). **2L group:** Experimental techniques employed to prepare reactants in a single entrance channel. **2L(a):** Artist's depiction of individually trapped, single Na and single Cs atoms at the focus of a microscope objective. **2L(b):** View of laser-cooled and trapped cloud of a million sodium atoms suspended inside the glass cell vacuum apparatus. Inset: Microscope view of fluorescence from a single sodium and single cesium atom trapped side-by-side. **2L(c):** Evaporative cooling of atoms inside a magnetic/optical trap. **2L(d):** associating ultracold atoms into molecules using magnetic fields and laser pulses. **2R group:** Experimental techniques employed to detect the exit channels of the products **2R(a):** a schematic illustration of the velocity map imaging (VMI) technique used to map out the quantum state distribution of the products. **2R(b)** photograph of electric field plates used in the VMI setup. **2R(c)** photograph of the microchannel plate (MCP) detector assembly used in the VMI setup.

As in a bulk sample, we have cooled individual Na and Cs atoms to their motional ground state in their respective tweezers<sup>7,8</sup> (see Fig. 2L(b)). After merging the two tweezers adiabatically, we are left with an isolated pair of Na and Cs atoms in a single reaction channel.

In a recent demonstration of the optical tweezer platform for chemistry, we were indeed able to strip a chemical reaction (albeit the much simpler  $\text{Na} + \text{Cs} \rightarrow \text{NaCs}$ ) down to its most basic ingredients: two atoms and a source of energy provided by a laser pulse.<sup>1</sup> This established a novel system where isolated gas phase reactions between single atoms could be triggered by a pulse of light. In addition to offering chemical reactions “on demand,” we could isolate the desired reaction process, adding another dimension of control to our quantum chemistry toolbox.

We are currently refining the process to maintain full quantum coherence throughout.<sup>7</sup> This will enable us to create molecules in a single quantum state, thereby extending the repertoire to more complex chemical reactions. It will also be possible to realize a dense array<sup>9,10</sup> of such molecules, which would constitute an unprecedented resource for quantum computing<sup>2</sup> and simulation.

### State-Resolved Detection of Products: Velocity Map Imaging

After the ultracold KRb gas is prepared, the reactions spontaneously start, and we track the results by measuring the likelihood of the products escaping via the various available exit channels. Experimentally, this amounts to mapping out the products' quantum rotational and vibrational state distribution. Some of the energy released in each reaction goes into the products' rotational and vibrational degrees of freedom and the rest goes to their kinetic energy. In our experiment, we first aim to map out the kinetic energy distribution of the products and then use energy conservation to map into a rotational-vibrational (or “rovibrational”) state distribution. The measurement of kinetic energies or, equivalently, velocities starts with valence electrons by turning them into positive ions while maintaining their velocity. We then use an electrostatic lens (a set of electric field plates with carefully tailored voltages) to map each velocity vector into a unique position on a detector some distance away, much like a normal lens maps a bundle of parallel rays into a point at its focus. This allows us to record a probability distribution of velocities and, therefore, kinetic energies (See Fig. 2R(a)).

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## CONCLUSION AND OUTLOOK

Chemistry is fundamentally a quantum scattering process. Although the “quantumness” of the situation is generally washed out under ambient conditions, studying chemistry in the quantum regime offers two main benefits:

First, we can bring all the theoretical tools of quantum scattering to bear on the problem of understanding the mechanisms that determine reaction outcomes. And second, quantum mechanics offers an entirely new set of experimental knobs with which to manipulate the course of a reaction.<sup>11</sup>

The Ni group’s novel quantum state-resolved chemistry experiment—based on ultracold KRb<sup>3</sup> and NaCs<sup>1</sup> and featuring initial state

preparation, a low number of output channels, and product state resolved detection—will open a new window into the world of quantum chemistry.

Furthermore, an array of exquisitely controlled ultracold NaCs molecules, currently under development, will offer a novel resource for quantum computing<sup>2</sup> and simulation.

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## Kang-Kuen Ni: Bringing Quantum Control to Chemistry

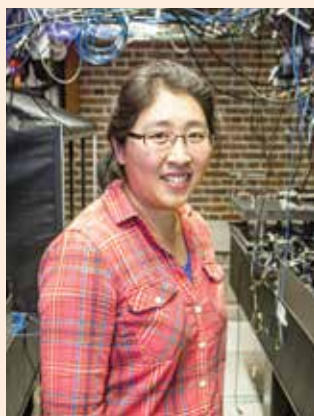


Photo by Nathan Fiske

by Steve Nadis

Many of the steps Kang-Kuen Ni has taken—from Taiwan, where she was born and raised, to California, Colorado, and Massachusetts—brought her closer to Harvard, both geographically and scientifically. Ni left Taiwan in 2000 for undergraduate studies at the University of California, Santa Barbara (UCSB). From there she headed to Boulder, Colorado, for graduate school and a postdoctoral fellowship (with another two-year stint at Caltech), before joining Harvard's Chemistry Department in 2013.

She's also affiliated with the Physics Department, having been around the subject a long time, given that her father teaches physics at Taiwan's National Tsing Hua University. "In some sense, I might have been brainwashed," Ni jokes. Her main interest in high school was astronomy, but during a research project in Santa Barbara she realized she was mostly stuck at a computer, operating a telescope remotely while performing data analysis. "I didn't want to do that every day, even though the science was interesting," she says.

After her first year at UCSB, Ni carried out precision gravity measurements with a torsion pendulum, finding that she enjoyed the hands-on nature of the work. That experience made her eager to measure gravity with more modern techniques, cooling atoms down almost to absolute zero—a point where the interference between them depends on their gravitational acceleration. She soon found there were a lot of interesting things one could study with this general approach, not just gravity, and she's been working on cold atoms and molecules ever since.

In Boulder, under the supervision of Deborah Jin and Nobel laureate Carl Wieman, Ni learned how to make and manipulate gases that were extremely cold and dense. "Quantum behavior becomes

pronounced when an atom's or molecule's wavelength becomes comparable to the inter-particle spacing," she explains. "Once we get systems to reveal their quantum behavior, we can then try to quantum engineer those systems to do what we want them to do."

Although her PhD and prior work had been strictly in physics, Ni joined Harvard's Chemistry faculty because a position was available and "because the department was open-minded enough to recognize that this could be a good area to grow into." She now spends time on both sides of Oxford Street, working at the boundary between chemistry and physics, which, she notes, "is not a clear-cut boundary at all."

Ni's group recently achieved a milestone, "single particle control," which was showcased on the May 25, 2018 cover of *Science*. "We made a molecule by grabbing one sodium atom and one cesium atom and putting them together like Lego blocks," Ni says. The next challenge will be to get this molecule into a single quantum state in which all the adjustable parameters—like vibration, rotation, and spin—are clearly identified.

Her lab also studies chemical reactions at the most fundamental level. "Quantum mechanics plays a crucial role in transformations from one molecule to another," Ni says. "But it's often hard to see the microscopic effects until you cool atoms and molecules down to really low temperatures." This work could eventually yield new insights on reaction dynamics and kinetics.

Being in the chemistry department while maintaining her longstanding ties in physics has its advantages, Ni says. "I'm continually being exposed to new ideas."



# Bringing “Active Learning” into the Physics Classroom

by Dr. Logan McCarty,  
Director of Science Education,  
Lecturer on Physics, and  
Lecturer on Chemistry  
and Chemical Biology

Think back for a moment to your experience in undergraduate physics courses. When you were in the classroom, what were you doing?

I recall well what I was doing—as a chemistry concentrator at Harvard in the early 1990’s, taking the Physics 15 and 143 sequence, I was scrambling to copy what the professors wrote on the board, occasionally circling something profound or confusing (or both), and walking out of class certain that my peers must have understood more than I did. I hardly ever asked a question, talked with a classmate, or actually tried to solve a physics problem myself during class. At the end of lecture, I usually felt like I had a reasonable

grasp of the material, but I still struggled to solve the problem sets, which stretched late into the evening. Without help from my study mates, and lots of careful review of the textbook and sample problems, I probably never would have finished them.

Somehow, I could emerge from 90 minutes of lecture feeling like I had learned something from transcribing notes and listening to the instructor, but when it came time to actually solve problems



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I still needed to put in a lot of additional effort. Perhaps you also felt that way about many of your undergraduate courses. Certainly my peers did. Yet in the end most of us managed to learn the material, finish the homework, and even do reasonably well on our exams. We certainly had a wide range of opinions about our instructors—some seemed particularly engaging and helpful, while others were less so—but the basic pattern of listening in lecture and then struggling on the homework was quite consistent from one class to another. This was just how people learned in college science courses.

Around that time, Eric Mazur, Balkanski Professor of Physics and Applied Physics at Harvard, started to doubt whether his teaching was really as effective as he and his students thought it was. Those of you who have seen Eric speak would undoubtedly agree that he is a captivating, charismatic, and compelling lecturer. He routinely got high scores on his teaching evaluations, and he had assumed that these scores meant that his students were learning a lot in his classes. One semester, when he was teaching introductory mechanics, he decided to assess his students' understanding of Newton's laws employing a widely-used instrument called the Force Concept Inventory (FCI). This test has 30 multiple-choice questions about basic concepts of force and motion. Eric was astonished to find that many of his students scored quite poorly on the FCI even though they could solve typical pencil-and-paper questions on his mechanics exams. A key insight came when a student asked him during the test, "Professor Mazur, should we answer these questions the way we think about them, or the way you taught us to solve them?" It seemed that his students had learned to solve specific kinds of mechanics problems without actually learning the fundamentals of mechanics!

In response, Eric made drastic changes in the way he taught his courses. Instead of just lecturing for 90 minutes, he would introduce a concept or equation and then immediately ask the class to answer a question about it. Students responded using "clickers"—handheld electronic devices that let them vote, anonymously, on what they thought was the correct answer. After their initial votes, students would discuss the question with their peers and vote again. As you might imagine, this peer instruction, as Eric called it, led more students to get the correct answer. He could then display the distribution of student responses and focus on some of the key misconceptions that persisted even after discussion. Eric's classes were no longer just a one-way flow of information from the teacher to the students. They were now more like conversations between the teacher and students, and among the students themselves. A casual observer would immediately note that the students were much more actively engaged during lecture, because they were required to answer questions and converse with their peers. Eric was a pioneer in

bringing what we now call active learning to the college physics classroom. He found that active engagement led to dramatically higher scores on the FCI and also improved students' performance on traditional tests of Newtonian mechanics.<sup>1</sup> Peer instruction is now used around the world in many disciplines beyond physics.

The 1990's saw a great variety of active learning approaches gain traction in physics departments around the country. Many instructors started to use clickers to make their lectures more interactive. Pioneers like Lillian McDermott at the University of Washington developed "physics tutorials" in which students worked through structured activities in small groups under the guidance of trained tutorial leaders. Other leaders like Priscilla Laws at Dickinson College developed "workshop physics," which integrated lectures, hands-on laboratories, and small-group problem solving. This appealing idea has inspired many subsequent efforts, like the more recent TEAL (Technology-Enhanced Active Learning) initiative at MIT. An influential review by Richard Hake, published in 1998 in the *American Journal of Physics*,<sup>2</sup> compared various active learning methods with traditional lectures in introductory mechanics courses. He used students' scores on the FCI to measure the learning gains from the beginning to the end of a one-semester introductory mechanics course, and found that students in actively-taught classes learned twice as much compared with students in traditional lecture courses. The message seemed quite clear: If students are actively engaged during class, they will learn more than if they are passively listening to lectures. Further research by Eric Mazur and others showed that active learning could reduce or eliminate notorious gaps in performance in physics courses between male and female students or between majority and underrepresented minority students.

By the end of the 1990's, within the growing community of faculty devoted to undergraduate physics education, there was wide agreement that courses should be taught using active learning, and researchers began to compare different kinds of active learning to find out which approaches worked best. Yet the broader physics community seemed mostly unmoved by these developments, and indeed many departments resisted efforts to introduce active learning more extensively across the curriculum. Faculty complained that it would be too much work to redesign their courses to include in-class activities like peer instruction, and they worried about not being able to cover as much content if they had to allow time for active learning. Both faculty and students felt that they had managed to learn just fine from passive lecture courses, and so there was no obvious need for change. Probably the most formidable obstacle came from students themselves, who expressed widespread displeasure with actively-taught classes, and gave lower course evaluations to faculty who taught that way. Eric Mazur recalls that his own course

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Today, the evidence for the superiority of active learning is so strong that Carl Wieman has quipped that simply comparing active learning with passive lectures is analogous to comparing chemotherapy with bloodletting as a treatment for cancer—we know that bloodletting is an inferior treatment.

evaluations went down when he switched from lectures to active learning, but he persisted because he had clear evidence that students were learning more. Many other faculty resisted active learning when they heard that it could lead to lower course evaluations.

Around this time, Professors Carl Wieman and Eric Cornell led the team at the University of Colorado that produced the first true Bose-Einstein condensate (BEC), an achievement that was recognized with the 2001 Nobel Prize in Physics. The physics faculty at Colorado had long been active in improving physics education, and Carl joined their crusade with a challenge to the scientific community as a whole. As scientists, Carl said, we faculty should approach our teaching with the same care, rigor, and skepticism that we use every day in our scientific research. After all, if empirical research shows that laser cooling is a superior method of attaining very low temperatures, then we expect that most scientists will adopt that technique in place of other methods. Likewise, if empirical data, like Richard Hake's results, suggest that active learning is superior to passive lectures, we should expect faculty to adopt active methods in the classroom. And if faculty aren't convinced by the existing data, then the physics education community should conduct better classroom "experiments" and collect more compelling data. Carl decided to switch his career to focus on improving science education, first at the University of Colorado and then, starting in 2007, at the University of British Columbia.

In 2011, Carl Wieman published a paper in *Science*<sup>3</sup> with Dr. Louis Deslauriers, a physicist who had also switched to science education and who was at that time a lecturer and researcher at the University of British Columbia. (Louis is now a faculty member in our department.) Their article, "Improved Learning in a Large-Enrollment Physics Class," described a tightly controlled experiment that compared active learning with passive lectures in an introductory

physics course at U.B.C. During one week in a physics course with over 500 students, half of the students got active learning, while the other half got traditional instruction from an experienced lecturer who had received strong evaluations and teaching awards for his lecturing. Students were not exposed to any other learning opportunities that week—there were no problem sets, labs, or discussion sections—because the researchers wanted to compare how much students learned from their class time alone. Both groups were taught the same topics with the same set of learning goals, and they all took the same exam at the end of the week to see how much they had learned. The results were astounding: students in the active learning group scored more than twice as well as the students who learned from traditional lectures. In addition, students in the actively-taught classes had higher attendance and engagement, compared with either their own behavior earlier in the course or the behavior of students in the group taught using lectures.

This article—which has now been cited over 850 times—had a remarkable effect on the views of science faculty. Here was an unambiguous experiment with extremely convincing results showing that active learning was superior to passive lectures. It was followed in 2014 by a large meta-analysis by Scott Freeman and colleagues in the *Proceedings of the National Academy of Sciences*,<sup>4</sup> which combined results from 158 individual studies across a wide range of fields in science, mathematics, and engineering. Once again, the message was clear: just about any kind of active learning was superior to passive lectures, and these results held across all disciplines. Today, the evidence for the superiority of active learning is so strong that Carl Wieman has quipped that simply comparing active learning with passive lectures is analogous to comparing chemotherapy with bloodletting as a treatment for cancer—we know that bloodletting is an inferior treatment. Instead, he says,

researchers should focus on discovering and improving the most effective forms of active learning.

In August of 2014, Louis Deslauriers joined our faculty, and today he is Director of Science Teaching and Learning and Senior Preceptor in Physics. When he arrived, he wanted to transform one of our large physics courses from traditional lectures to active learning, and I offered up my course as a test case. That course—Physical Sciences 2—is an introductory, calculus-based course in Newtonian mechanics aimed at pre-medical and life science students. It had a large enrollment (about 220 students) and served as a replacement for what had been Physics 1a. Louis insisted that we could avoid the common pitfalls that had hindered active learning. In particular, we could teach all of the same content, and student evaluations would be comparable or superior to those of traditional lectures.

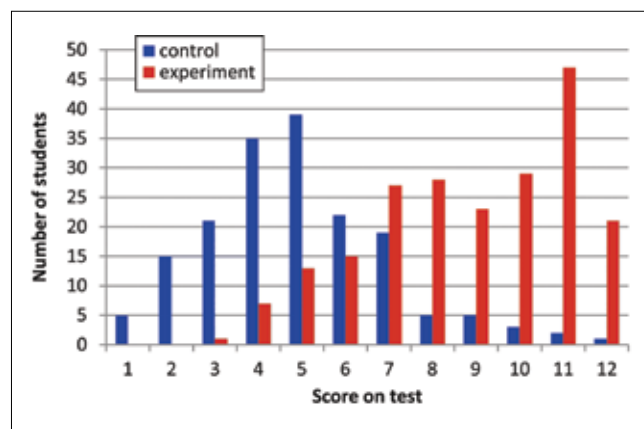
We spent that semester redesigning every lecture, while keeping exactly the same syllabus and course content that we had in previous years. The homework, discussion sections, and laboratory experiments were all unchanged. In class, though, instead of having lectures for 90 minutes, we offered a series of activities. Students would work in small groups on a physics problem for about 5–7 minutes, during which time we would walk around the lecture hall, along with our teaching assistants, and offer advice, answer questions, and look at how students were approaching the problem. Then we would interrupt the class, explain how to solve the problem correctly, point out common pitfalls that we had observed, and perhaps follow with a demonstration that illustrated some key concepts. Then students would start another activity. This cycle of activities followed by feedback continued throughout each class. Students were far more engaged, and class attendance was much higher than it had been in previous years. We covered precisely the same course content, and even gave students the same final exam that had been used in a previous year. Students’ final exam scores increased, the overall course evaluations were stronger, and my evaluations as an instructor were the same, compared with the course taught using traditional lectures. And it was far more enjoyable for me to teach in an active classroom full of engaged students than it was to give lectures, in part because students asked much more sophisticated questions that always kept me on my toes.

After experiencing active learning, I was determined never to go back to traditional lecturing in my own classes, and I used the same approach in the subsequent course, Physical Sciences 3, which covers electricity, magnetism, waves, and optics. I encouraged our faculty colleagues to try active learning in their own courses, and Professors Christopher Stubbs and Melissa Franklin adopted the same approach in their engineering physics courses, Physical Sciences 12a and 12b

(courses that replaced Physics 11a and 11b). This approach was equally effective with other student populations, such as the post-baccalaureate students at the Harvard Extension School, or the mix of college and high school students attending the Harvard Summer School. Eric Mazur has continued to pioneer new approaches to active learning with his recent development of Applied Physics 50, which teaches introductory physics for the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) in a fully interactive laboratory environment, with interspersed problem-solving, discussion, experimental work, open-ended student engineering projects, and a strong emphasis on getting students to work effectively in teams.

Among the courses in our traditional sequence for physics concentrators, Physics 16 with Prof. Howard Georgi, and Physics 15c with Prof. Matthew Schwartz as well as with Prof. Cora Dvorkin, have all incorporated active learning into their classes. This fall, Dr. Deslauriers is co-teaching Quantum Mechanics, Physics 143a, with our department chair Subir Sachdev, in part to demonstrate that these active learning techniques are effective not only for large introductory lecture courses but also for more advanced courses in the concentration. Indeed, the physics departments at the University of British Columbia and at Stanford (where Carl Wieman is now on the faculty) have also transformed a wide variety of courses to include active learning. Harvard is now among the top handful of physics departments in the country in leading the transformation away from passive lectures and toward active learning.

This recent success raises an obvious question: Why was there such resistance to active learning in the late 1990’s? A recent research study led by Louis Deslauriers may help us understand why students



Distribution of scores on a test comparing traditional lecture (control) with active learning (experiment) in a large-enrollment physics class. From Deslauriers, Schelew, & Wieman (2011).<sup>3</sup>



Dr. Louis Deslauriers (left) and Dr. Logan McCarty

had historically disliked active learning. With the help of Dr. David Morin, who was teaching Physics 15a, Louis and I took the students from that course, divided them randomly into two groups, and taught one group using active learning and the other with traditional lectures. We then swapped the groups for the next class meeting (passive versus active). We measured how much students had learned in each class using a multiple-choice test, and also assessed students' perceptions of their own learning by rating their agreement with questions like "I learned a lot from this class." We found that students in the active classroom felt like they had learned less, when in fact they had learned more than the group in the traditional lecture. In other words, students' perceived learning was precisely anti-correlated with their actual learning. Follow-up interviews confirmed that the cognitive effort associated with solving problems in class (the active learning approach) made students feel like they weren't learning, while the cognitive ease of listening to a fluent, clear lecture lulled students into thinking they had learned a lot. With this context, it was easy to understand why students were resistant to active learning—they felt like they weren't learning as much! But they were actually learning more, and the approach that Louis Deslauriers has implemented here at Harvard helps students appreciate the value of cognitive effort during class activities. This may explain why our recent efforts at active learning have been embraced by students, in contrast with some previous attempts.

The results of this study certainly resonated with my own recollections of undergraduate science courses: I emerged from lectures feeling like I understood what was being taught, but when it came time to work on problem sets it seemed like I was starting from scratch. In reality, I hadn't learned much at all from the hours spent each week listening to lectures. With active learning, students spend time in class actually practicing the kinds of problem solving and physical reasoning that we expect them to master. And they

get immediate feedback so they can gauge their own progress. In retrospect, the value of active learning is obvious: when students are first struggling to learn a new kind of problem solving, they are doing so in class, with the support of an expert instructor and teaching assistants, instead of doing so on their own or with only other peers for support. Classes are more cognitively taxing for students, but they learn more and it is easier for them to succeed on subsequent problem sets and exams.

A manuscript describing this recent research is currently under peer review and might be published by the time you read this article; please contact me if you would like more information about this study or about other aspects of active learning in the Department of Physics. This is an exciting time for undergraduate education in our department, and in science education more broadly. For over a century, college science courses have relied on textbooks, lectures, problem sets, and exams. The past decade has seen the first widespread changes to what students are doing in the classroom. The next frontier in educational innovation will involve interactive (electronic) textbooks, problem sets, and exams, and while those efforts are in their infancy, it is clear already that this coming wave of changes will be profound. Our department has long been at the forefront of major advances in physics, and it is thrilling now to lead the development of new approaches to teaching and learning as well.

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## Max Planck – Harvard Research Center for Quantum Optics

by Clare Ploucha

In January 2018, senior quantum scientists, postdoctoral associates, and members of the public descended on Munich, Germany, for the inaugural meeting of the Max Planck-Harvard Research Center for Quantum Optics (MPHQ). In the spirit of the Center's mission—to accomplish cutting-edge, frontier-defining research that could not be addressed by the individual partners alone—attendees represented six Harvard research groups, the Max-Planck-Institute for Quantum Optics (MPQ), MIT, Universität Innsbruck, and other institutions. They came to present research and take part in a community atmosphere that would ignite fresh synergies between Harvard and MPQ. Through research talks, social events, and public lectures, Center affiliates reflected on a rich history of collaboration between the institutions, while laying a foundation for work to come.

Over the past decade, individual collaborations between researchers at Harvard and MPQ have resulted in groundbreaking work in key areas of quantum science, such as quantum simulation, sensing and metrology, and quantum phases of matter. Launched in July 2017, the MPHQ builds on this legacy of discovery, taking advantage of the complementary expertise of Harvard and MPQ to foster new research directions that will shape the future of the field. With its emphasis on strengthening and expanding international collaborations and its mandate to train, promote, and exchange excellent young scientists, the MPHQ supports interdisciplinary research projects that could not be possible with the resources of individual institutions.

Leading this effort at Harvard are Prof. Markus Greiner and Prof. Susanne Yelin, Senior Research Fellow in Physics. Greiner and Yelin serve as Co-Director and Vice-Director, respectively, alongside MPQ counterparts Prof. Gerhard Rempe and Prof. Immanuel Bloch. The Center includes six additional Principal Investigators: Professors Eugene Demler, John Doyle, Mikhail Lukin, and Kang-Kuen Ni at Harvard; Professors Ignacio Cirac and Theodor Hänsch at MPQ.

The event in Munich began with a Young Scientists Symposium, an afternoon of postdoctoral research talks followed by a poster session. The symposium drew an audience of more than fifty scholars and represented the groundbreaking work being done in MPHQ groups. Senior faculty members who attended the event commented on the unusually high caliber of the research presentations. Prof. Greiner noted that it was “one of the strongest, most sophisticated programs of postdoc talks” he had seen. Mingling during the poster session, junior scientists discussed their work and arranged laboratory tours.

The formal opening ceremony was held at the Deutsches Museum. The world's largest museum of science and the site of a forthcoming



optics exhibition designed by Prof. Greiner, the museum offered an auspicious venue. The program unfolded in the museum's Hall of Fame, beneath the busts of pioneers like Albert Einstein. Fittingly, the morning program focused not only on the state of the field of quantum optics and the history of MPQ/Harvard partnerships, but also on the future.

Together, speakers presented a vision for the potential pathbreaking work expected to arise from strengthened institutional collaborations.

A spirit of partnership and scientific outreach permeated the event. Nobel laureate Prof. Wolfgang Ketterle gave a sophisticated but whimsical talk on “New Forms of Matter with Ultracold Atoms” (replete with liquid nitrogen demonstrations) to a standing-room-only audience of more than 200 people. After lunch and a signing ceremony, Max Planck Society President Martin Stratman and FAS Dean of Science Jeremy Bloxham offered remarks that highlighted the critical importance of international partnerships, noting the value of building bridges between cultures and collaborating to drive innovation. The afternoon concluded with a keynote address by Prof. John Doyle and a public lecture and demonstration by Prof. Greiner on the power and potential of quantum optics research. Of course, the Opening Ceremony was only the beginning of what is hoped to be a long and rewarding collaboration. As quantum science and its applications begin to shape the commercial products and technologies of the 21st century, the MPHQ partners will work together to ask fundamental questions and open new frontiers of research. As Prof. Doyle stated in his keynote address, “Our imagination goes beyond the physical constraints of the world.” By harnessing this imagination and building a community to support it, the MPHQ will help shape the next generation of quantum physics research.



## PROGRAMS

# Undergraduate Program

Above, clockwise from the left: Eric Jjemba, Jose Martinez Fernandez, Jenny Yao, Louise Estberg, Juliet Nwagwu Ume-Ejeoke, and Jacob Bindman study together during office hours in Dr. Morin's office.

Dr. David Morin,  
Associate Director of  
Undergraduate Studies;  
Lecturer on Physics

### NEW CONCENTRATORS

Last year, 62 enthusiastic sophomores signed up for the Physics and Chem/Phys concentrations, many of them pursuing joint concentrations or secondaries in other fields. These fields include computer science, philosophy, astrophysics, mathematics, earth & planetary sciences, comparative literature, and history & literature.

### CAREER PATHS

This past year's graduating class consisted of 70 Physics and Chem/Phys concentrators. This is the largest number in recent memory (and quite possibly ever!). Thirty six of these students moved on to graduate school; this exceeds the previous record from two years ago by a remarkable 50%.

They are now attending 13 different institutions (including nine students at Stanford and six at Berkeley) to study physics, chemistry, biophysics, astronomy, neuroscience, climate science, artificial intelligence, electrical engineering, statistics, and computer science. Others are attending medical school, one student joined the Navy, and still others have entered the workforce in teaching, journalism, software, consulting, data science, finance, and industry.

### PRIZES & AWARDS

Shaan Desai won a Rhodes Scholarship and is pursuing a PhD in Autonomous Intelligent Machines and Systems at Oxford. Seven graduating seniors were awarded National Science Foundation Graduate Research Fellowships for

their studies in graduate school: Trevor Chistolini, Aditya Raguram, Elaine Reichert, Andre Sanchez, Katie Fraser, Adam Frim, and Sebastian Wagner-Carena. Among these students, Andre also won a Ford Foundation Fellowship. Adam Frim was last year's recipient of the Physics Department's Sanderson Award, given to the graduating Physics concentrator with the highest grade average in concentration courses.

### STUDENTS' RESEARCH

This past summer, roughly 45 Physics and Chem/Phys concentrators engaged in full-time research on campus. Many of these students were part of the Program for Research in Science and Engineering (PRISE)—a vibrant 10-week program that provides students with housing and a wide range of social and academic activities. A number of other students performed research at institutions elsewhere, both in the U.S. and abroad.

### MONDAY NIGHT "COOL PHYSICS"

On occasional Monday nights, undergraduates gather in Leverett House for the Monday Night Cool Physics Talks. These talks are given by undergraduates, for undergraduates, with an emphasis on pedagogy. Topics can be either research that a student is working on (this is a good way for younger students to learn about what research opportunities exist), or a general physics topic that the speaker finds interesting and would like to teach other students. Examples of subjects presented include "Fast Radio Bursts" by Maya Burhanpurkar, and "The Physics of Möbius Transformations" by Nisarga Paul. The Cool Physics talks allow undergraduates to develop their public speaking and academic presentation skills—and to get to know each other over dinner.

### STUDENT PROFILE

Madeline Bernstein '19 has spent the past six months in Professor Roxanne Guenette's lab using deep learning techniques to investigate the performance of neutrino detectors. Neutrinos pose a unique opportunity to explore physics beyond the standard model, but detecting neutrinos is a huge experimental challenge. The Liquid Argon Time Projection Chamber (LArTPC) detector is used widely in neutrino experiments, and it allows physicists to extract rich details from neutrino interactions. The current LArTPC readout design uses planes of wires, each of which provides two dimensions of information. However, reconstructing 3D particle interactions from 2D images poses many challenges. The Guenette lab is exploring an alternate readout model, which instead uses one grid of pixels that is

able to directly capture three-dimensional information. Madeline has been using convolutional neural networks to compare the efficiency, purity, and misidentification rates of these two readout models. She and other members of the research group hope to compare the performance of the two types of detector technology to address the neutrino physics questions. This has been a fun project for Madeline, as it merges her interests in computer science and physics. She has been able to learn some useful data analysis skills and apply them to a compelling physics question. Last year, Madeline studied the cosmic muon background at CERN as a part of the Harvard ATLAS group, an experience she also enjoyed tremendously. Madeline is excited to continue with her neutrino project this fall, and she hopes to pursue experimental particle physics in her graduate studies (and beyond!).



Madeline Bernstein



PROGRAMS

# Graduate Program

by Dr. Jacob Barandes,  
Associate Director of Graduate  
Studies for Physics; Director  
of Graduate Studies for FAS  
Science; Lecturer on Physics

## THE PHD CLASS ENTERING IN 2018

The incoming students entering the Physics PhD program in Fall 2018 yet again demonstrate a notable geographic diversity. Their birthplaces include the American states of California, Illinois, Maine, Maryland, Massachusetts, Michigan, Missouri, New Jersey, New York, North Carolina, and Oregon, and the countries of Australia, Bulgaria, Canada, China, Georgia, Hong Kong, Iran, Israel, Jamaica, Japan, Russia, Turkey, and Ukraine.

## THE PHYSICS GRADUATE STUDENT COUNCIL

Created by our Physics PhD students in the spring of 2009, the Physics Graduate Student Council is an important part of the Physics Department. The council provides a forum for graduate students to propose new initiatives and discuss issues of common concern. It organizes social events like the popular biweekly Friday afternoon social hour and monthly movie nights. The council also administers annual surveys to physics graduate students on advising and the department's overall climate. The council's returning president this year is Elana Urbach, and its other members (in alphabetical order) are Delilah Gates, Jae Hyeon Lee, Cole Meisenhelder, Marios Michael, Aditya Parikh, Rhine Samajdar, and Steven Torrisi.

Above, top row (left to right): Albert Lee, Alex Thomson, David Bracher, Erik Bauch, and Christopher Frye. Bottom row (left to right): Shubhayu Chatterjee, Soonwon Choi (front), Robert Hoyt (rear), Daniel Kapec, Anders Andreassen, Ruffin Evans, Baojia (Tony) Tong, Seth Whitsitt, and Temple He.



## CAREER EVENTS

To assist graduate students in connecting with alumni of the program and in learning more about careers inside and outside academia, the Physics Graduate-Student Council has worked with the department over the past academic year to invite several speakers (including alumni) from different sectors to visit and discuss career opportunities. These visiting speakers have included Areez Mody (PhD, Physics, '04), Manager of Strategy Diversification at Quantlab; Igor Lovchinski (PhD, Physics, '17); and Ben Vigoda, CEO, Founder, and Principal Machine Learning Architect of Gamalon, and former director of Analog Devices Corporate Labs.

## PANEL EVENTS

As part of our physics program's efforts to inform students about opportunities to apply for outside funding, the department organized a panel discussion on issues related to external fellowships.

Moderated by the Prof. John Huth and the Associate Director of Graduate Studies, Dr. Jacob Barandes, the panel included senior PhD students Andrey Sushko, Harry Levine, Anne Hébert, and Jordan Kennedy (Applied Physics), Ellen Klein, Harry McNamara, and Elana Urbach, who shared their experiences and answered questions from the first- and second-year PhD students in attendance.

The department held a panel event to discuss the physics qualifying examination. Moderated by the Director of Graduate Studies, Prof. Mara Prentiss, and Dr. Barandes, the panel included senior Physics PhD students Abby Plummer, Mihir Bhaskar, Scott Collier, Linda Xu, Stephen Carr, and Sasha Brownsberger.

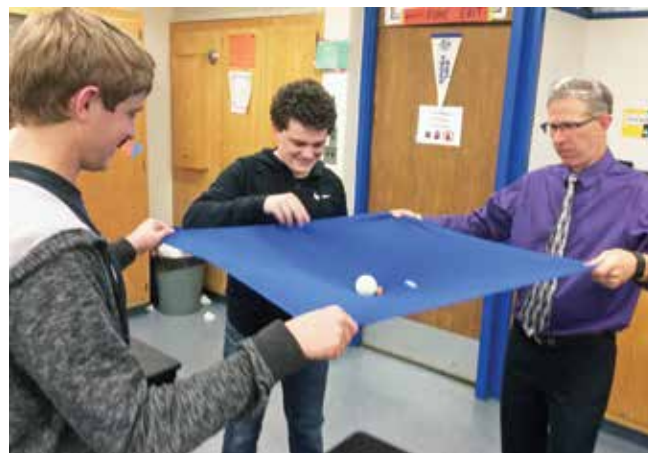
## INTRODUCING HIGH SCHOOLERS TO PHYSICS

Last summer, doctoral candidate Elizabeth "Mina" Himwich taught a week-long physics program on gravity at Oscoda Area and Alcona County Schools. Iosco and Alcona are rural counties in Michigan that have low average incomes and limited school district funding for advanced science programs. The gravity program, which ran hour-long sessions every day, provided a conceptual introduction to modern physics – including quantum mechanics, relativity, and cosmology – and offered students an opportunity to learn about scientific research and careers. Activities in the classroom emphasized learning through demonstrations of laboratory experiments, visualizations in models and videos, and small-group problem solving. Pictured to the right are students playing with balls and marbles on a spandex sheet—a visual analogy for matter and the curvature of spacetime.

Mina was joined by Dr. Peter Mapes, a retired Air Force pilot and FAA Certified Flight Instructor whom she has known since high school and with whose instruction she earned a private pilot certificate. To make the concepts of gravity tangible, Dr. Mapes decided to offer participating students an opportunity to experience "supergravity" at 2G and "microgravity" close to 0G, carried out in a light general aviation aircraft. Dr. Mapes conducted the flights under the "Young Eagles" program of the Experimental Aircraft Association (EAA), which ensures that parents are aware of the activity and provides students with free avenues to acquire subsequent flight training and instruction. Students also gained a "pilot's perspective" of the Earth and became acquainted with some of the physics of aviation. In addition, each student actually performed a takeoff and a landing.

The program generated a lot of interest among the students and received staunch support from the science teachers, principals, and superintendents of both schools, who would like to make it available to students again next year. Mina feels it could easily be expanded to include other school systems, as well.

"Elizabeth did a tremendous job of breaking down the mysteries associated with physics into pieces that our students could easily digest and then apply in the days that she spent with us," wrote Scott Moore, the Oscoda Area Schools Superintendent, in a letter addressed to our department. "We thank you for the gift."



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# Goldhaber Prize

The Maurice and Gertrude Goldhaber Prize fund was established in honor of two great physicists: Dr. Maurice Goldhaber, who was an experimental nuclear physicist and one of the pioneers of modern physics, and his wife Dr. Gertrude Scharff Goldhaber, a physicist who contributed to scientists' understanding of nuclear fission and the structure of atomic nuclei.

The Goldhaber Prize is awarded annually by the department to its most outstanding current PhD students based on their research accomplishments, as determined by a vote of the faculty. Winners of this award are recognized at the Historical Lee Lecture. They are guests at the dinner held prior to the lecture, and each receive a cash prize.



## Alex Keesling

### 2018 GOLDHABER PRIZE WINNER

Alex Keesling left his hometown in Mexico to attend MIT for his undergraduate studies. In the first two years, he enrolled in a broad array of classes and declared a major in biological engineering. After taking a class on quantum mechanics, Alex became fascinated with the subject and decided to switch fields to physics. Soon thereafter, he started to gain practical lab experience, first by working with single photons in nonlinear crystals, and later by joining the lab of Nobel laureate Prof. Wolfgang Ketterle, where he assisted in setting up a new ultracold-atom experiment.

After receiving his BS, Alex spent a year at the Max Planck Institute for Quantum Optics in Germany, working in Immanuel Bloch's group. There, Alex assisted in building a Fermi quantum gas microscope while becoming better acquainted with the field of atomic physics, as well as with the uses of highly controlled systems as quantum simulators to study condensed-matter models and more.

Since 2014, Alex has been a graduate student in physics at Harvard, where he has been working in Prof. Mikhail Lukin's group in collaboration with Profs. Markus Greiner and Vladan Vuletic, trapping multiple, individual neutral atoms with programmable interactions in independently controlled optical tweezers. Together with his teammates, Alex has used this platform to study the behavior of strongly interacting many-body systems, particularly while undergoing quantum phase transitions. In the future, Alex wants to study whether such a system may be suitable for demonstrating a clear quantum advantage for obtaining approximate solutions to hard computational problems, as well as for generating large entangled states. He is also interested in exploring the quantum dynamics of strongly interacting particles in new regimes.



## Alex Thomson

### 2018 GOLDHABER PRIZE WINNER

Alex Thomson completed her bachelor's degrees in Mathematics and Physics at McGill University in Montreal, Quebec. Although she was involved in research throughout her undergraduate studies, she started her PhD program at Harvard without knowing what field of physics she wished to study. By the end of her first year, she had become very interested in condensed matter and began working with Prof. Subir Sachdev.

Alex's work has focused on strongly correlated phases of matter containing emergent gauge fields and described by gapless fermions. In such

systems, the fermionic excitations are emergent; they are not adiabatically connected to the electrons that constitute the original building blocks of the system in question. Her work has potential relevance to materials like Herbertsmithite and the cuprates.



## Victor Buza

### 2018 GOLDHABER PRIZE WINNER

Victor Buza did his undergraduate studies at MIT, where he became interested in cosmology through Scott Hughes' class on special relativity. Victor subsequently worked for a number of years with Max Tegmark on 21cm cosmology and for a short stint with Alan Guth on hybrid inflation.

At Harvard for the past four years, Victor has been working alongside John Kovac as a member of the BICEP/Keck collaboration. They're hunting for primordial gravitational waves by studying the polarized cosmic microwave background (CMB) at the best site on Earth for observing this radiation – the South Pole. Victor is one of the main developers of the group's likelihood-analysis pipeline, which has allowed the group to perform joint analyses of various CMB datasets, such as the well-known BICEP/

Keck + Planck analysis in 2015. This framework has allowed the group to publish world-leading constraints on the tensor-to-scalar ratio, which indicates the energy scale of the Big Bang.

For the past two years, Victor has also been one of the only graduate student members of the new community-wide CMB-S4 collaboration, in which Victor has made central contributions toward designing the ultimate ground-based CMB polarization experiment. The performance-based forecasting framework that Victor developed has allowed the group to implement realistic experimental performance (scaled from BICEP/Keck) in a direct and unique way. The framework has since become the community's primary tool for forecasting the science reach of future CMB endeavors.

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# GSAS Merit Fellowship

The Merit Fellowship is awarded by GSAS to PhD students based on the quality of their academic work and research. To be eligible, students must be in their fourth year or earlier and have passed their qualifying exams. Students must be nominated by their home departments, and the Physics Department typically nominates one or two PhD students for the award each year. Students who win the award receive partial or complete stipend support from GSAS for one semester.



## Ana-Maria Raclariu

### 2018 GSAS MERIT FELLOWSHIP WINNER

Ana Raclariu completed her BA in Natural Sciences followed by Part III in Applied Mathematics and Theoretical Physics at the University of Cambridge. She is currently a fourth-year graduate student in Harvard's high-energy theory group, working with Prof. Andrew Strominger.

In her research, Ana is exploring various aspects of the recently discovered “infrared triangle” governing the low-energy dynamics of gauge theories and gravity. This three-fold equivalence relates the symmetries of asymptotically flat

spacetimes, the soft theorems in quantum field theory that constrain scattering processes involving arbitrarily low-energy particles, and the so-called memory effects that measure changes in the infinitely degenerate vacuum. Together with collaborators, Ana is currently working on a proposal to measure such a memory effect in quantum chromodynamics – in particular, in heavy-ion collisions at high energy. More broadly, she is interested in the potential implications of this correspondence for flat-space holography.

## Graduate Student Awards and Fellowships\*

Ashford Family Fellowship

Madelyn Leembruggen

Frederick Sheldon  
Traveling Fellowship

Jennifer Roloff

Gertrude and Maurice  
Goldhaber Prize

Victor Buza

Alexander Keesling  
Alexandra Thomson

GSAS Merit Fellowship

Ana-Maria Raclariu

Hertz Foundation  
Fellowship

Iris Cong

NPSC

Nicholas DePorzio

Masason Foundation  
Fellowship (Japan)

Xing Fan

Natural Sciences and  
Engineering Research  
Council of Canada (NSERC)  
Fellowship

Nathanan Tantivasadakarn

National Science  
Foundation Graduate  
Research Fellowship  
Program (NSF GRFP)

Sean Burchesky

Will Conway

Anne Fortman

Katie Fraser

Soumya Ghosh

Sooshin Kim

Ella King

Madelyn Leembruggen

Noah Miller

Andrew Saydjari

P.D. Soros Fellowship  
for New Americans

Iris Cong

2018 QuantBio  
Student Award

Lauren Niu

Yinan Shen

\*Includes awards from 2017–2018

# Recent Graduates

## Anders Andreassen

Thesis: Precision Tunneling Rate Calculations in Quantum Field Theory and the Ultimate Fate of our Universe

Advisor: Matthew Schwartz

## Erik Bauch

Thesis: Optimizing Solid-State Spins in Diamond for Nano- to Millimeter Scale Magnetic Field Sensing

Advisor: Ronald Walsworth

## David Olmstead Bracher

Thesis: Development of Photonic Crystal Cavities to Enhance Point Defect Emission in Silicon Carbide

Advisor: Evelyn Hu (SEAS)

## Stephen Kam Wah Chan

Thesis: Generically Orthogonal Decompositions of Collision Events and Measurement Combinations in Standard Model  $VH(bb)$  Searches with the ATLAS Detector

Advisor: John Huth

## Shubhayu Chatterjee

Transport and Symmetry Breaking in Strongly Correlated Matter with Topological Order.

Advisor: Subir Sachdev

## Soonwon Choi

Thesis: Quantum Dynamics of Strongly Interacting Many-Body Systems

Advisor: Mikhail Lukin

## Jake Connors

Thesis: Channel Length Scaling in Microwave Graphene Field Effect Transistors

Advisor: John Kovac

## Erin Katrina Dahlstrom

Thesis: Quantifying and Modeling Dynamics of Heat Shock Detection and Response in the Intestine of *Caenorhabditis Elegans*

Advisor: Erel Levine

## Tansu Daylan

Thesis: A Transdimensional Perspective on Dark Matter

Advisor: Douglas Finkbeiner

## Yuliya Dovzhenko

Thesis: Imaging of Condensed Matter Magnetism Using an Atomic-Sized Sensor

Advisor: Amir Yacoby

## Ruffin Eley Evans

Thesis: An Integrated Diamond Nanophotonics Platform for Quantum Optics

Advisor: Mikhail Lukin

## Stephen Fleming

Thesis: Probing Nanopore-DNA Interactions with MspA

Advisor: Jene Golovchenko

## Christopher Frye

Thesis: Understanding Jet Physics at Modern Particle Colliders

Advisor: Matthew Schwartz

## Wenbo Fu

Thesis: The Sachdev-Ye-Kitaev Model and Matter without Quasiparticles

Advisor: Subir Sachdev

## Michael Lurie Goldman

Thesis: Coherent Optical Control of Atom-Like Defects in Diamond: Probing Internal Dynamics and Environmental Interactions

Advisor: Mikhail Lukin

## Temple Mu He

Thesis: On Soft Theorems and Asymptotic Symmetries in Four Dimensions

Advisor: Andrew Strominger

## Robert Hoyt

Thesis: Understanding Catalysts with Density Functional Theory and Machine Learning

Advisor: Efthimios Kaxiras

## Daniel Steven Kapec

Thesis: Aspects of Symmetry in Asymptotically Flat Spacetimes

Advisor: Andrew Strominger

## Albert Lee

Thesis: Mapping the Relationship Between Interstellar Dust and Radiation in the Milky Way

Advisor: Douglas Finkbeiner

## Elise M. Novitski

Thesis: Apparatus and Methods for a New Measurement of the Electron and Positron Magnetic Moments

Advisor: Gerald Gabrielse

## Abhishek Pathak

Thesis: Holography Beyond AdS/CFT: Explorations in Kerr/CFT and Higher Spin DS/CFT

Advisor: Andrew Strominger

## Neil Peterman

Thesis: Sequence-Function Models of Regulatory RNA in *E. coli*

Advisor: Erel Levine

## Adi Pick

Thesis: Spontaneous Emission in Nanophotonics

Advisor: Steven Johnson (MIT)

## Hoi Chun Po

Thesis: Keeping It Real: An Alternative Picture for Symmetry and Topology in Condensed Matter Systems

Advisor: Ashvin Vishwanath

## Hechen Ren

Thesis: Topological Superconductivity in Two-Dimensional Electronic Systems

Advisor: Amir Yacoby

## Thomas Roxlo

Thesis: Opening the Black Box of Neural Nets: Case Studies in Stop/Top Discrimination

Advisor: Matthew Reece

## Alexandra Rose Thomson

Thesis: Emergent Gapless Fermions in Strongly-Correlated Phases of Matter and Quantum Critical Points

Advisor: Subir Sachdev

## Baojia Tong

Thesis: Search for Pair Production of Higgs Bosons in the Four b Quark Final State with the ATLAS Detector

Advisor: Melissa Franklin

## Seth Whitsitt

Thesis: Universal Non-Local Observables at Strongly Interacting Quantum Critical Points

Advisor: Subir Sachdev

## Kai Yan

Thesis: Factorization in Hadron Collisions from Effective Field Theory

Advisor: Matthew Schwartz



PROGRAMS

# Research Scholars

by Bonnie Currier, Research Scholar Coordinator

## Over 55 research scholars attended the 6th Annual Harvard Physics Department Postdoc/Research Scholar Retreat on September 12, 2018.

The day-long retreat, held at Nantasket Beach Resort in Hull, MA, included a talk about federal grants issues and opportunities by Dr. Peter J. Reynolds (Army Research Office), an interactive case study, led by Marco Iansiti, David Sarnoff Professor of Business Administration (Harvard Business School), and an address by Dr. Ashton Carter (Director of the Belfer Center for Science and International Affairs, Harvard Kennedy School, and former United States Secretary of Defense, 2015-2017). We had over 25 posters presented by the scholars during the poster session. The next retreat is scheduled for September 11, 2019, again at Nantasket Beach Resort.

During AY 2017-2018, our scholars enjoyed the following events here on campus, all part of our scholar development series. The series entails rotating panels and workshops given by faculty and current and former scholars to which we invite scholars and graduate students.

- How to Give an Academic Job Talk (Harvard faculty panel, Oct. 27, 2017)
- Scientific Ethics (Workshop led by Prof. Christopher Stubbs, Nov. 15, 2017)
- Chalk Talk Demystified (Workshop led by Prof. Stubbs, Dec. 6, 2017)
- How to Get a Post-Doc (Panel of current research scholars given to current graduate students, April 5, 2018)
- Transition from Academia to Industry (Panel of former scholars, April 25, 2018)

We invite you to connect with graduate students and former research scholars of the Department by agreeing to be included on our confidential list of physics alumni, administered by Bonnie Currier, Research Scholar Coordinator ([bcurrier@fas.harvard.edu](mailto:bcurrier@fas.harvard.edu)). Also please join the Official Group for the Harvard Physics Community at LinkedIn (<https://www.linkedin.com/groups?gid=4740923>). Be sure to identify yourself as a Physics Graduate Student or Research Scholar in your profile. You can remain in this group as an alumnus.

We appreciate any feedback on how the Department of Physics can support our scholars' career development.

## Celebrating Staff

by Mary McCarthy, Associate Director of Administration

Over the years, the role of administration in higher education has steadily evolved. Voice recognition tools have replaced shorthand, Lotus 123 once rendered landscape ledgers obsolete, and now Excel champions all. While technology has streamlined many processes, some of that very technology (including email and text) can also make debilitating demands on one's time. In the face of these rapid and sweeping changes, some things have remained constant. Physics staff, for example, continue to play a vital role, buying equipment for important experiments, submitting grant proposals, editing CVs, supporting physics lab teaching, registering countless participants in conferences, booking travel, organizing lunches, teaching students machining techniques or helping them design and build custom electronic instruments, processing visas, designing posters and flyers, reconciling accounts, and on and on.

The staff at the Department of Physics comprise a robust and high-performing crew. Our current team has played a key role in some historic moments—from transcribing class notes, recommendations, and scientific papers for Norman Ramsey, to helping with securing millions of dollars in Federal awards by getting proposals submitted under the wire and in perfect form, to fine-tuning logistics for Stephen Hawking's final visit to Harvard.

The staff are as diverse in our interests as we are varied in the personal stories of what brought us to Physics. We represent a beautiful cross section of New England—from animal rights enthusiasts to grandparents to new home owners. Our ranks even

include an ESL instructor, a museum docent, a performing artist, a choral singer, a tennis champion, an accomplished actress, a blogger, a bowling champion, a foreign language instructor, a motorcycle instructor, a movie star handler, and many part-time students and volunteers, several of whom are sending their first-born to college this fall. We are fortunate to report that one common theme among the staff is a unique dedication to the department—to the faculty, to the students, and to each other.

This year many of the staff participated in an annual outing, hosted by the all-staff Social Committee, to the Museum of Fine Arts for a stimulating (and competitive) treasure hunt that captivated our attention, tested our puzzle-solving skills, and strengthened our team spirit. We rounded out another successful year of supporting the department's faculty and students with a celebratory staff recognition luncheon, wherein we toasted each other and cheered the recipients of the annual Physics Phenom Award.

The Physics Phenom recognition program celebrates employees who have made meaningful and special contributions above and beyond their standard job responsibilities by awarding a modest cash prize and bestowing the moniker Physics Phenom for concrete achievement and contributions to the department in areas of collegiality, innovation, mentorship, professionalism, special projects, or teamwork. Congratulations to this year's winners and to everyone else on the staff who contributes every day to this department's well-being and success.



Top row, left to right: Carol Davis, Elise Krims, Hannah Belcher, Angela Allen, Samantha Dakoulas, Felice Gardner, Pattee McGarry, Tina Knight, Stephanie Clayman, Clare Ploucha, Jeffrey Derr, and Paola Martinez. Bottom row, left to right: Dionne Clarke, Silke Exner, Anne Trubia, Erica Colwell, Mary McCarthy (front), Jolanta Davis (rear), and Barbara Drauschke.

Below: Harvard Physics Annual Pumpkin Drop, October 29, 2018.

## Departmental Events

Our weekly colloquia with invited speakers are held at 4:15 PM in Jefferson 250, preceded by an all-community tea at 3:30 PM in the Physics Reading Room, Jefferson 450. If you are ever in town, we would be delighted for you to join us.

Among the colloquium speakers this academic year are Pablo Jarillo-Herrero (MIT), Cora Dvorkin (Harvard), Nathaniel Fisch (Princeton), Marcelle Soares-Santos (Brandeis), Matthew Fisher (UC Santa Barbara), Dmitri Chklovskii (Flat Iron Institute), and Chris Monroe (U. Maryland). Our Lee Historical Lecture speaker will be Anton Zeilinger (U. Vienna) on April 24, 2019. The Loeb Lecturer in the fall of 2019 will be Yann LeCun, the Chief Artificial Intelligence Scientist at Facebook AI Research (date TBD).

For more details about our upcoming colloquia, lectures, and other events, please consult the Harvard Physics Calendar webpage: [www.physics.harvard.edu/events/genca1](http://www.physics.harvard.edu/events/genca1).

## Stay Connected

We would love to hear from you. Please stay in touch and let us know if you would like to contribute news items to the newsletter at: [newsletter@physics.harvard.edu](mailto:newsletter@physics.harvard.edu)

Check out our website: [www.physics.harvard.edu](http://www.physics.harvard.edu).

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Join us on LinkedIn: <https://www.linkedin.com/groups/4740923/>.

Watch the videos of various events on our website: <https://www.physics.harvard.edu/events/videos>.

**BE SURE TO STOP BY ON MAY 30, 2019, FOR OUR COMMENCEMENT 2019 RECEPTION IN THE LIBRARY!**