

PHYSICS

Harvard University Department of Physics Newsletter

FALL 2014

COVER STORY

Probing the Universe's Earliest Moments

FOCUS

Early History of the
Physics Department

FEATURED

Quantum Optics

Where Physics Meets Biology

Condensed Matter Physics

NEWS

A Reunion Across Generations
and Disciplines



HARVARD UNIVERSITY
Department of Physics

**Detecting this signal is one of the most
important goals in cosmology today.
A lot of work by a lot of people has led
to this point.**

**JOHN KOVAC,
HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS
LEADER OF THE BICEP2 COLLABORATION**

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ON THE COVER:

The BICEP2 telescope at twilight, which occurs only twice a year at the South Pole. The MAPO observatory (home of the Keck Array telescope) and the South Pole station can be seen in the background. (Steffen Richter, Harvard University)

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Letter from the former Chair



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FELLOWS OF HARVARD COLLEGE

Just days before retiring my mantle as Chair of the Physics Department, I looked around my beautifully appointed office and thought about what had happened over the past year; what we had accomplished and what we had forgotten to do. I saw that my poor Christmas cactus that sits by the window was dry and went over to water it. Once there I realized that one thing I needed to do before leaving the office was to step outside the window and stand on the fire escape. I stood there in the summer breeze, as if on the prow of a very slow sailing ship, and watched the hustle and bustle of Harvard at 5pm. From this distance and looking outward, I adjusted my gaze and made a list of the activity that had taken place inside — the comings and goings of 150 physics majors, 120 post-doctoral fellows, 200 graduate students, 40 faculty, an uncountable number of visitors, and 50 support staff.

Every year starts with around 35 new graduate students arriving for orientation. Each one comes intent on making a huge contribution to science, and their eagerness is contagious. Their arrival is celebrated by a department-wide kickball game on the Cambridge Common. This year we offered 65 spots in the class: 40% were offered to women and 8% to other underrepresented minorities. The world is changing slowly, but changing nevertheless, and physics departments are changing with it, which is all to the good.

The G1's took their first year courses, learned how to teach in our new Teaching Practicum class, found professors to work with for the next summer, and even found time to do problem sets and play board games in the ever-more-densely packed graduate commons. Meanwhile, the G2's move up to the attic to study, take more classes, prepare for their orals, and make real inroads

into research, many of them becoming quite familiar with both Stan Cotreau's machine shop and the magnificent underground facility to fabricate and peer into, the Center for Nanoscale Science (CNS). And of course the G6+'s write their thesis table of contents and apply for jobs. Helping with all of this is our amazing graduate support team: Lisa Cacciabauda is our graduate coordinator; Carol Davis provides general support; Jacob Barandes holds our newly created position, Associate Director of Graduate Studies; and our new Director of Graduate Studies, Vinodhan Manoharan, has taken over for Masahiro Morii, the splendid young experimental physicist who has embarked on a new, multi-year "experiment" by becoming our department Chair.

And that's not all. The new in-house database (it works!- thanks Jacob) allows easy access to everything for both students and advisors. The graduate program has truly entered the 21st century.

The undergraduate physics concentrators declare themselves in the sophomore fall, just before the break, and come to lunch with the faculty in the library. They are encouraged to work in labs and many, many do, even those clearly bound for theory. As for the seniors, half brave the next step into academia, graduate school; the other half equally brave the step into the real world. We hear about their plans at a final student-faculty lunch, and we feel simultaneously very proud of them and sorry to see them go. The undergraduate team includes Carol Davis, who provides guidance and baked goods, and David Morin, the Associate Director of Undergraduate Studies who advises and teaches, and writes textbooks, including an updated version of Purcell's E&M text — in MKS! Rounding out this trio is Howard Georgi,

the Director of Undergraduate Studies who welcomes the students every Wednesday into the dining hall of Leverett House, where they do problems sets late into the night and partake of some strange comestible called monkeybread, which tastes better than it sounds. (But more on that later.)

Many postdocs arrive in the fall and fill our halls with new faces, making the department feel alive. Bonnie Currier, who ran the department for many years as administrator to the chair, now spends full time on the postdocs. We had our second-annual postdoc retreat this past September, an all-day conference where they shared research talks, posters, and trivia games and listened to an after-dinner speaker, MIT Professor Alan Guth, to round out a day of good, clean intellectual fun.

And last but not least—we reached out to our alumni with our first Physics Graduate Student Reunion on April 4th. It was a great success with 130 attendees, the distribution of graduating years almost uniform from 1950 to 2013. There were fascinating alumni panels and research updates by faculty, plus good food and drink and spirited conversations.

The faculty, students, and postdocs have been churning out physics like there is no tomorrow. Although it is a small department and we have just a few people in each field of physics, we are unusually productive and I am always amazed by the cleverness of my colleagues.

One of the classrooms in Jefferson Lab was renovated this summer. The uncomfy seats and sloping desks were replaced and the room outfitted with all manner of distance-learning accoutrements. Other classrooms are being updated to reflect new

ways of teaching—seminar and studio style. Our instructional laboratories have been changing in two ways. There are now faculty members in every laboratory session. The students start doing their own projects, even as freshmen, and the work spaces have been transformed into so-called SciBoxes—flexible industrial spaces where learning of all sorts can take place—including lectures, labs, and brainstorming study groups, funded, in part, by the Hauser Initiative for Learning and Teaching.

We welcome alumni to visit when you are in town, and please do so. Come to lunch Mondays with the faculty, visit a lab/lecture session, take in a seminar—of which there are at least 5 per day. You are always welcome at our Monday colloquium tea and lecture—4PM Mondays in the library. Let the administrator to the chair, Monika Bankowski, know you would like to come—or just show up! There you might well find our new chair Masahiro Morii presiding over a hot lunch, which prepares us for our weekly faculty meeting. My colleagues and I are thrilled to have Morii lead our department. Hopefully, I'll be at that lunch too, and at many others to come, enjoying the view from the other side of the table after an exciting, rewarding, and thoroughly exhausting four years as head of this amazing department.

Sincerely,

Melissa Franklin

MALLINCKRODT PROFESSOR OF PHYSICS

545

People every week

150

Undergraduate concentrators

200

Graduate students

120

Post-doctoral fellows

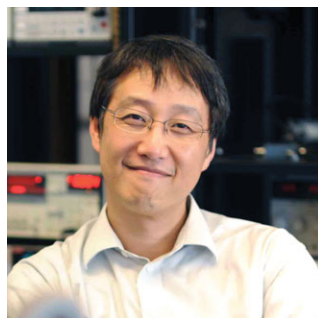
40

Faculty members

30

Visitors from other universities across the world

Faculty News



Philip Kim,

PROFESSOR OF PHYSICS

Professor Philip Kim was born in Seoul, Korea, in 1967. He received his BS in physics at Seoul National University in 1990 and his PhD in Applied Physics from Harvard University in 1999. He was a Miller Postdoctoral Fellow in Physics at the University of California, Berkeley, from 1999 to 2001. In 2002, he joined the Department of Physics at Columbia University. Kim enjoyed over twelve years at Columbia, and we are delighted to welcome him back to Harvard Physics.

Prof. Kim is a world-leading scientist in the area of materials research. His specific research area is experimental condensed matter physics with an emphasis on the physical properties and applications of nanoscale low-dimensional materials. The focus of the Kim group's research is the mesoscopic investigation of transport phenomena, particularly electric, thermal, and thermoelectrical properties of low-dimensional nanoscale materials. These materials include carbon nanotubes, organic and inorganic nanowires, two-dimensional mesoscopic single crystals, and single organic molecules. The use of modern, state-of-the-art semiconductor device fabrication techniques and the development of new methods of material synthesis/manipulation are essential parts of this research.

Prof. Kim has initiated these efforts very successfully and is continuously making innovations in microscopic experimental tools and methods in order to investigate the electric, thermal, and thermoelectric transport properties of nanoscale

materials. He has published more than 120 papers in professional journals, which are well cited. Many of his papers are published in high-impact journals such as *Nature*, *Science*, and *Physical Review Letters*. Kim has received numerous honors and awards, including the Oliver E. Buckley Prize (2014); Loeb Lectureship, Harvard (2012); Dresden Barkhausen Award (2011); Yunker Lectureship, Oregon State University (2011); Chapman Lectureship, Rice University (2009); IBM Faculty Award (2009); Ho-Am Science Prize (2008); American Physical Society Fellow (2007); Columbia University Distinguished Faculty Award (2007); Recipient Scientific American 50 (2006); and the National Science Foundation Faculty Career Award (2004). In addition, he has given more than 300 presentations as a keynote speaker, plenary speaker, and invited speaker at international and domestic conferences, colloquia, and department seminars. With his return to Harvard this summer, Prof. Kim feels he is fulfilling a circle of life, as he vividly recalled starting his graduate school work 20 years ago in the same place. "A new journey to explore exciting physics in novel material systems has just begun," he says.



Matthew Reece,

ASSISTANT PROFESSOR

The Department is delighted to announce the hiring of Assistant Professor Matt Reece. Reece works on theoretical particle physics, mostly in the realm where theory and experiment meet. He grew up in Louisville, KY, and attended the University of Chicago as an undergraduate. During his four years at Chicago, he worked in the Collider Detector at Fermilab experimental group with Henry Frisch, gaining an appreciation for the complex and careful work of experimentalists while realizing that he was better suited to be a theorist. He attended graduate school at Cornell University, where he worked on collider phenomenology and models of new physics under the supervision of Csaba Csáki. After enjoying a respite from the Ithaca winter during a six-month stint as a graduate fellow at the KITP in Santa Barbara in 2008, he received his PhD from Cornell and moved on to a three-year postdoctoral fellowship at the Princeton Center for Theoretical Science. At Princeton, he became increasingly interested in how we can probe the nature of dark matter, looking into models of new physics that

would require the cooperation of both theorists and experimentalists to confirm or rule out. While these topics first interested Reece upon his arrival at Harvard as a postdoc, they continue to be central to his research now as an assistant professor.

Recently, Reece has been studying how novel models of dark matter could have surprising astrophysical signatures, and he hopes to build a closer connection between particle physics and astrophysics. He is also actively involved in interpreting LHC results and understanding their implications. Outside of physics, Reece likes to read widely and enjoys traveling to cities with good art museums and beautiful surroundings. In March, he enjoyed a visit to the Beijing Center for Future High Energy Physics, where he began to explore what future colliders—at higher energies than the LHC can produce—might tell us about whether our theories are fine tuned. In July, he visited Budapest to take part in a workshop on unsolved problems in astrophysics and cosmology, returning to Harvard with renewed excitement about the future of dark matter physics.



Daniel Jafferis,

ASSISTANT PROFESSOR

The Department is equally pleased to announce the recent hire of Assistant Professor Daniel Louis Jafferis. Jafferis works on quantum field theory, string theory, and quantum gravity. He has had an unusual trajectory. He was home-schooled before entering Yale University at the age of 14. There he received his BS in physics and mathematics in 2001, and went on to receive his PhD in physics from Harvard in 2007. He then conducted postdoctoral research at Rutgers University, and became a member at the Institute for Advanced Study in 2010, before returning to Harvard in March 2011 as a postdoctoral fellow.

He was one of the discoverers of the low energy, three dimensional, superconformal Chern-Simons-matter theory describing multiple M2 branes, which led to a new concrete arena for the gauge-gravity correspondence. His work on

supersymmetric quantum field theories in three dimensions involved finding an exact method for determining the dimensions of all chiral primary operators in strongly coupled conformal field theories. That advance, in turn, led to a conjecture for a quantity that measures the number of degrees of freedom in interacting quantum field theories in three dimensions.

Jafferis' current research includes nonperturbative calculations in supersymmetric quantum field theory and supergravity, aspects of entanglement entropy in quantum gravity, and theories derived from M5 branes. This semester he is teaching Topics in Field Theory and String Theory. Somewhat of a gourmet, Jafferis had a lovely traditional samovar in his office during his time here as a graduate student. When he is not doing research or teaching, Jafferis enjoys entertaining. He is known, among other things, for giving large soirees.

Faculty Prizes, Awards & Acknowledgements*

American Association for the
Advancement of Science Fellows:

PROF. MIKHAIL LUKIN
PROF. XIAOWEI ZHUANG

American Philosophical Society
Fellowship:

PROF. ERIC HELLER

American Physical Society
Einstein Prize 2013:

PROF. IRWIN SHAPIRO

Blavatnik National Award:

PROF. ADAM COHEN

Oliver E. Buckley Condensed
Matter Prize:

PROF. PHILIP KIM

Dirac Medal, Abdus Salam
International Centre for
Theoretical Physics:

PROF. ANDREW STROMINGER

Distinguished Educator Award,
Society for Risk Analysis:

PROF. RICHARD WILSON

HETL Lifetime
Achievement Award:

PROF. ERIC MAZUR

2014 Hinshelwood Lecturer,
Oxford:

PROF. DAVID NELSON

Howard Hughes Medical
Institute Investigator:

PROF. ADAM COHEN

I. I. Rabi Prize in Atomic,
Molecular or Optical Physics:

PROF. MARKUS GREINER

Junior BEC Award 2013:

PROF. MARKUS GREINER

Willis Lamb Medal:

DR. SUSANNE YELIN

Minerva Prize for Advancements
in Higher Education:

PROF. ERIC MAZUR

The Moore Foundation Emergent
Phenomena in Quantum Systems
Theory Research Grant 2014:

PROF. SUBIR SACHDEV
PROF. EUGENE DEMLER

The Moore Foundation
Experimental Investigator Award
in Emergent Phenomena in
Quantum Systems 2014:

PROF. JENNIFER HOFFMAN
PROF. PHILIP KIM
PROF. AMIR YACOBY

The Moore Foundation Measuring
Quantum Entanglement Entropy
in Synthetic Quantum Matter
Award 2013:

PROF. MARKUS GREINER

National Academy of Sciences:

PROF. SUBIR SACHDEV

NSF Brain Initiative Award:

PROF. ARAVI SAMUEL

Radcliffe Fellowship:

PROF. JENNIFER HOFFMAN
PROF. DAVID NELSON
PROF. L. MAHADEVAN

Phi Beta Kappa Excellence in
Teaching Award:

DR. JACOB BARANDES

Physics Frontiers Prize:

PROF. ANDREW STROMINGER
PROF. CUMRUN VAFA

2014 Rossi Prize, American
Astronomical Society:

PROF. DOUGLAS FINKBEINER

Salam Distinguished Lecturer,
Abdus Salam International
Centre for Theoretical Physics:

PROF. SUBIR SACHDEV

Scientist of the Year Award,
Harvard Foundation for Intercultural
and Race Relations:

PROF. LISA RANDALL

Simons Investigator:

PROF. XI YIN

Sloan Research Fellowship Award:

PROF. XI YIN
PROF. DANIEL JAFFERIS

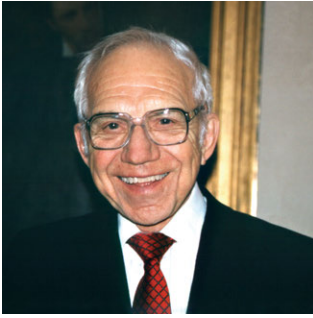
Thomson Reuters Highly-Cited
Researchers 2014:

PROF. EUGENE DEMLER
PROF. PHILIP KIM
PROF. MIKHAIL LUKIN
PROF. SUBIR SACHDEV
PROF. AMIR YACOBY

Trotter Prize in Information,
Complexity and Inference:

PROF. GERALD GABRIELSE

*Includes awards received over the past two years.



The extraordinary achievements of Leo Beranek

by Prof. Richard Wilson

In writing this appreciation of Leo Beranek, who just turned 100, I note that no summary nor slide show can compare with his personal autobiography, *"Riding the Waves,"* available at the Physics and SEAS libraries, and through MIT Press. He came to Harvard from a small town in Iowa in 1936 at a time when applied physicists were being moved to a new department. He was awarded a BSc in 1937 and a DSc in 1940 from that department. His thesis work is honored by a simple plaque that can be seen on the fourth floor of Lyman Lab.

In 1940, Leo was asked to form the Electro-Acoustics laboratory to find a way of silencing the noise of engines so that airplane pilots could hear instructions. It was a top secret laboratory located in the ground floor and first floor of Lyman. Interestingly, it was the first federally funded laboratory at Harvard, and the university charged only \$1 per year for overhead. In 1945, Harvard wanted to get rid of all secret work, but by that time Leo had collected more than \$2 million (in 1940 dollars).

Leaving Harvard in 1945, he went to MIT. More importantly, he started the consulting company, Bolt, Beranek and Newman, mostly focusing on acoustics work. Always active in Cambridge area music, he was involved in the Cambridge Society

for Early Music (which met in Sanders Theatre) and became President at various times of the American Society for Audio Engineering and the American Acoustical Society, receiving a gold medal from each. He was active in Boston Broadcasters Inc., which in 1962 tried to wrest a TV station from the Boston Herald-Traveler Corporation. After two Supreme Court decisions, he succeeded and became Director of Channel 5, which emphasized more local programming. In 1952, he was elected to the American Academy of Arts and Sciences. He served as President of the Academy from 1989 to 1994 and regularly attended meetings in the Cambridge building. He was very influential as President and became a major fundraiser. About that time he was elected to the Board of Overseers at Harvard University and was chairman of the visiting committee to the physics department where he made his influence felt. In Boston he was active with the Boston Symphony Orchestra, assuming various positions, including Chairman of the Board of Trustees. Finally, he was given honorary membership in the American Institute of Architects.

In all of this Leo has remained a fine, generous man and is an inspiration to us all.

In Memoriam



It is with great sadness that we announce that Dr. George Brandenburg, ex-director of the Laboratory for Particle Physics and Cosmology (LPPC), passed away on Saturday, September 14, 2013. Brandenburg graduated from Harvard College in 1965, and received his PhD from Harvard in 1969. After working at the Max Planck Institute, Stanford Linear Accelerator Center, and MIT, he became the Director of the High-Energy Physics Laboratory (which is now the LPPC) in 1980. He was also a Senior Research Fellow and

Lecturer on Physics. During his 33 years at Harvard, Brandenburg co-led our research projects with the CDF, CLEO, ATLAS, and BABAR experiments. He was a Fellow of the American Physical Society since 1992, and served as a co-spokesperson of the CLEO Experiment from 1997 to 1999. George was both a prolific scientist and a wonderful friend. We shall miss him.

COVER STORY

Probing the Universe's Earliest Moments

by Steve Nadis



For the past several years, a marvelous experiment has been underway at the South Pole, which has set the lofty goal of trying to understand what transpired during our universe's first second or less.

John Kovac, a Harvard Associate Professor of Astronomy and Physics, is the Principal Investigator of the team that has run this experiment, the BICEP2 Collaboration—a group consisting of about 50 researchers, including seven from Harvard. On March 17 of this year, Kovac and his colleagues announced that they had seen tantalizing hints of gravitational waves released within a tiny fraction of a second of the Big Bang. Although the detection was not ironclad, it may prove to be the strongest indication to date of gravitational waves of any sort—a prediction of the century-old theory of general relativity. If this preliminary result holds up, it would have far-reaching implications. First, it would provide evidence that gravity, like the other forces of nature, obeys the laws of quantum mechanics. It would also offer the strongest support yet for cosmic inflation—a theory conceived in late 1979 that proposed an exponential growth spurt during the universe's initial moments. Inflation resolved several longstanding cosmological puzzles, while offering an explanation for the driving force behind the Big Bang.

Alan Guth, the MIT physicist who hit upon the idea of inflation 35 years ago when he was a postdoc at Stanford, had a keen interest in the work of BICEP2. Kovac contacted Guth by email a week before the March press conference at the Harvard-Smithsonian Center for Astrophysics. “I need to talk to you about a topic that concerns both your research and mine,” Kovac wrote. “Please keep my request to speak with you confidential.” He met with Guth the next day at MIT's Center for Theoretical Physics, entering through the back door so as not to attract attention. He then presented Guth with a preprint of the BICEP2 team's main paper. Guth immediately saw that the group's findings might give inflationary theory a huge boost.

Kovac, of course, was gratified too, because the BICEP2 experiment represented the culmination of his more than two decades of work in the field, capping off an interest in the subject that dated back even further. As a high school student in the 1980s, Kovac was captivated by *The First Three Minutes*—a book written by the physicist Steven

Weinberg (who previously taught at Harvard). Kovac was particularly struck by a passage in Chapter 2 that described “a different kind of astronomy..., dealing not with observations of light emitted in the last few hundred million years from galaxies more or less like our own, but with observations of a diffuse background of radio static left over from near the beginning of the universe.” Weinberg was referring to observations of the cosmic microwave background (CMB)—residual light from the Big Bang that permeates the universe—and the emerging field of experimental cosmology. Even as a teenager, Kovac sensed that this was “the coolest thing in all of science” and resolved to make this his future area of study.

He went to Princeton as an undergraduate to learn from Robert Dicke, James Peebles, and David Wilkinson—faculty members who were leaders in CMB analysis. Wilkinson introduced Kovac to Mark Dragovan, and Kovac soon took on work-study projects in Dragovan’s CMB lab. Dragovan was mounting an expedition to the South Pole to measure the microwave background, and Kovac wanted in. He knew they wouldn’t take an undergraduate who was enrolled in school at the time, so he took a leave of absence during the 1990-1991 academic year in order to go to Antarctica. His first trip to the South Pole, “the best site in the world” for microwave astronomy, was, he recalls, “an extraordinary adventure. To work in a place that remote and to be entrusted with so much responsibility at that age [20] was empowering for me. I could use all the things I learned to make an impact.”

After graduating from Princeton, Kovac returned to the South Pole in 1993, the second of 23 trips so far, where he spent 14 months operating a different CMB telescope and “struggling to figure out how to manage sustained observations during the long [cold] polar winter,” he says. “It was a steep learning curve.” Although he did not secure useful measurements during that first winter, with a telescope that was literally sitting in the snow, “we learned a lot from these experiments, and we’ve applied that going forward to increasingly sensitive experiments.”

In 1995, Kovac joined John Carlstrom’s CMB group at the University of Chicago. He continued his research, while finding time for graduate studies as well. Along the way, he participated in the South Pole-based Degree Angular Scale Interferometer (DASI) experiment and was lead author of an accompanying 2002 *Nature* paper that showed, for the first time, that the CMB radiation was partially polarized—at the level of about one part per million. The DASI team had detected “E-mode” polarization, which relates to density fluctuations in the early universe.

But theorists have predicted since 1996 the existence of a fainter, “B-mode” signal—at the level of one part in 30 million—that would assume the form of a swirling pattern in the polarized CMB light. Gravitational waves unleashed during inflation, according to this hypothesis, would leave a permanent pattern of this sort in the background radiation, and experimental cosmologists like Kovac were determined to find it.

After completing his PhD at Chicago in 2003, Kovac accepted a postdoctoral position at Caltech under the direction of Andrew Lange, a CMB experimentalist who died in 2010. Lange’s team was gearing up for a series of South Pole experiments, the first of which was called BICEP1, aimed at measuring the B-mode signal. “Andrew entrusted me with the responsibility for the deployment and operation of the telescope, and by 2006 we had a working telescope at the South Pole,” Kovac says. BICEP1 operated for three years, setting an upper limit on the strength of the B-mode signal but failing to make an unequivocal detection. Hopes were then placed on BICEP2, an instrument that was more sensitive and 10 times faster than its predecessor. Lange invited Kovac to be BICEP2’s PI. It is now part of a series of telescopes led by Kovac and three co-investigators: Jamie Bock of Caltech, Chao-Lin Kuo of Stanford, and Clem Pryke of the University of Minnesota.

BICEP2 operated from 2010 to 2012 in the so-called “dark sector,” less than a mile from the geographic South Pole, searching the sky at an angular scale of about two degrees. The team spent several years analyzing their data, and by the fall of 2013, there were inklings of a spectacular result—a 5.2 sigma excess in the B-mode spectrum. However, some uncertainty remains as to whether the signal in question is actually cosmological in origin—coming, in other words, from the Big Bang—or whether it might be the result of dust emissions from within our own galaxy. An analysis using new data from the Planck satellite and other observatories, including the Keck Array currently operated by Kovac’s team at the South Pole, combined with the BICEP2 maps, should resolve this question before the end of the year.

If the additional data support BICEP2’s original findings, and a galactic source cannot account for the entire excess signal, there is, at present, no credible theory other than inflation that predicts the B-mode pattern at the intensity and angular scale measured by BICEP2. In that case, says Marc Kamionkowski of Johns Hopkins, one of the theorists who proposed the B-mode test in 1997, “We couldn’t prove that this signal was produced by inflationary gravitational waves, but it’s hard to come up with alternatives.”

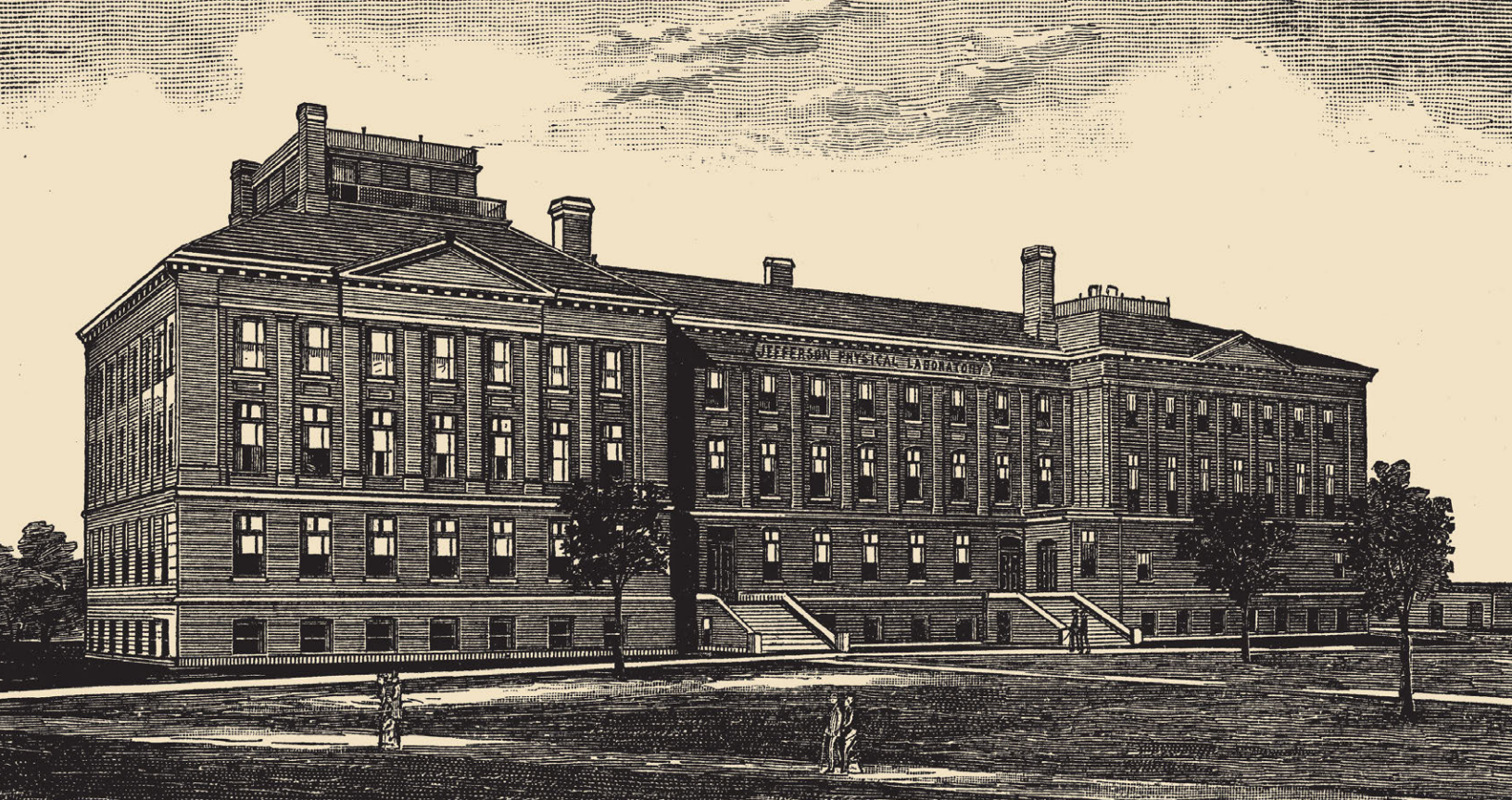
“These measurements need follow up. They need confirmation from multiple experiments and from multiple frequencies; they need confirmation from our own experiments with data we haven’t published yet.”

JOHN KOVAC, HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS
LEADER OF THE BICEP2 COLLABORATION

Guth agrees, saying, “There are no established [cosmological] models that can produce the same effect.” But before getting too carried away, he adds, “We’d like to see the BICEP2 results confirmed.”

Kovac would like to see that as well and has insisted, from the very beginning, on the importance of attacking the problem from different vantage points while making use of diverse observational strategies and technologies, from both the ground and space. The measurements reported in March, he says, “need follow up. They need confirmation from multiple experiments and from multiple frequencies; they need confirmation from our own experiments with data we haven’t published yet. And if all of this confirms that the B-mode pattern we’ve measured is originating from inflationary gravitational waves that come from the first trillionth of a trillionth of a trillionth of a second in the history of our universe, then we can apparently see back much farther than any of us dared to imagine possible.” It means that he and fellow astronomers and cosmologists have greatly refined our picture of the universe since 1977, when *The First Three Minutes*—a book that inspired Kovac and perhaps many of his peers—was published.

Kovac was also inspired by his former mentor, Andrew Lange, who challenged his colleagues by asking: “How far back can we see?” The BICEP2 experiment offers the potential to take us back very far indeed. Even though the final result is still unsettled, the experimental strategy itself is sound, offering the best chance yet identified for spotting primordial gravity waves and verifying inflation. The message Kovac takes away from this multi-year effort, which was set into motion by Lange, “is that it is a mistake in science to think that you ever know the limits to a question like that.” In point of fact, BICEP3, which is more sensitive and 10 times faster than BICEP2, is set to begin its probe of the CMB later this year, after a tune-up at a Harvard physics lab. And who can say what it—or future instruments—will find?



FOCUS

Early History of the Physics Department

by Prof. Gerald Holton

Physics at Harvard is a significant part of the story of the historic ascent of science in America. The subject has been taught at the University since its earliest years.

The curriculum at Harvard College, starting in 1642, included a course in physics that borrowed from the teachings of Aristotle. Students were required to take this course during the fourth quarter of their first year. Physics received a boost in 1726, when Thomas Hollis of London endowed a professorship in mathematics and natural and experimental philosophy, and also donated a shipment of scientific apparatus. John Winthrop, the second occupant of the Hollis chair starting in 1738, was a fine scientist who later became a member of the Royal Society. Winthrop taught physics based on Newton's *Principia*, as was then common at other colleges.

Like many of his fellow Founders, Thomas Jefferson, Winthrop's contemporary, had also studied physics in college based on Newton's work, and he was deeply impressed by it. The *Principia*, Jefferson felt, provided the vision of a majestic

universe held together by a few simple laws. So when he drafted the Declaration of Independence, he devoted its very first sentence to explaining to the world what "entitled" the United States to separate themselves from their former mother country, giving as the first reason "the Laws of Nature"—then widely understood as shorthand for the laws ("axioms") of Newtonian physics.

One of Winthrop's physics students at Harvard was young John Adams. Later, during a debate about the new Constitution, Benjamin Franklin held out for a unicameral legislative body. But Adams opposed him in public, arguing for a bicameral legislature and citing as his inspiration Newton's Third Law, which he simply called "action equals reaction." (But Adams also frankly admitted that he had forgotten much of Winthrop's lectures.)

Another “student” of Winthrop’s was Benjamin Thompson of Woburn, MA. Thompson, who later became Count Rumford, is said to have bootlegged the physics courses at Harvard when still a poor boy. At any rate, his experiments helped in the discovery of the Law of Conservation of Energy, and in 1814 he left Harvard the endowment for the Rumford Professorship.

1884 was a watershed year for physics at Harvard: The Jefferson Laboratory (named after the third President) opened—the first building in the Western hemisphere dedicated entirely to physics research and teaching. The laboratory was built with funds donated by Thomas Jefferson Coolidge, a businessman in Boston, and the scientist Alexander Agassiz. It was John Trowbridge of the Physics Department who had persuaded President Charles W. Eliot to support the idea, still unusual in the U.S., that laboratory research is essential for science—that faculty should not only teach physical knowledge but also do research, and that students should learn by actually doing experiments.

The new experimental spirit was widely disseminated, and not only in universities. Thus Edwin H. Hall—the discoverer of the Hall effect who joined the department in 1881—published a pamphlet, entitled “Provisional List of Experiments in Elementary Physics.” It described 40 experiments that would be required preparation for the College’s admission examination. This pamphlet greatly influenced the teaching of physics in American secondary schools.

The research wing of Jefferson Lab was designed primarily for experiments on Earth’s continually changing magnetic field, then a hot topic. The idea was to regard the lab itself as a great detector. So as not to interfere with the Earth’s field, no ferromagnetic materials were to be used in the construction of the lab. Yet despite all the precautions, when the building was finished it was still found to disturb the magnetic field. It turned out that the bricks contained small amounts of magnetic iron oxide. In a way, this blunder was lucky for physics. Unable to do the planned geophysical experiments, the physicists soon turned to other fields that proved extraordinarily fruitful.

For instance, in the top story of Jefferson Laboratory, Trowbridge set up a large storage battery of 5,000 (and later 20,000) test tube cells as a steady source of high voltages, which could be used, for example, in X-ray work. Edwin Hall remarked that this battery remained a “unique” feature of the laboratory, which was in great demand by researchers coming there from all parts of the country. This formidable battery amounted to Harvard building one of the nation’s first big accelerators.

Another faculty member, Wallace C. Sabine, was the pioneer of architectural acoustics. Theodore Lyman, director of the laboratory after Trowbridge’s retirement in 1910, conducted research in the field of ultraviolet spectroscopy. He discovered the Lyman series of spectral lines of hydrogen, though he was a bit slow to publish his results, so that in 1913 Niels Bohr only had the Balmer lines to guide him to his new atom.

Percy W. Bridgman started a research program on high-pressure phenomena as part of his PhD work at Jefferson Lab. After joining the faculty there, one of his first PhD students was Edwin C. Kemble, who wrote his doctoral dissertation on quantum theory, making him one of the first Americans to work in that area. After Kemble joined the faculty in 1919, his first graduate student was John H. Van Vleck. Later, Kemble, Van Vleck, and Wendell H. Furry made the theoretical wing of the department unusually strong by contemporary American standards. By the start of WWII, about one third of all American theorists in physics were students of one of these three or of one of their students.

In the late 1930s, the physics department built a cyclotron in collaboration with the School of Engineering. Kenneth Bainbridge, who had joined the faculty in 1934 (later known for his extraordinary precision measurements of isotopes), was the driving force behind this project. The cyclotron began operation in November 1939 and proved valuable in nuclear research. In 1943, at the government’s request, the cyclotron was shipped to Los Alamos for use in the Manhattan Project.

During World War II, Harvard physicists participated in a number of war-related research projects. They included the Electro-Acoustic Laboratory directed by Leo Beranek, the Psycho-Acoustic Laboratory under Stanley S. Stevens, and the Underwater Sound Laboratory (anti-U-Boat work) headed by Frederick V. Hunt. Many Harvard physicists, including Van Vleck, engaged in anti-radar work at Harvard’s Radio Research Laboratory and at MIT’s radar research lab. Faculty members involved in this effort, during and after the war, included J. Curry Street, Kenneth Bainbridge, Edward Purcell, Robert V. Pound, Nicolaas Bloembergen, Julian Schwinger, and Wendell H. Furry. Some of these physicists and others, such as Kemble, Bridgman, and Norman Ramsey, contributed their expertise to the nuclear physics research at Los Alamos and elsewhere.

Thus, throughout its history this department has advanced our ever-more important and wonderful field, through teaching and research. Many of Harvard’s faculty, students, postdocs, and alumni went further still, even helping in the great battle to defend civilization itself.

An artistic illustration of a quantum optics experiment. A large, textured blue sphere represents a living cell. Inside the cell, a purple oval represents a nucleus. A green laser beam enters from the top right, passing through a yellow sphere (gold nano particle) and hitting a gray diamond (NV center). A yellow planar structure (coplanar waveguide) is visible in the background, with microwave pulses (yellow spheres) being supplied through it. The entire scene is set against a dark blue background with other blue spheres and a yellow planar structure.

FEATURED

Quantum Optics

by Peter Maurer PhD '14,
Jeff Thompson PhD '14,
& Norman Yao PhD '14

**HARVARD QUANTUM
OPTICS GROUP**

The figure illustrates an artistic representation of a NV based nanoscale thermometer (gray diamonds) injected into living cells (blue objects). The local temperature in a single cell is controlled by the laser heating of individual gold nano particles (yellow spheres). To control the NV center's spin state, microwave pulses are supplied through a coplanar waveguide (yellow planar structure in the background).

[Reprinted by permission from Macmillan Publishers Ltd: G. Kucsko, P.C. Maurer, N.Y. Yao, M. Kubo, H.J. Noh, P.K. Lo, H. Park, M.D. Lukin, "Nanometre-scale thermometry in a living cell," *Nature* 500: 54–58 | doi:10.1038/nature12373 ©2013.]

Precision control of individual quantum systems is an enabling tool for exploring new physics and applications in the field of quantum science. This work involves a new scientific interface between quantum optics, nanotechnology, condensed matter, and quantum information science. Employing both experimental and theoretical techniques, the Harvard Quantum Optics group at the Physics Department and Harvard-MIT Center for Ultracold Atoms is engaged in research at the frontier of these new fields.

The ability to manipulate quantum mechanical systems with high precision is of great interest in many areas of science and technology. Unlike the classical case, where a bit of information is either 0 or 1, quantum bits may also take on superpositions of 0 and 1. Intriguingly, such “qubits” can be transmitted between two parties without the risk of eavesdropping by a third party. Moreover, the quantum mechanical nature of such qubits opens the door to a novel approach for measurements (quantum metrology) that enables the study of a large variety of systems with unprecedented accuracy.

MANY-BODY QUANTUM DYNAMICS AND NEW STATES OF MATTER

One particular question under current exploration involves the quantum dynamics of isolated, strongly interacting systems away from equilibrium, which can result in new physical phenomena and

many-body localization. This line of work is motivated by experimental advances that make it possible to produce and probe isolated, strongly interacting ensembles of disordered particles, as found in systems ranging from trapped ions and Rydberg atoms to ultracold polar molecules and spin defects in the solid state. The presence of strong interactions in these systems underlies their potential for exploring many-body localization. However, these interactions typically decay with a power-law, immediately raising the question: can localization persist in the presence of such long-range interactions?

While we recently made both analytic and numerical progress in answering this question, the complete story still eludes us. This poses a challenge that is being addressed in our group through complementary Nitrogen-Vacancy (NV) experiments. The NV is a defect color center found in diamond that consists of a nitrogen atom

Our experiments showed that it is possible to control chemical and biological processes inside a living system by applying local laser heating and calibrating its effects with nanodiamond temperature sensors inside the cell.

in the creation of new states of matter. One example involves the study of the breakdown of one of the central pillars of modern physics—statistical mechanics. This formalism connects thermodynamics to the microscopic world, and we are all familiar with its consequences. It is the reason heat diffuses through a metal pot and electricity conducts through a copper wire.

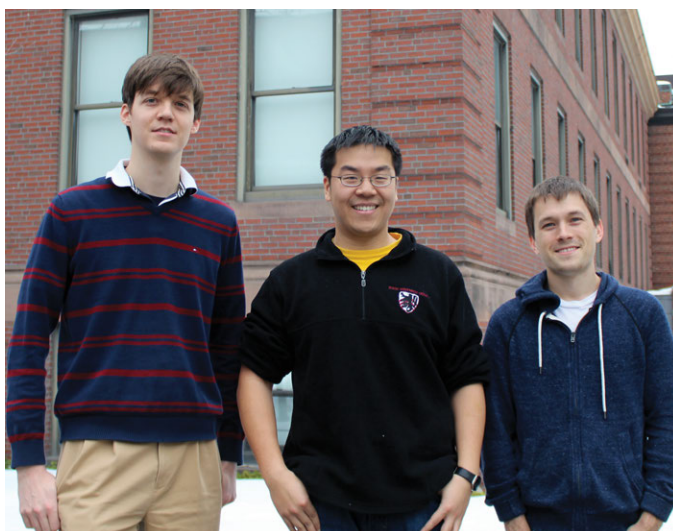
Underlying the theory of statistical mechanics is the assumption of equilibration. In isolated quantum systems, the failure of equilibration is exemplified by a phenomenon known as many-body localization. Many-body localized materials conduct neither charge nor heat. And due to intrinsically long storage times, they hold potential as a novel approach to the realization of quantum information systems. To date, none of these phenomena have been observed experimentally.

To this end, our group is exploring whether quantum optical systems of atoms, ions, and molecules may enable the direct observation of

and an adjacent vacancy substituted for two carbons in the lattice. Each NV behaves as an effective magnetic dipole and, when arranged in a disordered array, such a network of dipoles holds the promise of realizing a many-body localized phase of matter. In addition to probing fundamental questions about statistical mechanics and thermalization, the NV is also being explored for applications in both quantum information and metrology.

QUANTUM METROLOGY AND APPLICATIONS TO BIOLOGICAL SYSTEMS

Inspired by the intriguing potential applications of quantum information systems, enormous effort has been devoted towards identifying practical qubits. However, finding such a system is extremely difficult, since even the slightest interaction with the environment will cause a qubit to lose its quantum mechanical



Authors shown from left to right: Jeff Thompson PhD '14 currently a postdoctoral fellow at the Harvard-MIT Center for Ultracold Atoms, Norman Yao PhD '14 currently a Miller Fellow at UC Berkeley, Peter Maurer PhD '14 currently a postdoctoral fellow in the Steven Chu group at Stanford University

properties. In most cases, this places considerable experimental constraints on the system, such as keeping the qubits in an ultra-high vacuum or at temperatures close to absolute zero. Remarkably, the NV center can behave as an extraordinary qubit even at room temperature and under ambient conditions. Furthermore, it is possible to manipulate and read out NV centers using a combination of microwave and laser pulses.

Even though NV centers can store quantum mechanical information for relatively long times of about one thousandth of a second, they are still short-lived on macroscopic timescales. For many applications, ranging from quantum encryption to quantum computation, it would be desirable to have storage times on the order of several seconds. An increase of the bare NV storage time by three orders of magnitude, to approximately two seconds, was recently achieved in our group by employing a novel scheme to protect the memory qubit by subjecting it to a dissipative mechanism. These experiments elevate NV centers as a promising candidate for the real-world application of a quantum encryption scheme called “quantum money,” an unforgeable authentication protocol based on the fundamental properties of quantum-mechanical measurements.

While interactions with the environment reduce the storage time of quantum information, they can also be used as a resource to characterize temperature and magnetic and electric fields with unprecedented accuracy. Specifically, since the spin properties of NV centers are temperature-dependent, precise measurements of an NV's spin allow the local temperature to be probed. In collaboration with the group at Hongkun Park, we have used NV centers confined to diamond nanocrystals with sizes of a few tens of nanometers to realize a nanoscale thermometer, which enables temperature mapping in a wide variety of systems with extremely high spatial resolution.

Our experiments showed that it is possible to control chemical and biological processes inside a living system by applying local laser heating and calibrating its effects with nanodiamond temperature sensors inside the cell. One intriguing application of this technology is cell-specific thermal ablation of malignant cells without harming healthy tissue.

QUANTUM NETWORKS AND NANOPHOTONICS

To construct scalable networks for quantum communications, it is necessary to have efficient interaction between light and an atomic qubit. This goal is being pursued by our group on several fronts, with both solid-state “artificial” atoms in diamond (NV centers) and with laser-cooled, ultracold alkali atoms (such as rubidium).

Using only a microscope objective to focus an optical mode onto an atom, a few percent of the optical emission can be collected. This technique has been used to generate quantum entanglement between the electron spin of an NV center and the polarization of a single photon, and also to show interference between two single photons emitted from remote NV centers. These are important building blocks for a quantum network. To continue to develop this technology, it is necessary to improve the interaction of the optical mode and the atom.

There are two ways to achieve this: by focusing the optical mode more tightly, or by using a cavity to make multiple passes by the atom.

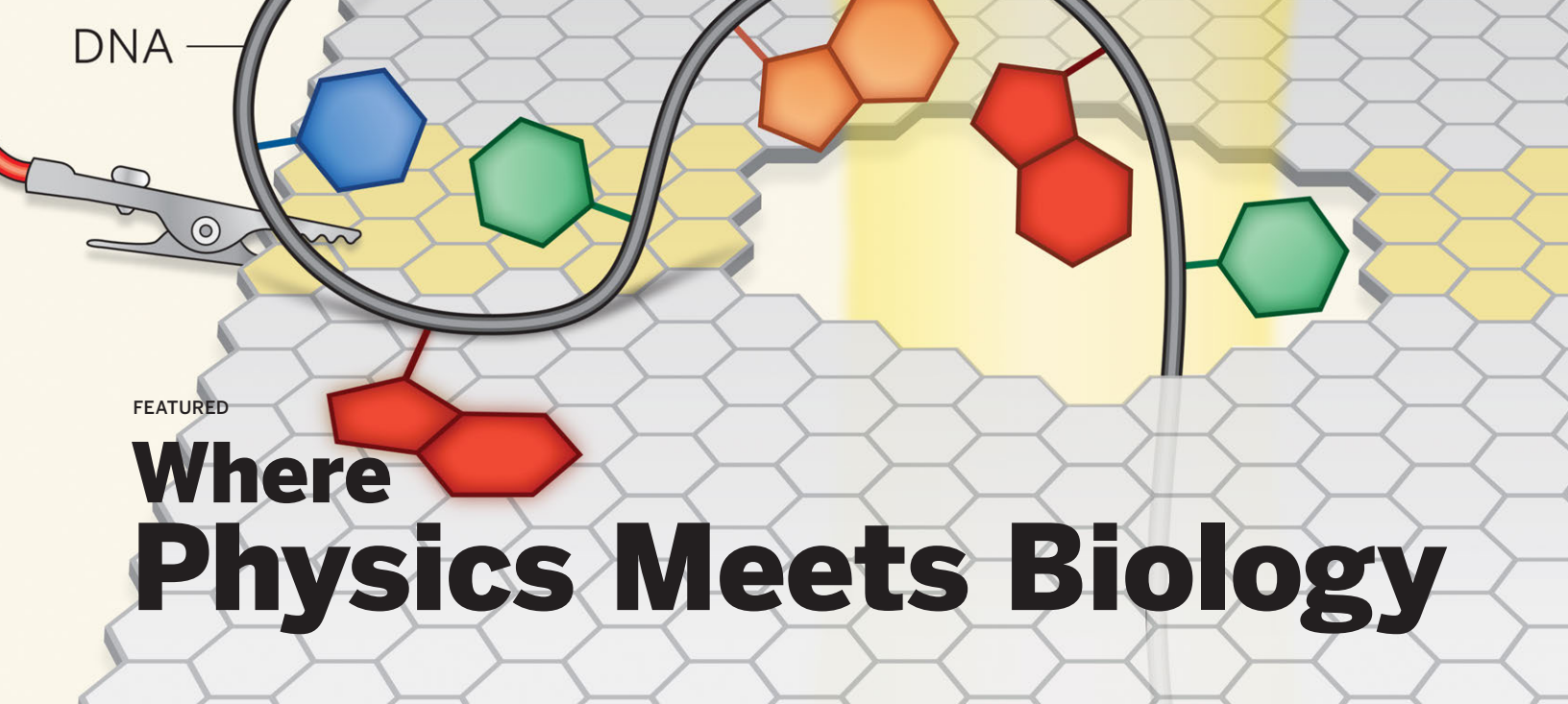
An intriguing new platform to realize these ideas involves nanoscale photonic devices. Lithographically patterned dielectric structures with sizes on the order of the optical wavelength allow light to be guided and reflected within very small volumes. Using a dielectric lattice known as a “photonic crystal,” it is possible to create optical-frequency band gaps containing localized defect modes that can confine light to a volume much less than one cubic wavelength. We have recently begun to explore the application of this technology to quantum optics for coupling to both NV centers and alkali atoms. In the first

The combination of these effects allows a single photon to control the propagation of many subsequent photons in a manner analogous to a classical electronic transistor.

case, the photonic crystals are fabricated directly from diamond. In the case of alkali atoms, the photonic crystal is made out of another dielectric (silicon nitride), and optical dipole forces are used to trap a single atom a fraction of a wavelength away from the surface of the photonic crystal.

Using this approach, we have recently demonstrated a quantum optical phase switch, which is a fundamental building block of a quantum network. In this experiment, the electron spin state of a single rubidium atom in the photonic crystal controls whether incident photons are reflected or transmitted. Furthermore, the polarization of a single incident photon can be used to change the spin state of the atom. The combination of these effects allows a single photon to control the propagation of many subsequent photons in a manner analogous to a classical electronic transistor.

We are presently working to extend these techniques to small networks of several atoms, with the goal of producing and distributing quantum entanglement. Because of the scalable nature of lithographic fabrication, it is also possible to make thousands to millions of copies of this experiment on a single chip, which might allow for the realization of large-scale quantum networks and for exploring complex quantum systems.



FEATURED

Where Physics Meets Biology

by Prof. Aravi Samuel and
Prof. Erel Levine

The last decade has seen an explosion of interest at the interface between physics and biology. The opportunities for tool-building, quantitative experiment, and sophisticated mathematical modeling in all areas of biology—from single molecule dynamics to brain science to evolutionary theory—have expanded, and a steady stream of physicists have “voted with their feet” to seize them. The idea of physicists becoming biologists is not new. Many of the giants of modern biology started as physicists: Max Delbruck and Francis Crick, as well as Harvard’s own Walter Gilbert and Howard Berg. What is different is the recent surge of activity at the boundaries between physics and biology, and the remarkable fact that physicists who get interested in biology no longer stop calling themselves physicists. A broad spectrum of collaborations between physicists and biologists, as well as genuine biological research by physicists, is being led by the undergraduates, graduate students, postdocs, and faculty of the Harvard Physics Department. Some highlights are reviewed below.

SEQUENCING SINGLE DNA MOLECULES

Several years ago, Dan Branton (Molecular and Cellular Biology (MCB)) and Jene Golovchenko (Physics and the School of Engineering and Applied Sciences (SEAS)) started thinking about whether it was possible to read the genetic code

from single strands of DNA. They hypothesized that monitoring the transit of a DNA molecule through a tiny hole not much bigger than the molecule’s diameter might provide a method for doing this. As each base moves through a nanopore embedded in a membrane, it can measurably change the electrical fluctuations across the membrane in a way that reveals the base’s identity. This project started out as a benchtop experiment in the Golovchenko laboratory, laying the groundwork for nanopore sequencing by exploring many fundamental issues in materials science and polymer physics. The project has now evolved into a biotech startup that is developing the first commercially available devices that will allow any biologist to read the genetic code from single strands of DNA (www.nanoporetech.com).

DYNAMICS OF DNA IN A LIVING CELL

DNA is not just a string of letters containing information. The physics of the DNA molecule dictate its dynamics and configuration, and the molecule’s physical properties thus have fundamental importance in its use by the living cell. The physical properties of DNA molecules are the focus of a fruitful collaboration between the labs of Nancy Kleckner (MCB) and Mara Prentiss (Physics), a leader in developing optical and magnetic trapping tools to study biology. Together, the Kleckner and Prentiss labs have

Above: An attractive strategy for single-molecule DNA sequencing is to pass single-stranded DNA through a nanopore in a graphene monolayer.

[Reprinted by permission from Macmillan Publishers Ltd: Hagan Bayley, Nanotechnology: Holes with an edge,” *Nature* 467: 164–165 | doi:10.1038/467164a.]

teamed up to build and apply a remarkable set of tools to manipulate single DNA molecules and visualize chromosomes in living cells with unprecedented resolution, resolving longstanding mysteries about the way a cell replicates its DNA with high efficiency and fidelity, despite the molecule's complexity and the presence of thermal noise.

POPULATION GENETICS

The remarkable successes that soon followed when Harvard physicists began working with biologists across Oxford Street led to a sea change. Harvard physicists, like David Nelson, started learning biology to develop questions of their own. Nelson got hooked on theoretical and experimental biology during a sabbatical at the Center for Systems Biology. He started developing new projects in population and evolutionary dynamics by quantifying and modeling the growth of mixtures of microorganisms as they expand across surfaces—competitively or collaboratively, depending on the species, genetic mutations, or environmental factors. The thriving success of this research program soon led to Nelson's joint appointment in MCB, opening up a new wealth of opportunities for theoretical physicists to work with Nelson and become, as he has done, a card-carrying "systems biologist."

NEW HIRES

Our Department has directly invested in the overlap zone between biology and physics, hiring faculty expressly to carry out biological research within the department. The first such hire was Aravi Samuel, an experimental neuroscientist who studies the connections between brain and behavior in small animals like the nematode *C. elegans* and the fruit fly *Drosophila melanogaster*. These animals represent the "hydrogen atoms" of neuroscience because they are small enough that every neuron and synapse can be fully mapped and measured, offering the hope of complete mathematical models of behavior in terms of quantifiable flows of information from sensory input to motor output. The spirit of this endeavor is shared with Samuel's graduate advisor in the Harvard Physics Department, Howard Berg, who has long pursued an understanding of navigational behavior in the even smaller "brain" of *Escherichia coli*.

The encounter between microbes and animals can lead to a wide range of outcomes, from new modes of symbiosis to vicious infections. In the eyes of Erel Levine's team, infection is an emergent phenomenon that can only be explained through the interactions between populations of hosts and populations of microbes. With the rapid increase in the number of antibiotic resistant pathogens, understanding the foundations of host-microbe interactions becomes an urgent need. The Levine lab is aiming to establish a minimal model of host-pathogen interactions using the microscopic worm, *C. elegans*, as a very simple host. Using theoretical tools of

nonequilibrium thermodynamics and developing novel microfluidic-based imaging methods, they study how physiological response, immunity, and behavior are coordinated—and how populations of bacteria make their collective decisions—to dictate the outcome of host-microbe encounters.

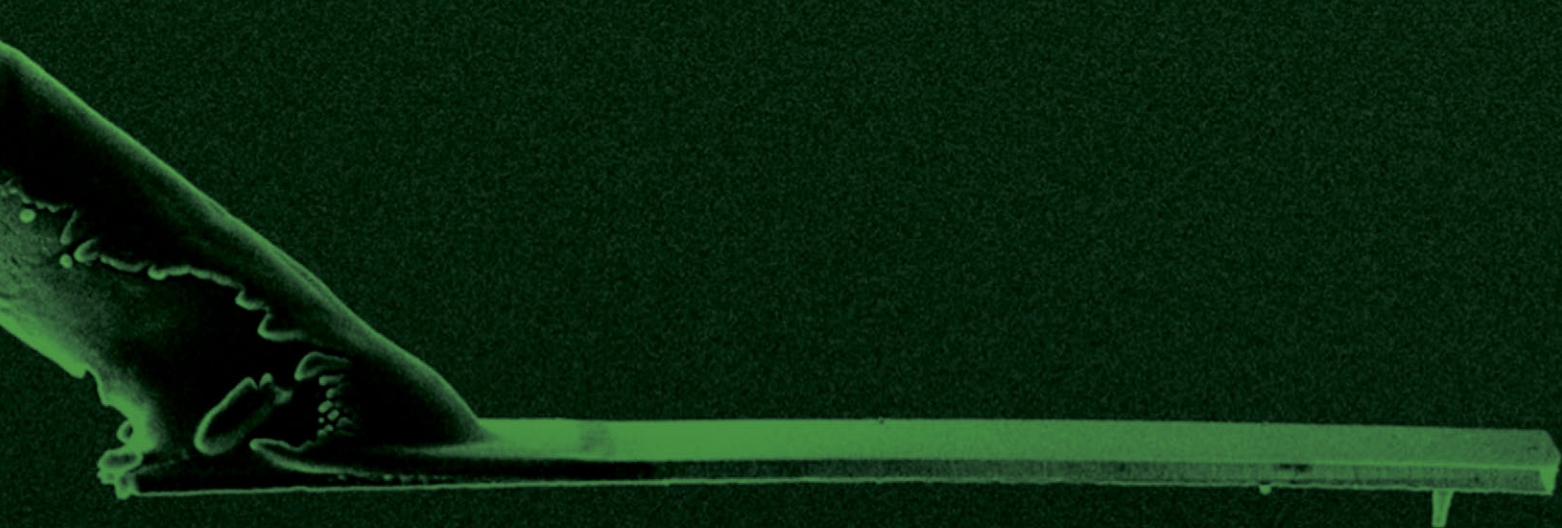
A HUB OF ACTIVITY

The thriving atmosphere for doing biological research in the Harvard Physics Department has led to a number of joint appointments with colleagues in other departments, greatly increasing the breadth and depth of research opportunities. Xiaowei Zhuang (Chemistry) is pushing the limits of optical microscopy with super-resolution, nanometer-scale techniques to visualize single molecules in live cells. Adam Cohen (Chemistry) has spearheaded new ways to measure voltage in live cells by running rhodopsin molecules "backwards," an all-optical approach that may obviate the need for electrodes in neuroscience. Michael Desai (Organismic and Evolutionary Biology) is combining theory and laboratory evolution to study the spread of mutations in an evolving population of yeast.

Meanwhile, colleagues in the closely-aligned area of soft-matter physics, which focuses on polymers, gels, colloids, and the like, have brought their experimental apparatus to bear on biological questions. David Weitz (Physics and SEAS) has used tracking and manipulation techniques originally developed for colloids to measure the force fluctuations caused by molecular motors in living cells. The results show that the motors play an underappreciated role in driving motion throughout the cytoplasm. His microfluidic techniques, developed for materials fabrication, are now being used to isolate single cells from a population and identify those with a particular phenotype. Vinny Manoharan (Physics and SEAS) is using a different approach, holographic microscopy—a tool developed to look at the three-dimensional motion of nanoparticles. Manoharan's goal is to understand how viruses self-assemble, an important and still mysterious step in the life cycle of these ubiquitous germs.

SUMMARY

At present, a full 25% of our faculty identify themselves as having an interest in biological research. Thus, biophysics is as large a part of our department as older disciplines like condensed matter and high energy physics, which is an extraordinary development in our field. Because of the forward-looking scientists in our department who drove this trend, the interdisciplinary boundary between physics and biology is becoming ever fainter, marking a positive step for research and discovery at this exciting frontier.



FEATURED

Condensed Matter Physics

by Michael Grinolds PhD '14,
Sean Hart PhD '15, Shannon
Harvey PhD '17, and Prof.
Amir Yacoby

Back in the 1980s, when Richard Feynman proposed the idea of a computer that could take advantage of the laws of quantum mechanics, it was a technological impossibility, and most people thought it would always remain purely theoretical. But experimental breakthroughs in the 1990s and beyond have paved the way for a proliferation of platforms from which researchers are attempting to build a quantum computer today.

Meanwhile, a number of algorithms that could be run efficiently on quantum computers, but not on classical computers have been discovered, thereby increasing demand. The challenges are high: computers will need thousands of qubits (the quantum analog of a bit) and computational error rates of at most about one percent to perform effective quantum algorithms—a scaling of several orders of magnitude above current systems.

While much of the excitement about quantum computing research is derived from the potential applications, this research has also unveiled new physics due to qubits' ability to function as sensors. To perform quantum operations, qubits must be exquisitely sensitive to the fields that drive them, which also makes them unparalleled sensors. They can be adapted to measure other systems, working,

for instance, as a magnetometer that can sense biological molecules. Additionally, qubits can be used to study their own environment, which yields information on their noise bath—knowledge that can be used to improve qubits. The search for a long-lived qubit has also motivated the field of topological quantum computing, where emergent new particles would store quantum information in a way that is protected from environmental perturbations.

Professor Amir Yacoby works on three promising solid-state implementations of quantum computers: exploring computation with semiconductor spins, nitrogen vacancy centers in diamond, and topological qubits in mercury telluride.

Above: SEM image of a single crystalline diamond nanopillar probe with a single NV centre at its tip, able to scan within tens of nanometres of a sample surface. The nanopillar is used as the tip of an atomic force microscope, enabling magnetometry measurements of unprecedented sensitivity and spatial resolution.

SEMICONDUCTOR SPIN QUBITS

One of the Yacoby Lab's projects uses spins in semiconductor quantum dots as qubits. Electrons can be confined within quantum dots, also known as "artificial atoms," to a space small enough that their energy levels become quantized. At tens of millikelvin, where the experiment is run, electrons occupy the orbital ground state of the dot, and noise in the system is reduced significantly enough that quantum superpositions of electron spin states are long-lived. Using the spin state of electrons in quantum dots as the basis for the qubit takes advantage of a spin's isolation from its environment to achieve long coherence times essential for low error rates, while still allowing for rapid control techniques available for quantum dots.

growth or device processing to mitigate it. Or you can use your knowledge of the frequency spectrum of the noise to drive the qubit so that it's insensitive to noise." Graduate student Michael Shulman adds, "No one knows yet what the building block of the quantum computer will be, or what the essential advances that will render them practical are, but by employing a range of approaches and considering the successes and failures of other types of qubits, we can advance the field in a synergistic way."

NV CENTERS IN DIAMOND

Another team in the Yacoby Lab is working on improving qubits made with defects in diamond. Nitrogen-vacancy (NV) color centers are atomic defects in diamond where one carbon atom is replaced by a

Amir Yacoby works on three promising solid-state implementations of quantum computers: exploring computation with semiconductor spins, nitrogen vacancy centers in diamond, and topological qubits in mercury telluride.

The team has two major research directions: enhancing the coupling between qubits and improving the qubits' coherence times, both of which act to increase the number of coherent multi-qubit operations, a metric for the capabilities of the system. While semiconductor qubits can take advantage of miniaturization and mass production methods developed to manufacture classical computer chips, before adapting these technologies the group must develop a robust scheme for coupling large numbers of qubits. Quantum computers require entanglement, non-classical correlations between the states of multiple qubits, which can be generated in this system using electrostatic dipole interactions. Current work is directed toward extending the range of the interaction by putting metal gates that extend between the qubits onto the device, which could pave the way for large 2D arrays of qubits useful for error correction.

In order to improve coherence times, the team is pursuing research into noise that affects the qubit. Noise decoheres the delicate quantum superpositions necessary for quantum computing, and remains the major obstacle to effective quantum computers. To remedy this, the group is studying the rich magnetic and electric environment that interacts with these semiconductor qubits. As graduate student Shannon Harvey puts it, "doing so, you might discover the ultimate source of the noise and use that information to direct your material's

nitrogen atom that is adjacent to a carbon vacancy. These defects are essentially solid-state molecules: They have quantized energy levels that can be manipulated electromagnetically, and at the same time they are rigidly held in a diamond lattice so that their surroundings can be fabricated using micro- and nano-fabrication techniques. One hope is that, like early research efforts on trapped ions, several NV defects can be entangled together to process quantum information. There is also the expectation that the scalability of solid-state fabrication techniques will allow for building up to many-qubit systems.

In the Yacoby Lab, the research is focused on understanding how these defects interact with their solid-state environments. Postdoctoral fellow Marc Warner outlines the challenge: "With solid-state defects like NV centers, each defect has a different environment, and so unlike atomic or ionic systems, every quantum bit is unique." On the most basic level, he says, as NV defects are created by nitrogen-ion implantation—a stochastic process—their exact locations are unknown. Given that entanglement between the spins of defects is often achieved using distance-dependent magnetic dipole interactions, it is critical to be able to position the defects in three dimensions with atomic precision.



From Left to Right. Back Row: Toeno van der Sar, Amir Yacoby, Rainer Stöhr Front Row: Lan Luan, Andrei Levin, Yuliya Dovzhenko, Monica Allen, Shannon Harvey, Angela Kou, DiDi Wei, Ben Feldman, John Nichol

To this end, the Yacoby group NV team developed a new kind of microscope for nanoscale imaging of NV centers. Noting that NV centers have a paramagnetic ground state with unpaired spins, they built a spin microscope that uses magnetic resonance imaging (MRI) techniques to visualize these individual defects in three dimensions. The microscope combines the optical readout of NV centers and scanning nanomagnets with large magnetic field gradients. Graduate student Michael Grinolds describes the process this way: “By moving the nanomagnets in space and optically monitoring the NV electron spin resonances, we can map out their locations.” As an added benefit, he notes, the magnetic field gradient also spectrally distinguishes different NV centers, which affords individual control over each potential quantum bit.

TOPOLOGICAL QUBITS

A different approach, called topological quantum computing, forms the third component of the Yacoby Lab’s effort to harness the power of quantum information. Conventional approaches to building a

quantum computer typically focus on localized nodes or particles —qubits in other words— that are coherently integrated into a larger computing network. A continuing challenge of this strategy is that the qubits need to be isolated from their environment for enough time to execute an interesting computation. The topological approach takes the view that if the quantum information can be stored nonlocally, then any type of local disturbance would be incapable of destroying coherence.

Obtaining such a nonlocal system may seem quite difficult, but the key lies in the interactions among the building blocks of the quantum computer. Rather than having a network of connected nodes, one might instead imagine a two-dimensional liquid of interacting electrons, so that the emergent behavior of the electron system can become intrinsically nonlocal. Under certain conditions, moreover, the electrons can conspire to create new emergent particles, where each pair of these new particles encodes a two-level quantum system. The only way to evolve between the two states would be to cause one of

These special particles, Majorana fermions, are named after their inventor, Ettore Majorana. The Yacoby Lab is designing electronic systems to support these exotic particles by carefully controlling the parameters that dictate how electrons interact with each other.

these special particles to completely encircle another. If one can localize the two particles far from one another, then the quantum information becomes spread out and more resistant to local environmental perturbations.

These special particles, Majorana fermions, are named after their inventor, Ettore Majorana. The Yacoby Lab is designing electronic systems to support these exotic particles by carefully controlling the parameters that dictate how electrons interact with each other. The Topology team uses a semiconductor heterostructure, where electrons live inside a two-dimensional sheet of HgTe located between two CdTe layers. By coupling this system to superconducting leads, they are able to study the effect of pairing between electrons in the presence of strong spin-orbit coupling and reduced dimensionality. By exploring the emergent effects of this unique confluence of parameters, they hope to realize a new and robust way of processing quantum information.

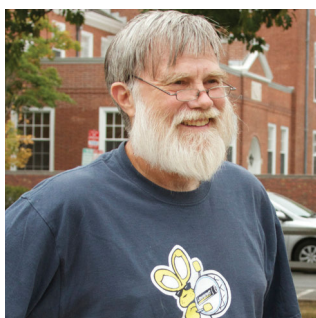
DIVERSE PROJECTS

In addition to the three topics discussed here, the Yacoby Lab also studies the Quantum Hall Effect in graphene as well as graphene-based technologies. Although the Yacoby group studies a diverse set of projects, they share a number of fundamental ideas and experimental techniques, and students enjoy exchanging advice on everything from how to fabricate devices in the clean room to the ins and outs of running a dilution refrigerator. Many students like being surrounded by people doing research in a variety of fields. As graduate student Hechen Ren put it, “Sharing an office with people studying so many different systems keeps me informed about what’s happening at the forefront of so many topics in condensed matter physics. It’s a very exciting place to be.”



PROGRAMS

Undergraduate Program



A MESSAGE FROM THE

Head Tutor, Howard Georgi

Many things have changed in the 50 years since I attended my first Physics class in Jefferson 250 in the fall of 1964. Back then, there was a 10 foot long slide rule hanging over the blackboard in the big lecture hall; Bob Pound and his students had just finished weighing photons; and a new Physics Library had been built on Jefferson Lab's 4th floor. Julian Schwinger, about to share the Nobel Prize for quantum electrodynamics, was churning out spectacular theory PhDs and laying the ground-

work for the Standard Model. The brilliant physicist and teacher Ed Purcell was teaching the freshman mechanics course for advanced placement students, then called Physics 13. We had typewriters and landline phones, and computers filled a room but didn't do much.

Now we have a research computing center, experimenters creating highly entangled quantum states in the basements, about a half-dozen different beginning mechanics courses, freshman seminars spanning the gamut from Vafa's "Physics, Math and Puzzles" to Golovchenko's "Freshman Physics Laboratory," and a meeting room and frequent "Monkeybread evenings" for our undergraduate students. But one thing that hasn't changed is the sense of excitement that fills our buildings where outstanding students and faculty have the fun of grappling with the most interesting questions in science.

NEW CONCENTRATORS

An enthusiastic new group of 55 sophomores signed up for the Physics and Chem/Phys concentrations this past year, many of them pursuing joint concentrations or secondaries in other fields, for example Classics, Computer Science, Engineering, and Mathematics.

PRIZES & AWARDS

Phillip Yao received a Rhodes Scholarship in May '13 and is presently studying at Oxford, concentrating on the intersection between technology and education. Leah Weiss received a Gates Cambridge Scholarship in May '13, which she is using to pursue scientific computing with applications to problems in organic solar cells. Mariel Pettee '14 received a Harvard-Cambridge Scholarship and is studying Physics at Cambridge (in the UK). Eric Bersin and Laszlo Seress both received Fulbright Scholarships in May '14 and are using them to pursue bioengineering in Germany, and chemistry in England, respectively. The Sanderson Award is annually presented to the graduating Physics concentrator with the highest grade average in concentration courses. This year's winner is Daniel Ranard. Daniel is spending a year at the Perimeter Institute before heading to Stanford to pursue a PhD in Physics.

INSTRUCTIONAL LABS

The Instructional Physics Labs constitute a cluster of creative spaces that support undergraduate inquiry and innovation. A dedicated group of staff, preceptors, and teaching fellows works closely with faculty to design and lead customized activities for students in the Instructional Labs, drawing upon a series of introductory physics and electronics courses. These activities—which cater to three unique sequences of courses, each with a distinct student population, emphasis, and goal—are taught in a manner that attempts to engage students in the process of actually doing science rather than passively hearing about it.

For the introductory physics sequence 15a (or 16)/15b/15c, which is taken by many concentrators in physics and allied fields, we have developed a lab component called "Principles of Scientific Inquiry" (or PSI for short). Each semester has a different focus. In 15a or 16 (Mechanics), students learn how (and perhaps even why) to design

experiments and how to create and use mathematical models in scientific inquiry. They work first with structured activities in a lab section group and then with less guidance on systems of their own choosing. In the segment of PSI taught with the E&M course, 15b, the emphasis is on scientific communication, ethics, the use of the published literature, and lab exercises to develop intuition about the course subject matter and explore applications of electromagnetism. In the 15c waves course, students get a chance to pursue a substantive research project in the last half of the semester with mentoring from faculty, staff, and graduate students.

The 15c PSI experience begins with a series of four defined labs that introduce students to equipment and methods for investigating vibrations and optics. They explore mechanical oscillators and modes, assemble an interferometer, play with Fourier optics, and "discover" the basis of holography. They build on this experience to pursue an experimental research project, working in groups of two or three. In 15c last fall, projects included the measurement of vibration with speckle interferometry, making color holograms, holographic microscopy, acoustic lensing, and a "prehistoric laser" built with parts that would have been available a century ago.

The "prehistoric laser" project is a good example of how mentors and students can work together to create a significant learning experience in a very short time. The idea came from Professor Markus Greiner, based on a popular science publication from several decades ago. Markus and the lab staff and teaching fellows spent some time preparing equipment, including the restoration of a large Wimshurst machine to generate high voltages in a safe (but spectacular) way. A group of three students then took up the challenge of building the laser, working under the supervision of the teaching team. They quickly learned enough soldering and fabrication skills to make a prototype (that, unfortunately, did not work). In the next couple of weeks, however, they made a second prototype that fared much better. Attaching it to the Wimshurst machine, they were able to observe light output as the high voltage generated a spark across the gap between the electrodes.

Apart from instruction that is geared to specific courses of study, a major emphasis is placed on making physics fun—just as it typically is for researchers on the cutting edge of their fields. In many labs, the operating staff is able to introduce students to puzzles and interesting applications of physics, while challenging them with guided, small group projects. This type of hands-on learning and project support has been quite effective in helping students discover that doing physics can be an exciting and creative endeavor—nothing like the dry exercise that some people, far removed from this field, might imagine.

STUDENTS' RESEARCH

Thirty Physics and Chem/Phys concentrators stayed on campus this past summer to undertake full-time research in physics, chemistry, engineering, and related fields. Another fifteen students carried out research at other institutions, many of them abroad.

Eric Bersin, for example, spent the summer in the laboratory of Professor Mikhail Lukin, working on quantum optics as part of his senior thesis. His project sought to use the nitrogen vacancy system in diamond to measure the magnetic fields from nuclear spins in biologically relevant molecules. The hope was to be able to demonstrate the sensing of nuclei from a single protein and to show how this might be used to perform a kind of “single-molecule NMR.” The opportunity to work in the Lukin Group was pivotal in cementing Eric’s desire to continue his research in graduate school.

CAREER PATHS

This past year’s graduating class consisted of 40 Physics and Chem/Phys concentrators. Seventeen of these students have gone off to graduate school at ten different institutions to study Physics, Astrophysics, Applied Physics, Chemistry, Physical Chemistry, Bioengineering, and Math. Others are pursuing medical, law, and music degrees. And still others have joined the workforce in software, consulting, aerospace, finance, teaching, and various startups. One student is even working as a comedy writer in LA, while another is dancing in a professional ballet company.

THE UNDERGRADUATE STUDY: A NEW PLACE TO THINK ABOUT PHYSICS (OR NOT THINK AT ALL)

The Physics Undergraduate Study, a gathering place constructed in 2009, provides a friendly environment for students to study and relax between classes or to hang out late at night. Several regular events take place in the Study, ranging from office hours to Society of Physics Students (SPS) events to Monday lunches with colloquium speakers. The Study is located on the second floor of Jefferson near the Lyman lobby, conveniently across the hall from the office of Carol Davis, the Undergraduate Student Coordinator. Carol has been a devoted staff member in the Physics Department since 1971. She works closely with the students, helping to organize numerous social and academic events.

PHYSICS NIGHT AT LEVERETT

If you were to stop by the Leverett House dining hall on Wednesday nights, you would encounter a truly fascinating sight—a room packed with a hundred students working diligently on physics problem sets.

Professors and teaching fellows regularly stop by to offer late-night office hours. Some students work quietly in small groups, while others operate more in a “Eureka!” mode, bouncing around between tables. Regardless of one’s preferred learning style, it can be an immensely productive time. And there’s nothing like bonding over problem sets at 3 am.

FUN STUFF

The Society of Physics Students had its usual share of fun this past year with a number of offbeat events, including a liquid nitrogen ice cream party in September and a pumpkin drop on Halloween. In the words of former SPS president, Joanna Behrman ’13, “The pumpkin drop celebrates the coming of fall and tests that the laws of gravity still hold in the present academic year. If Newton had been born in the New World, a falling pumpkin might have inspired him. But even if we don’t inspire the next Newton, we do have a smashing good time.”

MONKEYBREAD

Prof. Georgi’s Masters Residence in Leverett House is home to many “Monkeybread” gatherings throughout the year, where students can mingle and get advice from faculty and other students. The Monkeybread itself is a delicious treat, best described as a mound of cinnamon bun nuggets. If you wish to make it yourself, the full recipe can be found here: http://leverett.harvard.edu/wiki/Monkeybread_Recipe.

SPRING COOKOUT

Organized by the Society of Physics Students and a dedicated army of Physics Department staff, our annual cookout is held at the end of finals period in May. If you are in town and would like to have lunch on a warm spring day with 400 like-minded physicists, students, and staff, please contact David Morin (morin@physics.harvard.edu) to find out the exact date.

CURRICULUM COMMITTEE

The Undergraduate Curriculum Committee is working on ways to improve our undergraduate course offerings. We welcome any thoughts from alumni about your experience—what worked for you and what you think we could do better. Please send any suggestions to Howard Georgi (georgi@physics.harvard.edu) or David Morin (morin@physics.harvard.edu).



PROGRAMS

Graduate Program

by Dr. Jacob Barandes

THE INCOMING PHD CLASS

The Physics PhD classes that entered in the fall of 2013 and the fall of 2014 were both remarkable in their geographic diversity and included students from the American states of Alabama, Arizona, California, Colorado, Connecticut, Florida, Illinois, Louisiana, Maryland, Massachusetts, Minnesota, New Mexico, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Tennessee, Texas, Utah, Washington, and Wisconsin, as well as the District of Columbia. Beyond the United States, these incoming classes also included students from Brazil, Canada, China, Germany, India, Kazakhstan, Korea, Mexico, Moldova, Norway, Romania, Switzerland, Taiwan, Turkey, and Ukraine.

NEW INITIATIVES

Introduced for the first time in the spring term of 2012, and a required part of the PhD curriculum as of the spring term of 2013, the Physics Department has created a 10-session, practice-based workshop on teaching and communicating physics for all first-year PhD students. In the workshop—known officially as Physics 302 but popularly as the “teaching practicum”—students learn the nuts and bolts

of presenting and teaching at Harvard, and give lessons and presentations to each other in small groups with continuous instructor and audience feedback.

THE PHYSICS GRADUATE STUDENT COUNCIL

Created by Physics PhD students in the spring of 2009, the Physics Graduate Student Council has become an integral part of the Physics Department. The council provides a forum for graduate students to propose new initiatives and discuss issues of common concern. The council also organizes social events like the popular biweekly Friday afternoon social hour and monthly movie nights, assigns desks to second year students, and administers annual surveys to the graduate students on advising and the overall academic climate. Most recently, the council has launched an annual research week, consisting of a research poster event and a series of laboratory open houses for new graduate students to learn about research opportunities in the department. The council’s leadership for the 2014-2015 academic year is Jae Hyeon Lee (President), Arthur Safira, Olivia Miller, Nicholas Langellier, and Victor Rodriguez.

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.



Nicholas Schade

2013 GOLDHABER PRIZE WINNER

One of the two winners in 2013 was Nicholas Schade, currently in his fifth year of the PhD program. As an undergraduate at Brown, Schade studied the biological side effects of simulating microgravity in living organisms. He worked with Prof. Jim Valles, studying the effects of intense electromagnetic fields on *Paramecium caudatum*, writing his honors thesis about this project. Schade graduated from Brown magna cum laude with a ScB in Mathematical Physics in 2005, where he received the R. Bruce Lindsay Prize for Excellence in Physics.

Schade worked for four years before graduate school, including one year teaching AP physics and engineering at Andover High School. While there, Andover High received a Siemens Foundation award for having the best Advanced Placement math and science courses in the state. He also spent three years working as a systems analyst at the MIT Lincoln Laboratory, where he was part of a team that developed a novel airborne sensor prototype for the US Air Force. The team received several accolades, including a letter of gratitude from the Secretary of the Air Force.

Schade came to Harvard in 2009 and joined the Manoharan group. His research goal is to engineer a “metafluid”—a material, unlike any known to exist naturally, that could be used to build an invisibility cloak or a “super lens” with unlimited imaging resolution, making it possible to image

molecules or atoms with visible light. He and his collaborators discovered a critical diameter ratio at which tetrahedral clusters self-assemble in arbitrarily high yield. Their results were published this year in *Physical Review Letters*. Schade was awarded the US Department of Energy Office of Science Graduate Fellowship for this work. He has also been awarded the An Wang and Wallace-Noyes Fellowships by the Harvard Physics Department.

In addition to his research, Schade participates in Harvard’s Graduate Consortium on Energy and Environment and enjoys doing science outreach. He gave a “Science In The News” public lecture about his work at Harvard in 2012, and has also been invited to present his research to local high schools, as well as to Boston University’s undergraduate physics club.

The Goldhaber Prize is awarded annually by the department to its two most outstanding current PhD students based on their research accomplishments, as determined by a vote of the faculty. Winners of this award give presentations at the Historical Lee Lecture. They are guests at the dinner held prior to the lecture, and each receive a \$3,000 check.



Norman Yao

2013 GOLDHABER PRIZE WINNER

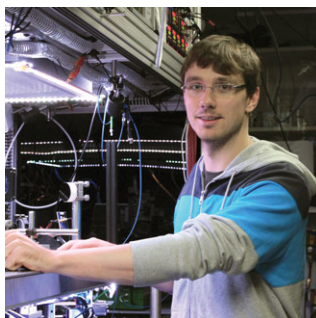
The other winner of the 2013 Goldhaber Prize was Norman Yao, who just graduated after finishing his sixth year in the PhD program. Yao graduated from Harvard College in 2009 with an AB in physics and mathematics and an AM in physics. For all four of his undergraduate years at Harvard, Yao worked in Prof. David Weitz's soft-matter lab studying the nonlinear mechanics of biopolymer networks, an experience that Yao regards as the cornerstone of his undergraduate education. His time in the Weitz group, he says, "taught me to be curious and persistent in my research endeavors."

Upon graduating from the college, Yao was the recipient of both the Hoopes Prize as well as the Captain Jonathan Fay Prize, the latter of which is given to the student with the most outstanding undergraduate thesis in any field. He was also awarded the DOE Computational Science Graduate Fellowship, the NSF Graduate Research Fellowship, and the NDSEG Fellowship, the last of which he declined.

During his time as a graduate student here at Harvard, Yao served as a referee for a number of important journals, including *Nature Communications*, *Physical Review Letters*, *Physical Review A*, *New Journal of Physics*, *Journal of Chemical Physics*, *Optics Express*, *Journal of Physics: Condensed Matter*, *Annals of Physics*, and *Biophysical Journal*.

Yao recently finished his PhD in Prof. Mikhail Lukin's group, where he worked at the interface between atomic physics, quantum information science, and condensed-matter theory. He is currently pursuing several different research directions: investigating fractional Chern insulators in dipolar spin systems, understanding the effects of power laws on many-body localization, and exploring the effect of superconductivity on RKKY interactions.

Goldhaber Prize



Florian Huber

2014 GOLDHABER PRIZE WINNER

A winner of the 2014 Goldhaber Prize, Florian Huber was an undergraduate at the Technical University of Munich, Germany, where he worked in theoretical atomic physics. Later, at the Max-Planck-Institute for Quantum Optics, Huber participated in a rubidium Bose-Einstein condensation experiment. During that time he also spent one semester abroad at the National University of Singapore, working on a single-atom/single-photon entanglement experiment at the Centre for Quantum Technologies.

Huber enjoyed working in such a different cultural environment, so he decided to go abroad again for the one-year research project required for his studies. He ended up in Prof. Markus Greiner's lab here at Harvard, where he was able to join an experiment on lithium degenerate Fermi gas at almost the very beginning of the project. It was then clear to Huber that he wanted to apply to Harvard's Physics PhD program, in which he is now enrolled and continues to work with Prof. Greiner.

Huber studies ultracold quantum gases in optical lattices, which are prime candidates for mimicking and studying condensed-matter systems, and even for creating novel states of quantum matter. The recent development of site-resolved imaging in sub-micron lattices has brought quantum simulations with neutral atoms to a new level—one where it is now possible to create an in-situ snapshot of the density distribution and directly extract local correlations, for example. Extending this technique to fermionic atoms (whereas previous experiments were done with bosonic rubidium atoms) allows researchers to address a separate class of problems, most prominently the search for high- T_c superconductivity in the Fermi-Hubbard model.



Ilya Feige

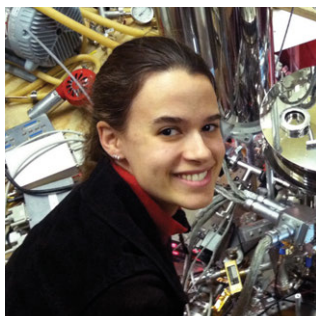
2014 GOLDHABER PRIZE WINNER

Ilya Feige was the other winner of the 2014 Goldhaber Prize. Feige did his undergraduate work at McGill University in Montréal, Canada, where he studied mathematics and physics. As an undergraduate, he had the opportunity to do research on ground-based gamma-ray astronomy at McGill, experimental particle physics at CERN, and mathematical physics in Paris.

Feige came to Harvard and started working with Prof. Matthew Schwartz on theoretical collider physics. With Prof. Schwartz, he calculated

collider physics observables; he also proved a theorem describing how physics at different scales in high-energy particle collisions separates naturally into universal factors that can be used to facilitate high-precision calculations. Feige continues to be interested in the basic properties of the fundamental theories of nature that can be tested experimentally.

GSAS Merit Fellowship



Elise Novitski

2013 GSAS MERIT FELLOWSHIP WINNER

In 2013, Elise Novitski won a GSAS Merit Fellowship, a highly selective award for PhD students who have passed their qualifying exams. The Merit Fellowship provides full research funding for one semester. Currently a fifth-year student in the PhD program, Novitski is a 2008 graduate of Yale University. During her undergraduate years at Yale, she studied the structure of the ^{196}Pt nucleus at the Wright Nuclear Structure Laboratory with Volker Werner and worked on the design of the Energy Recovery Linac at Cornell University under Matthias Liepe as part of the NSF Research Experiences for Undergraduates program. She also investigated the effect of electric field gradients on phase separation in a binary fluid in Eric Dufresne's Yale Soft Matter Lab.

For one year prior to matriculating at Harvard, Novitski taught in the Mechanical Engineering Department at Ngee Ann Polytechnic in Singapore, an opportunity made possible by the Princeton-in-Asia program.

Novitski is now in the Gabrielse group at Harvard, working toward measurements of the g -factors (magnetic dipole moments in units of Bohr magnetons) of the electron and positron, improving both beyond the current 0.28 parts-per-trillion uncertainty for the electron.

The comparison of these g -factors will improve on the most precise test in a lepton system of charge-parity-time symmetry, a proposed fundamental symmetry of the universe that is violated in some theories that extend beyond the Standard Model. The electron g -factor is also related to the fine-structure constant by calculations in quantum electrodynamics (QED). The comparison of this determination of the fine-structure constant to an independent measurement of the same constant made using different methods constitutes the most stringent test of QED today.

To improve these g -factor measurements, Novitski is working on a new cryogenic Penning trap apparatus with positron-trapping capability. This instrument incorporates many design advances, producing more stable magnetic fields and offering a microwave-cavity mode structure that allows for sideband cooling of the axial motion of a single trapped electron or positron.

GSAS Merit Fellowship, cont.



Debanjan Chowdhury

2014 GSAS MERIT FELLOWSHIP WINNER

One of the two winners of the 2014 GSAS Merit Fellowship, Debanjan Chowdhury completed his undergraduate studies at the Indian Institute of Technology in Kanpur and joined the PhD program at Harvard in 2010.

Chowdhury has been working on theories of various collective phenomena exhibited by a large number of interacting electrons at low temperatures in many modern quantum materials such as high-temperature superconductors and

quantum magnets. In particular, Chowdhury focuses on various conceptual issues that could eventually lead to a better understanding of why interacting electrons behave in a particular way—a result that could, in turn, help resolve many important questions in theoretical physics.



Elizabeth Jerison

2014 GSAS MERIT FELLOWSHIP WINNER

The other winner of the 2014 GSAS Merit Fellowship, Elizabeth Jerison did her undergraduate studies in physics at Yale University. While at Yale, she worked in Eric Dufresne's soft-condensed-matter group on capillary effects on soft solids. During her time as an undergraduate, she enjoyed learning about biophysics and spent one summer working on information flow in gene regulatory networks with Professor Bill Bialek in the biophysics theory group at Princeton.

At Harvard, Jerison does experimental and theoretical work in the laboratory of Professor Michael Desai. The Desai Lab studies the dynamics of the evolutionary process—how new genetic mutations arise from their origins in a single individual to spread through a population. On the experimental side, the group evolves baker's yeast in the lab and tracks the frequency

of new mutations in yeast populations through time with genome sequencing. Although the dynamics in any one population are inherently random, statistical properties of an ensemble of replicate populations are predictable. To make this connection, the group models the adaptive process using methods loosely akin to nonequilibrium statistical mechanics. Jerison's research focuses on adaptation under changing environmental conditions, where the growth advantage conferred by individual mutations is time-dependent. She is currently doing empirical and theoretical work aimed at understanding and modeling this process.

Graduate Student Awards and Fellowships

A*STAR Fellowship

Jing Shi (G3) 2012

American-Scandinavian Foundation, Norway-American Scholarship

Anders Andreassen (G2) 2014

Department of Energy Office of Science Graduate Fellowship (DOE SCGF)

Martin Blood-Forsythe (G4) 2012

Julian Kates-Harbeck (G1) 2014

Rebecca Krall (G3) 2012

Siddharth Venkat (G4) 2012

Andy Yen (G5) 2011

Goldhaber Prize

Ilya Feige (G5) 2014

Florian Huber (Graduated) 2014

Nicholas Schade (G6) 2013

Norman Yao (Graduated) 2013

Kwangjeon Fellowship

Soonwon Choi (G3) 2013

GSAS Merit Fellowship

Debanjan Chowdhury (G5) 2014

Elizabeth Jerison (G5) 2014

Elise Novitski (G6) 2013

Howard Hughes Medical Institute Fellowship

Nabiha Saklayen (G3) 2014

National Defense Science and Engineering Graduate (NDSEG) Fellowship

Ronald Alexander (G2) 2013

Erin Dahlstrom (G3) 2012

Shannon Harvey (G4) 2012

Alexander Isakov (G4) 2012

Sarah Kostinski (G4) 2013

Andrei Levin (G4) 2012

Igor Lovchinsky (G4) 2012

Andrew Marantan (G4) 2012

Arthur Safira (G3) 2014

Ming Tai (G6) 2011

Alyssa Wilson (G5) 2011

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

Rodrick Kuate Defo (G2) 2013

Aakash Ravi (G3) 2014

Shu Yang Frank Zhao (G1) 2014

Samsung Fellowship

Eunmi Chae (G6) 2010

Minjae Cho (G3) 2012

Hyungmok Son (G1) 2014

Dick Smith Fellowship

Stephen Chan (G3) 2013

Robert Hoyt (G3) 2013

Dan Kapec (G3) 2013

Andy Lucas (G3) 2013

Monica Pate (G2) 2014

Sabrina Pasterski (G2) 2014

Thomas Roxlo (G3) 2013

World Quantitative and Science Scholarship Program

Tansu Daylan (G2) 2014

Rodrick Kuate Defo (G2) 2014

Sabrina Pasterski (G2) 2014

National Science Foundation Graduate Research Fellowship Program (NSF GRFP)

Christie Chiu (G2) 2013

Jake Connors (G4) 2011

Michael Coughlin (G2) 2012

Ruffin Evans (G4) 2012

Stephen Fleming (G3) 2013

Julia Gonski (G1) 2014

Benjamin Good (G5) 2011

Shannon Harvey (G4) 2012

Temple He (G3) 2011

Elizabeth Jerison (G5) 2011

Ekaterina Kosheleva (G4) 2011

Shimon Kolkowitz (G7) 2010

Michael Kosowsky (G1) 2014

Nicholas Langellier (G4) 2011

Albert Lee (G4) 2011

Natalie Mashian (G4) 2013

Anton Mazurenko (G3) 2012

Aaron Meisner (G5) 2010

Max Parsons (G4) 2011

Anna Patej (G3) 2012

Matthew Rispoli (G2) 2013

Victor Rodriguez (G1) 2014

Thomas Rudelius (G3) 2012

Elliot Schneider (G4) 2012

Jeffrey Thompson (G7) 2009

Seth Whitsitt (G3) 2012

Xiang-Yu Zhou (G1) 2014

Graduate Student Career Events

The White Prizes are awarded annually to Teaching Fellows who have demonstrated teaching excellence in the introductory physics courses. This past year's winners are:

David Bracher
(Physical Sciences 2)
Paul Hess
(Physical Sciences 12b)
Yejin Huh
(Physical Sciences 2)
Natalie Mashian
(Physical Sciences 3)
Prahar Mitra
(Physics 15a)
Andrzej Nowojewski
(Science of the Physical Universe 27)
Elizabeth Petrik
(Physics 15c)
Suzanne Pittman
(Physical Sciences 2)
Nicholas Schade
(Physics 15c)
Elliot Schneider
(Physics 15b)
Meng-Ju (Renee) Sher
(Physics 15c)
Baojia Tong
(Physics 16)
Mary Wahl
(Science of the Physical Universe 27)

On June 19, 2013, Gregory Villar visited the Harvard Physics Department from NASA's Jet Propulsion Laboratory (JPL) to talk with students about his work on the Curiosity Mars rover mission. Students got an inside look at JPL's inner operations and heard about other interesting things one can do with a physics degree.

On November 1, 2013, the Harvard Physics Department held a question-and-answer seminar with Jake Klamka, the founder of the Insight Data Science Fellow Program. Insight is an intensive, six-week postdoctoral training fellowship, which is aimed at bridging the gap between academia and a career in data science and data analytics. Seminar attendees were given an introduction to data science and learned about scientists who had moved from academia to the tech industry, including the many Insight Fellows who are now working for top data-driven companies.

On both December 12, 2013, and again on February 26, 2014, Ben Vigoda, director of Analogy Devices Corporate Labs, came to the Harvard Physics Department to tell students about opportunities in

startups, industrial labs, and the field of stochastic computation. Students were given a look at career options that include opportunities at the cutting edge of statistical machine learning techniques and applications, probabilistic programming languages, data analytics and modeling, novel compiler and processor architectures, and cloud-based high performance computing platforms.

On May 8, 2014, David Duncan—a 2000 graduate of the Harvard Physics PhD program and a senior partner at Innosight, an innovative consulting firm—gave a talk on careers for scientists in the consulting industry. Attendees got a chance to learn about the challenges and successes of management consulting. Duncan spoke at length about Innosight's work to make pacemakers more available in Third World countries.

Recent Graduates

Mehrtash Babadi

Thesis: "Non-equilibrium dynamics of artificial quantum matter."

Advisor: Eugene Demler

Matthew Barr

Thesis: "Coherent scattering in two dimensions: graphene and quantum corrals."

Advisor: Eric Heller

Chi-Ming Chang

Thesis: "Higher Spin Holography."

Advisor: Xi Yin

Yang Ting Chien

Thesis: "Jet Physics at High Energy Colliders."

Advisor: Matthew Schwartz

Yiwen Chu

Thesis: "Quantum optics with atom-like systems in diamond."

Advisor: Mikhail Lukin

Sujit Datta

Thesis: "Getting Out Of A Tight Spot: Physics Of Flow Through Porous Materials."

Advisor: David Weitz

Jerome Fung

Thesis: "Measuring the 3D Dynamics of Multiple Colloidal Particles with Digital Holographic Microscopy."

Advisor: Vinothan Manoharan

Michael Grinolds

Thesis: "Nanoscale magnetic resonance imaging and magnetic sensing using atomic defects in diamond."

Advisor: Amir Yacoby

Michael Gullans

Thesis: "Controlling Atomic, Solid-State and Hybrid Systems for Quantum Information Processing."

Advisor: Mikhail Lukin

Patrick Herring

Thesis: "Low Dimensional Carbon Electronics."

Advisor: Amir Yacoby

Paul Hess

Thesis: "Improving the Limit on the Electron EDM: Data Acquisition and Systematics Studies in the ACME Experiment."

Advisor: Gerald Gabrielse

Florian Huber

Thesis: "Site-Resolved Imaging with the Fermi Gas Microscope."

Advisor: Markus Greiner

Nicholas Hutzler

Thesis: "A New Limit on the Electron Electric Dipole Moment: Beam Production, Data Interpretation, and Systematics."

Advisor: John Doyle

Gregory Kestin

Thesis: "Light-Shell Theory Foundations."

Advisor: Howard Georgi

Angela Kou

Thesis: "Microscopic Properties of the Fractional Quantum Hall Effect."

Advisor: Bert Halperin, Charles Marcus

Ruichao Ma

Thesis: "Engineered potentials and dynamics of ultracold quantum gases under the microscope."

Advisor: Markus Greiner

Peter Maurer

Thesis: "Coherent control of diamond defects for quantum information science and quantum sensing."

Advisor: Mikhail Lukin

Andrew McCormick

Thesis: "Discrete Differential Geometry and Physics of Elastic Curves."

Advisor: Lakshminarayanan Mahadevan

Gim Seng Ng

Thesis: "Aspects of Symmetry in de Sitter Space."

Advisor: Andrew Strominger

Daniyar Nurgaliev

Thesis: "A study of the Radial and Azimuthal Gas Distribution in Massive Galaxy Clusters."

Advisor: Christopher Stubbs

Douglas Rubin

Thesis: "Properties of Dark Matter Halos and Novel Signatures of Baryons in Them."

Advisor: Douglas Finkbeiner

Emily Russell

Thesis: "Structure and Properties of Charged Colloidal Systems."

Advisor: David Weitz

Brendan Shields

Thesis: "Diamond platforms for nanoscale photonics and metrology."

Advisor: Mikhail Lukin

Benjamin Spaun

Thesis: "A Ten-Fold Improvement to the Limit of the Electron Electric Dipole Moment."

Advisor: Gerald Gabrielse

William Spearman

Thesis: "Measurement of the mass and natural width of the Higgs boson in the H to ZZ to 4l decay channel with the ATLAS detector."

Advisor: Joao Guimaraes da Costa

Norman Yao

Thesis: "Topology, Localization, and Quantum Information in Atomic, Molecular and Optical Systems."

Advisor: Mikhail Lukin

Michael Yee

Thesis: "Scanning Tunneling Spectroscopy of Topological Insulators and Cuprate Superconductors."

Advisor: Jennifer Hoffman



PROGRAMS

Research Scholars

by Bonnie Currier, Research Scholar Coordinator

On September 18, 2014, the Harvard Physics Department held its second annual Research Scholar Retreat. The daylong event took place at the Rolling Ridge Retreat and Conference Center in North Andover, MA. Approximately 45 of our postdoctoral scholars in physics and closely related fields attended. The day's agenda started with one-minute "elevator-talk" presentations by each participant, followed by an interactive presentation by Dr. Krastan Blagoev from National Science Foundation on the topic of Science Funding in the U.S. After lunch, a poster session illustrating a full range of Harvard Physics projects was held, and votes were cast for the best Theory and Experimental Poster. Participants spent the early afternoon engaged in various outdoor activities, including a whiffle ball game, canoeing on the retreat's Lake Cochichewick, or walking the site's lovely grounds. Eight concurrent breakout sessions allowed small group discussions on a variety of topics concerning postdoc preparation for future career development in the areas of leadership, group management, cultivating collaborations, giving talks, getting published, improving citations, and building your professional networks. Dr. Jacob Barandes, the department's Associate Director of Graduate Studies, hosted his rousing and now-legendary trivia games, followed by socializing and a seated dinner. MIT theoretical physicist and cosmologist Prof. Alan Guth, father of the theory of cosmic inflation, gave an after-dinner plenary address filled with humorous anecdotes from his postdoc years. The event was organized

by our research scholar advisory committee, composed of scholars with appointments in Physics, in conjunction with the Department's Research Scholar Coordinator.

In July, we held our first-ever barbecue for our scholars, faculty, and staff. It was set in our own "backyard," just behind Jefferson Lab. Ever focused on strengthening and supporting our robust community of scholars, we hosted a research scholar welcoming social on September 4, 2014, in the Physics Library. The scholars had their first official chance to meet our new Chair, Professor Masahiro Morii, and key personnel in our department, as well as each other.

During the 2014-2015 academic year, we have scheduled scholar lunches to occur twice a month. The lunches are open only to scholars for socializing, and networking, without faculty or administration. We are also eager to help our scholars develop their presentation and teaching skills. Therefore, those who wish to practice giving talks have access to our video camera to record themselves, with the option of meeting privately for a one-on-one evaluation of their video by a Derek Bok Center for Teaching and Learning specialist. These scholars truly are an integral part of our department. They represent an international group of energetic scientists engaged in vital research collaborations with our faculty. Please check out the listings concerning this exciting research at: <https://www.physics.harvard.edu/people/researchers>.



A Reunion Across Generations and Disciplines

by Steve Nadis

Hundreds of Physics alumni, faculty, and students convened on April 4th to revel in the department's illustrious history, catch up with old friends, and hear about the latest research being carried out on a broad array of theoretical and experimental fronts.

The day was largely devoted to the alumni, some of whom had graduated more than 60 years ago and others just this year. Faculty and students briefed the audience on their current investigations, while alums discussed careers far outside the confines of classical physics. In her opening remarks to the standing-room-only crowd in Jefferson 250, Department Chair Melissa Franklin owned up to some trepidation regarding how the big day might come off. "Then I realized we had food, physics, and drink, and what could possibly go wrong?" That comment set the tone for the entire event, which was a celebration in the truest sense of the word.

The first panel was devoted to alumni who had opted for "alternative careers." Ronald Kahn (PhD '85), the global head of scientific equity research at the investment firm, BlackRock, noted that he encountered two kinds of people during his graduate school days in the early 1980s: those who thought physics was everything and those who merely considered it interesting. Kahn fell squarely into the latter camp, taking a job in finance long before many physicists explored that avenue.

David Land (PhD '93) pursued a similar route, which has led him to become the Chief Investment Officer for Rothesay Life, a UK-based

pension insurance company. Land was a victim of unfortunate timing, earning his degree in the same year (1993) that the Superconducting Super Collider was canceled. At that time, “you had to be very, very good to get a postdoc position,” he said, “and you still needed to be lucky. I gave up my boyhood dream of becoming a physicist to become a money man.” He soon found that the environment in the business arena was different from what he’d experienced in academia. Here at Harvard, he said, people that are cleverer than you “try to correct you. In the outside world, they try to take advantage of you.”

Early in his career, Robert Socolow (PhD ’64) coauthored papers with Sidney Coleman and Sheldon Glashow before leaving “frontier physics” in 1969 to study issues related to energy and the environment. “Science needs to be endorsed as an ethical and social activity,” said Socolow, a Princeton professor. His current work is still a part of physics, he maintained. “There is a middle ground that is not Wall Street.”



Following in Socolow’s footsteps, Daniel Kammen (PhD ’88) also went into the energy field, after a three-day stint working as a “techie” (specializing in wiring) for the Grateful Dead. A lead author for the Intergovernmental Panel on Climate Change—a group that shared the 2007 Nobel Peace Prize—Kammen is the former energy czar for the World Bank and a current professor of energy at the University of California, Berkeley. “Find the hardest and most important problem and hold onto that,” he told the crowd, “even if you have to learn new fields.”

This advice resonates with another panelist, Alexia Schulz (PhD ’07), who studied dark energy at Harvard but is now a cyber systems analyst at MIT Lincoln Laboratory. “This was not my plan all along; my plan was to be a professor,” Schulz said of her career path, although she admits to being extremely happy with her job. “When you write a paper, do not be too attached to any particular outcome. The same is

true in life: When an opportunity comes along, you have to be prepared to go with it.”

Six graduate students—all PhD candidates in physics—spoke next, and the overriding sentiment was the strong sense of camaraderie they had found with their peers in the program. Greg Kestin, who is studying high-energy particle physics with Professor Howard Georgi, talked about falling asleep during a late-night session with fellow students. That moment, Kestin said, “is a microcosm of grad school—you work until you are asleep and then you wake up. You’re still working, but that’s OK because your friends are still there.”

Alex Lupsasca, who came from Romania to work on black hole physics with Andrew Strominger, echoed those remarks. “The reason I’m really happy here is that we’re living in a time of great discovery. But it’s more fun to do that when you’re living with a great community.”



After lunch at the Harvard Faculty Club, the physics faculty took the stage in Lecture Hall C at the Science Center, with theorists going first and the experimentalists next. Their presentations showed, in dramatic fashion, that traditional boundaries between physics, chemistry, biology, and other disciplines are no longer so sharply drawn. These fields are overlapping to an increasing degree, in some cases completely merging, so that it’s no longer easy—nor especially fruitful—to say where physics leaves off and another field takes over.

Particle physicist and cosmologist Lisa Randall (PhD ’87) discussed possible experimental signatures for extra dimensions, before turning her attention to dark matter. Referring to the fact that 95 percent of the universe consists of dark matter and dark energy, whose precise nature is still unknown, Randall noted, “it’s often said that we only understand five percent of the universe, which is made of atoms. But we don’t understand that well either,” she added, because we still can’t explain why there is so much more matter than antimatter.

Photos by Tom Kates

Subir Sachdev (PhD '85), a condensed matter theorist, described his investigations of a single compound— BaFe_2As_2 —that have yielded insights into the phenomenon of high-temperature superconductivity. Cumrun Vafa discussed the challenges of connecting string theory with experiment, while also touching on his favorite dark matter candidate—the gravitino. David Nelson explained his work in “physical biology,” focusing on a study of the range expansion of large mammals, which can relate to the spread of cancerous tumors and to inanimate systems like avalanches in sandpiles.

During an intermission, graduate students held court at a poster session on such topics as wide-field astronomical surveys, exoplanet



searches, the magnetic detection of cancer cells, decoding black hole entropy, and possible gamma ray signals associated with annihilating dark matter. First-year graduate student Anders Johan Andreassen explained why the mass of the Higgs boson—as recently measured at the LHC—suggests that our universe is metastable. Andreassen, however, made no predictions as to when the universe as we know it would come to an end.

Back in the lecture hall, experimentalists had their turn at the podium, bearing witness to the diversity of research underway within the department. Incoming department chair, Masahiro Morii, who is participating in the ATLAS experiment at CERN, talked about what comes next after the Higgs discovery. “We dig a big hole,” he said by way of analogy. “We sift through lots of dirt, and we get lucky once every ten years.”

Amir Yacoby explained how particles like electrons change their properties when they are put inside a solid—research that has applications in quantum computing. Markus Greiner described the “quantum gas microscope” he developed with coworkers that can take pictures of single atoms. Vinothan Manoharan’s lab studies “soft matter,” like colloidal suspensions (milk being a familiar example), which ties into his underlying interest—the self-assembly of

structures. Aravinthan Samuel (PhD '99) told of clues into the brain and behavior gained through manipulations of neural circuitry in the roundworm, *C. elegans*.

Last up was John Kovac, holder of a joint appointment in Astronomy and Physics, who headed the BICEP2 team that recently saw hints of primordial gravitational waves in the cosmic microwave background. The team’s preliminary findings are now being reviewed in a joint study by scientists from the BICEP2 and Planck space telescope collaborations. The jury is still out, but if the initial BICEP2 results survive that test, this experiment would offer the most convincing evidence yet for the idea of cosmic inflation, a brief burst of

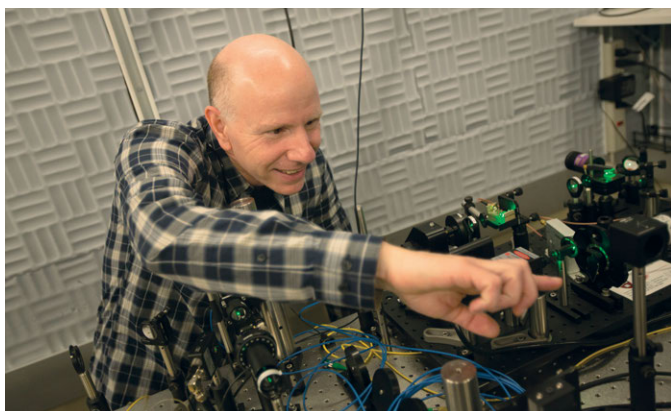


exponential growth that drove the Big Bang. A thumbs up for BICEP2 would also provide strong indications that gravitational waves, which had never been seen before, are quantized. “It would tell us that we need a theory of quantum gravity,” Kovac said. “But it doesn’t tell us the form of the theory of quantum gravity that we need.”

The moderator for this last panel, Professor Christopher Stubbs, told the audience that perhaps someone could work out that theory of quantum gravity as people walked from the Science Center to the Jefferson Library for a reception that would cap off an exhilarating day.

Remarks of Melissa Franklin summed up the sentiments that prevailed throughout the proceedings. “Physics is amazing!” she said. “It’s beautiful! It’s bountiful! When you read about these gravitational waves from the Big Bang, didn’t your knees buckle? So here’s to physics. I love it! You love it!” Resounding cheers broke out among the crowd, backing up Franklin’s assertion better than any words could have.

Faculty in the News



MRI of Individual Dark Spins in 3D

The trend in making more powerful magnetic resonance imaging (MRI) devices has been to produce larger magnets. A European consortium, for example, is building what will be the most powerful MRI, capable of producing a field of 11.75 teslas using a superconducting magnet strong enough to lift a 60-metric-ton battle tank.

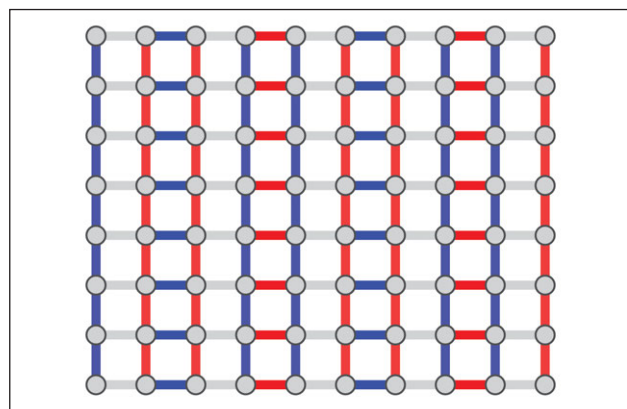
However, researchers at Harvard University have gone in the opposite direction and built a device with a magnet only 20 nanometers across, or approximately 1/300th the size of a red blood cell. Despite its small size, the researchers claim that the magnet can produce a magnetic field gradient 100,000 times larger than even the most powerful conventional systems.

The trick is that this nanoscale magnet can be brought within nanometers of the object being imaged to produce a spatial resolution down to the nanoscale. Most hospital MRI scanners can only reach a spatial resolution of 1 millimeter. With this capability, the Harvard researchers someday hope to produce detailed images of individual molecules.

“What we’ve done, essentially, is to take a conventional MRI and miniaturize it,” said Amir Yacoby, Professor of Physics, in a press release. “Functionally, it operates in the same way, but in doing that, we’ve had to change some of the components, and that has enabled us to achieve far greater resolution than conventional systems.”

From: Dexter Johnson, “Nanometer-Scale Magnet Makes Tiny, Powerful MRI,” IEEE Spectrum (Apr 22, 2014).

Photo by Kris Snibbe, Copyright © President and Fellows of Harvard College.



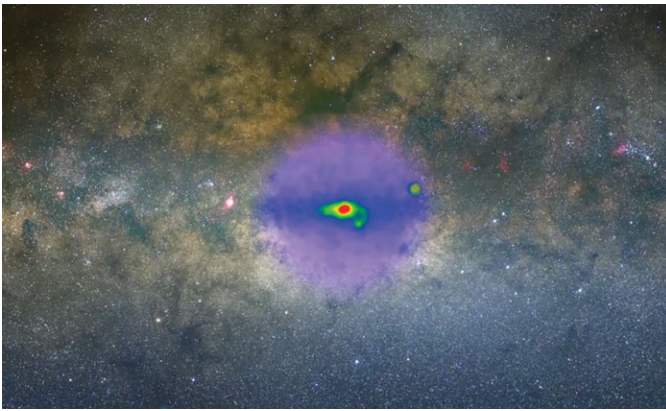
High-Energy Superconductivity

Antiferromagnetism has long been considered one of the likeliest agents to be responsible for high-temperature superconductivity. Proponents of the idea argue that the force coupling electrons is essentially an attraction between oppositely spinning neighbors. This explains why the electron pairs always form along the cardinal directions in the crystal lattice but never along the diagonals —another d-wave arrangement. This well-known d-wave nature of superconductivity is slightly different from that of charge density waves. But in a theory that Professor Subir Sachdev and his collaborators have developed, “we find that the two d-waves are indeed linked to each other.”

In 2010, Sachdev and his student Max Metlitski showed mathematically that antiferromagnetism could cause pairing not only between electrons, but also between electrons and “holes,” or places in the orbits of atoms where electrons could exist but are missing. Electron-hole pairs are widely regarded as the basic building blocks of charge density waves, just as pairs of electrons are the building blocks of superconductivity. Furthermore, in July 2013, Sachdev and another student, Rolando La Placa, showed that the resulting electron-hole pairs would arrange themselves in a d-wave form—in this case, the kind observed in Davis’ recent experiment.

In short, antiferromagnetism could generate the d-wave patterns of both superconductivity and its rival, charge density waves.

From: N. Wolchover, “Decoding the Secrets of Superconductivity,” Quanta Magazine (20 April 2014). Original story reprinted with permission from Simons Science News, an editorially independent division of SimonsFoundation.org whose mission is to enhance public understanding of science by covering research developments and trends in mathematics and the physical and life sciences.



Gamma-Ray Emissions from Dark Matter

When a galaxy forms, gravitational attraction brings together a huge mass that begins spinning. As they spin, large galaxies cool down and flatten out like a pizza, forming the familiar spiral shape seen in many telescope images. Dark matter, which actually makes up the bulk of a galaxy's mass, can't flatten out because it doesn't interact with the electromagnetic force, which would allow it to radiate away thermal energy. It stays in a spherical halo circling the galaxy. So any dark matter signal should come not just from within the galactic plane, but also from above and below it, where stars are few and far between but dark matter is abundant.

The problem is that the galactic center is extremely bright. Its billions of stars give off an incredible amount of light that shines far above and below the plane of the Milky Way. Showing that the gamma ray signal comes from dark matter and nothing else requires extremely precise mapping. But the Fermi telescope's data also happens to be a little blurry at the energy ranges where the dark matter signal shows up. Working with physicist Tracy Slatyer of MIT, Professor Doug Finkbeiner combed through the Fermi data and found a way to throw out the blurriest parts. This left a very sharp map showing exactly that the excess gamma ray signal was coming from areas where few stars should exist.

"The answers just got a lot better," said Finkbeiner. "It looked more like dark matter and less like pulsars."

From: Adam Mann, "Strange Signal From Galactic Center Is Looking More and More Like Dark Matter," wired.com (March 3, 2014).

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Image courtesy: NASA Goddard; A. Mellinger, CMU; T. Linden, Univ. of Chicago.



Dark Matter as a Trigger for Periodic Comet Impacts

Meteorites regularly pepper Earth's surface. Thirty years ago, physicists suggested that this bombardment intensifies cyclically, pointing to some underlying cosmic cause. One proposed explanation is that the Sun has an as-yet-undetected companion star, dubbed 'Nemesis' or 'Death Star', that regularly swings by, sending comets from the remote Oort cloud flying into the inner Solar System. In the latest paper, theoretical physicists Lisa Randall and Matthew Reece, of Harvard University in Cambridge, Massachusetts, reignite another proposal, which puts the supposed periodicity down to the way the Sun—and the Solar System with it—move inside the Milky Way. As the Sun follows the swirling motion of the Galaxy's arms, circling around the galactic centre, it also moves up and down, periodically crossing the plane that cuts the Galaxy into a top and a bottom half like the two bread slices in a sandwich. The authors suggest that as the Sun oscillates up and down, it crosses a denser layer of dark matter—like the ham in the middle—causing a gravitational push and pull that disturbs comets in the Oort cloud.

Previous models could not account for a gravitational force strong enough to cause the effect. But Professors Randall and Reece show that a thin disk of dark matter at the centre of the Galaxy could do exactly that, causing comet storms with a periodicity of about 35 million years. This would match some weak statistical evidence found in recent surveys of impact craters.

From Elizabeth Gibney, "Did dark matter kill the dinosaurs?" Nature (Mar 7, 2014).

Image courtesy: iStock/PaulPaladin.



Crystal Formation on a Curved Surface

A new study has uncovered a previously unseen phenomenon—that curved surfaces can dramatically alter the shape of crystals as they form. The finding could have applications ranging from applying coatings to nanoparticles used in industry to aiding in drug delivery, and may even help shed light on how viruses assemble. The work, conducted by researchers at Harvard's Materials Research Science and Engineering Center and funded by the National Science Foundation, is described in a February 7 paper in *Science*.

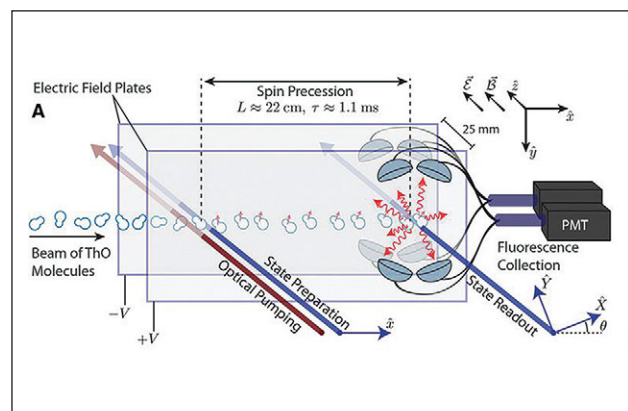
To investigate how curved surfaces affect crystallization, Vinothan Manoharan, the Gordon McKay Professor of Chemical Engineering and a Professor of Physics, worked with physics postdoc Guannan Meng to develop a system in which nanoscale colloidal particles were injected into water droplets. As the particles—about 10,000 times larger than atoms or molecules—organized themselves into crystalline structures, researchers were able to observe the process in real time.

"If you have the particles on a flat surface, like a piece of glass, they form a regular lattice, and they're compact, with no preferred direction for crystal growth," Manoharan said. "On a curved surface, however, they form a very different pattern. It looks like strips—almost like ribbons—and they branch out from different points."

"Meng and Manoharan brought their results to David Nelson, the Arthur K. Solomon Professor of Biophysics and a professor of physics and applied physics, and applied physics grad student Jayson Paulose. The two were able to create a model that helped explain the structure of the crystals."

From: Peter Reuell, "Curves alter crystallization, study finds," Phys.org (Feb 6, 2014).

Photo by Rose Lincoln, Copyright © President and Fellows of Harvard College.



Electron Electric Dipole Moment

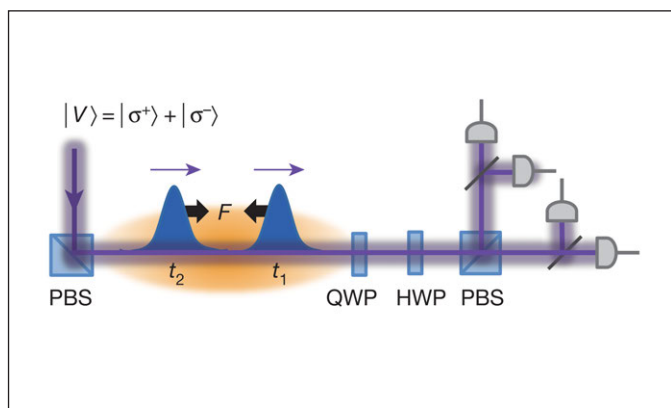
The Standard Model of particle physics makes incredibly precise predictions that have been confirmed by precise measurements. Yet, the Standard Model cannot be right. It is not able, for example, to account for why our universe made of matter arose from a Big Bang that the standard model predicts would produce nearly equal amounts of matter and antimatter. Many modifications have been proposed to fix the standard model, the most popular example postulating supersymmetric particles, which have not yet been observed.

The Standard Model and many of its proposed fixes predict a size for the electron's electric dipole moment that is only a few orders of magnitude smaller than the previous best search. Given the unique opportunity to experimentally distinguish between the prediction of the Standard Model and its fixes, Professors John Doyle and Gerald Gabrielse, along with David DeMille of Yale University, used cold polar molecules to search for the predicted electric dipole moment with a 12 times improved sensitivity. That the predicted moment did not show up despite the improved sensitivity casts some doubts on the proposed fixes to the Standard Model, for example supersymmetry. According to Doyle and Gabrielse, their ACME team should be able to increase their sensitivity by another factor of ten in the next five years, to either discover the elusive moment or to constrain or rule out most of the proposed fixes to the Standard Model.

The measurement was reported on the cover of *Science*, and soon after prompted more than 50 papers making use of the new measurement.

From: Clara Moskowitz, "Electron Appears Spherical, Squashing Hopes for New Physics Theories," Scientific American, Nov 11, 2013.

Image reprinted by permission from Macmillan Publishers Ltd: The ACME Collaboration, J. Baron, et al., "Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron," Science 343: 269–272 (2014) doi: 10.1126/science.1248213



Photon 'Molecules'

Working with colleagues at the Harvard-MIT Center for Ultracold Atoms, a group led by Harvard Professor of Physics Mikhail Lukin and MIT Professor of Physics Vladan Vuletic have managed to coax photons into binding together to form molecules—a state of matter that, until recently, had been purely theoretical. The work is described in a September 25 paper in *Nature*.

The discovery, Lukin said, runs contrary to decades of accepted wisdom about the nature of light. Photons have long been described as massless particles which don't interact with each other—shine two laser beams at each other, he said, and they simply pass through one another.

"Photonic molecules," however, behave less like traditional lasers and more like something you might find in science fiction—the light saber.

"Most of the properties of light we know about originate from the fact that photons are massless, and that they do not interact with each other," Lukin said. "What we have done is create a special type of medium in which photons interact with each other so strongly that they begin to act as though they have mass, and they bind together to form molecules. This type of photonic bound state has been discussed theoretically for quite a while, but until now it hadn't been observed..."

From: "Scientists create never-before-seen form of matter," Phys.org, Sep 25, 2013.

Image reprinted by permission from Macmillan Publishers Ltd: O. Firstenberg, T. Peyronel, Q.-Y. Liang, A.V. Gorshkov, M.D. Lukin & V. Vuletić, "Attractive photons in a quantum nonlinear medium," *Nature* 502 | doi:10.1038/nature12512.



Magnetic Charge of Single Antimatter Particle

A research team led by Harvard University scientists has measured the magnetic moment of the antiproton more accurately than ever before. "That is a spectacular jump in precision for any fundamental quality of the antiproton measurements. That's a leap that we don't often see in physics, at least not in a single step," said Prof. Gerald Gabrielse of the Harvard University's Department of Physics, co-author of the study published in *Physical Review Letters*.

The physicists were able to capture individual protons and antiprotons in a 'trap' created by electric and magnetic fields. By precisely measuring the oscillations of each particle, they were able to measure the magnetism of a proton more than 1,000 times more accurately than a proton had been measured before. Similar tests with antiprotons produced a 680-fold increase in accuracy in the size of the magnet in an antiproton.

"Such measurements," Prof. Gabrielse said, "could one day help scientists answer a question that seems more suited for the philosophy classroom than the physics lab—why are we here?"

From: Sergio Prostak, "Physicists Measure Magnetic Moment of Single Antimatter Particle" Sci-News.com, Mar 26, 2013.

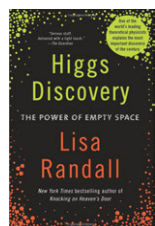
Photo by Katherine Taylor, Copyright © President and Fellows of Harvard College.



The Lost Art of Finding Our Way

John E. Huth, 2013
Harvard University Press

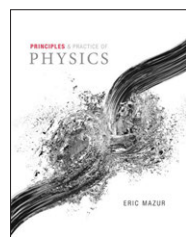
Long before GPS, Google Earth, and global transit, humans traveled vast distances using only environmental clues and simple instruments. John Huth asks what is lost when modern technology substitutes for our innate capacity to find our way. Encyclopedic in breadth, weaving together astronomy, meteorology, oceanography, and ethnography, *The Lost Art of Finding Our Way* puts us in the shoes, ships, and sleds of early navigators for whom paying close attention to the environment around them was, quite literally, a matter of life and death.



Higgs Discovery: The Power of Empty Space

Lisa Randall, 2013
Ecco

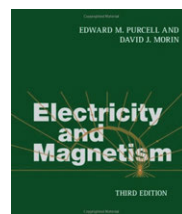
On July 4, 2012, physicists at the Large Hadron Collider in Geneva made history when they discovered an entirely new type of subatomic particle that many scientists believe is the Higgs boson. For forty years, physicists searched for this capstone to the Standard Model of particle physics—the theory that describes both the most elementary components that are known in matter and the forces through which they interact. This particle points to the Higgs field, which provides the key to understanding why elementary particles have mass. In *Higgs Discovery*, Lisa Randall explains the science behind this monumental breakthrough, its exhilarating implications, and the power of empty space.



Principles & Practice of Physics

Eric Mazur, 2014
Addison-Wesley

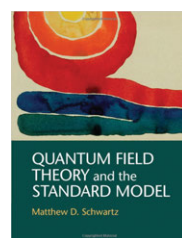
Traditional texts take a somewhat 19th-century approach to physics, delaying the introduction of ideas that we now see as unifying and foundational. Based on his storied research and teaching, Eric Mazur's *Principles & Practice of Physics* builds physics on those unifying foundations, helping students to develop a true conceptual understanding of the discipline that is stronger, deeper, and fundamentally simpler.



Electricity and Magnetism

3rd Edition
Edward M. Purcell and
David J. Morin, 2013
Cambridge University Press

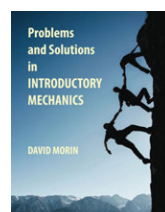
For 50 years, Edward M. Purcell's classic textbook has introduced students to the world of electricity and magnetism. The third edition has been brought up to date and is now in SI units. It features hundreds of new examples, problems, and figures, and contains discussions of real-life applications.



Quantum Field Theory and the Standard Model

Matthew D. Schwartz, 2013
Cambridge University Press

Providing a comprehensive introduction to quantum field theory, this textbook covers the development of particle physics from its foundations to the discovery of the Higgs boson. Its combination of clear physical explanations, with direct connections to experimental data and mathematical rigor, make the subject accessible to students with a wide variety of backgrounds and interests... Based on a course taught by the author over many years, this book is ideal for an introductory to advanced quantum field theory sequence or for independent study.



Problems and Solutions in Introductory Mechanics

David J. Morin, 2014
CreateSpace Independent
Publishing Platform

This problem book is ideal for high-school and college students in search of practice problems with detailed solutions. All of the standard introductory topics in mechanics are covered: kinematics, Newton's laws, energy, momentum, angular momentum, oscillations, gravity, and fictitious forces. The introduction to each chapter provides an overview of the relevant concepts. Students can then warm up with a series of multiple-choice questions before diving into the free-response problems which constitute the bulk of the book.

*2013 to present

Celebrating Staff



Carol Davis

After 45 years in the Physics Department, Carol Davis has worked with a score of professors, developed strong bonds with her staff colleagues, and intimately touched the lives of hundreds of students. Since 2008 she has served as the Undergraduate Student Coordinator, a new position created just for her.

Davis has a range of administrative duties, but her most important job, by far, is just being there for the students who file in and out of her office all day long. She answers questions, hears their

grievances, and doles out advice, candy, and hugs as needed. A beloved figure who won a Dean's Distinction Award in 2012, Davis is widely recognized as “the heart and soul” of the department. Students who graduated more than 30 years ago “still call to tell me about their life,” she says. “They always say they’re glad they went to Harvard, and that makes me happy.”



PHOTO BY JON CHASE,
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FELLOWS OF HARVARD COLLEGE

Stan Cotreau

For more than 20 years, Stan Cotreau has been training physics and engineering students in the machine shop located in the basement of Lyman Laboratory. Cotreau's approach to teaching, he says, “is strictly hands on.” In the shop he's been running since 1993, students learn to work with their hands—safely and adeptly operating band saws, drill presses, belt sanders, lathes, milling and welding machines, and laser cutters—“so they can take something that's in their heads and actually make it.”

Cotreau considers the job “fantastic,” and clearly excels at it, having earned a Dean's Distinction Award earlier this year. “What's not to like?” he asks. “I get to hang out with college kids every day and teach them new skills. You watch them grow into adults and succeed, and hopefully you had a little part in that.”



HARVARD UNIVERSITY
Department of Physics

17 Oxford Street
Cambridge, MA 02138

Upcoming Events 2014-2015

Science Research Public Lecture Series:

November 20

Philip Kim, Professor of Physics and Applied Physics
"Relativity, Quantum Physics, and Graphene"

February 5

Daniel Eisenstein, Professor of Astronomy

March 5

Jennifer Lewis, Hansjörg Wyss Professor

April 9

Susan Mango, Professor of Molecular and Cellular Biology

LECTURES ARE HELD AT 7PM THE HARVARD SCIENCE CENTER,
ONE OXFORD STREET, CAMBRIDGE, MA

Past talks are available on-line at:
<http://media.physics.harvard.edu/sciencelecture/>
or on the Harvard YouTube Channel.

To be added to our mailing list please email us at:
science_lectures@fas.harvard.edu

David M. Lee Historical Lecture in Physics:

December 1

Steven Weinberg,
Jack S. Josey-Welch Foundation Chair in Science,
University of Texas at Austin
Nobel Prize Laureate in Physics, 1979

"Glimpses of a World Within"

Abstract: Since the 1970s evidence has accumulated that the structures appearing in the laws of nature at a really fundamental level are vastly smaller than anything we encounter in our high energy laboratories.

The Morris Loeb Lecture in Physics:

April 27 – May 1, 2015

Brian P. Schmidt,
Distinguished Professor, The Australian National University,
Nobel Prize Laureate in Physics, 2011