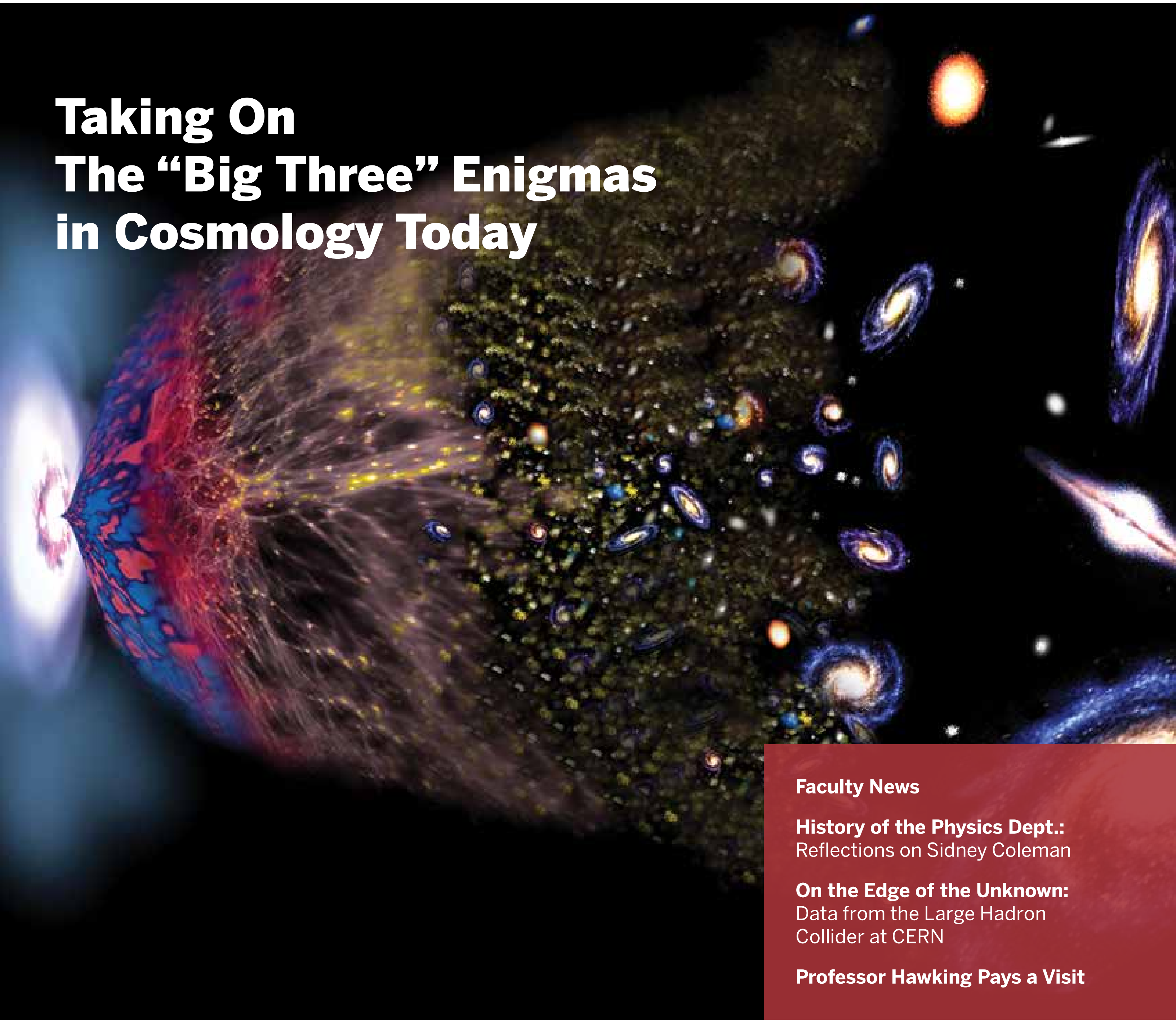
PHYSICS

Harvard University Department of Physics Newsletter

FALL 2016



Taking On The “Big Three” Enigmas in Cosmology Today

Faculty News

History of the Physics Dept.: Reflections on Sidney Coleman

On the Edge of the Unknown: Data from the Large Hadron Collider at CERN

Professor Hawking Pays a Visit

HARVARD UNIVERSITY
Department of Physics

“Black holes obey an elegant and simple equation that incorporates quantum mechanics, general relativity, and the laws of thermodynamics.” Andrew Strominger said at an April 2016 event inaugurating the Black Hole Initiative. The equation, which was developed both by Hawking and the physicist Jacob Bekenstein, shows that the entropy of a black hole is proportional to the area of the invisible, spherical surface surrounding it called the event horizon. Strominger ranked this formulation among “the three most important equations in the last century,” along with Einstein’s equations of gravity (general relativity) and the Heisenberg Uncertainty Principle.

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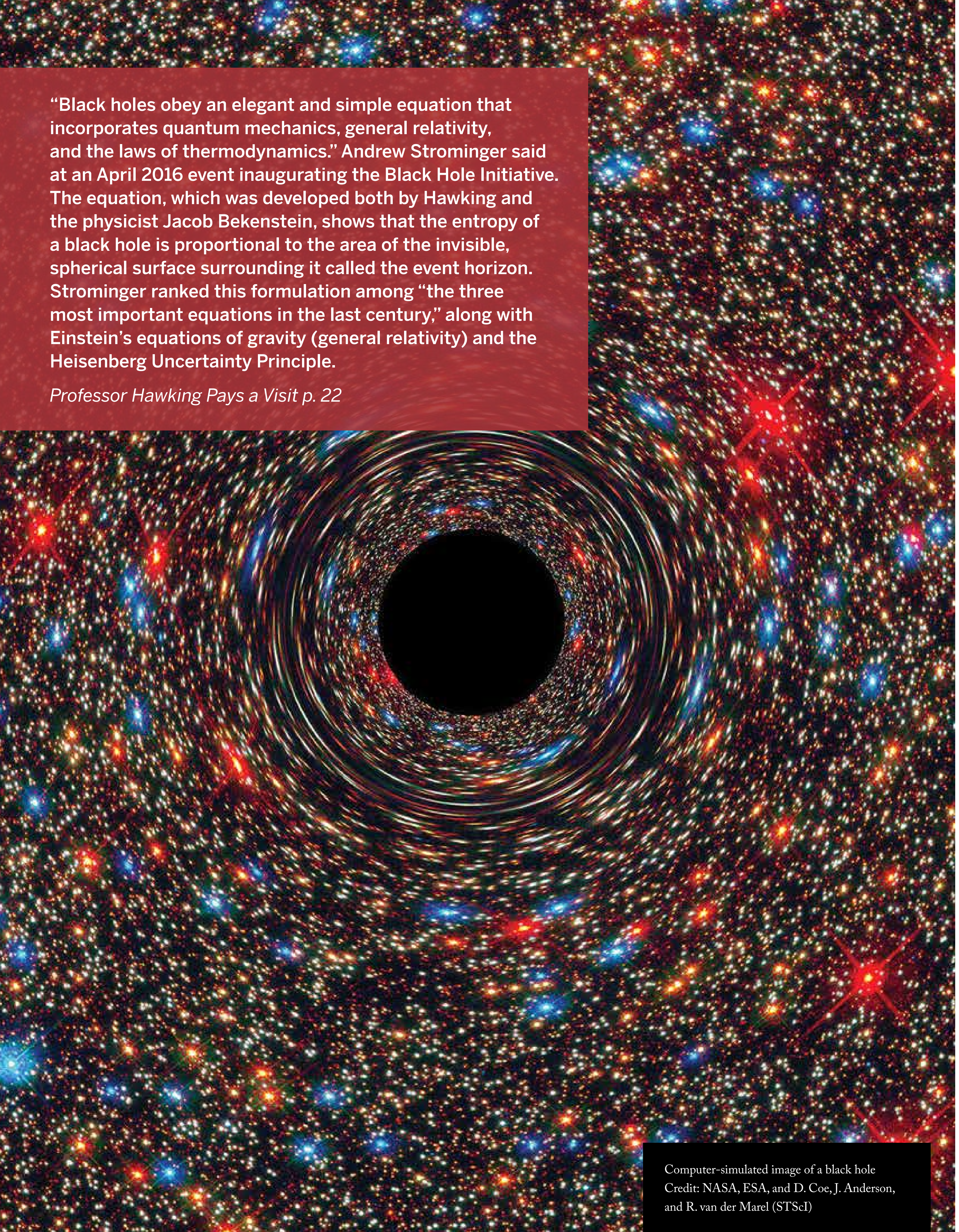

Computer-simulated image of a black hole
Credit: NASA, ESA, and D. Coe, J. Anderson, and R. van der Marel (STScI)

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ON THE COVER:

Cosmic Expansion. Observations by the High-z Supernova Search Team, described by Robert Kirshner, hint that we live in a “stop and go” universe whose expansion slowed under the influence of gravity before accelerating again due to an unexplained dark energy. This artist’s conception illustrates the history of the cosmos, from the Big Bang and the recombination epoch that created the microwave background, through the formation of galactic superclusters and galaxies themselves. The dramatic flaring at right emphasizes that the universe’s expansion currently is speeding up.

Image courtesy: David A. Aguilar, Harvard-Smithsonian Center for Astrophysics

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Letter from the Chair

Dear friends of Harvard Physics,

The spring semester is almost over, and the Law School yard behind the Jefferson Laboratory appears to be teeming with life under what is presently a clear blue sky. Whatever they've been doing with "organic landscaping" seems to encourage dandelions and clovers to thrive where there used to be a uniform flatness of lawn. It's less stately, perhaps, but also less monotonous and, therefore, somewhat more pleasing to the eyes and stimulating to the mind.

In this issue of the Department of Physics Newsletter, we are highlighting our faculty in cosmology. It's a relatively new field for our Department, which traditionally did not include astronomy-related disciplines. The Department has been strategically growing its cosmology faculty since the early 2000s. The faculty members featured in this issue—Cora Dvorkin, Doug Finkbeiner, and Chris Stubbs—seek answers to the mysteries of cosmic inflation, dark matter, and dark energy by pushing the technological boundaries of observational astronomy, drawing upon the latest ideas from fundamental physics, and combing the data for new theoretical insights.

The other feature article in this issue gives us a glimpse of a close collaboration between experiment and theory, this time in particle physics. John Huth, Matt Reece, Chris Rogan, and Matt Schwartz discuss how the interplay between theoretical and experimental work is facilitating the search for physics beyond the Standard Model at the Large Hadron Collider.

These are but two examples in which faculty members with different areas of expertise can work together to tackle a bigger problem than each could take on individually. Collaborations of this sort become possible when you have a faculty, as we do, made up of people with diverse backgrounds and a shared, as well as broad, vision for important questions in science. I hope the Department will continue to cultivate its strength by attracting outstanding scholars of all stripes in a sort of Organic Faculty Development.

Speaking of faculty development, I am happy to report that Ashvin Vishwanath, a rising star in condensed matter theory, has accepted a position as Professor with tenure. Ashvin will come to Harvard this fall. You will find his profile on page 7.

Just as we go to press, I received the wonderful news that Roxanne Guénette will be joining us as Assistant Professor of Physics, starting July 2017. Roxanne is an experimental particle physicist who studies neutrino oscillation. Stay tuned for a feature article on her research in the next issue of the newsletter.

In the last issue of the newsletter (Fall 2015), I mentioned the newly-established Bershadsky Distinguished Visiting Fellowship in Physics. We have had three Fellows in the past year: Profs. Sergio Cecotti, Malcolm Perry, and Francesca Ferlaino. (Prof. Ferlaino is profiled on page 39.) More Bershadsky Fellows, including Prof. Vaughan Jones, are expected in the coming year.

As a part of our effort to build a family-friendly department, we held the first Physics Department Reception on October 4, 2015. The gathering, which took place at the MIT Endicott House, was attended by about 75 faculty, staff, and their family members. I would like to thank Cumrun and Afarin Vafa for their generosity in supporting this and future events.

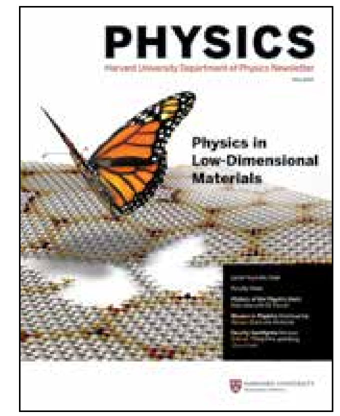
I hope you will enjoy this newsletter. As always, if you happen to be near the campus, please drop by the Department to see what we're up to. There is sure to be a variety of new programs and initiatives underway, but one thing remains constant: We are always striving to be at the forefront of physics research and education.

Sincerely,

Masahiro Morii
CHAIR AND PROFESSOR OF PHYSICS

Letters from our Readers*

WE THOROUGHLY ENJOYED HEARING FROM OUR READERS. HERE IS WHAT SEVERAL HAD TO SAY:



"I'm delighted with this new publication, which not only keeps me in touch but also revives many fading memories."

FRANK CHEN
AB '50, MA '51, PHD '54

"I want to thank you for sending me a copy of the "Harvard Physics Newsletter, which I have just spent a very enjoyable hour browsing through. Physics has changed almost unimaginably since I stopped being active myself… I got my AB in Physics from Harvard in 1948. Note that in order to get an AB rather than a SB I had to pass a tough exam in Latin! (The AB was considered to have more cachet at the time, and I had had four years of Latin in secondary school.) I remember well taking Norman Ramsey's graduate course (I think it was Physics 33) on "Introduction to the Quantum Theory" in 1947–48 and marveling over the special functions needed in treating the hydrogen atom."

WILLIAM J. CHILDS
AB '48

"Thank you very much. I really appreciate receiving the newsletter."

JOHN CRUES
AB '72, MS '75 (UNIV. OF ILLINOIS), MD '79

"I am enjoying the newsletter, both for information about what is going on now and also for the history—I still have fond memories of taking Professor Purcell's introductory graduate quantum mechanics subject."

ED GREITZER
AB '62, SM '64, PHD '70

"Professor Gerald Holton's early history of Edward Purcell brought back many happy memories of my Harvard Physics major (Field of Concentration in the Harvard-speak of 1951–55)… Harvard then had an insidious practice of assigning its first/introductory courses to the best lecturers. Every course leads you to want to major in that subject… Professor Purcell's lectures were so popular that guys would bring their football game dates to his Saturday noon lectures, skipping the Band pre-game recital, to hear his memorable introduction of new topics then. In addition, I couldn't get over having a recent Nobel laureate come by my laboratory bench and ask me about my experiment."

TERRY LILLY
AB '51, MBA '58

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

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Join us on LinkedIn:
www.linkedin.com/groups?gid=4740923

*Continued on the inside back cover.

Faculty Prizes, Awards & Acknowledgments*

Simons Investigator in the Mathematical Modeling of Living Systems:

PROF. MICHAEL DESAI

APS Fellowship:

PROF. DOUGLAS FINKBEINER

Thomson-Reuters Highly Cited Researcher 2015:

PROF. DOUGLAS FINKBEINER

DPF Mentoring Award, APS Division of Particles and Fields:

PROF. HOWARD GEORGI

Austrian Academy of Sciences:

PROF. GERALD HOLTON

Thomson-Reuters Highly Cited Researcher 2015:

PROF. PHILIP KIM

Julius Springer Prize for Applied Physics:

PROF. MIKHAIL LUKIN

Thomson-Reuters Highly Cited Researcher 2015:

PROF. MIKHAIL LUKIN

Royal Society of London Fellowship:

PROF. L. MAHADEVAN

Julius Wess Award, Karlsruhe Institute of Technology:

PROF. LISA RANDALL

Dannie Heineman Prize for Mathematical Physics:

PROF. ANDREW STROMINGER

Simons Fellow in Theoretical Physics:

PROF. ANDREW STROMINGER

Dannie Heineman Prize for Mathematical Physics:

PROF. CUMRUN VAFA

European Physical Society Condensed Matter Division Europhysics:

PROF. ASHVIN VISHWANATH

National Academy of Engineering:

PROF. DAVID WEITZ

Thomson-Reuters Highly Cited Researcher 2015:

PROF. AMIR YACOBY

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

A Tip of the Hat to Glauber and Wilson

Roy Glauber and Richard Wilson

We'd like to salute two distinguished faculty members, Roy Glauber and Richard Wilson, who've recently turned 90. Both Glauber and Wilson are Mallinckrodt Professors who've been in the Physics Department more than 60 years.

Born in New York City as the son of a traveling salesman, Glauber has often wondered: "What is it that makes a dedicated scientist out of a kid with an everyday background?" Clues can surely be found in his dazzling career. Glauber earned a Bachelor's Degree and PhD from Harvard. At the age of 18, while still an undergraduate, he was recruited to work on the Manhattan Project, alongside giants like Robert Oppenheimer. Glauber won a Nobel Prize in 2005 for his contributions to quantum optics—a field that focuses on the quantum interactions of light and matter.

Wilson, who was born in London, came to Harvard in 1955, specializing in nuclear and elementary particle physics. He quickly became an expert in nucleon-nucleon interactions and the scattering of leptons by nucleons. In the 1970s, Wilson got interested in policy matters, becoming one of the founders of the field of risk analysis. He summed up his feelings about science in a 2011 memoir called *Physics is Fun*. "There are so many questions that as yet have no answers," he wrote, "and we can only contemplate them with wonder."

IN MEMORIAM

Paul C. Martin

Paul C. Martin, former dean of the Harvard Division of Applied Sciences and the John Hasbrouck Van Vleck Professor of Pure and Applied Physics Emeritus, died on Sunday, June 19, 2016. He was 85 years old.

During more than five decades of service as a faculty member and dean, Martin helped to guide the development of engineering and applied sciences at Harvard, played a leadership role on a wide range of University initiatives, and was an influential voice on science and technology policy at the national level.

Martin earned an undergraduate degree and PhD in physics from Harvard in 1951 and 1954, respectively, before joining the faculty as assistant professor of physics in 1957. In 1964, he was appointed professor of physics....

"When you worked with Paul, you worked into the night hours and over the weekends, and you didn't work through intermediaries, because he had none," said former SEAS Interim Dean Harry R. Lewis, the Gordon McKay Professor of Computer Science. "He did things himself, to make sure everything was done right—every logical flaw was rooted out, every word was written properly, and every argument and viewpoint was taken into account and either incorporated or countered. And yet he was kind and supportive to those of us who couldn't keep up with him. He wanted the best from everyone, but he didn't expect that your best would be as good as his, as long as you shared in his ideals and in his hard work."

"Paul served for several decades as de facto dean of science under FAS Deans [Henry] Rosovsky and [A. Michael] Spence and had a lasting influence on the structure and future of science in the University," added Michael B. McElroy, the Gilbert Butler Professor of Environmental Studies. "He played a critical role in the creation of the Department of Earth and Planetary Sciences, forging a new vision for the field that recognized the essential unity of the solid Earth, atmospheric, and ocean sciences, and in the creation of a new undergraduate concentration on environmental science and public policy. He was an individual of exceptional intellectual quality and depth."

Martin was a member of the National Academy of Sciences, the American Academy of Arts and Sciences, the American Association for the Advancement of Science, the New York Academy of Sciences, and a fellow of the American Physical Society....

From "SEAS mourns the loss of Paul C. Martin," www.seas.harvard.edu, June 21, 2016. Reprinted with permission from Harvard School of Engineering and Applied Sciences.

Ashvin Vishwanath: Making All the Right Moves

by Steve Nadis

At various junctures in his education and career, Ashvin Vishwanath had critical decisions to make. So far, everything seems to have worked out for the best. And after joining Harvard's Physics faculty in July of this year, he is confident that coming to Cambridge will prove to be another rewarding move.

Vishwanath grew up in Bangalore in southern India, attending school there through high school. He moved north for college at the Indian Institute of Technology (IIT) in Kanpur where he majored in physics, even though engineering was regarded as the safer, more practical choice. Unlike most of his physics peers, who focused on particle physics and string theory, he opted for condensed matter physics because he wanted to do research in an area where theory was closely connected to experiments that could be carried out by no more than a handful of people.

Vishwanath graduated from IIT in 1996 with a master's degree. He started his doctoral studies later that year in Princeton—chosen, in part, because of a brochure stressing that graduate students are expected to work independently, learning how to do research by doing it. In his PhD thesis, he compared the structure of high-temperature superconductors to lower-temperature superconductors, where the orbits of electron pairs in the different materials assume different shapes, along with departures of a more quantum mechanical nature. "My work was not so spectacular," he admits, "but people were impressed by the fact that I was asking new questions and answering them on my own."

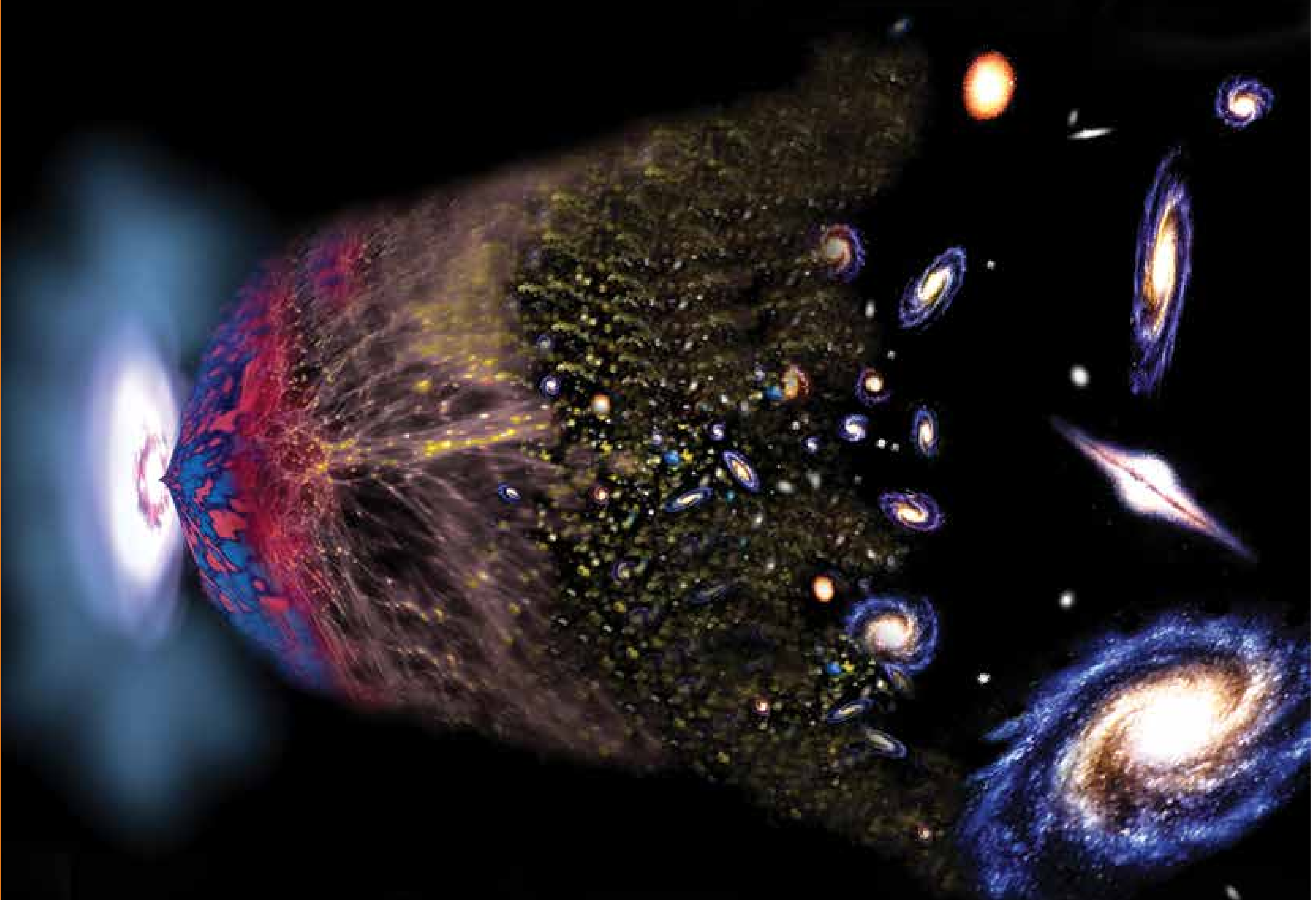
While at Princeton, he struck up a correspondence with Senthil Todadri, an MIT condensed matter physicist who graduated from IIT in Kanpur a few years before him. These conversations led to a research collaboration on superconductivity, which prompted Vishwanath to do his postdoctoral work at MIT. There, he, along with Todadri, Subir Sachdev of Harvard, and other colleagues, investigated a kind of topological defect found in magnets. This configuration is called a "hedgehog" —a place where electron spins and magnetic field lines emanate from a single point, sticking out in divergent directions, Vishwanath says, "like the quills of a curled-up hedgehog." The researchers soon realized that studying this type of defect could shed light on the unusual phase transitions that take place in high-temperature superconductors, drastically changing a material's properties.

In 2004, he joined Berkeley's Physics Department and continued his study of phase transitions in condensed matter systems. One of his primary interests then, and still, involves searching for three-dimensional analogues of graphene. Vishwanath's research group and others have since uncovered a new class of materials, Weyl semimetals, which fulfill predictions made more than 85 years ago by the mathematician and physicist Hermann Weyl.

Coming to Harvard, for Vishwanath, "is an opportunity to branch out and explore new directions." One of his new themes will be to understand what happens to quantum effects, observed at the level of individual atoms, as you scale up to macroscopic systems with large numbers of particles. He also hopes to find out whether he can see quantum phenomena at much higher temperatures than normally deemed possible. He is eager to strike up new collaborations. "The concentration of topnotch researchers at Harvard and in the wider Boston area is unmatched in terms of the intellectual environment it provides," he says, "and I'm excited to be part of it."

COVER STORY

Taking On The "Big Three" Enigmas In Cosmology Today



As cosmologists struggle to understand dark matter, dark energy, and inflation, Harvard researchers are striving to shed some light on these matters.

by Steve Nadis

Cosmic Expansion
Image courtesy: **David A. Aguilar, Harvard-Smithsonian Center for Astrophysics**

In the 21st century, scientists have ushered in the era of "precision cosmology." A field that was once data poor—with practitioners compelled to lean rather heavily on speculation—now has vast (and growing) quantities of data to draw upon. While tremendous strides have surely been made, work in cosmology still has somewhat of a Sisyphean quality to it. For the more we learn about the universe, the more we appreciate just how much we don't understand. Recent measurements suggest that ordinary matter—including familiar things made of atoms and molecules—comprises only about 5 percent of the stuff of the universe. Some 27 percent of the total is thought to consist of dark matter, which is unlike any known particles, while the remaining 68 percent is classified as dark energy. Both are labeled "dark" because they don't emit or reflect light, nor do they interact with photons in a noticeable way. The terminology also reflects the fact that we don't know what these unseen entities really are. In the case of dark matter physicists can, at least, make some educated guesses. When it comes to dark energy, however, theorists are pretty much in the dark.

The latest theories in cosmology hold that the driving force behind the Big Bang was a brief though volatile period of exponential growth known as inflation, lasting a tiny fraction of a second before relinquishing its energy in the form of light and matter (both ordinary and dark) that now permeate the universe. Dark energy is thought to bear some likeness to inflation, though it appears to be accelerated growth of a much more subdued and longer-lasting variety. But again, physicists can't identify the precise mechanism behind inflation (out of myriad possibilities), nor can they be certain that this process actually took place. That is why the practice of cosmology can, at times, seem like an exercise in humility—albeit one punctuated by occasional moments of sheer joy. "There are lots of things we just don't understand," acknowledges Douglas Finkbeiner, a Harvard Professor of Astronomy and Physics. His colleague Cora Dvorkin, an Assistant Professor of Physics, agrees. In many instances, she says, "there is no shortage of models," though picking out the right one can be a daunting challenge.

In early May, Finkbeiner and Dvorkin met with Christopher Stubbs, Harvard's Samuel C. Moncher Professor of Physics and Astronomy, to discuss the current state of their field, as well as to contemplate its future. Finkbeiner has been active in dark matter research, while Stubbs is focusing on dark energy and Dvorkin on inflation. Taken together, their work encompasses the three enigmas lying at the center of the so-called standard model of cosmology. Of course, many others at Harvard are engaged in these avenues of research, including Daniel Eisenstein, Robert Kirshner, John Kovac, Avi Loeb, Lisa Randall, and Matthew Reece.

Finkbeiner, for his part, admits to having "backed into the dark matter game." He was initially interested in unexplained high-energy signals—in the form of synchrotron and gamma radiation—observed by astronomers in and around the galactic center. He wondered what was behind the inordinately energetic electrons that had been seen and started thinking, in 2003, that dark matter annihilation might be a possible source.

Weakly interacting massive particles, or WIMPs, are prime candidates for dark matter, signs of which could potentially be discerned in various ways. Such particles might be produced in high-energy accelerators, detected deep under-ground after scattering off atomic nuclei, or observed in space amidst cosmic and gamma rays. These general strategies constitute what Finkbeiner calls "the three pillars of WIMP detection, and we need all three. While proponents might claim that their method is better, you need multiple approaches or no one will believe anything." Given that other, non-WIMP forms of dark matter could be much more difficult to spot, he says, "we should be careful not to focus only on the things we can detect (i.e., WIMPs) because nature may not be so kind."

"Twenty-five years from now," Finkbeiner says, "we might know what dark matter is, and maybe it will no longer be one of the biggest mysteries of cosmology." Something new will presumably come to our attention by then, he adds. "And I'm betting that we still won't know what dark energy is."

Stubbs dropped the hunt for dark matter more than 20 years ago, after having spent "a good solid decade of my life unsuccessfully chasing it," and started to investigate dark energy instead. This new interest was sparked in 1993, while he was on the faculty of the University of Washington, when astronomers in Chile found a way to calibrate distances using Type 1a supernova. "That was the conceptual step that allowed us to map out the history of cosmic expansion," Stubbs explains. "We all had the expectation that this would lead to precise measurements of cosmic deceleration." But in 1998, two teams of astronomers (one led by Brian Schmidt, a former Harvard graduate student and research fellow) found the opposite to be true: The universe's expansion was speeding up rather than slowing down. This startling discovery gave rise to the notion of dark energy and the ongoing campaign to unravel the mysteries surrounding it.

Dark energy is far from being grasped at a basic level. We still don't know, for instance, whether it is a quantum mechanical phenomenon or strictly a consequence of gravitational physics or, instead, a manifestation of quantum gravity for which we don't yet have a viable theory. "We're presently in the confused phase," Stubbs says. "It's a very sophisticated state of confusion, but we're confused nevertheless."

Some clarity should come in 2020, or shortly thereafter, when the 8.5-meter Large Synoptic Survey Telescope (LSST) in Chile is due to achieve first light. "This telescope is part of the first generation of projects engineered from the ground up to address fundamental questions in cosmology, and dark energy in particular," notes Stubbs, who has played a leading role in the endeavor from the outset. He is heading a team of Harvard undergraduates, graduate students, postdocs, and engineers who are working on the detectors, making sure they are optimally calibrated in order to realize a dramatic improvement over the current state of the art.

Dvorkin, meanwhile, is engaged in a similar kind of effort as head of the statistics and parameters group of a proposed initiative called CMB-Stage IV. The experiment will pool together some of the world's best microwave telescopes in an attempt to map out the cosmic microwave background (CMB) to as full an extent as possible while reaching unprecedented levels of precision. The main hope of this undertaking is to pick out a distinctive pattern in the polarized CMB light called B-modes, which would be attributable to gravitational waves produced during the inflationary epoch. Seeing signs of such waves, and determining their amplitude, would tell us about the energy scale of inflation.

Dvorkin and her collaborators are specifically charged with designing a technique for disentangling the B-modes associated with primordial gravity waves from those due to gravitational lensing as the path of CMB photons is bent by massive structures in the universe. "Discovering primordial gravity waves would open up a new window on early universe physics," she asserts. "If we don't discover them, we can start ruling out whole classes of inflationary models."

It's clear from the foregoing, not that there was any doubt, that the "Big Three" issues in cosmology are going to keep researchers busy for awhile—at Harvard and indeed throughout the world. But if the past is any guide, these problems won't maintain their lofty status forever. Twenty-five years ago, dark energy would not have made the top three list, because it had not been discovered yet. But Big Bang nucleosynthesis probably would have been on the list, Finkbeiner suggests. It has been dropped since then, because the problem was largely solved in the interim.

"Twenty-five years from now," Finkbeiner says, "we might know what dark matter is, and maybe it will no longer be one of the biggest mysteries of cosmology." Something new will presumably come to our attention by then, he adds. "And I'm betting that we still won't know what dark energy is."

Artist's impression of the three-dimensional distribution of dark matter in the universe (Image courtesy: NASA, ESA and R. Massey (California Institute of Technology)

Douglas Finkbeiner: Searching for Elusive Dark Matter

Many ideas have been advanced to describe the nature of dark matter, but the most important steps still lie ahead—figuring out what it really is.

A major goal in cosmology, alongside parallel efforts to characterize dark energy and identify the driving force behind the Big Bang, is to find dark matter and determine its nature. We know that 5/6th of the matter in the universe is non-baryonic (i.e., not made of the protons, neutrons, and electrons of "ordinary" matter). It does not interact appreciably with ordinary matter by nuclear scattering, or by scattering or absorbing photons. There is no particle in the Standard Model that could be dark matter, but many candidates are under investigation, ranging from the very light (axions) to the very heavy (primordial black holes). One candidate, the weakly interacting massive particle (WIMP), is especially appealing because it would be thermally produced in the early universe, interact only weakly, and undergo annihilations resulting in gamma rays and high-energy particles.

Professor Douglas Finkbeiner's group has been engaged in the search for these gamma-ray and particle signals for over a decade. His interest began when the Wilkinson Microwave Anisotrophy Probe (WMAP) satellite observed a hazy microwave signal in the inner regions of the Milky Way in 2003. These microwaves could have been produced by high-energy electrons from WIMP annihilation, spiraling around in the galactic magnetic field. This hypothesis made specific predictions for gamma-ray observations from the Fermi Gamma-ray Space Telescope, which started noticing a similar haze of gamma rays in 2008. It turns out that the source of these signals was a large-scale energy injection at the center of the galaxy, producing giant gamma-ray bubbles extending 25,000 light years above and below the galactic disk. These structures have nothing to do with dark matter but are interesting in their own right. Unfortunately, they substantially complicate the search for gamma-ray dark matter signals from the inner galaxy.

WIMP annihilation could reveal itself in another way. The high-energy photons and particles produced by WIMPs could have a measurable impact around the time the universe became (electrically) neutral and most of the CMB anisotropy was produced. Additional energy injected into the primordial gas by WIMPs would change the ionization history of the universe, increase subsequent photon scattering, and alter the statistical properties of the CMB. The Finkbeiner group has been active in analyzing the exact effects on the CMB as a function of WIMP mass and annihilation mode, including annihilations to additional new particles that would then decay to Standard Model particles. Recent data from the Planck satellite has severely constrained the parameter space for such an effect, but it remains a powerful probe of new physics in the first million years of the universe.

Working with particle physicists Neal Weiner and Nima Arkani-Hamed, Finkbeiner's group has also developed a framework for WIMP models that could explain positron excesses at low energy (INTEGRAL/SPI) and at high energy (PAMELA and AMS-02), along with other observational surprises. These models made specific predictions for direct detection experiments (e.g. XENON-100 and LUX) and were ruled out. Although the WIMP scenario is appealing, it is important to keep in mind that dark matter could be any number of other types of particle, or even many types of particles. The search continues.

Christopher Stubbs: The Quest to Characterize Dark Energy

We have known since the 1920s that the universe is expanding, and this observation is one of the empirical pillars of the Big Bang cosmological model. The discovery in 1998 that this rate of expansion is continuously increasing, however, came as a total surprise.

An artist's conception of the Large Synoptic Survey Telescope (LSST), Cerro Pachón, Chile. (Image courtesy: Todd Mason, Mason Productions Inc./LSST Corporation)

Understanding the physics mechanism that is driving this accelerating expansion, termed "dark energy," is one of the major objectives of contemporary cosmology. Professor Christopher Stubbs was a member of one of the two teams that announced the discovery of cosmic acceleration, and he has been working to understand dark energy ever since.

As the study of dark energy shifted from the discovery phase to its characterization, Stubbs has been involved in multiple projects that have led to a better grasp of dark energy's properties. The ESSENCE and Pan-STARRS projects measured the distances and redshifts of hundreds of supernovae, allowing for a direct measurement of the history of cosmic expansion. Another technique—measuring the abundances of massive galaxy clusters that were detected by the South Pole Telescope through the scattering of cosmic microwave background photons from hot gas in the cluster core—also set limits on the tension between dark matter promoting the growth of large-scale structure and the countervailing effect, dark-energy-driven expansion that is impeding such growth.

All of these observations are attempting to address what Steven Weinberg has called the "bone in the throat" of modern physics. We don't know presently whether to ascribe dark energy to quantum mechanical or gravitational physics. The fact that dark energy rears its ugly head at this seam in the theoretical structure of physics—compounded by the fact that we don't yet have a quantum mechanical description of gravity—might someday lead us to a deeper understanding of how these pieces fit together.

The problem that confronts us is that there are only two natural values for the amount of vacuum energy arising from quantum fluctuations in the vacuum. Integrating all fluctuations up to the Planck scale yields a result that is 120 orders of magnitude too large to be compatible with our existence—or compatible, more generally, with a universe providing the conditions under which life as we know it could have possibly arisen! So theorists were led to conclude that a perfect cancellation must drive the effective vacuum energy to be identically zero. But the observational value (in units scaled to the critical density) is Ω_{de}=0.7, which is manifestly neither zero nor 10^{120}. Figuring out why the dark energy content of the universe has this value, and gaining clues about the underlying mechanism, are among the most pressing open questions in fundamental physics.

Recognizing the imperative of undertaking more sensitive measurements in order to tease out the subtle differences that might help us discriminate between disparate models of dark energy, the Department of Energy, the National Science Foundation, and NASA have embarked on two flagship projects. One of these, the Large Synoptic Survey Telescope (LSST), is a ground-based 8.5 meter telescope with an unprecedented field of view that is slated to begin observations from Chile in the year 2020. The other, the Wide Field Infrared Survey Telescope (WFIRST) is a complementary, space-based survey system at infrared wavelengths, which is scheduled for launch into orbit in the early 2020s.

Stubbs was the inaugural Project Scientist for LSST and is still playing a central role in bringing the project into full operation. The CCD sensors for LSST have been undergoing comprehensive testing and evaluation in Stubbs' lab at Harvard, and his research group bears primary responsibility for delivering the wavefront sensing and real-time guiding sensors for the focal plane.

Uncertainty in flux calibration vs. wavelength is the dominant source of systematic error that presently limits the use of supernovae as probes of the nature of dark energy. In order to address this challenge, Stubbs and his colleagues have devised a new calibration scheme that relies on photodiodes as the primary metrology standard. Used in conjunction with illumination of the telescope system from a tunable laser, this method promises to provide an order of magnitude improvement in flux calibration, allowing these next-generation projects to advance the quest to fathom the nature of dark energy.

Cora Dvorkin: Uncovering the Explosive Truth Behind the Big Bang

A major question in cosmology concerns the original source of the matter perturbations that later grew into the stars, planets, and galaxies that we observe today.

An artist's conception of the Big Bang (Image courtesy: iStock/kyoshino)

A theory that attempts to explain the origin of these perturbations is known as "inflation." The idea of inflation was first introduced (in a peer-reviewed journal) in 1981. According to this theory, the universe had a very short period of exponentially fast expansion, which occurred a tiny fraction of a second after the Big Bang.

Inflation is generally assumed to be driven by a field (the inflaton) whose physical properties are as-of-yet unknown. The postulated field, nevertheless, would still leave imprints in the cosmic microwave background (CMB) radiation, the vestigial light from the Big Bang, and in the large-scale structure of the universe that can be examined today. By studying the observational consequences of the epoch of inflation, Professor Cora Dvorkin hopes to reconstruct the detailed physics of this era—or at least make progress in this direction.

Dvorkin's research is best described as "data-driven cosmology." She uses theoretical ideas in fundamental physics to make predictions for observable cosmological phenomena, and she then puts those predictions to the test by analyzing data from cosmological surveys. In particular, Dvorkin has worked extensively on testing inflation with cosmic microwave background data measured by space-based observatories such as WMAP and Planck, and various ground-based instruments, including the South Pole Telescope, Atacama Cosmology Telescope, and BICEP telescope.

Dvorkin developed a formalism to test inflation beyond some of the assumptions commonly made in the field. Her work enabled tests of the physics of inflation in a model-independent way, and she has made predictions for the polarization of the CMB that can be tested only now with new data from the Planck satellite.

An interesting prediction from the theory of inflation is the emergence of gravitational waves. These waves are ripples in space-time left over from quantum fluctuations in the universe's earliest moments. A possible way to look for primordial gravitational waves is through the imprints they would leave in the polarization of the CMB. In particular, gravitational waves would give rise to a certain type of polarization known as "B-modes." This was noted in a flurry of papers in 1996 by Seljak, Zaldarriaga, Kamionkowski, Kosowsky, and Stebbins. If gravitational waves were observed, their amplitude would tell us the energy scale at which inflation occurred, bringing us closer to understanding the Big Bang.

Dvorkin has worked extensively on the implications of a possible primordial CMB B-mode polarization detection, and she called attention to some new information about the physics of the early universe that such a signal would bring to light. She has also been involved in the analysis of CMB data. In the fall of 2014, for example, Dvorkin was invited to join the team conducting a joint analysis of the data from the BICEP2, Keck Array, and Planck experiments. The investigators cross-correlated the BICEP2 and Keck maps with the Planck maps at different frequencies. Dvorkin worked, along with other members of the team, on the likelihood analysis of these data for which they used a multi-component model that includes foregrounds and a possible contribution from inflationary gravity waves. They found strong evidence for dust in the BICEP2 region and no statistically significant evidence for gravitational waves.

Dvorkin is currently leading the statistics and parameters team for a next-generation ground-based CMB experiment called "CMB-Stage IV." The Stage IV experiment will have the sensitivity to detect inflationary gravity waves an order of magnitude below the current limits. In the upcoming decade, future measurements coming from multiple of experiments—that are either currently taking data, being constructed, or proposed—should afford new insights into the physics of the earliest moments of our universe.

FOCUS

History of the Physics Department: Reflections on Sidney Coleman

by Prof. Howard Georgi

If some crucial deadline kept you working to the wee hours of the morning in your office in Lyman or Jefferson in the late '60s or '70s, you were likely to see a solitary figure wandering the halls, deep in thought. This was not the ghost of Albert Einstein (although there was an uncanny resemblance). It was Sidney Coleman, one of the great minds and characters in particle physics and quantum field theory.

With his remarkable intellect and unique persona, Sidney put his personal stamp on theoretical physics at Harvard for decades.

Sidney arrived at Harvard in the early '60s, riding a wave of new ideas about the application of approximate symmetry arguments to particle physics. With his thesis advisor Murray Gell-Mann at Caltech, his Harvard colleague Shelly Glashow, and others, he showed the community how to calculate many measurable properties of strongly interacting particles using the algebraic techniques of group representations for continuous groups like SU(3).

These new uses of approximate symmetry had grown out of desperation. After the spectacular success of quantum electrodynamics in the late '40s and early '50s, the analytic tools of quantum field theory had been of very limited help in understanding the strong and weak interactions. Gell-Mann, Coleman, Glashow, and company made progress by isolating the symmetries from analysis and the use of algebraic tools. But nature, as she so often does, had a surprise in store. The same algebraic structures, SU(2) and SU(3), that appeared as approximate symmetries were buried deeply, in a completely different way, in the quantum field theoretic dynamics of particle physics interactions. This picture began to emerge in the '60s with the work of Glashow, Abdus Salam, and Steven Weinberg. At the beginning of the '70s, Gerard 't Hooft put all the pieces together and made sense of Yang-Mills theories with non-Abelian gauge invariance. Since then, symmetry and dynamics in quantum field theory have been inextricably linked in the standard model and beyond.

When Gerard 't Hooft (1971a,b); 't Hooft and Martinus Veltman (1972); and others finally figured this out in the early 1970s, the floodgates opened because quantum field theorists had a huge new world of theories that they suddenly had the tools to explore. At the same time, experimental particle physicists were pushing their machines beyond the 1 GeV energy scale and beginning to see evidence of new and surprising physics at (what we then thought of as) "high energy." The next few years brought a remarkable confluence of progress in theoretical and experimental particle physics. While Coleman's contributions to the tremendous progress made in particle theory in the 1970s were huge, he was usually not directly involved in interpreting the exciting experimental results. But he was always among the first to understand new theoretical ideas, often much more clearly than the inventors themselves. He was often the first to put new theoretical ideas on a firm footing and to understand their connection with deep issues in the foundations of physics. And he frequently took the lead in explaining them clearly to the community.

Indeed, it was characteristic of Coleman that many of his deepest and most important contributions are hidden in long papers that might seem to the casual observer to be purely technical, working out some minor mathematical detail. Two wonderful examples of this from the 1970s are the papers, "Radiative Corrections as the Origin of Spontaneous Symmetry Breaking" (Coleman and Weinberg, 1973) and "Quantum sine-Gordon Equation as the Massive Thirring Model" (Coleman, 1975). In the first of these, Coleman and his student Erick Weinberg solve a puzzle. They begin as follows:

Massless scalar electrodynamics, the theory of the electromagnetic interactions of a mass-zero charged scalar field, has had a bad name for a long time now; the attempt to interpret this theory consistently has led to endless paradoxes. In this paper we describe how nature avoids these paradoxes: Massless scalar electrodynamics does not remain massless, nor does it remain electrodynamics.

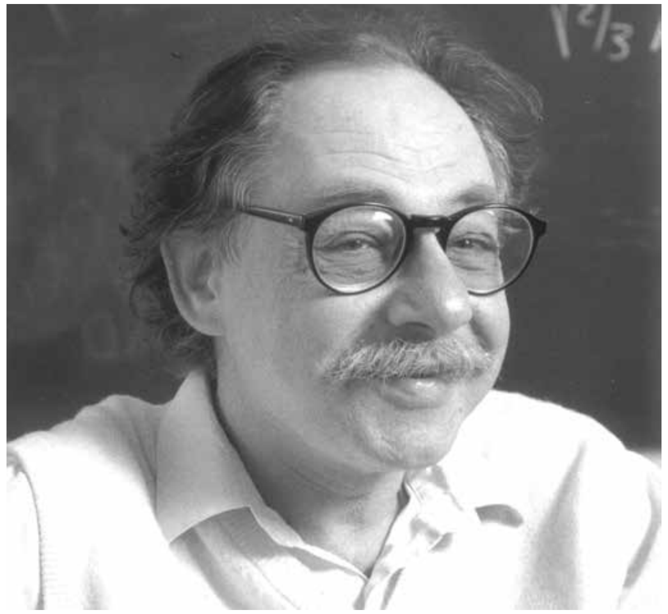
In fact, this paper was much more than a consistent account of a pathological theory. It was enormously influential as a handbook for dealing with scale violation in quantum field theory. Coleman had been thinking hard about scale invariance since the late 1960s. In this paper, written soon after the revolution of spontaneously broken non-Abelian gauge theories, Coleman and Erick Weinberg pulled together all of the most useful techniques and described them with his characteristic clarity. In the process he discovered an important and very general phenomenon. They say:

The surprising thing is that we have traded a dimensionless parameter, a, on which physical quantities can depend in a complicated way, for a dimensional one … on which physical quantities must depend in a trivial way, governed by dimensional analysis. We call this phenomenon dimensional transmutation."

We now know that dimensional transmutation is responsible for many of the surprising features of the strong interactions at high energies that were appearing in experiments when this paper was written.

Coleman's student David Politzer collaborated with Coleman and Erick Weinberg on some parts of the Radiative Corrections paper, and it was in this process that Politzer became interested in calculating the scaling properties of a non-Abelian gauge theory with no scalars. This led Politzer to the discovery of asymptotic freedom, also found at Princeton by David Gross and Frank Wilczek, for which the trio were awarded the 2004 Nobel Prize. Asymptotic freedom and dimensional transmutation, along with quark confinement, are the three dynamical pillars of QCD—our theory of the strong interactions based on the non-Abelian gauge theory SU(3). This theory incorporates and explains Gell-Mann's approximate SU(3) symmetry that was the subject of Coleman's thesis (Fritzsch et al., 1973; Weinberg, 1973). As developed by Politzer and others, this theory also led to the QCD parton model that now allows us to interpret the results of high-energy experiments with protons in terms of the fundamental physics of the quarks and gluons inside.

In "Quantum sine-Gordon equation as the massive Thirring model," Coleman (1975) studied a pair of quantum field theories in one space and one time dimension. Neither of these theories is particularly important in itself (and certainly not very relevant to our world of three spatial dimensions). But in a masterful (and, as usual, exquisitely documented) analysis, Coleman identified a precise equivalence between the two. He says:



We now go to the dullest part of the lecture in which I set up my notation...

It will be both the dullest and the most obscure since I will go through these things very fast because I presume that 90% of you have seen 90% of what I am going to say. Thus you will be bored 90% of the time and the other 10% of the time you will be baffled because I am going so fast. But since it is a different 90% and a different 10% for each member of the audience, there is no other way to organize it.

Thus, I am led to conjecture a form of duality…for this two-dimensional theory. A single theory has two equally valid descriptions in terms of Lagrangian field theory: the massive Thirring model and the quantum sine-Gordon equation. The particles which are fundamental in one description are composite in the other… Speculation on extending these ideas to four dimensions is left as an exercise for the reader.

This concept of duality—that what seem to be totally different classical theories can nevertheless describe exactly the same physics at the quantum level—became a central theme in the superstring revolution of the mid-1990s and continues to be central in field theory and string theory to this day.

For much of his career Coleman was the preeminent teacher of quantum field theory in the world, and his approach to the subject, naturally relying heavily on symmetry arguments, exerted a powerful influence. He had 40 Ph.D. students, many of whom became leaders in high-energy theory and other areas of physics. Many hundreds of students from all over the Boston area attended his superbly organized and witty lectures on quantum field theory, and his notes formed the basis of courses and eventually textbooks used worldwide. Students and colleagues alike learned from his classic papers and summer school lectures, which were masterpieces. Coleman tinkered with them until no word was out of place and no pedagogical opportunity was missed. Andrew Cohen describes this in a personal story:

"[It] happened when I was a beginning grad student while we were working on the Evaporation of Q-balls [Cohen et al., 1986]. Aneesh [Manohar] (who was my roommate at the time) was worried that Sidney's exacting writing standards would mean that the paper would take forever to write. I suggested we go talk to Sidney and try to get him started early on the writing. When we went into Sidney's office, Aneesh blurts out, "Andy has volunteered to write a draft of the introduction." After Sidney gave me the evil eye for a moment, he (seemingly reluctantly) agreed. I was terrified. I eventually went to Sidney's previous paper where he introduced the notion of Q-balls, and through cutting and pasting managed to produce most of a coherent introduction, using essentially Sidney's own words. The next morning I slipped it under his door and waited for him to come in. Sometime in the middle of the afternoon Sidney comes to find me and says, "I was worried about having you work on the introduction, but this writing is fantastic!"

Some of Coleman's lectures were collected in his book, *Aspects of Symmetry* (Coleman, 1988b). In 1989 he received the Award for Scientific Reviewing from the National Academy of Sciences for his "lucid, insightful, and influential reviews."

While his first love was teaching graduate-level quantum field theory, Coleman also gave wonderful undergraduate lectures. This was a personal sacrifice, because Coleman was renowned for doing his best work in the wee hours of the morning, and it was never clear whether he was better off getting a few hours of sleep before a late morning undergraduate class or simply staying up for it.

Fortunately, some of his lectures survive and are collected on the Harvard Physics Department Web page. Perhaps the most famous is "Quantum mechanics in your face" given at the New England sectional meeting of the American Physical Society (Apr. 9, 1994) in which Coleman pokes very edifying fun at the notion of reduction of the wave packet. The talk contains a great selection of Coleman jokes. For example, explaining that the talk is pedagogical and that nothing in it is original, he says, "I claim some responsibility but no credit—the reverse of the usual scholarly procedure." But he goes on to explain clearly, with just first-year quantum mechanics, that there is no problem with the interpretation of quantum mechanics. "The problem is the interpretation of classical mechanics."

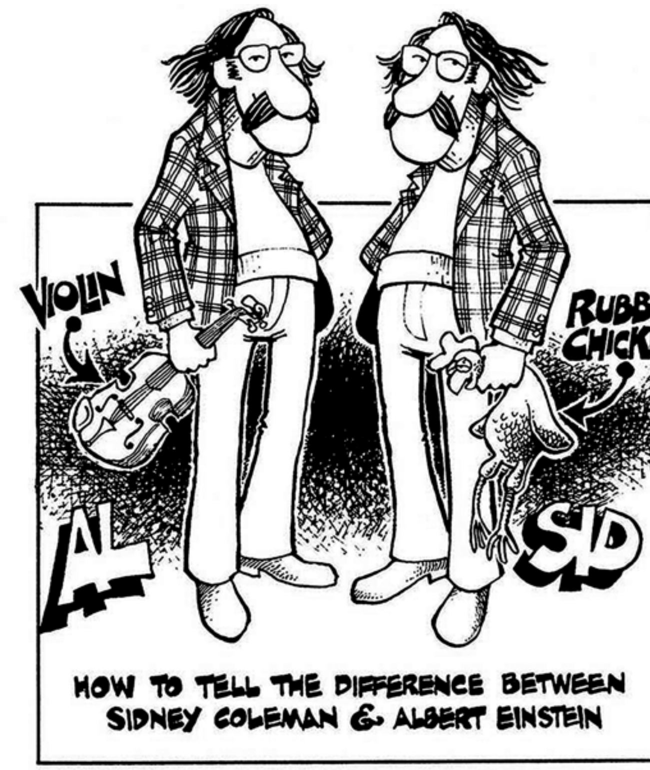
Before his marriage to Diana Coleman in 1982, Coleman was a flamboyant character with a unique sense of humor. He often lectured in pink or purple bell-bottom suits, which he obtained from a tailor in New York. He didn't really like the clothes, he said, "but the fitting was fabulous." He once threatened to sue the Harvard Crimson when it suggested that his purple suits were polyester. "They are wool!"

When a colleague declined to march in a peace rally in the late '60s, declaring that consulting for the government was his "bread and butter," Sidney quipped, "I too consult for the government—but it is only my cake."

Sidney's "carefully rehearsed spontaneous jokes" were legendary. Many of these were very intricate, and always beautifully delivered. Here is a standard one from almost the beginning of his field theory course.

"We now go to the dullest part of the lecture in which I set up my notation... It will be both the dullest and the most obscure since I will go through these things very fast because I presume that 90% of you have seen 90% of what I am going to say. Thus you will be bored 90% of the time and the other 10% of the time you will be baffled because I am going so fast. But since it is a different 90% and a different 10% for each member of the audience, there is no other way to organize it."

A polymath like his thesis advisor, Murray Gell-Mann, Sidney had a particularly deep outside interest in science fiction. As a teenage college student, he was one of the cofounders of Advent Publishers, which is devoted to science fiction criticism, and he continued his involvement for many years. Coleman's friend and cofounder of Advent, Earl Kemp, collected many Coleman memories for his online efanzine, *eI* Issue #36 of *eI* was devoted to Sidney Coleman and Kurt Vonnegut. Sidney cultivated a natural resemblance to Einstein, and his science fiction friends were duly amused. Here is Grant Canfield's cover art for *eI* #36.



Albert & Sid cartoon by Grant Canfield, originally published in Fandom Harvest by Terry Carr, Laissez Faire Produktion, 1986.

Coleman's wit could be as biting as it was clever, and his friends bore the brunt of this and loved it. They could count on him to keep their head sizes under control. "Courtesy," Coleman argued, "is for strangers. Kindness is for friends."

Health problems bedeviled the end of Coleman's life and deprived the world of what would surely have been an affectionately irreverent elder statesmanship. In January 2003, Coleman gave up teaching and took a medical leave. In 2005, to honor him, the Physics Department organized the SidneyFest, which was also a summit of the world's theoretical physicists. He retired in 2006 and died a year later. In the words of Sheldon Glashow, one of Coleman's best friends throughout his adult life and, in a scientific association that lasted almost 40 years, Coleman's first and last collaborator on theoretical particle physics (Coleman and Glashow, 1961, 1962, 1964,1997, 1998, 1999; Coleman et al., 1964, 1966): "Sidney was both an incomparable teacher and the most learned sage and sharpest critic in the world of theoretical physics: He was Pauli's tongue in Einstein's image. We have been deprived all too soon of one of our generation's most profound and imaginative minds."

From left: Chris Rogan, John Huth, Matthew Schwartz, and Matthew Reece.
Photo courtesy of Alejandro Avila.

On the Edge of the Unknown

by Professors Huth, Reece, Schwartz, and Junior Fellow Chris Rogan, PhD

"I remember that little talk as clearly as if it were yesterday," recalls Professor John Huth, referring to a lecture in 1980 by future Nobel laureate Martinus Veltman.

In this talk, Veltman explained how "theorists know more or less what is going to be found at accelerators for the next thirty years. But, once we reach the TeV [tera-electron-volt] scale of the World Machine, our knowledge runs out. At that point, we will very much need experimental guidance to make any progress." What Veltman meant by a 'World Machine' was a putative accelerator so large, complex, and expensive that it would require a global collaboration to build.

The thirty years of particle physics after 1980 have shown Veltman's pronouncement to be essentially spot on. There have been many discoveries over those years: The W and Z bosons were produced directly; the top quark was found, and found to be unusually heavy; and neutrinos were shown to have mass after all. Along with these discoveries, precision measurements of Standard Model parameters allowed for a tightening of that model, which describes the behavior of known particles in stunning detail. While exciting new physics beyond the Standard Model could have been seen in these intervening years, so far, unfortunately, it has not. This is disappointing, but not, as Veltman indicated, entirely surprising. What Veltman knew was that the key to extending our knowledge beyond the Standard Model would require the TeV energy scale of a World Machine. We are at the moment Veltman envisioned. Our knowledge has run out. Veltman, Huth, and thousands of other physicists around the world have patiently waited decades to get to this point and are now charting the next steps forward.

The Large Hadron Collider (LHC), currently running at CERN, is truly a World Machine. It is housed within a 17-mile tunnel, passing through two countries. The LHC first ran from 2009-2013 at energies of 7-8 TeV. Theory suggested that the Higgs boson, if it existed, might be visible in that early run. Indeed, by the 4th of July, 2012, enough data had accumulated to warrant an announcement by both the ATLAS and CMS experiments that a new Higgs-boson-like particle had been discovered, with a rest mass of 0.125 TeV. Starting last year, the LHC has been running at 13 TeV. This, in a sense, is the end of the road that Veltman had forecast back in 1980.

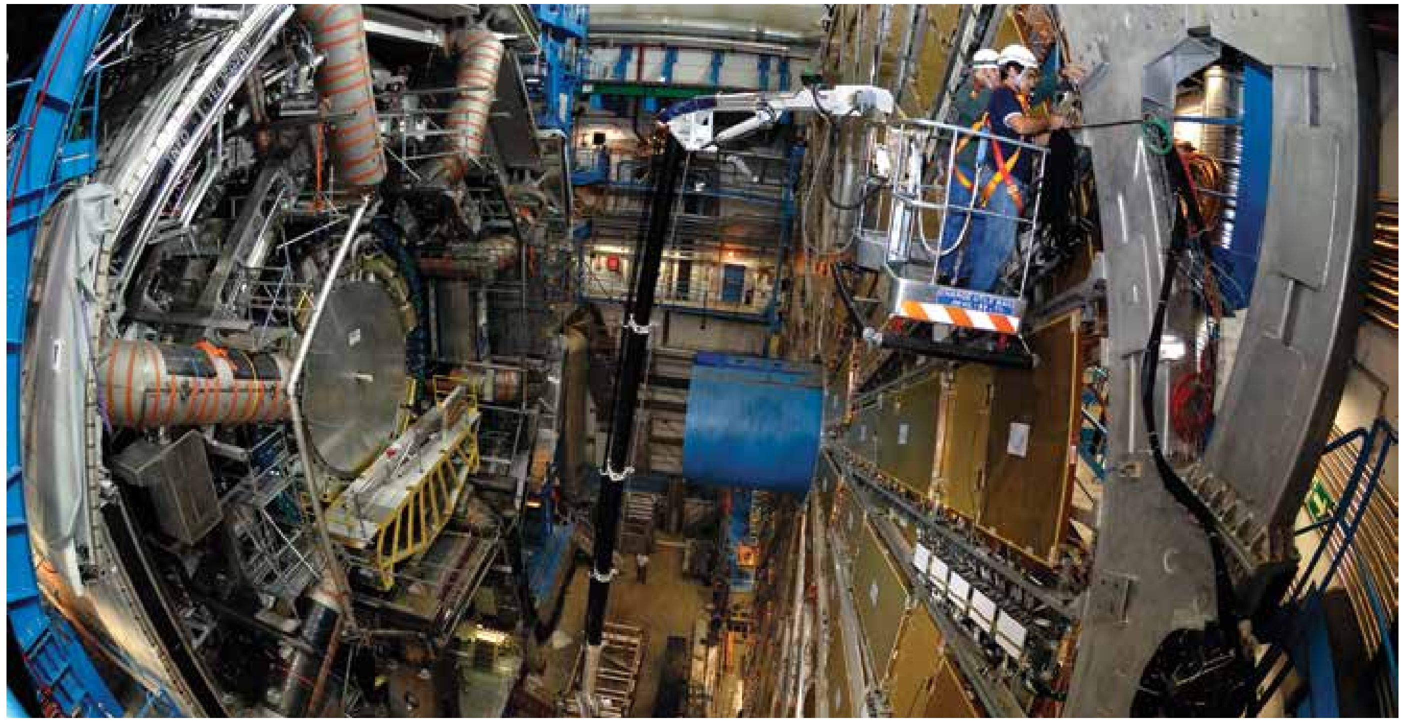
While the Higgs boson constitutes an extension of our knowledge of fundamental physics, it produces more questions than it answers. As the LHC continues to run, exploring different corners of the TeV scale, there is reason to hope some of these questions will be answered. But to do so will require new insights from both experimental and theoretical particle physics.

One crucial question raised by the LHC discovery can be simply stated though difficult to answer:, "What is the Higgs boson?" This particle is unlike any other particle we have seen before. It has no spin, while all other elementary particles do. It interacts more strongly with heavy particles than with light ones. It is associated with a field, permeating all space, that allows some particles, like the top quark, to be 350,000 times heavier than the electron. Some heavy particles like the proton are composite: They get their mass from the energy (using $E=mc^2$) holding their constituents (quarks) together. Are Higgs bosons and other particles like the top quark heavy because they are composite? We do not know, but we hope data from the LHC over the next few years can tell us.

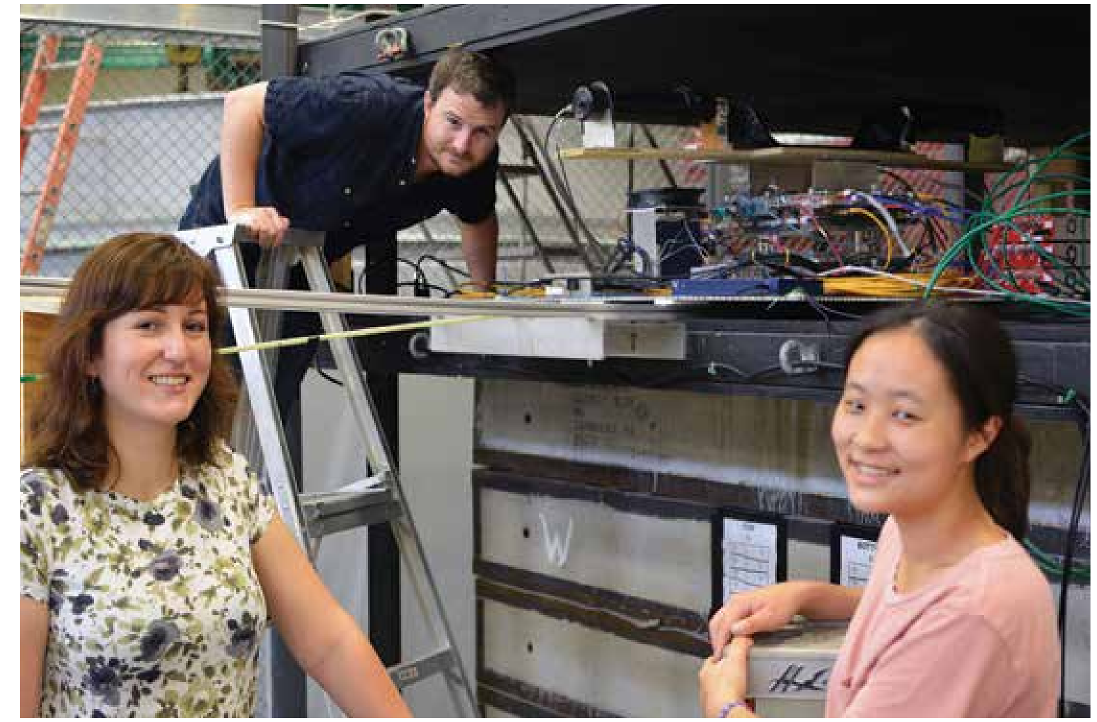
In the initial 7-8 TeV run of the LHC, the compelling evidence for the existence of the Higgs boson relied only on its couplings to force-carrying particles: The strong force particle (the gluon) was required to produce it, and the weak and electromagnetic force particles (the W and Z bosons and the photon) were involved in its decay signatures. The discovery did not rely at all on the Higgs boson interacting with matter particles, like the quarks or the electron. The Higgs boson's interactions with matter particles are hard to measure but absolutely essential to understanding what the Higgs boson is. As the Higgs boson interacts more strongly with heavier particles, the easiest interactions to see should be those with the heaviest quark, the top quark (mass of 0.175 TeV). However, as the top quark is heavier than half of the Higgs boson, the Higgs boson cannot decay to top quarks directly. The heaviest quark the Higgs boson decays to is the bottom quark (or b-quark), with a mass of 0.004 TeV, which is significantly lighter and hence much more weakly coupled to the Higgs boson. When the multi-purpose detectors at the LHC were being designed, it was thought that it would be impossible to find the Higgs coupling to b-quarks.

Over the past several years, Professors John Huth and Matthew Schwartz have teamed up to take a closer look at the b-quark question. They realized that the reason the Higgs coupling to b-quarks was thought to be so hard to measure was that the studies were based on using only techniques developed and applied at previous machines. The great precision, in both energy resolution and angular resolution, of the LHC allows for new characterizations of collision events. For example, at the Tevatron (the collider at Fermilab in Illinois that ran from 1983-2011, peaking at 1.96 TeV), ultra-relativistic b-quarks were observed as collimated collections of particles known as b-jets. These b-jets were treated as indivisible objects. At the LHC, physicists, including Huth and Schwartz, realized that they could break apart these b-jets and look inside them. Doing so led Huth and Schwartz to new ways of distinguishing b-jets and thereby finding more of them. By looking in depth at a variety of reconstruction techniques and new ways of analyzing jets, they concluded that an examination of the coupling of the Higgs to the b-quark pairs was indeed viable. Measurements that tie the Higgs boson to the b-quark decay rate have now turned into a major enterprise at both the ATLAS and CMS experiments, serving as one of the primary goals of the current 13 TeV LHC run.

Returning to the question of the Higgs boson's possible compositeness, we have some candidate theories about how this could possibly work. Models of a composite Higgs trace back to



Harvard experimentalists and theorists, with colleagues from around the world, are probing the frontiers of fundamental physics with data from the Large Hadron Collider at CERN. *Photo courtesy of ATLAS Experiment © 2016 CERN.*



Graduate students Emma Tolley (left) and Ann Wang (right) working with Chris Rogan on a new device called Micromegas, which is part of the ATLAS detector upgrade project.

pioneering work by Professor Howard Georgi and his former student David Kaplan in the mid-1980s. Remarkably, these models, which take place in the 4 spacetime dimensions, are closely related to models of Professor Lisa Randall and Raman Sundrum that take place in 5 spacetime dimensions. These models often dovetail nicely with models of supersymmetry. Supersymmetric models usually aim to explain not so much what the Higgs boson is (it is an elementary particle of spin 0 in these theories, as in the Standard Model), but rather why it gives mass to the matter particles in the Standard Model. In the simplest supersymmetric theories, a quantum effect arising from repulsive interactions between the Higgs boson and a virtual scalar top quark can cause a state with a nonzero Higgs field to be energetically favored, which is what then gives particles mass. Supersymmetry has other appealing features: It fits well with the GUT theories developed by Georgi and Sheldon Glashow in the 1970s; it can help resolve the fine-tuning puzzle of why the Higgs mass is much smaller than the fundamental scale of gravity; and it naturally includes particles called neutralinos that could be =dark matter.

Motivated and informed by these theoretical considerations, the Harvard ATLAS group is systematically searching for evidence of physics beyond the Standard Model in LHC data, doing so in a variety of ways. Professor Masahiro Morii, with postdoc Valerio Ippolito and graduate students Emma Tolley and Julia Gonski, are looking for an excess of events with visible Standard Model particles recoiling against a system of unseen ones, possibly related to dark matter. This measurement is particularly challenging. Exploiting conservation of momentum to infer the presence of missing particles requires monitoring every sub-system of the ATLAS detector and, correspondingly, understanding the noise and spurious signals that each can introduce.

In his work on ATLAS, Junior Fellow Christopher Rogan has developed new techniques to mine LHC events for more information. Escaping with these missing particles is information about their number and individual momenta; by using the particles that are observed in the ATLAS detector, along with generic observations about the new physics possibilities that could lead to missing particles, experimenters can recoup some of this information. Professor Melissa Franklin, Rogan, and graduate student Sun Siyuan use these ideas to search for signs of supersymmetric top, or "stop," quarks, while postdoc Stefano Zambito looks for subtle signatures of a variety of supersymmetric particles in events with leptons, jets, and missing momentum.

In concert with the experimental effort, high-energy theorists at Harvard are exploring models that predict a variety of signals that may be possible (although difficult) to dig out of LHC data in order to make sure that these models are not missed. For example, Professor Matthew Reece developed new Stealth Supersymmetry models that lack the missing momentum signal. His recent work with student Rebecca Krall and others discusses experimentally challenging signatures with top quarks. Harvard researchers Prateek Agrawal, Ben Heidenreich, Yuichiro Nakai, Jakub Scholtz, and Matthew Strassler, along with Randall and Reece, have investigated theories predicting unusual experimental signatures like particles whose decays mimic Standard Model processes and are therefore hard to pick out, or long-lived particles that require new experimental methods to reconstruct.

A common theme in all of this work is that given the vast amount of data the LHC provides, we should test not only the most popular theories like supersymmetry but exhaustively explore the data in search of surprises. The Harvard ATLAS group is particularly attuned to these possibilities. For example, rather than decaying immediately or flying undetected through ATLAS, new particles may fly millimeters, meters, or more before decaying to particles that can be observed, leaving a decay vertex some distance away from the proton-proton interaction point. Huth, Rogan, and graduate student Jennifer Roloff are currently studying this kind of signature.

As the World Machine continues to collect data this year and next, we have every reason to believe that a new discovery may lie just around the corner. Harvard experimenters and theorists, meanwhile, are playing a critical role in making sure such a discovery is not lost in the data. "Theorists at Harvard and world-wide have shown that the next discovery in particle physics could appear in any number of ways," says Rogan. "We are trying to get ready for each of them while also expecting the unexpected."

Photo courtesy of Nicole D'Aleo.

Professor Hawking Pays A Visit

by Steve Nadis

In April of this year, the Physics Department was afforded a rare treat: Cambridge University cosmologist Stephen Hawking, surely the world's most famous scientist, spent two weeks at Harvard—his first visit to the University since 1999.

Hawking came to Harvard at the invitation of Andrew Strominger, in part to continue the theoretical work on black holes they've been pursuing with Cambridge physicist Malcolm Perry, who is currently a Bershadsky Visiting Fellow in the Department.

Hawking is in frail condition. In 1963, when he was 21 years old, he was diagnosed with a rare form of amyotrophic lateral sclerosis (ALS) and told he had just two years to live. Yet 53 years later, he is still amazingly productive, keeping up an active research, writing, and public speaking schedule, while enduring a debilitating, degenerative disease that has rendered him almost completely paralyzed. Prior to his journey to the United States this spring, his doctor had advised him not to travel overseas, yet Hawking was adamant about coming, insisting that this work was so important, it might earn him a Nobel Prize. That argument prevailed, and he flew across the Atlantic in a private Medevac jet, stopping first in New York City to promote the Breakthrough Starshot Initiative—a bold plan to send small, robotic spacecraft to our nearest stellar neighbor, Alpha Centauri.

Hawking arrived at Harvard in time to deliver the 2016 Morris Loeb Lecture in Physics. On the afternoon of April 18, more than 1,000 spectators jammed into Sanders Theatre to hear his lecture on "Quantum Black Holes." An additional 500 or so people watched the talk, as it was broadcast live at the Harvard Science Center and Jefferson Laboratory. The lecture also marked the inauguration of the Black Hole Initiative (BHI)—an interdisciplinary venture based at Harvard, drawing on faculty from the Astronomy, Physics, and Mathematics Departments. BHI director Avi Loeb, who also chairs the Astronomy Department, served as the emcee for the event, describing the new endeavor as "the only center worldwide dedicated to the study of black holes."

In his introductory comments, the physicist Robbert Dijkgraaf, who heads the Institute for Advanced Study in Princeton, said "there is no greater honor than being an opening act for Stephen Hawking." Strominger also called it an honor to introduce his "colleague and friend and personal hero, Stephen Hawking." Strominger went on to discuss a 1974 proof by Hawking, which showed that "black holes obey an elegant and simple equation that incorporates quantum mechanics, general relativity, and the laws of thermodynamics." The equation, which was developed both by Hawking and the physicist Jacob Bekenstein, shows that the entropy of a black hole is proportional to the area of the invisible, spherical surface surrounding it called the event horizon. Strominger ranked this formulation among "the three most important equations in the last century," along with Einstein's equations of gravity (general relativity) and the Heisenberg Uncertainty Principle. The Bekenstein-Hawking formula, said Strominger, "has launched us on a voyage of discovery that may have more far-reaching consequences than the equations of Einstein and Heisenberg."

Next up was the featured speaker, Hawking himself, who was helped onto the stage in his computerized wheelchair. Hawking can communicate through a speech synthesizer that responds to movements of one of his cheek muscles. But that is a slow and tiring process, so the lecture had been prepared in advance. "It is sometimes said that fact is stranger than fiction," Hawking noted in his opening remarks. "Nowhere is that more true than in the case of black holes"—an object whose gravity is so strong, it can drag light back and prevent it from escaping. "Black holes are stranger than anything dreamed up by science fiction writers, but they are clearly matters of science fact." These objects are so strange, he added, that one might fall into a large, rotating black hole and end up in another universe. "But you could not come back to our universe. So although I'm keen on space flight, I'm not going to try that."

The talk was laced with the characteristic humor for which Hawking is known. (A frequent guest star on The Simpsons, Hawking was called "the funniest physicist on Earth" by Motherboard, an online science and technology magazine.) But the main subject was rather weighty. His lecture traced the evolution of our thinking about black holes over the past century, going back to Karl Schwarzschild's 1915 solution to Einstein's general relativity equations—a fitting topic given that Hawking has probably contributed more to our understanding of these exotic objects than any other person, living or dead. The term "black hole" was introduced in 1967 by Princeton physicist John Wheeler, Hawking said. "Who can resist a name that is such a winner?" Yet his research would soon call that catchy phrase into question.

In 1974, Hawking was studying the behavior of matter in the vicinity of a black hole and found something rather astounding. On really small scales, the laws of general relativity break down and quantum theory takes over. As a result, peculiar things could happen in miniscule black holes. The aforementioned uncertainty principle states that the more precisely you know the position of a particle, the less precisely you can know its speed. For a particle inside a tiny black hole, its position would be known with great accuracy, but there would be considerable uncertainty regarding its speed. The speed of such a particle, Hawking concluded, could even exceed the speed of light, which would enable it to escape the gravitational grip of a black hole. A black hole, in other words, would "emit particles at a steady rate"—a phenomenon now known as Hawking radiation. "I put a lot of effort into trying to get rid of this embarrassing effect [but] finally had to accept that it was correct."

The takeaway message of this insight is rather profound. "Black holes are not as black as they have been painted," Hawking told the rapt audience in Sanders. "Things can get out of a black hole."

Much of Hawking's talk focused on a related issue called the "black hole information paradox"—the problem he is working on with Perry and Strominger that, in a sense, brought him to Harvard in the first place. Simply put, the question boils down to this: What happens to the matter that falls into a black hole? Or, stated in another way, if a black hole forms from the terminal collapse of a star, does it contain any information about its history and about the original configuration of matter that led to its genesis? Is it possible, for example, to discern any hints about the progenitor star: Was it spherical or irregular, composed of matter or antimatter?

John Wheeler famously declared that "a black hole has no hair," meaning that from the outside, you can completely characterize a black hole by just three parameters—its mass, angular momentum,

Andrew Strominger, Stephen Hawking, and Malcolm J. Perry (image courtesy: Anna N. Żytkow)

and electric charge. If "records" concerning the materials that make up black holes are somehow retained, Hawking said, "black holes contain a lot of information that is hidden from the outside world."

And if a black hole continues to emit particles in the form of Hawking radiation, steadily evaporating until it ultimately disappears, what happens to the information about the stuff that at one time had been inside? Does this information disappear completely, along with the black hole that housed it, or can it somehow be recovered? Perhaps, Hawking suggested, "it's like burning an encyclopedia. The information is not lost if you keep all the ashes, but it's difficult to read."

The stakes in this matter couldn't be higher, he claimed. "For more than 200 years, we have believed in the science of determinism, which says that the laws of science determine the evolution of the universe." Knowledge about the state of a physical system at one time, this tenet holds, can be used to compute its state at another time. "If information were lost in black holes," Hawking said, "we wouldn't be able to predict the future. Even worse, if determinism breaks down, we can't be sure of our past history either, [and] it is the past that tells us who we are. Without it we lose our identity."

Hawking initially believed that information would be lost in black holes. The outflowing particles, he wrote in a 1976 paper, would have random properties, bearing no traces of the matter that fell in. He also speculated that information regarding a black hole's formation might seep out into another universe, in which case it would still be irretrievable. In 1997, Hawking and Caltech physicist Kip Thorne made a bet with John Preskill, a physicist also based at Caltech. Hawking and Thorne contended that information is lost, in violation of quantum theory, whereas Preskill took the opposing viewpoint. But after coming up with new ideas for how information might be preserved, Hawking changed his mind, conceding the bet in 2004. "I gave John Preskill an encyclopedia," he said. "Maybe I should have just given him the ashes."

Hawking regards black holes as "the most efficient hard drives in the universe," capable of storing enormous amounts of information. Figuring out how they are able to do that, he claimed, "is one of the greatest mysteries that we're working hard to unravel." His latest work with Perry and Strominger, which he touched on briefly, suggests that information coming into a black hole is encoded on the event horizon and can be recovered when the black hole evaporates.

Hawking ended the lecture on a note of levity, offering some measure of reassurance to those who might, someday, find themselves in a seemingly hopeless situation. Because matter can eventually escape from a black hole, he told the crowd, such objects "are not the eternal prisons they were thought to be. So if you feel like you are in a black hole, don't give up. There is a way out."

Hawking regards black holes as "the most efficient hard drives in the universe," capable of storing enormous amounts of information. Figuring out how they are able to do that, he claimed, "is one of the greatest mysteries that we're working hard to unravel."

He received an exuberant standing ovation and was soon ushered to the nearby Harvard Art Museums for a banquet with his physics and astronomy friends to celebrate the Black Hole Initiative. The next day, at a BHI conference held at the Harvard University Center of Mathematical Sciences and Applications (HMSA), Hawking had a chance to interact with leading figures in black hole physics from all over the world.

He was given an office in Jefferson during his two-week stay at Harvard, where many physics students and faculty members met with him. "People felt inspired by his presence and incredible persistence that has enabled him to be so actively involved in theoretical physics, despite his disability," Strominger said.

Hawking made time for various social gatherings and outings. He accompanied an entourage of Harvard physics affiliates to the Boston Symphony and on a Boston Harbor cruise. He went to a party at Strominger's house, celebrated Passover at Loeb's house, and joined about 70 people, including a good portion of the Physics Department, for an authentic Persian feast at the home of Harvard Physicist Cumrun Vafa. But his focus was clearly on black hole research.

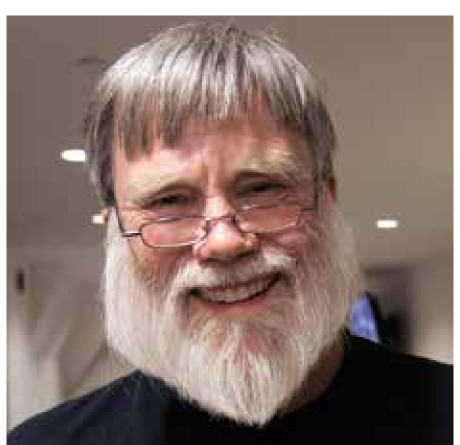
The work he is pursuing with Perry and Strominger on the information paradox may offer a way out of the current logjam. They are challenging the "black holes have no hair" premise, which has stood as gospel for decades. Instead, the three physicists suggest, black holes could have an infinite amount of hair—or "soft hair," as they call it, which is related to "soft particles," massless particles that carry no energy. Every time a charged particle enters a black hole, according to this idea, a "soft photon" and "soft graviton" are added to the black hole. In this way, Strominger explains, these particles record information about what went into a black hole.

Hawking, Perry, and Strominger don't claim to have the final answer to the longstanding paradox but are hopeful they have taken a step toward its resolution. Given that Hawking, in his present condition, can only produce about one sentence an hour, the collaboration has proceeded at a slow pace. But Strominger is patient, as well as optimistic. "This is a big program," he says. "There's a lot we still have to understand. Although we cannot look ahead and see a direct line to a solution, we are working our way forward and learning many new things along the way."

Might this work result in the Nobel Prize that Hawking alluded to before his trip? Strominger doesn't think so, partly because their work is "too theoretical. But that argument was good enough to satisfy Stephen's doctor and get him here, which was great for all of us at Harvard—and hopefully it will lead to something of value to the science world in general."

PROGRAMS

Undergraduate Program



Professor of Physics and Director of Undergraduate Studies, Howard Georgi
Photo by Jon Chase/Harvard University.

Words From the Director

At Commencement in May, we celebrated the graduation of one of our most remarkable classes of Physics and Chem/Phys under-graduate concentrators ever. At least seventeen of them are going on to graduate school in physics or a related field at outstanding schools including MIT (3), Stanford (2), Harvard (2), Boulder (2), Columbia (2), Berkeley, Caltech, Cambridge, Cornell, Princeton and UCSB. Another dozen (including a Rhodes Scholar) are going on to graduate work in other fields or going to graduate school or medical school after time in the work force. Some of the other interesting plans include studying Sanskrit in India, campaigning for Hillary, and playing Major League Baseball.

Pictures from the Open House showcasing the experimental projects created by students for "Principles of Scientific Inquiry," the lab component of Physics 15c. **At left and above:** Phelan Yu, Anthony Munson, Stephanie Carr, Anthony Taylor, Jonah Philion, and Shawn Best.

NEW CONCENTRATORS

Seventy-two sophomores, a record number, signed up for the Physics and Chem/Phys concentrations last fall, many of them pursuing joint concentrations or secondaries in other fields. These fields include Astrophysics, Mathematics, Engineering, Computer Science, and Philosophy.

CAREER PATHS

This past year's graduating class consisted of 57 Physics and Chem/Phys concentrators. Twenty-four of these students (the largest number in recent memory) are heading off to graduate school at 15 different institutions to study Physics, Biophysics, Chemical Physics, Neuroscience, Materials Science, Earth Sciences, Math, and Political Science. Others will be attending medical school, and still others have joined the workforce in software, consulting, finance, industry, and various startups.

PRIZES & AWARDS

Grace Huckins received a Rhodes Scholarship and will be pursuing a PhD in Neuroscience at Oxford. Eli Weinstein received a Hertz Fellowship and will be staying at Harvard to pursue a PhD in Biophysics. Olivier Simon was this year's recipient of the Physics Department's Sanderson Award, which is presented to the graduating Physics concentrator with the highest grade average in concentration courses.

STUDENTS' RESEARCH

This summer, roughly 30 Physics and Chem/Phys concentrators are pursuing full-time research on campus. These students are working in physics, astrophysics, engineering, and other related fields. Many other students are researching at institutions elsewhere, both in the U.S. and abroad.

Cyndia Yu, who graduated in May, undertook research throughout her undergraduate years. She spent the summer of her junior year working in Professor Philip Kim's group, where she studied electrochemical intercalation of graphene-based heterostructures. Graphene, the two-dimensional limit of carbon atoms, takes the molecular form of a hexagonal lattice. By inserting atoms into these hexagons via an electrolyte gel, her project attempted to manipulate the graphene's behavior in a variety of ways, including possibly causing the graphene to superconduct. She continued this research after the summer, developing new techniques for working with $Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO), a high-temperature superconductor with a transition temperature around 90K. Due to the instability of the crystal structure, experimentalists have found it difficult to conduct tunneling and thin-layer experiments to probe the mechanism for cuprate-based high-temperature superconductors. This research ultimately seeks to enable a large array of experiments on BSCCO and other high-temperature superconductors, which show substantial promise in both research and commercial applications. The opportunity to work with nanofabrication techniques with the Kim Group was instrumental in Cyndia's decision to pursue graduate studies in device physics.

Members of the CUWiP Local organizing committee develop a collaborative design challenge which will kick off the CUWiP Conference. **Clockwise from bottom center:** Ellen Klein, Delilah Gates, Elise Novitski, Lisa Cacciabaudo (Graduate Program Administrator), and Anna Klales (Preceptor).

FRESHMAN SEMINARS

The Physics Department offers a number of Freshman Seminars, covering a wide range of interesting topics. These seminars provide a small-group learning experience involving close and early interaction with professors. Course titles include "All Physics in 13 Days" and "Quantum Mechanics Face to Face." For many years, Prof. Cumrun Vafa has taught a freshman seminar titled "Physics, Math, and Puzzles." Despite the complexity of the universe, Prof. Vafa says, the fundamental laws of physics can be rather simple to grasp if viewed properly. His seminar was created to convey this simplicity in an introductory way. The course uses mathematical puzzles that encode physical principles as a springboard for launching into discussions of the fundamental laws of physics. Main aspects discussed include the role of symmetries, as well as the power of modern math (including abstract ideas in topology) in unraveling the mysteries of the universe. Examples are drawn from diverse areas of physics including string theory.

Here's an example of a puzzle that might be featured in this course: Consider four towns located at the vertices of a square. What is the shortest highway system that can connect all four cities together? This puzzle helps introduce the notion of spontaneous symmetry breaking, which is central in modern particle physics and is crucial to understanding the theory behind the Higgs mechanism—and accompanying Higgs particle—in the Standard Model.

FUN STUFF

The Society of Physics Students was active again this year with many events, including the mainstays: physics movie nights on the big screen in Jefferson 250, the pumpkin drop, and the Visitas liquid nitrogen ice cream party. On the more academic side, the SPS helped organize the first-ever Harvard-MIT SPS Research Conference, organized a grad-undergrad mentorship program, and held a panel on grad schools hosted by graduating seniors. Plans for next year include a panel hosted by upperclass concentrators who will discuss summer experiences working in the private/public sector, geared toward students not planning on going into academia.

HARVARD WILL HOST THE 2017 NORTHEASTERN SATELLITE CONFERENCE FOR UNDERGRADUATE WOMEN IN PHYSICS (CUWIP)

The Harvard University Physics Department is extremely pleased to host a site of the APS Conference for Undergraduate Women in Physics (CUWiP) on January 13-15, 2017. With this conference, we aim to provide a supportive atmosphere for all young physicists to connect with their peers and with mentors in the field. We hope the event inspires attendees to pursue careers in physics and to embrace a positive, enthusiastic vision for the future of science.

We invite physicists in the Boston area to share their experiences at our Career Fair on Sunday, January 15, 2017 from 1:00 p.m. to 3:00 p.m. and eat lunch with participants beforehand. The Fair will showcase the many careers available to physicists, and we hope that you will enjoy interacting with a spirited group of young scientists. We welcome the participation of anyone with at least a Bachelor's degree in physics. We are also seeking corporate and individual sponsors for this event. If you are interested in participating in the career fair please email CUWiP2017@g.harvard.edu

Our CUWiP is one of nine APS-organized conferences taking place simultaneously across the country. Our conference will bring together 250 undergraduate physicists as well as a variety of academic and industrial leaders, chosen to represent a broad range of fields and life experiences. Unique to the Harvard site is the first Supporting Inclusion of Underrepresented Peoples (SPIN UP) Workshop, an event held on Thursday and Friday, January 12-13. SPIN UP will bring together 50 undergraduates in order to promote the inclusion of students who are members of racial and ethnic minorities, members of gender and sexual minorities, have physical, mental, or learning disabilities, are from low-income backgrounds, are first-generation college students, and/or are members of other underrepresented or underserved communities. The full conference program and more information about both events are available at http://cuwip2017.physics.harvard.edu.

Renewing Leverett House

PROFESSOR HOWARD GEORGI HELPS HIS RENOVATED HOUSE COME ALIVE FOR TODAY'S STUDENTS AND FACULTY

Howard and Ann Georgi
Courtesy of Martha Stewart.

Howard Georgi has his hands full. As Mallinckrodt Professor of Physics, he pursues theoretical research and teaches Physics 16 and other courses. As Director of Undergraduate Studies, he advises current and potential concentrators. And as Faculty Dean of Leverett House, the largest of Harvard's 12 undergraduate residential Houses (and the home of Wednesday Physics Night), he and his wife Ann Georgi—affectionately known as Chief and Coach to Leverites—lead a lively household of about 500 students.

McKinlock Hall, one of Leverett's primary buildings, recently underwent a major transformation. It was the second project in Harvard's ongoing House Renewal initiative, one of the largest and most ambitious capital improvement campaigns in Harvard College history. Like most of Harvard's Houses, McKinlock Hall was built more than 80 years ago for a very different generation of students. House Renewal has brought a welcome change, making Leverett and other Houses more accessible, more sustainable, and better equipped to support the learning and living needs of 21st-century undergraduates, while carefully preserving the historic features that give each House its unique character.

Howard and Ann Georgi are helping Leverett take full advantage of the new opportunities that the renewed McKinlock brings, particularly in renovated informal spaces like common rooms, the dining hall, and a new light court —a neglected alleyway that was completely reimagined and repurposed by the renewal project. "It is hard to adequately describe what a transformation these informal spaces have wrought on House life," Howard Georgi says. "The architects did a splendid job of knitting them together. This has allowed us to do things that we could not even have imagined before the renovation."

Howard Georgi's favorite new feature of Leverett life is Faculty Family Thursdays, when the House invites FAS faculty and their children to come to Leverett for dinner and fellowship. The House provides dinner and high chairs, plus toys, crafts, and rabbit ears (in honor of the Leverett House mascot) for the kids. Faculty get to interact with Leverett students without having to miss quality time with their own families—a powerful example of the strength and warmth of the Georgis' extended House community.

House Renewal is a priority of The Harvard Campaign for Arts and Sciences currently underway (http://campaign.harvard.edu/fas), and there are more great changes on the horizon. The renewed Dunster House opened in the fall of 2015, Winthrop House is undergoing renovations and expected to reopen in fall of 2017, and Lowell House will follow.

For the latest news on House Renewal, visit http://news.harvard.edu/gazette/tag/house-renewal. To learn how alumni and friends can get involved and help support the effort, visit http://alumni.harvard.edu/house-circle-giving.

PROGRAMS

Graduate Program

by Dr. Jacob Barandes

THE PHD CLASS ENTERING IN 2016

The students entering the Physics PhD program in Fall 2016 are, as usual, notable for their geographic diversity, hailing from the American states of Illinois, Maryland, Massachusetts, New Jersey, New Mexico, New York, Pennsylvania, Texas, and Wisconsin, and from the nations of China, Cyprus, Germany, Greece, Iceland, India, the Netherlands, Russia, Serbia and Montenegro, South Korea, Spain, Turkey, and the United Kingdom.

THE PHYSICS GRADUATE STUDENT COUNCIL

Created by Physics PhD students in the spring of 2009, the Physics Graduate Student Council continues to play a key role in the Department. The council provides a forum for graduate students to propose new initiatives and discuss issues of common concern. It organizes social events like the popular biweekly Friday afternoon social hour and monthly movie nights. The council also administers annual surveys to graduate students on advising and the school's overall climate. The council's new president is Arthur Safira, and its other members are (in alphabetical order) Erin Dahlstrom, Delilah Gates, Jae Hyeon Lee, Cole Meisenhelder, Olivia Miller, Anna Patej, and Elana Urbach.

NEW INITIATIVES

To assist graduate students in connecting with alumni of the program and in learning more about careers inside and outside academia, the council has worked with the Department over the past academic year to invite alumni from different sectors to visit and discuss career opportunities. These visiting alumni have included: Prof. Protik Majumdar (PhD '89), Professor of Physics and former physics department chair at Williams College; Dr. Kevin Mercurio (PhD '14), Data Scientist and Program Director at Insight Data Science; Dr. Esteban Real (PhD '07), Software Engineer at Google; and Dr. Gilad Ben-Shach (PhD '15), representing the Boston Consulting Group. The Department was also pleased to invite back Dr. Ben Vigoda, CEO and Founder of Gamalon Labs, who spoke to our students about career opportunities in machine learning, start-ups, and corporate research.

As part of the council's work toward improving student familiarity with the process of embarking on PhD research, the council held a panel discussion on that subject on November 17, 2015. Moderated by the Director of Graduate Studies, Prof. Vinothan Manoharan, and the Associate Director of Graduate Studies, Dr. Jacob Barandes, the panel included (in alphabetical order) senior Physics PhD students Chris Frye (theoretical particle physics), Monica Pate (quantum gravity), Matthew Rispoli (experimental atomic physics), and Nabiha Saklayen (experimental biophysics), who shared their experiences and answered questions from the first- and second-year PhD students in attendance.

2016 NORTHEASTERN SATELLITE CONFERENCE FOR UNDERGRADUATE WOMEN IN PHYSICS (CUWIP)

The annual Conference for Undergraduate Women in Physics (CUWiP) consists of several satellite conferences, all run simultaneously in different regions of the country. The Department was represented at the 2016 northeastern satellite conference at Wesleyan University on January 16 by Dr. Jacob Barandes (Associate Director of Graduate Studies) and Lisa Cacciabaudo (Graduate Program Administrator), as well as by Physics PhD student Ellen Klein (soft-matter physics) and Applied Physics PhD student Thomas Plumb-Reyes (biophysics and laser physics).

by Steve Nadis

Jacob Barandes: Expanding His Role Across All Sciences At Harvard

Jacob Barandes, Associate Director of Graduate Studies and Lecturer in the Physics Department, took on some additional responsibilities on May 1st of this year. While retaining his Physics appointments, Barandes also became Director of Graduate Studies for FAS Science.

In his Physics Department role, Barandes mainly works with graduate students. However, in his FAS Science capacity, he'll primarily be working with the faculty and staff who run the graduate programs in the various science departments. "Historically, these departments have structured their graduate programs differently," Barandes notes. "I'll work with the departments to figure out what they're doing well and share best practices." He expects to learn things that could benefit physics studies at Harvard. "I'm looking forward to seeing what's working and where there's room for improvement."

Goldhaber Prize

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

The Goldhaber Prize is awarded annually by the department to its most outstanding current PhD students based on their research accomplishments, as determined by a vote of the faculty. Winners of this award 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.

Michael Coughlin

2016 GOLDHABER PRIZE WINNER

Michael Coughlin did his undergraduate studies at Carleton College in Northfield, Minnesota. He then received an MPhil in Astronomy from Cambridge University as a Churchill Scholar.

Michael is currently a third-year PhD student working with Prof. Christopher Stubbs's research group on the Laser Interferometer Gravitational-wave Observatory (LIGO) and the Large Synoptic Survey Telescope (LSST). Michael has focused his research on calibration and site characterization for LSST and the detection of gravitational waves using data from observatories in the United States and Italy. He also works on the implications of the recent binary black-hole detection on a potential stochastic gravitational-wave background of such sources. Outside of his academic and research interests, he is an active member of Harvard's competitive dance team.

Christopher Frye

2016 GOLDHABER PRIZE WINNER

As an undergraduate, Christopher Frye studied physics and mathematics at the University of Central Florida. During that time, Chris became interested in theoretical high-energy physics. Toward the end of his first year in the Physics PhD program at Harvard, he joined Prof. Matthew Schwartz's research group, where his work has focused on making precision theoretical predictions for the Large Hadron Collider (LHC).

Over the past couple of years, Chris has explored precision electroweak observables that will become useful as the LHC accrues more data. By exploiting the symmetries of the Standard Model, Chris and his group have identified certain ratios of diboson production rates that can be predicted with very small theoretical uncertainty.

Most recently, Chris has become interested in quantum chromodynamics and the collimated sprays, or "jets," of particles that are produced in nearly every event at the LHC. He and his collaborators have just completed the most accurate calculation of a jet-substructure observable. Moreover, they showed how these kinds of calculations can be systematically improved, despite the numerous sources of contaminating radiation present in the LHC environment. In March of 2016, Chris presented his group's results to other experts in the field at the Soft Collinear Effective Theory workshop in Hamburg.

GSAS Merit Fellowship

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

Shubhayu Chatterjee

2016 GSAS MERIT FELLOWSHIP WINNER

Shubhayu Chatterjee is a native of Kolkata, India. He did his undergraduate studies at the Indian Institute of Technology (IIT) Kanpur, majoring in physics, where he was awarded the President's Gold Medal (for best academic performance among all disciplines in the graduating class) and the General Proficiency Medal (for best academic performance in physics).

As an undergraduate, Shubhayu explored physics projects in diverse subfields, including numerical studies of Bose-Einstein condensates, Ricci flow in general relativity, analysis of heavy-ion collision (simulated) data from CERN, studying equilibrium properties and dynamics of hard-core bosons in the presence of magnetic fields, and the preparation and characterization of iron-based high-temperature superconductors, before finally deciding to specialize in theoretical condensed-matter physics.

At Harvard, Shubhayu's research focuses on solid-state materials, where fascinating new behavior emerges due to the large number of interacting particles. In particular, he works on theoretical models of complex, unconventional magnets and high-temperature superconductors that have a close connection with experiments. These materials hold immense possibilities for technological use, ranging from efficient power transfer over long distances to providing essential ingredients for quantum computation.

Outside of physics, Shubhayu loves music and enjoys playing with the World Music Ensemble at Harvard.

Monica Pate

2016 GSAS MERIT FELLOWSHIP WINNER

Monica Pate completed her BS in Physics at MIT. As an undergraduate, she first explored her interest in theoretical physics in her work with Prof. Liang Fu on topological insulators.

At Harvard, Monica shifted her research attention toward topics in high-energy theory, including quantum field theory and string theory. Her current research with Prof. Andrew Strominger focuses on the symmetries that govern the infrared structure of gauge and gravitational theories in asymptotically flat spacetimes. In the context of quantum field theory, these symmetries imply a set of relationships known as "soft" theorems, which relate scattering processes involving arbitrarily low-energy (or soft) particles. In addition, these symmetries give rise to a set of observable changes to the vacuum known as "memories." Monica is interested in the implications this line of research will have on the development of flat-spacetime holography.

Graduate Student Awards and Fellowships*

Amherst College Forris Jewett Moore Fellowship
Andrei Gheorghe

Frederick Sheldon Traveling Fellowship
Siyuan Sun

Gertrude and Maurice Goldhaber Prize
Michael Coughlin
Christopher Frye

GSAS Merit Fellowship
Shubhayu Chatterjee
Monica Pate

Harvard University Center for the Environment Fellowship
Cedric Flamant
Rodrick Kuate Defo

Hertz Foundation Fellowship
Paul Dieterle

National Defense Science and Engineering Graduate (NDSEG) Fellowship
Geoffrey Ji
David Levonian
Harold McNamara

National Science Foundation Graduate Research Fellowship Program (NSF GRFP)
Benjamin Augenbraun
Rebecca Engelke
Anne Hébert
Elizabeth Himwich
Emil Khabiboulline
Bartholomeus Machielse
Aditya Parikh
Daniel Pollack
Colleen Werkheiser

Sir Keith Murdoch Fellowship from the American Australian Association
Yichen (Lily) Shi

Top left: Andrew Lucas and Cristina Popa; Upper right: Anna Wang; Bottom Left: Junhyun Lee.

*Includes awards from 2015-2016.

Recent Graduates

Kartiek Agarwal

Thesis: Slow Dynamics in Quantum Matter: the Role of Dimensionality, Disorder and Dissipation

Advisor: Eugene Demler

Monica Allen

Thesis: Quantum Electronic Transport in Mesoscopic Graphene Devices

Advisor: Amir Yacoby

Eunmi Chae

Thesis: Laser Slowing of CaF Molecules and Progress towards a Dual-MOT for Li and CaF

Advisor: John Doyle

Thiparat Chotibut

Thesis: Aspects of Statistical Fluctuations in Evolutionary and Population Dynamics

Advisor: David Nelson

Debanjan Chowdhury

Thesis: Interplay of Broken Symmetries and Quantum Criticality in Correlated Electronic Systems

Advisor: Subir Sachdev

Brian Clark

Thesis: Search for New Physics in Dijet Invariant Mass Spectrum

Advisor: John Huth

David Farhi

Thesis: Jets and Metastability in Quantum Mechanics and Quantum Field Theory

Advisor: Matt Schwartz

Martin Forsythe

Thesis: Advances in Ab Initio Modeling of the Many-Body Effects of Dispersion Interactions in Functional Organic Materials

Advisors: Alan Aspuru-Guzik (CCB)/Kang-Kuen Ni

Benjamin Good

Thesis: Molecular Evolution in Rapidly Evolving Populations

Advisor: Michael Desai

Sean Hart

Thesis: Electronic Phenomena in Two-Dimensional Topological Insulators

Advisor: Amir Yacoby

Yang He

Thesis: Scanning Tunneling Microscopy Study on Strongly Correlated Materials

Advisor: Jenny Hoffman

Andrew Higginbotham

Thesis: Quantum Dots for Conventional and Topological Qubits

Advisors: Charlie Marcus/ Bob Westervelt

Dennis Huang

Thesis: Nanoscale Investigations of High-Temperature Superconductivity in a Single Atomic Layer of Iron Selenide

Advisor: Jenny Hoffman

Alexander Isakov

Thesis: The Collective Action Problem in a Social and a Biophysical System

Advisor: L. Mahadevan

Anna Klales

Thesis: A Classical Perspective on Non-Diffractive Disorder

Advisor: Eric Heller

Timothy Koby

Thesis: Development of a Trajectory Model for the Analysis of Stratospheric Water Vapor

Advisors: Jim Anderson (EPS)/Eric Heller

Peter Komar

Thesis: Quantum Information Science and Quantum Metrology: Novel Systems and Applications

Advisor: Misha Lukin

Georg Kucscko

Thesis: Coupled Spins in Diamond: From Quantum Control to Metrology and Many-Body Physics

Advisor: Misha Lukin

Tomo Lazovich

Thesis: Observation of the Higgs Boson in the WW* Channel and Search for Higgs Boson Pair Production in the $b\bar{b}\,b\bar{b}$ Channel with the ATLAS Detector

Advisor: Melissa Franklin

Junhyun Lee

Thesis: Novel Quantum Phase Transitions in Low-Dimensional Systems

Advisor: Subir Sachdev

Ying-Hsuan Lin

Thesis: Conformal Bootstrap in Two Dimensions

Advisor: Xi Yin

Andrew Lucas

Thesis: Transport and Hydrodynamics in Holography, Strange Metals and Graphene

Advisor: Subir Sachdev

Dougal Maclaurin

Thesis: Modeling, Inference and Optimization with Composable Differentiable Procedures

Advisors: Ryan Adams (SEAS)/Adam Cohen

Maxwell Parsons

Thesis: Probing the Hubbard Model with Single-Site Resolution

Advisor: Markus Greiner

Anna Patej

Thesis: Distributions of Gas and Galaxies from Galaxy Clusters to Larger Scales

Advisors: Daniel Eisenstein/ Avi Loeb (CfA)/Doug Finkbeiner

Suzanne Pittman

Thesis: The Classical-Quantum Correspondence of Polyatomic Molecules

Advisor: Eric Heller

Cristina Popa

Thesis: Simulating the Cosmic Gas: From Globular Clusters to the Most Massive Haloes

Advisors: Mark Vogelberger (MIT)/Lisa Randall

Achilleas Porfyriadis

Thesis: Gravitational Waves from the Kerr/CFT Correspondence

Advisor: Andy Strominger

Philipp Preiss

Thesis: Atomic Bose-Hubbard Systems with Single-Particle Control

Advisor: Markus Greiner

Shu-Heng Shao

Thesis: Supersymmetric Particles in Four Dimensions

Advisor: Xi Yin

Andy Yen

Thesis: Search for Weak Gaugino Production in Final States with One Lepton, Two b-Jets Consistent with a Higgs Boson, and Missing Transverse Momentum with the ATLAS detector

Advisor: John Huth

PROGRAMS

Research Scholars

The Post-doc and Research Scholar Program continues to thrive, celebrating bi-monthly social lunches, monthly Pub Night at the Queen's Head Pub, a research scholar poster session in February, and a terrific grant writing panel in April hosted by Professors Gabrielse, Stubbs, and Westervelt, along with the Director of Research Development and Strategy, Susan Gomes. The discussion was moderated by two members of the Research Scholar Advisory Committee, Dr. Viva Horowitz and Dr. Andreas Eberlein.

We'll begin the 2016-2017 academic year with an all-department barbeque, currently planned for September 7, 2016. We'll follow up on that event with our 4th Annual Research Scholar Retreat, also in September, featuring talks by Emanuel Derman of Columbia University, the author of *My Life as a Quant,* and Stefanie Tompkins, Director of the Defense Sciences Office at DARPA. We have also begun planning a panel for Spring 2017 that should be of broad interest, concerning effective strategies when applying for faculty positions.

THE HARVARD PHYSICS MENTOR NETWORK

A recent initiative within the department, the Harvard Physics Mentor Network, has one overriding objective—to make it easier for graduate students and research scholars to embark on satisfying professional careers. The department has compiled a list of physics alumni who are willing to talk about career options in academia and industry, both in the United States and abroad. We are always eager to recruit more volunteers, so please contact our Research Scholar Coordinator, Bonnie Currier (bcurrier@fas.harvard.edu), if you'd like to be added to our list or might consider doing so. Be sure to inform us of your email address, your place of work, your title, and the area of physics (if any) that you currently work in.

Harvard research scholars, graduate students, and alumni of our programs can access the Physics Department LinkedIn Group at the following weblink:

https://www.linkedin.com/groups?gid=4740923

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Trevor David Rhone: Probing the Nature of Exotic Matter in the Flatlands of Physics

by Steve Nadis

Trevor David Rhone came to Harvard in December 2015 as the first Future Faculty Leaders Fellow in the Physics Department—a three-year program established in 2014 to help prepare research scholars for independent faculty positions. For Rhone, the path to Cambridge has been a long one, in both a geographic and cultural sense.

Born and raised in Kingston, Jamaica, he became interested in physics in high school where he had "a really fantastic teacher." He stuck with the subject at Macalester College in Minnesota—a place whose harsh winters contrasted with Jamaica's tropical climate. During the summers, he engaged in condensed matter physics research at Macalester and the nearby University of Minnesota.

Both a physics and premed major, Rhone had long planned on being a medical doctor. For top students growing up in Jamaica, the options seemed limited, he says. "You're supposed to go into medicine, or become an engineer or a lawyer." As the latter two didn't appeal to him, he opted for medicine. He scored well on the MCATs during his final year of college, but when it came time to apply to medical schools he had a change of heart. "I realized I'd have to spend the next four years studying biology, chemistry, and biochemistry—subjects that weren't nearly as interesting to me as physics. So I decided to go to graduate school in physics instead."

Rhone graduated from Macalester in 2005 and started graduate work at Columbia that same summer, participating in a high-energy cosmic ray physics project in Argentina. "I'd only done condensed matter physics, so it was nice to try something different," he says. "But I found that I still preferred condensed matter research and went back to it at Columbia." There he studied electrons confined to two dimensions (sometimes just a single atomic layer) at temperatures close to absolute zero and magnetic fields a million times stronger than the Earth's—conditions under which "electrons can have exotic properties, exhibiting some really unexpected behavior."

He went to Japan in 2012, immediately after earning his PhD, for a postdoc at NTT Basic Research Laboratories. NTT's research facilities were ideal for continuing his investigations of two-dimensional systems in high magnetic fields and low temperatures. In fact, he had the exclusive use of two dilution refrigerators, which operated at 10 millikelvin and cost hundreds of thousands of dollars apiece—a situation that would be hard to match in most U.S. labs. Although Rhone sometimes felt isolated in Japan, he reveled in "the sights and sounds" of that country, which were different from anything he had experienced before. He also found time to resume his training in karate.

At Harvard, he is studying, among other things, the magnetic properties of two-dimensional materials like graphene, making use of techniques involving so-called nitrogen-vacancy (NV) centers in diamond. His work—which is being supervised by Amir Yacoby and Ronald Walsworth and sponsored by Masahiro Morii—could have many intriguing applications. But for now Rhone is focusing on "the more fundamental research side of things," noting that "a lot remains unknown regarding the microscopic origins of magnetic order in these exotic materials."

Harvard, he says, is a stimulating place for the physics questions he is driven to pursue. "There are some amazing researchers and faculty here, and being around people like that can really inspire great achievements."

The Work of this Bershadsky Fellow is Truly Magnetic

by Steve Nadis

Image courtesy:
University of Innsbruck

In March and April of this year, Francesca Ferlaino spent six eventful weeks in the Harvard Physics Department. Ferlaino, a Physics Professor at the University of Innsbruck and at the Institute for Quantum Optics and Quantum Information (IQOQI), came to Cambridge under a Bershadsky Distinguished Visiting Fellowship. The main purpose of her sojourn was to work with Markus Greiner, with whom she's in the midst of an ambitious joint project. While at Harvard, Ferlaino also had stimulating conversations with Eugene Demler, John Doyle, and Mikhail Lukin of the Physics Department and Kang-Kuen Ni of the Chemistry Department —interactions that may grow into more formal collaborations. "This is a very pleasant community," she says. "People work well together, and there seem to be strong connections. It's like a big family—and one whose company I enjoy very much."

Ferlaino focuses on atomic physics in the quantum regime. She earned her undergraduate degree in Naples, Italy, the city in which she was born, and got her PhD in Florence before coming to Innsbruck in 2006—first as a visiting scientist and eventually becoming a full professor who heads the Physics-Research Center.

Ferlaino found her specialty about seven years ago, shortly after arriving at Innsbruck. She wanted to continue the work on ultracold atoms she had started in graduate school but needed a more specific agenda before applying for grants to support new experiments. She came across a paper, written by researchers in Maryland, showing that it was possible to use lasers to cool down a complex atom like erbium, which has 14 valence electrons. The Maryland group was interested in nanotechnology applications, but Ferlaino and her co-workers in Innsbruck realized their technique could be adapted for quantum physics purposes.

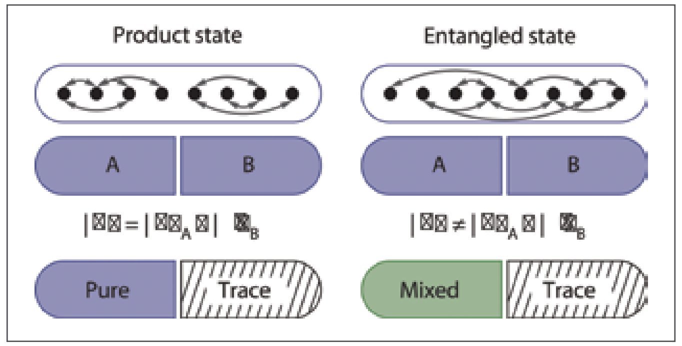
She had found her calling in erbium, a strongly magnetic atom, and is now a leading pioneer in uncovering the physics of strongly magnetic atoms. Her experiments still take place at ultracold temperatures measured in millionths or billionths of a degree above absolute zero—a realm chosen because systems can be kept essentially free of impurities while investigators can exercise exquisite control over the strength of interactions between particles.

The magnetic nature of erbium offers other advantages. Atoms normally need to touch each other to interact, but large magnetic moments allow researchers to study interactions between atoms that are physically separated from one another, perhaps by a barrier made of light called an optical lattice. In an April 2016 paper published in *Science,* Ferlaino and her colleagues reported on measurements of long-range interactions between erbium atoms confined to such lattices.

One limitation, Ferlaino notes, "is that we don't have the ability to see how an individual atom organizes itself with respect to other atoms in an optical lattice. You need a quantum gas microscope for that."

That's where Greiner comes in. He is one of the inventors of the quantum gas microscope, whereas Ferlaino is one of the world's top authorities on magnetic atoms. They are now combining their expertise, in experiments set to be run both at Harvard and Innsbruck, with the expectation that exciting results will soon emerge. "We'll have the same basic technology at our disposal," Ferlaino says. "We might decide to explore different aspects of the same question or different questions altogether. The situation is rich enough to allow for many possible directions—all of which will push up against the scientific frontier."

Faculty in the News



Measuring Entanglement Entropy

Markus Greiner

Until now, entanglement entropy has been a purely theoretical construct in condensed-matter physics, because it is difficult to partition a solid-state system and measure its constituents. Islam et al.* have performed the first such measurements using two identical copies of a small system of four atoms trapped in an optical lattice (an array of interfering laser beams). If the potential-energy 'landscape' of the optical lattice is not too deep, the particles can tunnel from one site to the next and feel the presence of their neighbours. This leads to a many-body state that exhibits entanglement. But if the lattice is deep, the particles act as individuals and are free of entanglement.

The authors performed their experiment in a quantum gas microscope in which a single layer of an optical lattice is generated just below a high-resolution optical microscope. When Islam et al. relaxed some of the optical confining fields, the two copies of the four-atom systems could tunnel into one another and, through quantum interference (the Hong–Ou–Mandel effect), leave a signature of their state in the number of atoms in each lattice site. The authors simply counted the atoms using the microscope and extracted the entanglement entropy (the second-order Rényi entanglement entropy, for those in the know) from the number of atoms. In this way, they show that their four-atom system can have less entropy as a whole than when it is partitioned, something that is not possible without entanglement, nor in any classical system.

As the first measurement of its kind, this is a milestone.

From: Steven Rolston, "Quantum physics: Getting the measure of entanglement," Nature 528 (2015): 48–49. doi:10.1038/528048a.

Image reprinted by permission from Macmillan Publishers Ltd: Nature ©2015.

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*Rajibul Islam, Ruichao Ma, Philipp M. Preiss, M. Eric Tai, Alexander Lukin, Matthew Rispoli & Markus Greiner, "Measuring entanglement entropy in a quantum many-body system," Nature 528 (2015): 77–83. doi:10.1038/nature15750.

The Art of Wayfinding

John Huth

When Huth met Genz at an academic conference in 2012 and described the methodology of his search for the Higgs boson and dark energy—subtracting dominant wave signals from a field, until a much subtler signal appears underneath—Genz told him about the di lep, and it captured Huth's imagination. If it was real, and if it really ran back and forth between islands, its behavior was unknown to physics and would require a supercomputer to model. That a person might be able to sense it bodily amid the cacophony generated by other ocean phenomena was astonishing.

Huth began creating possible di lep simulations in his free time and recruited van Vledder's help. Initially, the most puzzling detail of Genz's translation of Joel's description was his claim that the di lep connected each atoll and island to all 33 others. That would yield 561 paths, far too many for even the most adept wave pilot to memorize. Most of what we know about ocean waves and currents… comes from models that use global wind and bathymetry data to simulate what wave patterns probably look like at a given place and time. Our understanding of wave mechanics, on which those models are based, is wildly incomplete. To improve them, experts must constantly check their assumptions with measurements and observations. Perhaps, Huth and van Vledder thought, there were di leps in every ocean, invisible roads that no one was seeing because they didn't know to look.

From: Kim Tingleymarch, "The secrets of the wave pilots," New York Times, March 17, 2016. http://www.nytimes.com/2016/03/20/magazine/the-secrets-of-the-wave-pilots.html.

Image courtesy: John Huth.

A Metal that Behaves Like Fluid

Philip Kim

Making graphene is simple enough, all that's needed is a piece of adhesive tape to peel graphite crystals over and over down to a single layer. But because the end product is only one atom thick, studying the properties of graphene in isolation has not been nearly as easy.

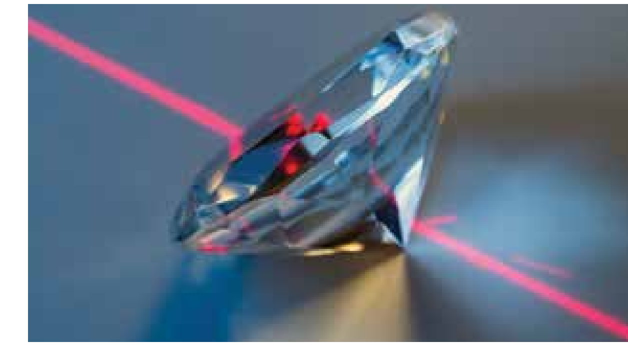
Researchers led by Prof. Philip Kim have now found a way to isolate high-purity graphene and have used it to discover yet another remarkable property of this wonder-material. For the first time in a metal, scientists have found that the charge-carrying particles in graphene behave as a fluid, where, rather than avoiding each other, particles collide trillions of times a second.

Kim and colleagues first isolated a sample of pure graphene by protecting it between layers of hexagonal boron nitride, an insulating, transparent crystal also known as "white graphene" for its similar properties and atomic structure. The scientists then covered the (still exposed) ends of the graphene sheet with charged particles and observed how charge flowed as they applied both thermal and electric currents.

When most materials are subjected to an electric field, their negatively charged electrons and positively charged "electron holes" are driven in opposite directions; by contrast, a difference in temperature causes both types of charges to move in the same direction. In either case, the charged particles hardly ever interact with each other.

From: Dario Borghino, "Liquid-like graphene could be the key to understanding black holes," gizmag.com February 15, 2016. http://www.gizmag.com/liquid-graphene-dirac-fluid/41801.

Image courtesy: Peter Allen/Harvard SEAS.



NMR Detection and Spectroscopy of Single Proteins Using Quantum Logic

Mikhail Lukin

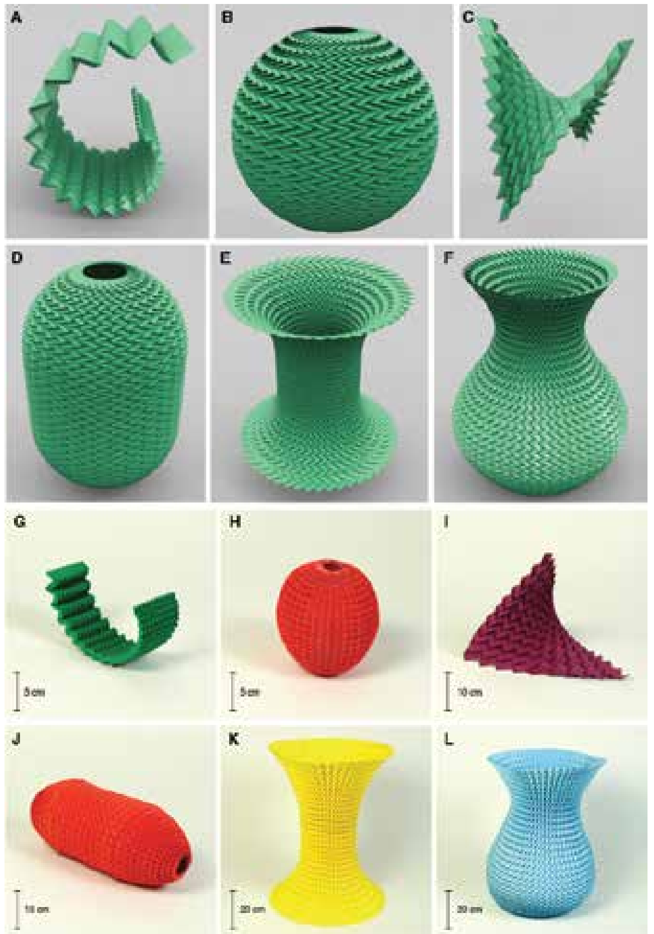
Zero-field NMR [Nuclear Magnetic Resonance] has recently been developed to make NMR spectroscopy less difficult and less expensive. Instead of studying the coupling of the nuclei to an external field, the technique records the molecular fingerprint created when neighbouring magnetic moments couple to one another. This in itself does not increase the sensitivity of the technique, but in 2013, two independent groups—one led by Wrachtrup—showed that a single nitrogen vacancy (NV) centre in diamond can detect a zero-field NMR signal from a tiny sample containing as few as 10,000 nuclear magnetic moments. A NV centre occurs when two adjacent carbon atoms in a diamond lattice are replaced with a vacancy and a nitrogen atom. NV centres are essentially tiny magnets that are isolated from their surroundings and can be manipulated using laser pulses.

In 2014, Mikhail Lukin and colleagues at Harvard University used NV centres to detect the magnetic moment of a single proton on the surface of a diamond. However, nobody had been able to detect the NMR signal from just one biomolecule.

Now, Lukin's Harvard group has joined forces with Fedor Jelezko and colleagues at Ulm University in Germany to make two key innovations to the NV technique. First, they improved the sensitivity of the NV sensor by locating it as close as possible to the surface of the diamond. Previous research had suggested that the closer the NV centre is to the surface, the more prone it is to having its quantum coherence degraded by external noise. "But we found that, by controlling the surface very carefully, we could dramatically improve its coherence."

From: Tim Wogan, "Diamond defects and quantum logic give NMR a boost," Physics World, February 4, 2016. http://physicsworld.com/cws/article/news/2016/feb/04/diamond-defects-and-quantum-logic-give-nmr-a-boost

Image courtesy: iStock/villorejo.



Programming Curvature Using Origami Tessellations

L. Mahadevan

What if you could make any object out of a flat sheet of paper?

That future is on the horizon thanks to new research by L. Mahadevan, the Lola England de Valpine Professor of Applied Mathematics, Organismic and Evolutionary Biology, and Physics at the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS). […]

Mahadevan and his team have characterized a fundamental origami fold, or tessellation, that could be used as a building block to create almost any three-dimensional shape, from nanostructures to buildings. The research is published in *Nature Materials*.

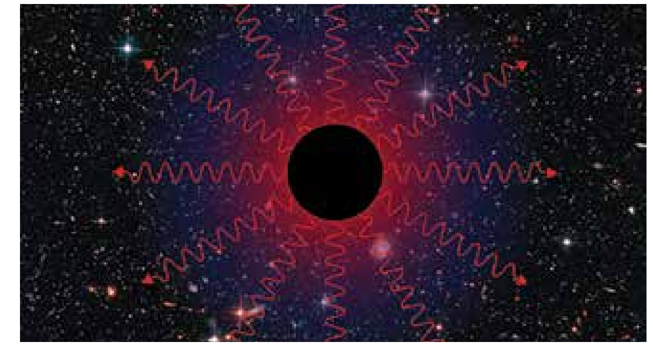
The folding pattern, known as the Miura-ori, is a periodic way to tile the plane using the simplest mountain-valley fold in origami. It was used as a decorative item in clothing at least as long ago as the 15th century. A folded Miura can be packed into a flat, compact shape and unfolded in one continuous motion, making it ideal for packing rigid structures like solar panels. It also occurs in nature in a variety of situations, such as in insect wings and certain leaves.

"Could this simple folding pattern serve as a template for more complicated shapes, such as saddles, spheres, cylinders, and helices?" asked Mahadevan.

"We found an incredible amount of flexibility hidden inside the geometry of the Miura-ori," said Levi Dudte, graduate student in the Mahadevan lab and first author of the paper. "As it turns out, this fold is capable of creating many more shapes than we imagined."

From: Leah Burrows, "Designing a Pop-Up Future," Science Newsline, January 27, 2016. http://www.sciencenewsline.com/news/2016012701290026.html

Image courtesy: Mahadevan Lab.



Soft Hair on Black Holes

Andrew Strominger

By the late 1990s, other developments in physics, most notably in string theory, convinced most researchers that all the information that falls into a black hole must come out when the black hole evaporates. How this might happen is still unclear. But one can start with a simpler question: What is wrong in Hawking's original argument that information must be lost? The paper by Hawking, Perry, and Strominger provides a possible answer. They point out problems with two underlying assumptions that originally led Hawking to his conclusion. The first is that the vacuum in quantum gravity (the quantum state with the lowest possible energy) is unique, and the second is that black holes have no hair. Instead, they argue that there is an infinite family of degenerate vacua in the quantum theory, and that black holes can carry what the authors call "soft hair"—quantum hair associated with very-low-energy quanta.

Strominger had an important insight in 2014 while investigating a different problem. He realized that there are an infinite number of conservation laws that govern the scattering of gravitons—the elementary excitations in a quantum theory of gravity. Working with his students, Strominger realized soon thereafter that a similar result holds for electromagnetism. Currently, he is collaborating with Hawking and Perry to apply this insight to black holes. In the new paper, the authors illustrate their ideas by considering electromagnetism in the presence of a black hole.

The key to their argument about black hole hair is provided by new conservation laws that generalize the usual notion of conservation of electric charge.

From: Gary T. Horowitz, "Black Holes Have Soft Quantum Hair," Physics 9, 62 (2016) DOI: 10.1103/Physics.9.62.

Image courtesy: APS/Alan Stonebraker

Unveiling Jupiter's mysteries

Isaac Silvera

One of the biggest mysteries surrounding Jupiter is how it generates its powerful magnetic field, the strongest in the solar system.

One theory is that about halfway to Jupiter's core, the pressures and temperatures become so intense that the hydrogen that makes up 90 percent of the planet - molecular gas on Earth—loses hold of its electrons and begins behaving like a liquid metal. Oceans of liquid metallic hydrogen surrounding Jupiter's core would explain its powerful magnetic field.

But how and when does this transition from gas to liquid metal occur? How does it behave? Researchers hope that Juno will shed some light on this exotic state of hydrogen—but one doesn't need to travel all the way to Jupiter to study it.

Four hundred million miles away, in a small, windowless room in the basement of Lyman Laboratory on Oxford Street in Cambridge, Massachusetts, there was, for a fraction of a fraction of a second, a small piece of Jupiter.

Earlier this year, in an experiment about five-feet long, Harvard University researchers say they observed evidence of the abrupt transition of hydrogen from liquid insulator to liquid metal. It is one of the first times such a transition has ever been observed in any experiment....

In the experiment, Zaghoo, Ashkan Salamat, and senior author Isaac Silvera, the Thomas D. Cabot Professor of the Natural Sciences, recreated the extreme pressures and temperatures of Jupiter by squeezing a sample of hydrogen between two diamond tips, about 100 microns wide, and firing short bursts of lasers of increasing intensity to raise the temperature."

From: Leah Burrows, "Spacecraft Juno nears planet orbit, but Harvard team may already have predicted part of what it will find," phys.org, June 30, 2016. http://phys.org/news/2016-06-spacecraft-juno-nears-planet-orbit.html#jCp.

Image courtesy: Mohamed Zaghoo/Harvard SEAS

Celebrating Staff

A Career in Giving: Jan Ragusa

The Department celebrated, with considerable sadness, the retirement of Janet (Jan) Ragusa, in January 2016. Having rounded out more than a quarter century with the Department, she was the sole and steadfast support for Professor Gabrielse, both having arrived at Harvard Physics at the same time. Jan also worked with Prof. Doyle and his group, and with several other professors over the years—always with a marked consistency and kindliness. Jan was an extremely conscientious worker who supported her professors and their groups with diligence and care. For many years, her faithful companion, Isaac, a pug, accompanied her to work each day and brought a smile to the face and heart of many a student, post-doc, or colleague. While we miss Jan dearly, we are so happy to hear she is loving her retirement with dog-filled days and her passion for hiking.

Jan Ragusa retires after 26 years with the Department.

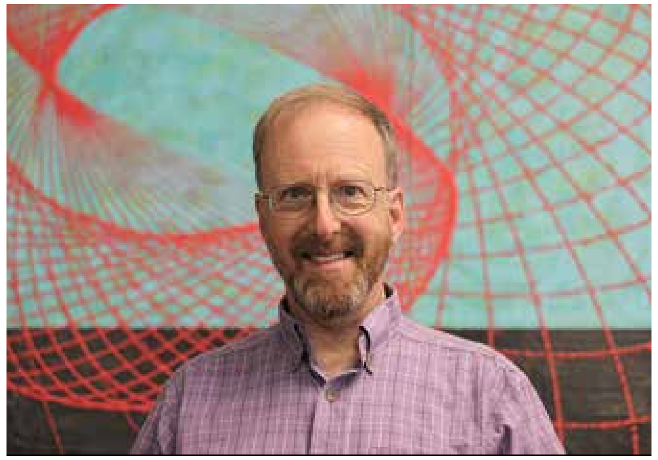
Innovation and Initiative: Robert Hart

The Department was delighted to have Rob Hart selected as a recipient of the Dean's Distinction award, which honors the Faculty of Arts and Sciences staff members whose contributions, citizenship, and skillful collaborations deliver outstanding results for the FAS.

Rob's nomination excerpted below heralds his singular creativity, initiative, and innovation.

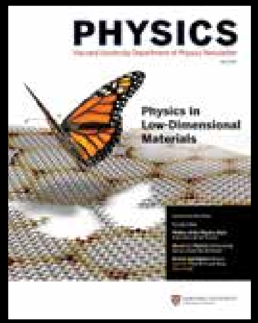
Rob's primary job is to support laboratory-based teaching in the Physics Department. His contributions in enhancing our core mission and in expanding our horizons have been remarkable. Rob also has shown tremendous initiative in developing a new course offering at Harvard. For years, MIT has offered a fabrication course, which Rob took a few years ago. It so inspired him that he has developed and is teaching the laboratory component of the MIT course. Harvard students are excited about the course as it provides an excellent opportunity for them to exchange expertise and build networks with students from different schools. Some students in the course are from the Physics Department and the Harvard John A. Paulson School of Engineering and Applied Sciences, but many are from the Graduate School of Design. There are few opportunities for students to develop expertise in engineering, science, and design, but Rob's course offers exactly that experience. Rob not only supports the work of the Physics Department, but also broadens connections between the arts and the sciences, offering Harvard students an invaluable educational experience that will enable them to lead innovation in the coming decades.

Nominated by: Masahiro Morii and Mara Prentiss



Rob Hart receives the Dean's Distinction Award.

Letters from our Readers



WE THOROUGHLY ENJOYED HEARING FROM OUR READERS. HERE IS WHAT SEVERAL HAD TO SAY:

"Just writing to say I love getting the Physics newsletter/magazine. I ended up starting a clean energy company after college, and while my firm (Carbon Lighthouse, if you are curious) does a lot of great engineering I sadly no longer get to engage technically. The physics magazine goes into the perfect amount of detail to re-engage the math side of my brain."

BRENDEN MILLSTEIN
AB '06

"I was especially grateful for your "Story from the History of the Physics

Department: Ed Purcell's Early Days." In my grad student days I admired Purcell as some sort of giant and still do. His lucid Physics 33, Introduction to Quantum Theory (1946), has served me well.

Purcell's contemporaries, named in the article as other interviewees —Bainbridge, Bloemergen, Kemble, Ramsey, Street, Van Vleck, and Wilson—are magic to me and names to conjure with. In fact, Kemble was the first one to greet me as a new grad student in 1942.

Thank you for that vignette. Please publish more interviews."

JOHN M. RICHARDSON
MA '47, PHD '51

"Enjoyed the newsletter much. Thank you. I particularly enjoyed the interview with Prof. Edward Purcell. I had freshman physics from him in 1955—during the semester he was awarded the Nobel Prize. But what I really remember is his very effective and enjoyable teaching methods.

Regarding the weather, in the Fall of 1955, I stayed in Cambridge over Thanksgiving weekend, and I remember sitting in the dining hall and watching the first snow come down."

ARNOLD ROMBERG
AB '55, SM '58

"I very much enjoyed reading your Fall 2015 edition of your Department of Physics Newsletter."

MARIAN HEINEMAN ROSE
PHD '47

"Thank you for sending the Fall 2015 Issue of the Newsletter. It is spectacularly beautiful, and I enjoyed reading it very much. More articles concerning the history of the Department would be greatly appreciated, especially by those of us old enough to remember Bainbridge, Bloembergen, Coleman, Glashow, Kemble, Martin, Purcell, Ramsey, Street, Tinkham, Van Vleck, and Wilson, not to mention Furry, Schwinger, Glauber, Pipkin, and Strauch (and, of course, Gerry Holton!)."

BRIAN SALZBERG
PHD '72

"Thank you so much for the alumni newsletter, particularly the article about Edward Purcell. I took Physics 12b in the spring of 1974 and I still remember the thrill of Professor Purcell's lectures showing how the Lorentz transformation, applied to a current-carrying wire, led to the existence of a magnetic field."

DAVID SCHREIBER
AB '77

"I read with interest both the Fall 2014 and Fall 2015 Physics Newsletters since, with regard to the 2014 issue, I am probing, theoretically, the Universe's later moments, and with regard to the 2015 issue, I was delighted to read excerpts from Prof. Holton's interview with Ed Purcell. I took Ed's course in Electron Physics in the summer semester of 1947 and I learned a lot from it."

FRANK R. TANGHERLINI
SB '48

HARVARD UNIVERSITY
Department of Physics

17 Oxford Street
Cambridge, MA 02138

Departmental Events

The Morris Loeb Lecture in Physics

October 31 – November 3, 2016

Ali Yazdani
Class of 1909 Professor of Physics, Director of the Princeton Center for Complex Materials, Princeton University

Physics Monday Colloquium

Our weekly colloquia with a single invited speaker are held at 4:15PM in Jefferson 250, preceded by an all community tea at 3:30PM in the Jefferson Research Library.

If you are ever in town, we would be delighted for you to join us. Drop in or email us at: colloquium@physics.harvard.edu

To watch past Colloquia, go to the Monday Colloquium Archive at: https://www.physics.harvard.edu/events/colloq_archive

For a listing of upcoming Monday Colloquia and other seminars and events in the department, check out our Calendar webpage: https://www.physics.harvard.edu/events/gencal

Science Research Public Lecture Series

Dates and speakers to be announced

Please check here: https://www.physics.harvard.edu/events/science_lectures

Lectures are held at 7pm at the Harvard Science Center, One Oxford Street, Cambridge, MA

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

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