PHYSICS

Harvard University Department of Physics Newsletter

Fall 2026



MIKHAIL LUKIN:
Indomitable Explorer of the Quantum Domain

also in this issue:

- Nicolaas Bloembergen: Invention of the Solid-State Maser
- Quantum Machines, From Atoms to Algorithms
- Leinweber Institute for Theoretical Physics
- Friends of the Harvard Physics Department

and much more

HARVARD UNIVERSITY
Department of Physics

Contents

LETTER FROM THE CHAIR 1

FACULTY HIGHLIGHTS

Promotions: Carlos Argüelles-Delgado 2

Promotions: Matteo Mitrano 4

Faculty Prizes, Awards, and Acknowledgments 5

COVER STORY

Mikhail Lukin: Indomitable Explorer of the Quantum Domain 6

HISTORICAL FOCUS

Nicolaas Bloembergen: Invention of the Solid-State Maser 20

FEATURED

Quantum Machines, From Atoms to Algorithms 32

New Institute to Strengthen Fundamental Physics Research, Collaboration 38

Friends of the Harvard Physics Department 40

ACADEMIC PROGRAMS

Undergraduate Program 42

Graduate Program 46

Research Scholars 52

Farewell from Bonnie Currier 53

ALUMNI NOTES 54

STAFF NEWS: Meet Virginia Davis 60

ON THE COVER

Photo of Professor Mikhail Lukin by Niles Singer / Harvard Staff Photographer

ACKNOWLEDGMENTS

Newsletter Committee:

Professor Aravinthan Samuel (Chair)
Despina Bokios
Professor Jordan Cotler
Professor Paul Horowitz
Dr. David Morin
Dr. Sonia Paban

Editor:

Marina Werbeloff

Letter from the Chair



Dear Friends and Colleagues,

Welcome to the Fall 2026 issue of the Harvard Physics Department Newsletter, my first as department chair.

Our cover story focuses on Mikhail Lukin, Joshua and Beth Friedman University Professor, and his research group. From early experiments in stopping light to recent work on neutral-atom quantum computers, quantum error correction, and long-distance quantum networks, Lukin has long pursued bold ideas at the boundary between theory and experiment. Equally important, the story recognizes the many students, postdocs, faculty colleagues, and staff whose expertise and dedication make this progress possible.

The historical article by Paul Horowitz, Professor of Physics and of Electrical Engineering, Emeritus, describes an earlier landmark achievement of our atomic, molecular, and optical physics community: the invention of the solid-state maser by Nicolaas Bloembergen, a Harvard faculty member from 1951 to 1990 and co-recipient of the 1981 Nobel Prize in Physics.

We celebrate the promotions of Carlos Argüelles-Delgado and Matteo Mitrano from Assistant Professor to Associate Professor. Their research exemplifies our department's strengths, from high-energy neutrinos to the control of quantum materials with light. Our Academic Programs section highlights the many achievements of our students, from undergraduate research and mentorship programs to graduate prizes, fellowships, and dissertations spanning the full range of modern physics. Our young people are the foundation of our future.

Today, artificial intelligence and quantum computation are energizing physics research, from experiment to theory. Our department is at the forefront of both fields. We will cover Harvard's AI advances in our next issue. In this issue, you can read about recent quantum computing efforts in "Quantum Machines, From Atoms to Algorithms," by one of our newest faculty members, Jordan Cotler, Assistant Professor of Physics. Jordan describes how researchers across fields are working together to build, protect, connect, and use quantum systems, demonstrating how many important discoveries emerge at the intersections of disciplines.

We also celebrate new initiatives that are strengthening our department during a challenging time. The Leinweber Institute for Theoretical Physics, supported by a $20 million gift from the Leinweber Foundation, will strengthen fundamental research, support emerging scholars, and promote collaboration with other Leinweber Institutes across the country. We are also growing our Friends of the Harvard Physics Department community, creating new opportunities for alumni and friends to reconnect with our research, students, and laboratories. You can read about both initiatives in this issue.

As many of you know, this is also a difficult time for our department and for the Harvard Faculty of Arts and Sciences. Financial instability and the resulting FAS reorganization have led to the loss of some key members of our staff. Many of them faced unwelcome uncertainty and stress over the past year, and some careers were painfully shortened. Those who have given so much to Harvard deserved more consideration. This issue is dedicated to them, with gratitude for their many contributions to our department.

As we look ahead, I am confident that everyone in our department — staff, students, and scientists — will continue to draw on its resilience, creativity, and hard work to advance knowledge while nurturing and protecting the community that makes discovery possible.

Warm regards,

Aravinthan Samuel

Professor of Physics and Chair of the Department of Physics



Faculty Promotions:

CARLOS ARGÜELLES-DELGADO

The Department of Physics is excited to share the promotion of Carlos Argüelles-Delgado to the position of Associate Professor.

Professor Carlos Argüelles-Delgado earned his Ph.D. at the University of Wisconsin–Madison under Francis Halzen, recipient of the 2026 Nobel Prize in Physics for discovering high-energy astrophysical neutrinos at IceCube, the South Pole neutrino observatory. Today, Argüelles and his research group build on that foundation to uncover the nature of neutrino masses and use high-energy neutrinos as a probe of new physics. He and his group pursue these questions through several research projects that draw on data from the IceCube Neutrino Observatory and KM3NeT (The Cubic Kilometre Neutrino Telescope in the Mediterranean) while also building TAMBO (Tau Air-shower Mountain-Based Observatory), the next-generation neutrino telescope in the Peruvian Andes.

Many models that aim to explain the origin of neutrino masses rely on the introduction of new, heavy neutrino species. The group is currently searching for a "smoking gun" signature such particles would leave in IceCube data: two spatially separated light depositions from a single event. They are also exploring neutrino oscillations across extremely long baselines, where neutrinos act as extremely sensitive interferometers.

This work includes two ongoing analyses of IceCube data. The first is a search for unexpected flavor transitions of galactic neutrinos, with sensitivity to mass differences as small as 10^{-7} eV, probing the potential hyperfine neutrino mass structure. The second applies new machine learning methods to identify high-energy, astrophysical tau neutrinos, increasing the available sample size and thus improving the characterization of the tau neutrino spectrum. This spectrum is key to testing neutrino oscillations at cosmic scales, since tau neutrinos are only expected to arise from neutrino flavor changes.

Atmospheric neutrinos, detected in large numbers by IceCube, provide a unique tool for precision testing of particle physics. By analyzing the coherent length of atmospheric neutrinos, the Argüelles group has been able to place the strongest constraint to date on quantum decoherence of neutrinos. The group also searches for rare neutrino processes where neutrinos produce di-muons in neutrino-nucleon interactions, probing the strange content of the proton in new regimes. And finally, it has used IceCube's data to produce the most precise measurement yet of Earth's mass using only the weak force, offering a window into our planet's otherwise unreachable interior. Using the KM3NeT data, the Argüelles group also worked on the data analysis of the highest-energy neutrino ever observed, pushing the boundaries of ultra-high-energy neutrino astrophysics.

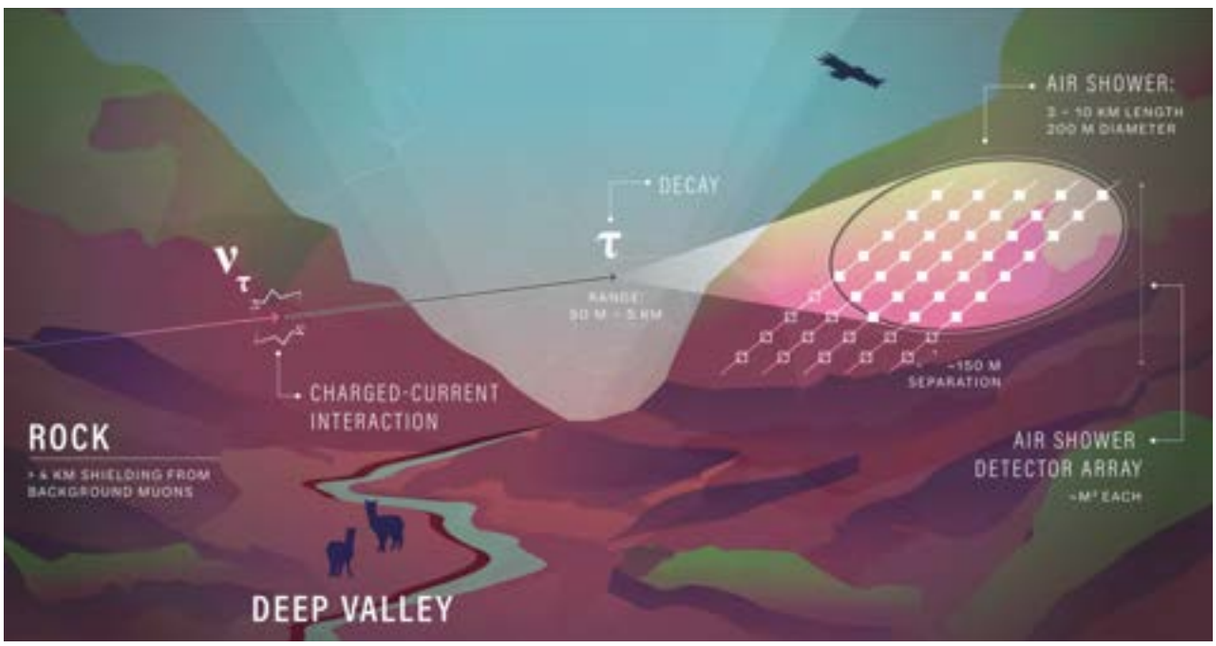
Much of the research of the Argüelles group is conducted within the framework of large international projects. The team works closely with peers across the IceCube, KM3NeT, and TAMBO collaborations, each of which brings together hundreds of scientists worldwide. Closer to home, Argüelles is an active member of the IAIFI (Institute for Artificial Intelligence and Fundamental Interactions) community in the Boston area and maintains an ongoing collaboration with Professor Janet Conrad at MIT.

This body of work has been recognized through multiple major awards in recent years, such as Packard Fellowship for Science and Engineering, Cottrell Scholar Award, TAMBO grant from the John Templeton Foundation, Dean's Competitive Fund for Promising Scholarship, National Academy of Sciences Frontiers of Science Fellowship, and many others.

Teaching innovation is an area of interest for Argüelles, particularly the use of artificial intelligence in the classroom. Together with Dr. Louis Deslauriers, he has deployed AI tools that gather real-time feedback from students in large classes to allow effective and timely instructor intervention.

Beyond the lab and classroom, the Argüelles group is invested in science outreach. For the past three years, it has hosted a summer program for low-income, first-generation students from the Four Corners region. Now in its third year, with two more years already planned, the program has been particularly rewarding and meaningful, as it reaches students who wouldn't normally get an opportunity to get involved in cutting-edge research. Another highly successful initiative the group has developed is an IceCube Master Class: a one-day event in which high school students learn about neutrino physics and work through exercises alongside the group's students.

For the foreseeable future, Argüelles plans to continue using IceCube data to probe the nature of neutrino masses, while incorporating new data from KM3NeT, which has improved particle identification capabilities. A major long-term goal is TAMBO, an interdisciplinary project to construct the world's first mountain-based neutrino telescope.[1] Unlike traditional water- or ice-based detectors, mountain-based telescopes offer easier deployment, lower costs, and a large aperture at higher energies, potentially opening a new chapter in high-energy neutrino physics.



Visual overview of TAMBO's neutrino detection concept. [Creative Commons Attribution 4.0 International]

1. See the recently published paper: TAMBO collaboration, "Measuring the high-energy neutrino sky using the deep-valley neutrino observatory TAMBO," *Nature Astronomy* 10 (2026). https://doi.org/10.1038/s41550-026-02916-4.



Faculty Promotions:

MATTEO MITRANO

The Department of Physics is delighted to announce the promotion of Matteo Mitrano to the position of Associate Professor.

Mitrano's lab investigates how light can manipulate quantum materials and drive them into states far from equilibrium. The team combines ultrafast optical techniques with time-resolved X-ray spectroscopy to probe and control the microscopic interactions, collective excitations, and quantum correlations of strongly interacting electron systems. In particular, Mitrano has pioneered time-resolved resonant inelastic X-ray scattering (RIXS) at X-ray free-electron lasers and has contributed to building this capability at several major facilities, such as qRIXS at the LCLS-II Accelerator in the United States, hRIXS at the European XFEL in Germany, and the Furka Experimental Station in Switzerland. Over the past six years, he and his collaborators have carried out roughly 50 experiments at facilities worldwide, alongside an active experimental program at Harvard.

One central direction of the Mitrano group's work is Hamiltonian engineering: namely, using optical fields to transiently amplify, suppress, or activate specific interactions that determine a material's properties. In a 2025 *Nature Materials* paper,[1] Mitrano and colleagues described using this approach to uncover a dynamical phenomenon they named "symmetry-protected electronic metastability." The key idea is that an optical field allows electrons to tunnel through a pathway that is forbidden by symmetry at equilibrium, transferring charge between different parts of the material and leaving the system trapped in a long-lived state after the field has disappeared. The result established a mechanism for stabilizing nonequilibrium states through purely electronic interactions and suggested strategies for designing metastable states without sustained illumination.

A second major research direction brings concepts from quantum control into strongly correlated solids. Mitrano's goal is to move beyond controlling macroscopic material properties and selectively manipulate the wavefunctions of specific many-body excitations. In a 2026 *Nature Materials* paper,[2] his group demonstrated coherent rotations of a Hubbard exciton wavefunction in a one-dimensional Mott insulator. An intense mid-infrared field continuously rotated the excitation between bright and dark configurations, achieving rotations up to $\pi/2$, a basic operation underlying more sophisticated quantum control protocols. The team is now developing programmable mid-infrared and terahertz pulse sequences to implement controlled sequences of rotations and free evolution, and to investigate many-body excitons as sensors of microscopic interactions, electric fields, chemical potentials, and dielectric environments.

Finally, an emerging research frontier at the Mitrano lab tackles fractionalized quantum liquids and the generation of macroscopic quantum coherence. These are highly entangled states in which an electron can separate into independent spin and charge excitations. In quantum spin liquids, the resulting charge excitations can have bosonic character while remaining localized in the equilibrium insulating state, raising the possibility that they can be mobilized and condensed into a coherent state. Together with Herchel Smith Professor of Physics Subir Sachdev and collaborators, the group recently explored this idea in an organic quantum spin liquid system and observed a transient superconducting-like response after optical excitation. Its strength tracks the equilibrium population of fractionalized spin excitations, consistent with the light-

1. H. Padma, F. Glerean, S.F.R. TenHuisen, Z. Shen, H. Wang, L. Xu, J. D. Elliott, et al., "Symmetry-protected electronic metastability in an optically driven cuprate ladder," *Nature Materials* 24 (2025), https://doi.org/10.1038/s41563-025-02254-2.

2. D.R. Baykusheva, D. Carmichael, C.S. Weber, I.-T. Lu, F. Glerean, T. Meng, P. B. M. De Oliveira, et al., "Quantum control of Hubbard excitons," *Nature Materials* 25 (2026), https://doi.org/10.1038/s41563-026-02517-6.

induced condensation of fractionalized charge carriers. This work, currently under review, identifies electron fractionalization as a possible microscopic route to macroscopic quantum coherence and motivates a broader search for optically controlled coherent states in frustrated and strongly correlated materials.

Mitrano's work has been recognized with a 2026 Alfred P. Sloan Research Fellowship, a 2025 Mercator Fellowship of the German Research Foundation, and the 2024 IUPAP C10 Early Career Scientist Prize in the Structure and Dynamics of Condensed Matter. His program is primarily supported through an Early Career Award by the U.S. Department of Energy and has recently received additional support from the Julian Schwinger Foundation. At Harvard, in addition to the ongoing partnership with Sachdev, his group is now collaborating with Professor of Physics and Applied Physics Philip Kim on THz microscopy of superconducting devices and cavity quantum materials.

Teaching and mentoring are closely connected to Mitrano's research. In Harvard's Advanced Laboratory course (Physics 191/247), he developed an undergraduate ultrafast pump-probe experiment that allows students to measure femtosecond lattice dynamics in real materials. The experiment was subsequently published in the *American Journal of Physics*, with an undergraduate researcher as lead author.[3]

Since arriving at Harvard, Mitrano has supervised 28 young researchers, including undergraduates, graduate students, and postdoctoral fellows. His former postdocs have gone on to faculty and scientific staff positions at the Institute of Science and Technology Austria, Case Western Reserve University, and Brookhaven National Laboratory, and his first Ph.D. student graduated in the spring of 2026. He also serves as Chair of the Scientific Advisory Committee of the Linac Coherent Light Source (LCLS) at SLAC, appointed in 2025 for a three-year term.

Looking ahead, Mitrano plans to pursue several directions at the intersection of ultrafast spectroscopy, quantum materials, and quantum control. These include the study of metastable and light-induced superconducting states, the development of time-resolved RIXS methods to probe many-body entanglement, programmable optical control of correlated excitons, and terahertz microscopy of superconductors coupled to cavities.

3. N.J. Brennan, J. Peidle, A. Wang-Holtzen, J. Fang, K. Ledbetter, and M. Mitrano, "Probing coherent phonons in the advanced undergraduate laboratory," *American Journal of Physics* 92 (2024).

Faculty Prizes, Awards, and Acknowledgments*

R. ABRAMSON AWARD FOR EXCELLENCE IN UNDERGRADUATE TEACHING:
Julia Mundy

JOHN STEWART BELL PRIZE:
Mikhail Lukin

BROWN INVESTIGATOR AWARD:
Kang-Kuen Ni

CLARIVATE ANALYTICS HIGHLY CITED RESEARCHERS 2025:
Michael Brenner, Douglas Finkbeiner, Markus Greiner, Efthimios Kaxiras, Philip Kim, Mikhail Lukin, Hongkun Park, Andrew Strominger, Ashvin Vishwanath, David Weitz, Suyang Xu, and Xiaowei Zhuang

DICKSON PRIZE IN MEDICINE:
Xiaowei Zhuang

ICTP DIRAC MEDAL:
Haim Sompolinsky

SUZANNE EATON PHYSICS OF LIFE AWARD:
L. Mahadevan

LARKIN JUNIOR RESEARCHER AWARD:
Eslam Khalaf

MCKNIGHT SCHOLAR:
Sue-Yeon Chung

NATIONAL ACADEMY OF SCIENCES:
L. Mahadevan

NSF FRONTIERS OF SCIENCE FELLOWSHIP:
Carlos Argüelles-Delgado

OUTSTANDING YOUNG RESEARCHER AWARD (OYRA) ARDENTEC PRIZE:
Norman Yao

RESEARCH CORPORATION FOR SCIENCE ADVANCEMENT (RCSA) BRIDGE AWARD:
Carlos Argüelles-Delgado

SLOAN RESEARCH FELLOWS:
Eslam Khalaf, Matteo Mitrano

STAR-FRIEDMAN CHALLENGE FOR PROMISING SCIENTIFIC RESEARCH:
Xing Fan

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

COVER STORY

MIKHAIL LUKIN:

INDOMITABLE EXPLORER of the QUANTUM DOMAIN



By Steve Nadis

Photograph by Niles Singer / Harvard Staff Photographer

There is a curious tension at the heart of quantum mechanics: Macroscopic objects are composed of atoms and smaller particles that, individually, are subject to the dictates of this strange, counterintuitive branch of physics where "spooky action at a distance" reigns, and – contrary to some well-known protestations – God does indeed play dice with the universe. Nevertheless, large-scale objects as a whole, despite their minute constituents, betray no signs of quantum behavior. Mikhail ("Misha") Lukin, the Joshua and Beth Friedman University Professor in Harvard's Department of Physics, has long been intrigued by this curious dichotomy. And though his body, itself, cannot interact directly with the quantum realm, Lukin's mind is free to visit it whenever he so chooses. That happens quite often, fortunately, and the world of humans has learned a lot about the world of quanta thanks to his frequent intellectual forays into this subatomic space.

His illustrious career – as a member of the National Academy of Sciences and the winner of prestigious awards from the American Physical Society, the Optical Society of America, and other organizations – might not have happened if Lukin had realized his youthful ambitions of becoming a documentary filmmaker. He grew up in the Soviet Union and spent much of his free time, from the ages of 9 to 15, in a Moscow studio set up to familiarize young people with various aspects of filmmaking.

His parents, both of whom were scientists, didn't consider movies, documentary or otherwise, to be the loftiest goal their son could aspire to. They told him he could do anything he wanted in life, but he first must get an education. "And by their standard," Lukin recalls, "that meant studying physics or, in the worst case, mathematics – subjects I wasn't really excited about at the time."

That attitude changed during his last year of high school, as he started attending physics classes outside of his school given by "an amazing teacher" named Victor Chivilev, whom Lukin found to be so inspirational that he decided to study physics after all. He entered the Moscow Institute of Physics and Technology in 1988, which he describes as "the Soviet version of MIT." A few years later, the Soviet Union collapsed, which cast considerable doubt on the future of science but also created an opportunity that didn't exist before – namely, the option of attending graduate school abroad.

At a conference in Moscow, Lukin met the physicist Marlan Scully, who encouraged him to pursue a Ph.D. at Texas A&M University. Lukin took him up on that offer. He knew nothing about Texas before meeting Scully (a part-time cattle rancher known as "the Quantum Cowboy"), but he ventured to the Lone Star State in 1993 and immersed himself in the field of quantum optics – the study of how atoms and subatomic particles interact with light at the quantum level.

In the middle of Lukin's graduate research, Scully, a theoretical physicist, asked him to build his own experiment, realizing that it would entail a lot of effort to find an experimentalist willing to take on the ideas they were exploring. In general, it is rare for physicists to engage in both theory and experiment, but Lukin relished the chance, and he has continued to work on both sides of the proverbial divide ever since. And in the intervening years, the blending of these two branches of the field has become much more common.

Lukin earned his Ph.D. in 1998 and began postdoctoral work later that year at the Institute for Theoretical Atomic, Molecular and Optical Physics (ITAMP) at the Harvard-Smithsonian Center for Astrophysics (CFA). "The 'T' in ITAMP suggested that I was supposed to do theory," Lukin says. "But a year into my postdoc, my colleagues and I came up with an idea for an experiment and discussed it with a CFA staff scientist, Ron Walsworth,[1] and we realized it could be implemented with some very simple tools, similar to those that I used in Texas." In January 2001, that work, together with an independent experiment carried out by Professor Lene Hau's group at Harvard, ended up on the front page of the *New York Times*.[2]

The idea at the core of this work had a somewhat unusual origin. In the spring of 1999, Lukin received an invitation to attend a 60th birthday celebration for Scully, which was to be held in June at the Max Planck Institute for Quantum Optics in Garching, Germany. Lukin couldn't attend the event because he didn't have a visa to travel to Germany. Another of Scully's former students – Susanne Yelin, now Professor of Physics in Residence at Harvard who was then at the CFA too – couldn't attend the festivities either. As his former students, Lukin and Yelin were asked to contribute to the colloquium proceedings that would include the lectures and other miscellaneous reflections on Scully. Since they were not able to travel, they decided to at least

1. Ronald Walsworth is now Minta Martin Professor and Founding Director of the Quantum Technology Center at the University of Maryland.
2. James Glanz, "Scientists Bring Light to Full Stop, Hold It, Then Send It on Its Way," *New York Times*, Jan. 18, 2001.



Alexandra Geim and Mikhail Lukin [Photo by Paul Horowitz]

try to make "some kind of interesting contribution" to that book. They achieved that modest goal and then some.

On the weekend before the deadline for submissions to the Scully volume – published a year later under the title, Ode to a Quantum Physicist – Lukin, Yelin (who later became his wife), and Michael Fleischhauer, a former postdoc of Scully's who was then visiting the CFA, wrote a short paper. An updated version of this work, which was published in the May 1, 2000, edition of *Physical Review Letters*[3] ended up having a big impact. The basic scenario they sketched out went as follows: First you take a pulse of light that is carrying some "quantum state" – related to an individual photon's polarization or wavelength, for instance – and make it collide with a dense cloud of atoms. "That can slow the light down to a complete stop, simultaneously converting the quantum information stored in light to quantum information stored in atoms," Lukin explains.

Up until this point, the idea was strictly theoretical, but Lukin joined forces with Walsworth and three others to demonstrate that the ideas presented in their theory paper could be carried out in practice. They used a container of rubidium gas to stop light in its tracks. Information stored in the photons was transferred to the spin state of rubidium atoms. This result was published in *Physical Review Letter*s on January 29, 2001.[4] At the same time, a paper written by a team led by Hau (now a Mallinckrodt Professor of Physics and of Applied Physics) appeared in *Nature*, announcing very similar results achieved via the same protocol, although Hau and her colleague used a cloud of ultracold sodium Bose condensate atoms (rather than warm rubidium atoms) to bring light to a grinding halt.

That's just part of the theoretical ideas conceived by Lukin and his colleagues around 1999 to 2000. They didn't only describe how information could be transferred from light to atoms, Lukin says. "This work inspired us to start thinking about how one could actually process the information stored in these atoms. And that is how the idea for what has become a leading approach to quantum computing was first developed."

A starting point for this work draws on the notion of exciting atoms with a precisely tuned laser to what are called Rydberg states in which the outermost electron is boosted to a tremendously larger orbit – 100 or more times farther from the nucleus than usual – enabling the atom to interact more strongly with other atoms that can be much farther away than would otherwise be possible. When controlled with finely tuned laser light, those interactions can give rise to quantum entanglement – a close connection between particles whereby the state of one dictates the state of others, and vice versa, regardless of the distance between them.

Entanglement, in turn, is built on a key principle of quantum mechanics called superposition, which holds that a single particle can exist in multiple states at the same time. A simple way to visualize the concept of superposition is through a so-called Bloch sphere, where the north pole represents the 0 state of the atom, and the south pole represents the 1 state of the atom. Every other spot on the sphere represents a combination of 0 and 1, while points along the equator hold an equal superposition of both. These superpositions form the core building blocks of quantum information — the bits of a

3. M. D. Lukin, S. F. Yelin, and M. Fleischhauer, "Entanglement of atomic ensembles by trapping correlated photon states," *Physical Review Letters* 84 (2000), https://doi.org/10.1103/PhysRevLett.84.4232.

4. D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, "Storage of light in atomic vapor," *Physical Review Letters* 86 (2001), https://doi.org/10.1103/PhysRevLett.86.783.

quantum computer called qubits – which can be encoded in neutral atoms, charged atoms (ions), atom-like impurities in solids, or in superconducting circuits. All of these can also occupy superposition states, existing as combinations of 0 and 1 at the same time.

When two particles are entangled, instead of each particle having its own superposition state, both have a superposition state in common. Or as Lukin puts it, "quantum entanglement is basically a quantum superposition that is nonlocal – separated in space and shared between more than one particle." Quantum entanglement and superposition are foundational principles of quantum mechanics that govern interactions between photons, atoms, and electrons in microscopic systems of all sorts. "And in quantum computers – or, more generally – in quantum information systems," Lukin says, "superposition and entanglement are the critical elements that provide the potential for incredible power."

As an illustration of that power, a single quantum computer with a processor containing 300 qubits, according to Lukin, "can, in principle, store and process more information than the number of particles in the entire universe" – estimated at 10^{80} to 10^{90} (or roughly 10^{60} times larger than the World Wide Web, which is estimated to contain about 10^{24} bits of information).

While the theoretical foundations of quantum computing and quantum information emerged, in large part, from the visionary ideas of Richard Feynman in the early 1980s, assembling a machine with that kind of computing power and storage capacity remains a daunting goal, and it might have seemed completely out of reach in 2001 when Lukin became an assistant professor of physics at Harvard. In December of that year, a 7-qubit quantum computer made by IBM carried out the most complex quantum calculation that had been performed up to that point. It involved a quantum algorithm developed by Peter Shor (now a professor at MIT) to determine the factors of the number 15 – a feat more technologically challenging than it might

ALEXANDRA GEIM: A Platform Upon Which Quantum Computing Depends

Alexandra (Sasha) Geim entered the University of Cambridge as an undergraduate knowing that she liked natural sciences. Her interests sharpened over time, as she came to believe that physics lay at "the core of all science," and that "quantum physics is as fundamental as you can get." Geim worked as a research assistant in the Lukin lab from 2022 to 2023 to more fully explore the quantum world. Evidently, she liked what she saw and, in 2023, she officially enrolled as a Ph.D. student.

Part of Geim's work focuses on atom arrays, developing ways to arrange and control hundreds of neutral rubidium atoms so they can be used for quantum computations and for various simulations and experiments. The first step in preparing such an array is to take a cloud of several million atoms, confined within a vacuum chamber, and cool them down with lasers. Cooling occurs when the atom interacts with the photon, and the photon takes away some of the atom's energy. Focused laser beams called optical tweezers are then used to trap a small fraction of the atoms, with the rest of the cloud being allowed to disperse. "You can use these lasers to move the atoms to any position you want," Geim explains, and to selectively perform operations on some of them, such as changing their spin state from 0 (spin down) to 1 (spin up), or vice versa.

It is at this stage, when you're beginning to use the atoms, or qubits, in actual computations that you need to think seriously about error correction, she says, "in order to keep the error rates down to as low as you need them to be."

The error rate for a quantum algorithm should be on the order of one in ten billion or less, and to achieve that goal, the error rate for an individual atomic qubit typically has to be below 1%. Geim was one of two lead authors of a November 2025 *Nature* paper,* which demonstrated that this (below 1%) threshold can be reached in a reconfigurable atom array that holds up to 448 neutral rubidium atoms. That work constituted an important milestone, yet achieving it was in some ways straightforward, she notes. "It's just a matter of keeping your physical errors down at every step of the process."

One form of error, called atom loss, can occur when an atom is inadvertently heated (typically by lasers), gaining enough energy to fly out of the trap. Consequently, a concerted effort is being made to keep these losses to a minimum, which is part of the general objective of keeping error rates low. A related priority, accordingly, is to develop a "readout" capability so that experimenters know when an atom escapes. "But beyond knowing that an error happened somewhere," Geim says, "we'd like to be able to detect where – and on which atom – this error happened." That knowledge, in turn, can provide information that improves the performance of error correction overall.

"We're continuing to develop more sophisticated ways of controlling atoms so that we can manipulate them ever more precisely – doing exactly what we want without making a mistake," Geim says. Rather than just being an end unto itself, error correction is also a means to an end, she adds. "And that end, of course, is always the advancement of science."

* D. Bluvstein, A.A. Geim, S. H. Li, S. J. Evered, J. P. Bonilla Ataides, G. Baranes, A. Gu, et al., "A fault-tolerant neutral-atom architecture for universal quantum computation," *Nature* 649 (2026), https://doi.org/10.1038/s41586-025-09848-5.

SOPHIE LI: Better Chemistry Through Quantum Computing?

Sophie Li, a Ph.D. student in the Lukin lab, grew up in China and moved to Germany when she was 14. She initially got interested in physics through popular science books. As a high school student in Germany, she talked her way onto a field trip for students at a different school, one she was not even enrolled in. That led to a visit to CERN in Geneva, Switzerland – home to the world's biggest and highest-energy particle accelerator in the world. That outing boosted Li's preexisting curiosity about physics to the level of high-energy excitement. She pursued research in experimental physics as an undergraduate at Caltech, and she's continued in that direction since coming to the Lukin lab in 2022 and joining the atom array subgroup. When asked to sum up her work in a dozen words or less, she says: "We trap these atoms, and then we take images of them."

While preparing for an atom array experiment, the first step is to arrange the atoms in a specific geometry, moving them into place with lasers, she says, "and we then boost their energies through a Rydberg excitation so they start interacting with their neighbors. We have to shine very specific laser pulses to get the atoms excited to these high-energy states" in which an electron is kicked out to an orbit that takes it far from the atomic nucleus. If two atoms are close to each other, and one of them gets excited through the Rydberg interaction, then the neighboring one can't get excited in the same way. This is due to a phenomenon called the Rydberg blockade – discovered by her advisor, Mikhail Lukin, and his colleagues in 2000 – which physicists can exploit to create controlled interactions between atoms and qubits. Even if atoms are only interacting with their nearest neighbors, Li says, it is possible to get entanglement to spread across the array – into a checkerboard pattern, for example, in which alternating excited and nonexcited atoms are spread across the array.

In an experiment described in a February 2025 paper in *Nature* (of which Li was one of the lead authors), researchers from Lukin's group and other groups at Harvard and MIT looked at what would happen in an array that was split into two different checkerboard patterns.* In such a configuration, the highest energies – and the points of greatest tension – can be found along the boundaries, Li explains, "and the system will always try to move to a lower energy state."

As an analogy, if a container with oil and vinegar is shaken, you will start off with a lot of small bubbles, but the surface energy can be decreased by forming bigger and bigger bubbles until, eventually, there are just two layers – oil and vinegar. Something similar happened in their checkerboard experiment: Over time, as the spins of individual atoms are gradually flipped, the system moved to a lower energy arrangement in which more and more atoms become part of the same checkerboard pattern.

In yet-to-be-published work, Li and colleagues are using quantum computing to calculate the energy states of large molecules that have complex chemistry. Calculations of this sort are hard to do on classical computers because the computation grows exponentially with the size of the molecule. Li is hopeful that this can prove to be a positive application of quantum computing, helping with the design and synthesis of useful chemical products, because the computational cost in the quantum realm grows linearly – rather than exponentially – with molecular size. "This can potentially lead to applications that are beneficial to society," Li says, "as opposed to advances in cryptography that are often discussed in the context of quantum computing, which may or may not be put to good purposes."

* T. Manovitz, S.H.Li, S. Ebadi, R. Samajdar, A. A. Geim, S. J. Evered, D. Bluvstein, et al., "Quantum coarsening and collective dynamics on a programmable simulator," *Nature* 638 (2025), https://doi.org/10.1038/s41586-024-08353-5.

sound. But in those early days, a quarter-century ago, no one had an inkling as to the kind of problems a 300-qubit device might take on.

Upon joining the Harvard faculty, Lukin knew from the outset that he would like to have an experimental component within his research group. That component has grown substantially, and he now estimates that more than 80% of the work in his group is devoted to experiment. By the time he started at Harvard, some important concepts upon which quantum computing might be based had been developed. But, to him, ideas on their own were not enough. The question that has long motivated his work is a practical one: "How can we actually build these quantum computers?"

Much of the progress made toward this goal, he says, "has been enabled by the ability to fully control systems and devices all the way down to the single-atom level developed within the atomic, molecular, and optical physics community over the past four decades." That is being done today, with an exquisite degree of control, mainly due to the advent of optical tweezers (invented at Bell Labs in 1986), which are sharply focused laser beams that can trap atoms and hold them in place. Once you have a means of immobilizing atoms, keeping them in an organized configuration called an array, and moving them around at will, the atoms can then be made to interact in different ways, sharing information and engaging in what are called quantum logic operations.

Those operations, in turn, serve as the core, sequential steps in executing a quantum algorithm. For example, one operation could be to flip the spin state of an atom or a qubit, where spin-up might stand for 1 and spin-down for 0. A somewhat more involved operation might proceed as follows: If qubit a is in state 0, do nothing to qubit b. But if qubit a is in state 1, flip qubit b regardless of what state it is in.

Operations of this sort become more complicated in an entangled system, Lukin says, "where you want to flip one qubit in a way that depends on the state of another

qubit." The May 2000 theory paper[3] he wrote with Yelin and Fleischhauer proposed that "we can use atoms as a form of quantum memory," he says. "But then to process the information we stored, we need these kinds of logic operations." And with a large number of small steps like this strung together, one following the other, a sophisticated calculation can be carried out.

Two papers in 2000[5] and 2001,[6] which Lukin published with several collaborators, introduced the notion of a Rydberg blockade. "It's actually a very simple idea," Lukin explains. "If you have two atoms that are far apart and you excite them to Rydberg states, both become larger in size, and they start to interact very strongly." But if the atoms are brought closer together, the blockade comes into effect, meaning that you can excite one atom but not its nearest neighbor. Consequently, both atoms can be in a non-excited (0,0) state – or one can be excited, (0,1) or (1,0) – but you never see (1,1). "The 'digital' character of this interaction allows you to perform quantum logic operations in an extremely reliable way," Lukin adds.

A couple of years later, he teamed up with the physicist Vladan Vuletić, who had joined MIT's faculty in 2003, to demonstrate various aspects of the blockade in a series of experiments carried out within the Center for Ultracold Atoms – an NSF research facility jointly operated by Harvard and MIT. Lukin believes that he has benefitted greatly from collaborations with Vuletić and other Harvard and MIT scientists.

In 2014 Lukin and Vuletić joined forces with George Vasmer Leverett Professor of Physics Markus Greiner, another of the world's top experts in the physics of ultracold atoms, to build a Rydberg atom array, an experimental system that has contributed to dramatic advances in quantum computing. Lukin has high praise, in particular, for the Center for Ultracold Atoms, which he says has had "a transformative impact on quantum science and engineering throughout the world, both in terms of the ideas created there but also in training generations of researchers."

Lukin considers the Cambridge-Boston area "a very special place" for doing science owing to the density of topnotch researchers and the ferment of activity they collectively unleash. To him, the Harvard physics department and, more broadly, the Harvard-MIT quantum community, are particularly remarkable. He attributes much of his group's success to the talented postdocs and graduate students he's been fortunate enough to work with – more than 150 to date – who have gone on to leading positions around the world in academia and industry. He says that, sometimes, he finds it hard to believe that "every new generation elevates the science to a completely new level, totally unimaginable just a few years back, and then the following generation comes along and supersedes that." One thing that sets this community apart, in his opinion, is the unbridled collaborative spirit that exists between different groups with different kinds of expertise, which he considers to be "unique in the world."

A case in point, Lukin says, is work that started in the early 2000s with his former graduate students, Lilian Childress (now an associate professor at McGill University) and Jacob Taylor (now at NIST). Together, they explored possible uses, in theory, of so-called nitrogen-vacancy centers for processing quantum information and transmitting it along networks for communications and sensing applications. A nitrogen-vacancy (NV) center consists of a nitrogen atom sitting in a diamond crystal next to an empty spot, or vacancy, that would normally be occupied by a carbon atom. These early theoretical efforts showed promising results, but Childress told him they needed to do some experiments if they wanted other people to take their ideas seriously.

Though her suggestion made sense, acting upon it posed several challenges. First, Lukin notes, they would need exceedingly pure diamond samples which would be hard to come by. And second, they didn't have any lab space available to them for this work. The first problem was solved in 2005 when German colleagues from the University of Stuttgart obtained a sliver of pure diamond from a mine in Siberia and cut it into two pieces, sharing half with the Lukin lab.[7]

As for the second concern, John Doyle – Lukin's colleague and a Henry B. Silsbee Professor of Physics – generously offered some of his lab space in the basement of the Lyman Laboratory. Lukin later learned that this was the same room that, in 1960, Norman Ramsey and his then graduate student Daniel Kleppner used to create the first atomic hydrogen maser – work that helped Ramsey win a Nobel Prize 29 years later. Once their research got underway, Lukin and Childress faced an additional problem in the form of a sewage leak that was befouling their work space. The building manager, Stuart McNeil, came to their aid, putting a camera on a snake that revealed an obstruction in the sewer system, which was quickly unblocked.

5. D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté, and M. D. Lukin, "Fast quantum gates for neutral atoms," Physical Review Letters 85 (2000), https://doi.org/10.1103/PhysRevLett.85.2208.

6. M. D. Lukin, M. Fleischhauer, R. Côté, L. M. Duan, D. Jaksch, J. I. Cirac, and P. Zoller, "Dipole blockade and quantum information processing in mesoscopic atomic ensembles," Physical Review Letters 87 (2001), https://doi.org/10.1103/PhysRevLett.87.037901.

7. See E. Gibney, "Quantum physics: Flawed to perfection," Nature 505 (2014), https://doi.org/10.1038/505472a.

After their room was dried out and sanitized, experiments resumed and a number of groundbreaking papers eventually came out in *Science*,[8] *Nature*,[9] and other journals. One work showed, for example, how a system with NV centers in diamond serving as qubits could be used to store and process quantum information. Another paper described a very different application in which NV centers can act as highly sensitive magnetic field sensors with nanoscale resolution. "None of this could have happened without a community-wide effort," Lukin comments, "and that's the kind of thing that makes this place special."

This example, he says, points more broadly to the cooperation among a wide range of people – faculty colleagues, students, postdocs, and support staff – which makes all of these advances possible. He specifically mentions a group of "amazing administrators" he has worked with over the years, including Bonnie Currier, Joan Hamilton, Adam Ackerman, Clare Ploucha, Samantha Dakoulas, and Elaine Mangelinkx. Each of them, he says, has elevated lab operations to a new level and made a major impact on our community beyond the Lukin group. In particular, Ackerman completely overhauled grants operations within the Physics Department, while Ploucha and Dakoulas are currently working with Lukin on Harvard's Quantum Initiative for Science and Engineering, a new interdisciplinary program at Harvard that Lukin co-directs with Evelyn Hu, Tarr-Coyne Professor of Applied Physics and Electrical Engineering. Lukin also expresses appreciation for Jim McArthur, the manager of the electronics shop, and Alexander (Sasha) Zibrov, a senior research scientist, both of whom enabled the realization of a wide range of projects in his lab.

Scientific collaborations of this kind have changed the way science is done, he adds. "When I started in the department, people like me with a background in atomic physics, working on systems with a few particles, did not interact with people in many-body, condensed matter physics who work on systems with, say, 10^{23} particles." That changed in the early 2000s when Lukin began teaming up with former Harvard professors Eugene Demler, a condensed matter theorist, and Charles Marcus, a condensed matter experimentalist. "Collaborations like that, which started here at Harvard, have completely transformed our field of physics," Lukin says.

On the quantum computing front, he and his lab members have, over the years, explored a number of different platforms – experimenting with different kinds of qubits and trying out different ways of storing them and processing the information they hold. Meanwhile, with other researchers in the group, Lukin has approached the subject from a theoretical perspective, devising algorithms, for example, that can solve a particular problem or execute a given task.

One issue, however, has remained top-of-mind for Lukin throughout his quarter century appointment at Harvard: How do you build truly large quantum machines? An aspect of this relates to the specific design that might be adopted for the device. But another aspect is more subtle: As the size of a quantum system grows – how do you maintain its quantum nature? "To build these large-scale systems, we almost have to defy the laws of nature," Lukin says. "Look at the world around us: Big systems do not like to be in a state of quantum superpositions, which means these superpositions will be extremely fragile and hard to maintain."

Any practical approach to quantum computing will therefore have to incorporate a method for protecting superposition states, so the information held within a quantum system doesn't instantly vanish. Strategies to retain information and ward off this dire prospect fall under the heading of quantum error correction. The fact that quantum states contain much more information than just 0s and 1s means there is much more information to safeguard than in a classical computer, making quantum state protection all the more important. Indeed, the viability of quantum computing overall depends on the success of the effort to correct errors in quantum operations and devise a protective, self-correcting capacity. And until recently, it was not known whether that viability could be assured.

It was known, however, that the approach used in conventional computing of relying strictly on redundancy to protect information will not work in the world of quantum computing. To play it safe with classical computers, Lukin says, instead of just saving (0,1), you might save (000,111), knowing that if you lost one of the extra 0s or 1s, you could still reconstruct the original. But in quantum mechanics, there's a principle called the no-cloning theorem, which holds that you can't make an exact copy of an unknown quantum state. The reason is that in order to copy the state, you must first measure it, thereby destroying the superposition and compelling it to become either a 0 or 1. This is a consequence of a central tenet of quantum mechanics: While a system can be in multiple physical states at the same time, the act of measurement forces it to collapse into one state or the other.

Consequently, in quantum computing, as mentioned before, information cannot be backed up by making exact copies – on

8. M. V. Gurudev Dutt, L. Childress, L. Jiang, E. Togan, J. Maze, F. Jelezko, A. S. Zibrov, P. R. Hemmer, and M. D. Lukin, "Quantum register based on individual electronic and nuclear spin qubits in diamond," *Science* 316: 5829 (2007), https://www.science.org/doi/10.1126/science.1139831.

9. J. R. Maze, P. L. Stanwix, J. S. Hodges, S. Hong, J. M. Taylor, P. Cappellaro, L. Jiang, et al., "Nanoscale magnetic sensing with an individual electronic spin in diamond," *Nature* 455 (2008), https://doi.org/10.1038/nature07279.

something like a hard drive, for example. "The way to encode information in a robust manner," Lukin explains, "is essentially by delocalizing it" – having the information distributed among many different physical qubits that are entangled with each other. That way, the failure of any single qubit will not destroy the fidelity of the so-called logical qubits encoded in the entire system; the information can still be recovered. While the theoretical foundation for quantum error correction was established in the late 1990s – led, notably, by Peter Shor – realizing it in practice has been a formidable challenge. First, the errors in individual physical operations have to be sufficiently low to take advantage of quantum encoding. Second, implementing these ideas can incur significant costs in terms of the number of physical qubits required and the added complexity of controlling such systems.

In an October 2023 paper published in *Nature*,[10] researchers led by Lukin,

10. S.J. Evered, D. Bluvstein, M. Kalinowski, S. Ebadi, T. Manovitz, H. Zhou, S. H. Li, et al., "High-fidelity parallel entangling gates on a neutral-atom quantum computer," *Nature* 622 (2023). https://doi.org/10.1038/s41586-023-06481-y.



Left: Postdoctoral fellow Muqing Xu and graduate student Sophie Li [Photo by Paul Horowitz]

J. PABLO BONILLA ATAIDES: How to Reduce Errors, Theoretically

J. Pablo Bonilla grew up in Uruguay and moved to Australia for middle school and high school. He studied physics and math at the University of Sydney owing to what he called "a desire to understand the world." In August 2022, he came to Harvard to begin graduate studies in physics and pursue research in the Lukin lab. He was drawn to quantum physics because he recognized it as "a fundamental area of physics that could have a big and positive impact on society if controlled appropriately."

A main focus of Bonilla's research is the study of quantum error correction from a theoretical perspective. The individual qubits in the Lukin lab today have errors at the rate of 1 in 100 to 1 in 1000 operations, he says. "But to run anything useful, we require overall error rates that are much lower; some algorithms require an error rate of 1 in a trillion."

There is some room for improvement in single physical qubits, or atoms, but to reach much more stringent requirements (such as the 1 in a trillion goal), the bulk of the improvement has to come from a different approach. That's where the work of a theorist comes in through devising quantum error correction codes. These codes, in turn, generate a logical qubit – a collection of physical qubits or atoms arranged in a well-prescribed configuration.

Suppose you're at a restaurant at a train station, Bonilla suggests, and the choice of your order comes down to either pasta (0) or pizza (1). It is noisy because of the trains, and you might order many times without the waiter hearing you. If you want pasta, however, you can keep repeating yourself until the waiter finally gets the message.

In quantum mechanics, you can't copy information directly in this same way. But you could have code that says: If the sum of the qubits is even, you get a 0, and if it's odd you get a 1. So 0,1,1 would be another way of saying 0, only this time you've distributed the answer among three linked and correlated qubits. With this approach, the information is no longer encoded in a single physical atom, or qubit, but is instead distributed among a group of physical atoms that are interacting in an entangled way.

If you want to create a code that is good enough to limit the error rate to one in a trillion, and you assume that a single qubit is likely to fail one in 1000 times (which is close to the lab's current record), Bonilla might then run some simulations to estimate the number of physical qubits needed to create a code good enough to keep the error rate down to the 1 in a trillion target. "The number of physical qubits I estimate might be 10,000 or 1 million, which is way more than quantum computers can accommodate at present," he says. "So part of my work as a theorist would then be to create a better code that can reduce the number of physical qubits required." Or, more specifically, the idea is to reduce the number of physical qubits needed per logical qubit, while still getting good error suppression.

There are other factors to consider as well, such as using the same physical qubits in multiple logical qubits and making sure that reducing the number of physical qubits won't incur a penalty in calculation time. "In the past, a lot of these things were explored in isolation," Bonilla says. "I'm trying to consider them together. This is becoming an active area of research and, I think, a very exciting one."

MUQING XU: Can Simulations Illuminate the Mystery of Quantum Gravity?

When Muqing Xu came to the Lukin Lab as a postdoctoral researcher in 2024, he did not have to travel far. He'd been working in the lab of his Ph.D. supervisor, Markus Greiner, which is literally next door to the Lukin lab. Xu did, however, have a longer trip when he came to Harvard for graduate studies in 2017, as his undergraduate work had been carried out at Tsinghua University in China, which is where he grew up. After earning a Harvard Ph.D. in 2024, he made the big move across the hallway to the Lukin lab.

Since joining the group, he has been deeply involved in quantum error correction research. He is, in fact, one of three lead authors of a 2026 paper – soon to come out in *Science** – that demonstrated a record low error rate of 0.15% or, conversely, 99.85% fidelity.

Another portion of Xu's current research falls in the area of quantum simulations. "A quantum simulation is not like running a computer program that shows you how things behave," he explains. "It's actually doing an experiment." A proper analogy would be with aerodynamics, where one can do numerical simulations on a computer or carry out wind tunnel experiments, he says. "What we do is like a wind tunnel in quantum physics. For problems that are too complicated to be simulated on classical computers, we run actual experiments."

One thing that he and his colleagues are trying to understand is whether quantum simulators can provide a new way to approach one of the deepest problems in theoretical physics: how gravity and quantum mechanics fit together. The simulation he's engaged in, curiously, is not set in our universe – one in which the cosmological constant or dark energy that is propelling an accelerated cosmic expansion has a positive value. Instead, it is set in a so-called anti-de Sitter (AdS) universe – one in which the cosmological constant has a negative value. AdS space is particularly valuable for this purpose because of one of the most influential ideas in modern theoretical physics – the AdS/CFT correspondence, a theoretical link between theories with gravity in AdS space and lower dimensional conformal field theories (from quantum physics), which do not include gravity. The correspondence was proposed in 1997 by the physicist Juan Maldacena when he was at Harvard. (Maldacena moved to the Institute for Advanced Study in Princeton in 2001.)

In the work undertaken by Xu and others in the Lukin group, in concert with Harvard physicist Jordan Cotler, qubits represent quantum particles characterized by their intrinsic spins, which interact like magnets. The researchers hope to study emergent gravity dynamics through simulations involving a specially designed quantum spin system. They believe that if they can bring this system to the so-called "critical point," where it behaves similarly across different length and energy scales, then the behavior of the quantum particle spins can be transposed to an entirely different setting – that of particles moving and interacting under gravity in a higher-dimensional space. Once the quantum spin system is constructed, Xu says, "we plan to create two particles in the AdS universe and see how they fall toward each other."

Many-body dynamics is a very challenging topic in physics, and the problem becomes even more challenging in settings relevant to quantum gravity. "Those calculations are notoriously difficult to solve on classical computers, but they might become much more tractable on quantum machines," Xu says. "Even so, we aren't yet able to explicitly solve the equations but are instead working with approximations – essentially with a toy model." Once we have a full-fledged quantum computer at our disposal, he adds, "we should be able to move beyond some of those simplifications and study increasingly complex systems. But we still have to develop the right quantum algorithm to drive that calculation."

* S. J. Evered, M. Xu, S. H. Li, A. A. Geim, J. P. Bonilla Ataides, M. Kalinowski, D. Bluvstein, et al., "High-fidelity entangling gates and nonlocal circuits with neutral atoms," arXiv:2604.25987v1 [quant-ph] 28 Apr 2026.

Assistant Professor of Applied Physics Giulia Semeghini, Greiner, and Vuletić from MIT looked at how well a system – consisting of 60 cold rubidium atoms trapped by lasers – could do in performing logic operations. The outcome of this experiment was pretty impressive: Logic operations involving two qubits could be carried out with a reliability above 99.5% or, equivalently, a failure rate below 0.5%, which was a record for neutral atom systems at the time. This result was noteworthy because it had previously been established that if a failure rate of less than 1% could not be guaranteed, error correction would barely be effective at all. Recently, moreover, Lukin and his collaborators broke their own record: In a paper published in *Science*,[11] they demonstrate failure rates as low as 0.15%.

A year earlier, a November 2025 *Nature* paper[12] reported on another consequential advance on this front, which was achieved by researchers from the Lukin, Greiner, and Vuletić labs. They were again able to obtain error correction rates well below the 1% threshold, this time on a much larger quantum system with arrays holding up to 448 neutral rubidium atoms. The most significant part of this accomplishment, according to Lukin, is that they demonstrated quantum error correction – and fault-tolerant quantum circuits with up to 96 protected logical qubits – in a system that had an architecture that could be readily scaled up, thereby laying the groundwork for large-scale quantum computation. Regarding the "large-scale" theme, in separate work that came out in *Nature* on October 30, 2025,[13] the same collaboration

11. S. J. Evered, M. Xu, S. H. Li, A. A. Geim, J. P. Bonilla Ataides, M. Kalinowski, D. Bluvstein, et al., "High-fidelity entangling gates and nonlocal circuits with neutral atoms," Science 349 (2026), https://doi.org/10.1126/science.aei1312

12. D. Bluvstein, A.A. Geim, S.H. Li, S. J. Evered, J. P. Bonilla Ataides, G. Baranes, A. Gu, et al, "A fault-tolerant neutral-atom architecture for universal quantum computation," *Nature* 649 (2026; published online November 2025), https://doi.org/10.1038/s41586-025-09848-5.

13. N.-C. Chiu, E.C. Trapp, J. Guo, M. H. Abobeih, L. M. Stewart, S. Hollerith, P. L. Stroganov, et al., "Continuous operation of a coherent 3,000-qubit system," *Nature* 646 (2025), https://doi.org/10.1038/s41586-025-09596-6.

demonstrated the continuous operation of a 3,000-qubit system for a period of more than two hours, without any stops or restarts during that time. "The most important aspect of this work," Lukin comments, "was not the number of qubits but rather the fact that we could really operate the system continuously." Usually, what his group and others had done in the past was to use optical tweezers to trap within an array a number of atoms that serve as qubits. The researchers would then change the internal states of these atoms by means of logic operations and read out the atomic states with lasers. "Next, we would stop this and rebuild an array from scratch, basically repeating all of these procedures," he says. "And that's how the experimental cycle would go on."

This traditional approach, Lukin says, would not be practical for large-scale quantum computing. Given the effort required to prepare a batch of error-corrected qubits, "which can preserve quantum information and enable algorithms to run for a long time – potentially for hours and even days – you cannot afford to simply throw those atoms out after a fraction of a second and start the process over again with new ones," he said. "You need to be able to run the system continuously."

Doing so is difficult, he acknowledges. "These qubits – these atoms in traps that we use – don't live forever. They have finite lifetimes because they will eventually escape from the traps." What he and his fellow researchers have hit upon is a way of replacing lost atoms with fresh ones to maintain an array of qubits for at least two hours and hopefully much longer. That is a big step, in itself, Lukin says, noting that they haven't done any quantum computations with this system yet – a follow-up project that is currently in progress.

It bears mentioning that the work of Lukin and his colleagues has had impacts that extend far beyond the Harvard campus. Dozens of companies are pursuing commercialization strategies that build upon research and discoveries made in the Lukin lab. One example is QuEra Computing, a company that Lukin co-founded in 2018 with Greiner and Vuletić. Located across the Charles River, just two miles from the Harvard Physics Department, QuEra Computing now has more than 200 employees striving to show that the future of practically useful quantum computing will be built on neutral atom arrays. Other companies are pursuing the use of atom-like color centers – microscopic defects in a diamond's crystalline structure – as magnetic sensors for applications ranging from navigation to biomedical sensing.

Meanwhile, back in the academic world, research is proceeding on multiple fronts within the Lukin lab in areas ranging from quantum sensing[14] and computing to networking. Quantum networks are, in fact, based on many of the same scientific principles as quantum computing and utilize many of the same approaches. The two concepts are not necessarily distinct in that distributed quantum computing, for instance, can be carried out with networked quantum computers. In quantum networks, as with quantum computing, Lukin says, "what we're trying to do is to prepare entangled states, which are superposition states, only in this case they can be separated by great distances."

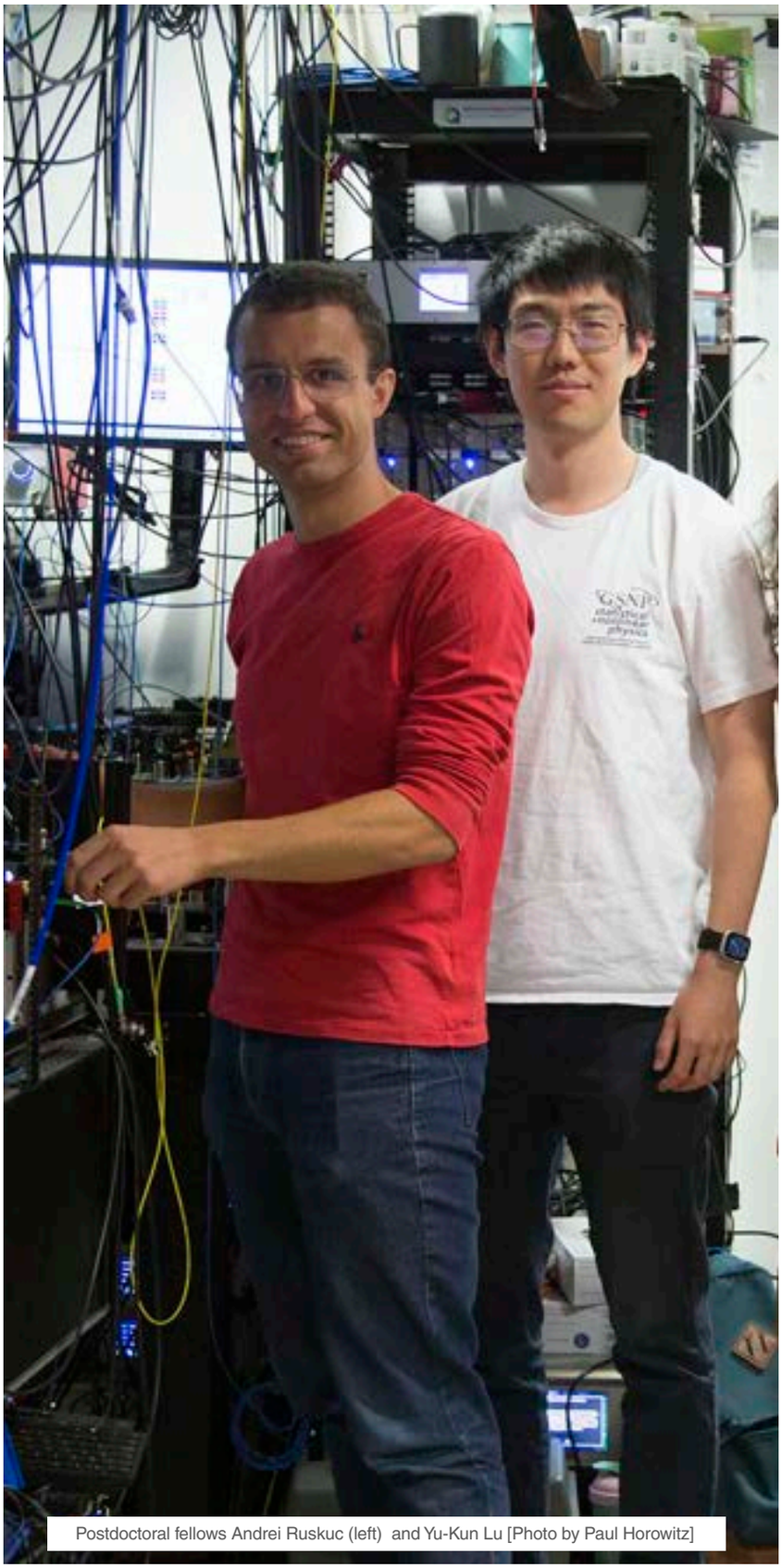
For both of these concepts, the same set of challenges come into play that physicists have been grappling with for decades. With regard to quantum computers, Lukin says, "the question relates to how big you can make them: How many qubits can they have and how many operations can they perform? For quantum networks, it's a slightly different question: How far can you distribute your entangled states?"

He and his group obtained a preliminary answer to that question in an experiment they described in a May 2024 issue of *Nature*.[15] The starting point was to place two nodes located on different floors of Harvard's Laboratory for Integrated Science and Engineering (LISE). Each of these nodes is a spin qubit – a different kind of qubit from the ones discussed so far because it is neither a rubidium atom nor a nitrogen-vacancy center. Instead, it is a variant of the latter – a diamond defect called a silicon-vacancy center in which a silicon atom occupies a lattice position between two missing (or "vacant") carbon atoms. These two nodes, or qubits, are no more than 20 meters apart within the lab, but they are connected by an optical fiber loop 35 kilometers long – starting from the first qubit and then passing through sections of Cambridge, Somerville, Boston, and Watertown before returning back to LISE, where the optical fiber connects with the second node. Each qubit has both an electron spin and a nuclear spin, and both of these quantum states in the two-node system become entangled over this 35-km-long network.

"The way we do that, the way we generate this long-distance entanglement, is that we first entangle the qubit with a photon," explains Yan-Cheng Wei, a Lukin Ph.D. student who was one of the lead authors of the Nature paper. "To obtain our results, we had to overcome two challenges. The first is to make the photon entangle with the qubit. The second is getting the photon to travel over this distance

14. See two papers:
- H. Gao, L. S. Martin, L. B. Hughes, N. T. Leitao, P. Put, H. Zhou, N. U. Koyluoglu, et al., "Signal amplification in a solid-state sensor through asymmetric many-body echo," *Nature* 646 (2025), https://doi.org/10.1038/s41586-025-09452-7.
- X. H. Le, P. E. Dolgirev, P. Put, E. L. Peterson, A. Pillai, A. A. Zibrov, E. Demler, H. Park, and M. D. Lukin, "Wideband covariance magnetometry below the diffraction limit," *Physical Review Letters* 135 (2025), https://doi.org/10.1103/7xlj-52xt.

15. C.M. Knaut, A. Suleymanzade, Y.-C. Wei, D. R. Assumpcao, P.-J. Stas, Y. Q. Huan, B. Machielse, et al., "Entanglement of nanophotonic quantum memory nodes in a telecom network," *Nature* 629 (2024), https://doi.org/10.1038/s41586-024-07252-z.



Postdoctoral fellows Andrei Ruskuc (left) and Yu-Kun Lu [Photo by Paul Horowitz]

[35 kilometers] without getting lost, because if there is something in between, the light will be attenuated and the photon will be lost."

The team managed to keep that from happening and, consequently, made the prospect of a quantum internet look a bit brighter. Their work advances the possibility of secure, unhackable communications, owing to the fact that information in the network is distributed among superpositions – a format that cannot be directly copied, thanks to the aforementioned no-cloning theorem.

That work builds on the foundations created over two decades, starting with the experiments in the basement of the Lyman lab. It relies on advances in fabricating tiny devices made from synthetic diamond, called nanophotonic cavities, which contain silicon-vacancy centers. Lukin says that these advances – achieved through collaborations within Harvard between the Lukin group and the groups of Marko Lončar, Tiantsai Lin Professor of Electrical Engineering, and Hongkun Park, Mark Hyman Jr. Professor of Chemistry and Professor of Physics – were completely unimaginable when these researchers started this work: "They literally learned how to carve these things out of diamond."

Research on long-distance entanglement also led to the spin-out of several start-up companies from the Lukin lab – including LightSynq (now a part of IonQ) and CavilinQ – that are commercializing quantum networking technologies.[16]

On a parallel track, research taking place at Harvard continues to yield surprises. For example, a recent proof of concept project led by Lukin brought together ideas from quantum networking and quantum sensing – using properties like superposition and entanglement to measure physical quantities to great precision – in order to

16. Alvin Powell, "Building useful quantum com-puters 'in our direct line of sight,'" T*he Harvard Gazette* (May 1, 2026), https://news.harvard.edu/gazette/story/2026/05/building-useful-quantum-computers-in-our-direct-line-of-sight/.

create a new kind of quantum telescope. "The traditional approach to improving the resolution of telescopes is to make the mirror size bigger and bigger, but at some point, you just can't make a big enough mirror," explains Andrei Ruskuc, a postdoctoral fellow in Lukin's group who works in a related area. Another way to improve the resolution is through a distributed approach called interferometry, which makes use of multiple telescopes, spread over a bigger area, to boost resolution. "You need to send photons from A to B and do so in a way that preserves their quantum state, so that's where you can take the approaches that have been developed for quantum networks and apply them to these telescopes," Ruskuc says.

And when you do that, Lukin adds, "we're starting to see the potential for fundamentally new ways of optical imaging. So this is a completely new angle for a problem in astronomy that you might have thought quantum information techniques didn't have anything to do with."

This novel and unexpected application in optical imaging, Lukin notes, reflects the fact that we still don't have a good sense of what these quantum systems can do for science and society. These are new scientific tools that will likely contribute to scientific knowledge in a variety of ways – starting with understanding complex quantum systems that can't be fully modeled with conventional computers.

"But we're just beginning to explore this frontier," Lukin says. "Usually in science, you wander around and, every once in a while, you end up in a corner of the universe where no one has been before. In the quantum field, we can now wander further and further into these corners, creating entangled states of a size and complexity that no one has previously contemplated. As a result, we're just scratching the surface regarding what we can do with systems of this kind."

ANDREI RUSKUC: Step Aside, Social Network, and Make Way for the Quantum Network

Andrei Ruskuc, a postdoctoral fellow in the Lukin lab, studied physics as an undergraduate at the University of Cambridge, although he had initially considered going into electrical engineering because, as he put it, "I'm not just interested in fundamental concepts. I'm also interested in the technologies we can generate using these concepts." As a physics PhD student at Caltech, he studied quantum networking, which has continued to be one of the main projects he's been pursuing at Harvard since joining the Lukin group in 2024. "The basic idea is to network quantum computers in much the same way that the classical internet links classical computers," Ruskuc explains. "And that is one of the ultimate goals of the research that we do in our team."

This goal is closely coupled with the objective of developing quantum computing in general, he says. "If you want to scale up quantum computers to ever larger numbers of qubits, at some point you might not be able to fit enough atoms into a single physical system, and quantum networking then becomes the way you can increase system size."

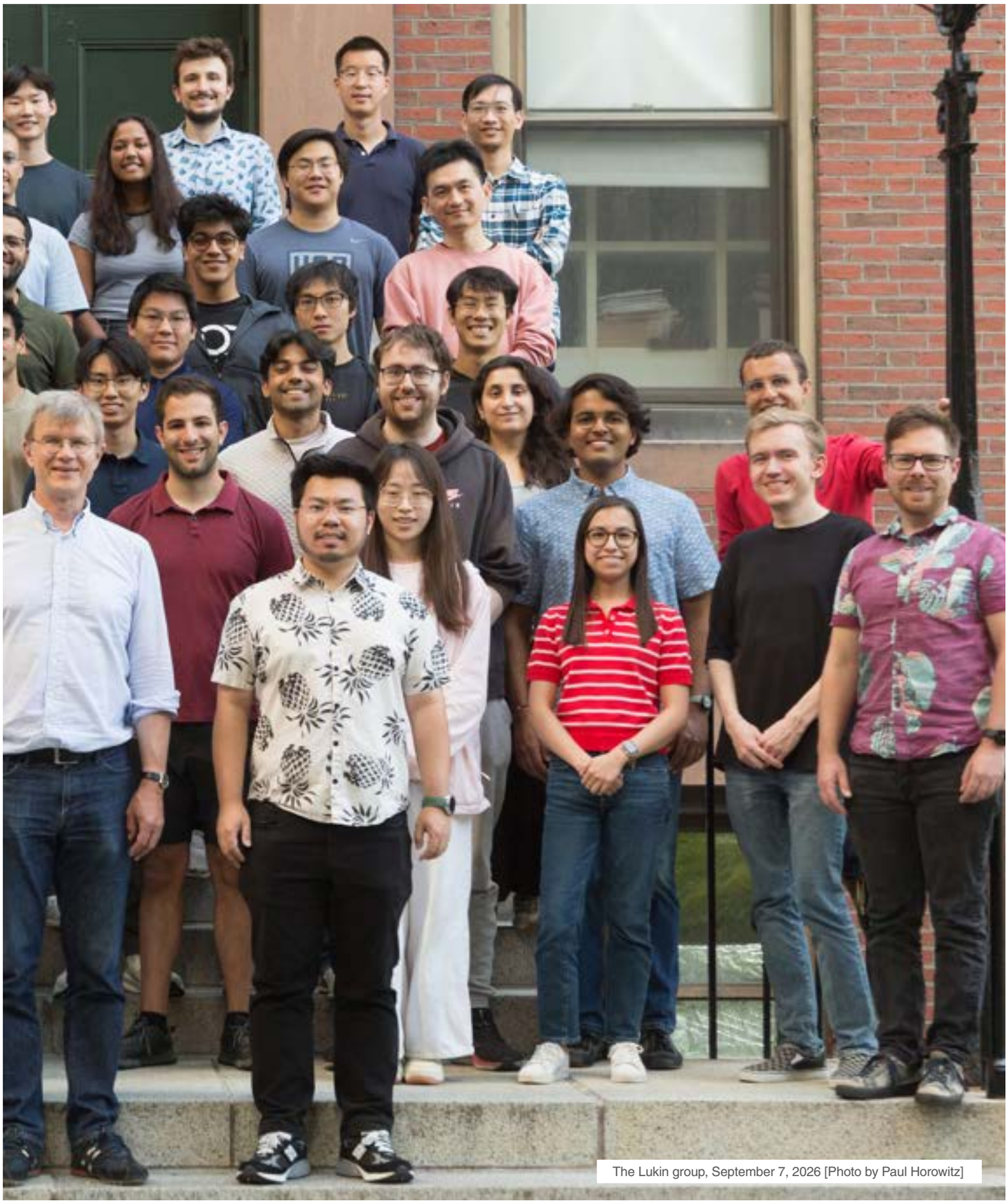
But quantum networking is about more than just that, he adds, "because it enables you to distribute entangled states over very long distances, using photons as the way to entangle two qubits that are geographically separated." Photons can travel through optical fiber generating entangled links over kilometer-length scales. And if plans to create devices called quantum repeaters are realized, Ruskuc says, "we're not just talking about entangling quantum systems over kilometers; we're talking about global length scales." Quantum repeaters offer a way to overcome the exponential attenuation of light as it travels through an optical fiber, and the premise is pretty simple: You just create a chain of entanglement links over the length of the cable, from the very start to the very end.

"However, if you want to take this idea and make it really fast – fast to the point where it's actually useful – you need to use an additional technique called entanglement multiplexing," Ruskuc says. Instead of entangling two qubits along every intermediary section of the fiber – which might have just a 1 percent chance of success for each attempt – multiplexing involves the parallel entanglement of large numbers of qubits simultaneously. If you try to link 100 qubits at each node, for example, you can increase your success rate 100-fold and reduce the time needed to generate an entangled state by the same factor. Ruskuc is eager to implement this idea at Harvard and "hopefully get really meaningful advances in the performance of quantum networks."

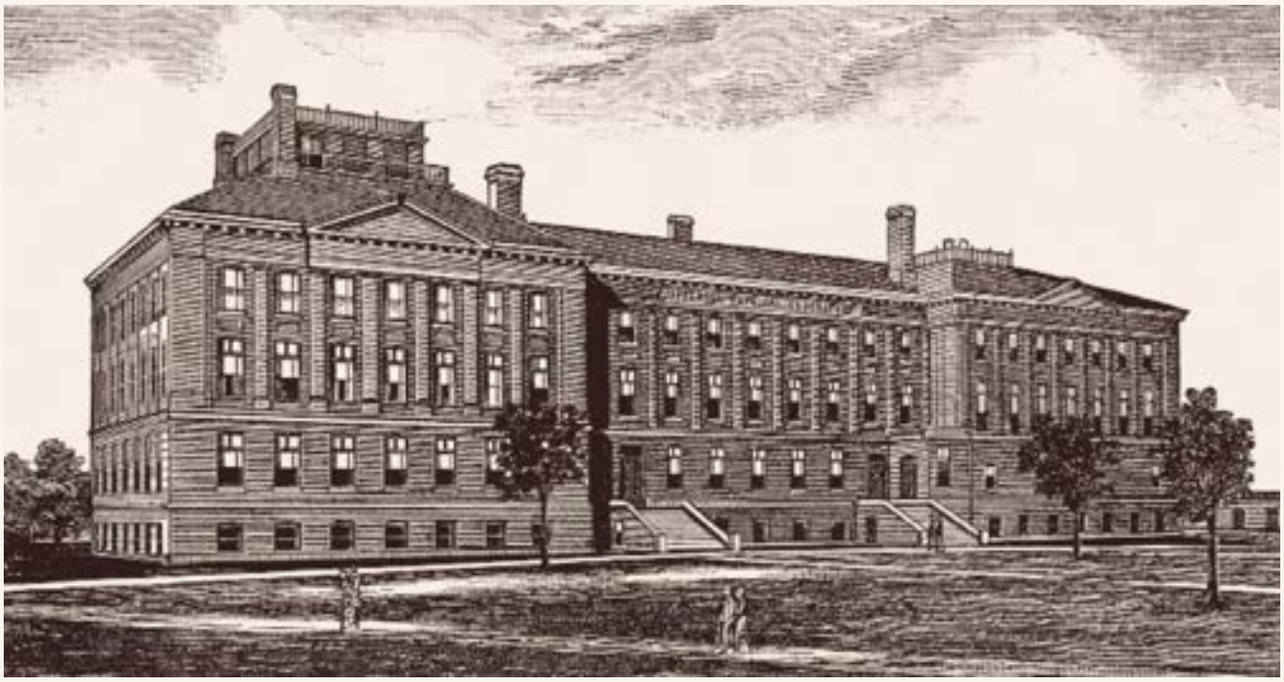
His platform of choice, currently, is a neutral (rubidium) atom array enhanced with an "atom cavity," which essentially consists of a pair of mirrors placed within the vacuum chamber of a quantum computer that is used to confine light and boost atom-light interactions. Ruskuc is excited about a collaboration between his atom cavity team and a separate team within the Lukin lab that works with a different kind of qubit called a silicon vacancy center. This alternative qubit makes use of a defect within a tiny sliver of diamond in which a silicon atom sits between two vacant spots in the lattice that would normally be occupied by carbon atoms. The idea behind this project is to generate a quantum connection between two different quantum systems.

"We're trying to create an interface between these heterogeneous quantum systems that enables us to link one with the other – to literally entangle rubidium atoms with silicon-vacancy centers," Ruskuc says. "This is a nice example of the unique collaborations between different teams that frequently arise in the Lukin lab – unique because it's hard to find this level of expertise on so many different teams within the same group." He considers this one of the lab's greatest strengths. There's a lot of crosstalk between teams that can lead to "some very cool experiments and applications you might never have considered," Ruskuc adds. "You could be casually talking with someone over lunch and suddenly realize, 'Oh, we should try that!'"


PUMA



The Lukin group, September 7, 2026 [Photo by Paul Horowitz]



HISTORICAL FOCUS

NICOLAAS BLOEMBERGEN: Invention of the Solid-State Maser

by Paul Horowitz

"Bloembergen said something to Scovil about having an idea for a maser, and he was obviously quite excited about it, but said 'I'm not going to tell you till I've got it all worked out.' Scovil went home, overnight – 'what is it that Bloembergen would be thinking about?' And the next morning he had the same idea, and he spoke with Bloembergen and said 'is this it?' And Bloembergen said 'yes.'"

Thus was the moment captured by Charlie Townes in his oral history interview,[1] when the now-universal scheme for the 3-level pumped solid-state maser (and, later, laser) was born.

WHAT CAME BEFORE

To set this discovery in context, we need to step back 40 years, to Einstein's 1917 paper "The Quantum Theory of Radiation,"[2] where he famously noted, in a section titled "Hypotheses about the Energy Exchange Through Radiation," that a molecule can transition from a higher to a lower energy state "under the action of the radiation" with the emission of radiation whose

1. AIP oral history, June 1979, available at https://repository.aip.org/node/127973 or https://doi.org/10.1063/nbla.eknn.fmjs.
2. Albert Einstein, "Zur Quantentheorie der Strahlung," *Physikalische Zeitschrift* 18 (1917): 121.



Fig. 1: Nicolaas Bloembergen with the three-level solid-state microwave maser he demonstrated at Harvard University, March 26, 1958. He is holding a crystal of chromium-doped hexacyanocobaltate. [Harvard University Archives, Cruft Memorial Laboratory, courtesy AIP Emilio Segrè Visual Archives, Hecht Collection]

energy corresponds to the difference of the molecule's energy states. This is *stimulated emission* of radiation, at the heart of the maser and laser.

In the following decades there were occasional hints of properties and possibilities. For example, in a 1924 article[3] Richard Tolman remarked, "The possibility arises, however, that molecules in the upper quantum state may return to the lower quantum state in such a way as to reinforce the primary beam by 'negative absorption.'"[4] J.H. Van Vleck, in a paper that same year,[5] coined the term *induced emission* for what had been called negative absorption. The next year Hans Kramers noted, "...lightwaves of this frequency [of an emission line], passing through a great number of atoms in the state under consideration, will increase in intensity."[6]

In C.V. Raman's famous 1928 paper of the eponymous effect,[7] he and co-author K.S. Krishnan noted the existence of faint spectral lines of higher energy (shorter wavelength), with the remark:

3. R.C . Tolman, "Duration of Molecules in Upper Quantum States," *Physical Review* 23, no. 6 (1924): 697.

4. Amusingly, in hindsight, his concern was that such stimulated emission would affect his calculation of resonant absorption; he dismisses it with the comment "The process of negative absorption, however, from analogy with classical mechanics, would presumably be of such a nature as to reinforce the primary beam, and we must assure ourselves that the magnitude of this reinforcement is negligible." Thus Tolman discarded the maser/ laser, a nuisance term in his calculations!

5. J. H. Van Vleck, "The Absorption of Radiation by Multiply Periodic Orbits, and its Relation to the Correspondence Principle and the Rayleigh-Jeans Law. Part I. Some Extensions of the Correspondence Principle," *Physical Review* 24, no. 4 (1924): 330.

6. H. A. Kramers, "On the Behaviour of Atoms in an Electromagnetic Wave Field," *Proceedings of the 6th Scandinavian Mathematical Congress* (Copenhagen, 1925); 151.

7. C. Raman and K. Krishnan, "The Negative Absorption of Radiation," *Nature* 122, no. 3062 (1928): 13.



Fig. 2: Induced RF radiation from a nuclear spin system with an inverted population (Purcell and Pound, 1951), demonstrating stimulated emission, and often cited as leading directly to the maser and laser. Momentary sampling of the NMR signal at 30s intervals initially shows 'normal' absorption (positive deflection), but a minute later, after spin reversal, the sign of absorption is reversed (negative deflection), decaying back to normal with a time constant of several minutes. [Scanned from the original 5×7" photographic negative of the chart recorder strip.]

> "The presence of these lines proves simultaneously the existence in the liquid of molecules at levels of energy correspondingly higher than the normal, and the fact that the incident radiation induces a return to a lower state of energy; in other words, that there is a negative absorption of the radiation."

Interestingly, as Charles Townes has observed,[8] "All the ideas essential to make a laser were known before 1930, but there was no operating laser before 1960."

Around 1936–37 the German physicist Siegfried Levy remarked to Vitaly Ginzburg (of the Ginzburg–Landau theory of superconductivity) "create an overpopulation at higher atomic levels and you will obtain an amplifier; the problem is that it is difficult to create a substantial overpopulation of levels."[9] A few years later, in his Ph.D. thesis,[10] the Russian physicist Valentin Fabrikant proposed creating such an inverted population in a gas by "collisions of the second kind" (where an atom or molecule in an excited state transfers its excitation to the other atom or molecule – the working principle of the helium-neon laser).

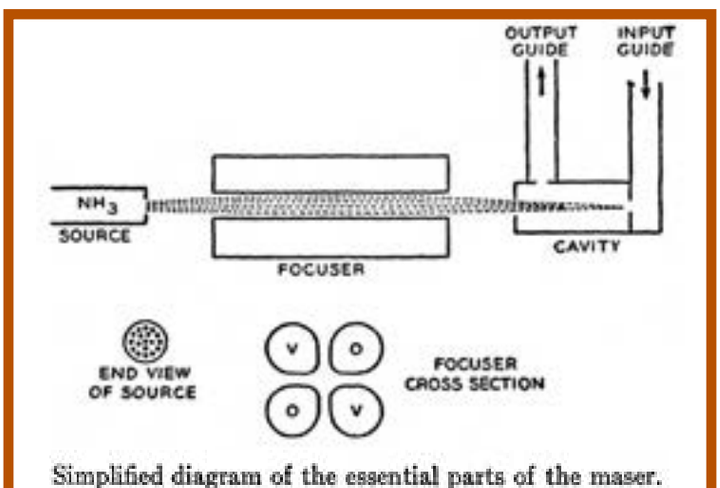


Fig. 3: The first maser: ammonia molecules in their higher energy state (focused by an electric quadrupole) enter a resonant cavity where they amplify 24 GHz microwaves. [J. P. Gordon, H. J. Zeiger, and C. H. Townes, "The Maser—New Type of Microwave Amplifier, Frequency Standard, and Spectrometer," *Physical Review* 99 (1955): 1265.]

The first observation of stimulated emission (but not of amplification) from a system with population inversion was a 1950 laboratory demonstration by Robert Pound and Edward Purcell: the nuclear spins of a lithium fluoride crystal of particularly long relaxation time, initially in thermal equilibrium in a strong magnetic field at room temperature, were flipped (by a cleverly tailored asymmetric pulsed *B*-field) to achieve a reversed Boltzmann distribution. The resulting NMR trace (Figure 2) exhibited emission rather than absorption – hence their paper's title, "A Nuclear Spin System at Negative Temperature."[11]

A few years later Joseph Weber, inspired by this negative temperature experiment, proposed several ideas in his paper "Amplification of Microwave Radiation by Substances not in Thermal Equilibrium," including population inversion in flowing ammonia gas. He proposed a possible method (an electric field that reverses along the path), but he missed the ideas that made it practicable (and that won Townes a Nobel prize) – an upstream state selector, and, most importantly, a resonant cavity.

THE FIRST MASER

On April 26, 1951, in a moment of inspiration (and frustration, because his expert ONR committee, on its last meeting and after site visits, had failed to come up with good ideas for mm-wave and shorter sources), while sitting "on a bench in front of beautiful blooming azaleas,"[12] Townes had an epiphany: a molecular gas need not be heated *thermally* to the extreme temperatures required

8. C. H. Townes, "Early history of quantum electronics," *Journal of Modern Optics* 52, no. 12, (2005): 1637.
9. ibid.
10. V. A. Fabrikant, "The emission mechanism of a gas discharge" (Ph.D. diss., P. N. Lebedev Physical Institute, 1939).
11. E. M. Purcell and R. V. Pound, *Physical Review* 81, (1951): 279.
12. Townes, "Early history of quantum electronics," 1639.



Fig. 4: Townes' ammonia maser, with the cover of the vacuum chamber removed: an unwieldy beast! Left to right: C.H. Townes and J.P. Gordon, with T.C. Wang next to the first maser (the second was built to measure the frequency stability). [Credit: AIP Emilio Segrè Visual Archives, Hecht Collection.]

(which would destroy the molecules); all that was needed was to put more molecules in a higher than lower excitation state. Being familiar with microwave techniques, he also realized that this should be done in a resonant cavity.

Back at Columbia, Townes and graduate student Jim Gordon set to work on their ammonia maser. But not without their doubters: luminaries like Polykarp Kusch and I.I. Rabi (both of whom won Nobel prizes) "...sat down in my office and said 'Look, Charlie, that is not going to work. We know it won't work and you know it won't work. You are wasting departmental money [Kusch was department chair, succeeding Rabi], and must stop!'"

Evidently Townes knew better, and remarked, "I was also by then a Professor, and the department chairman could not fire me simply because of stupidity."[13]

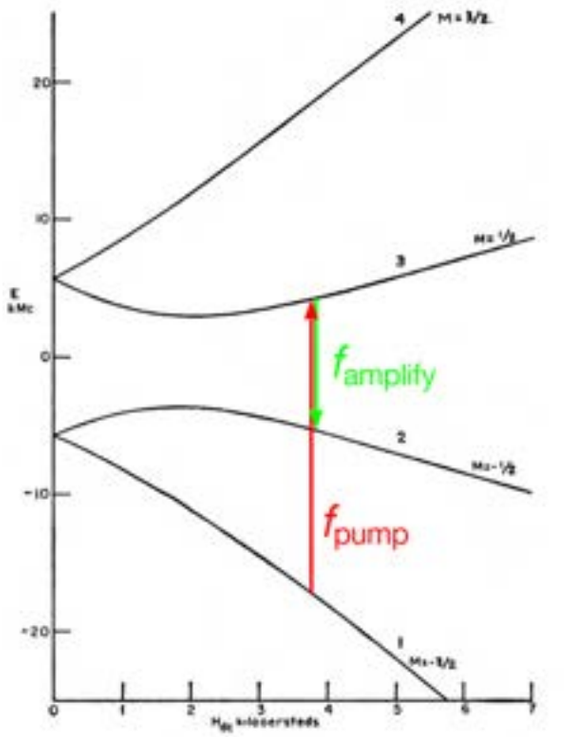
The dramatic moment came a couple of months later, when Gordon interrupted Townes' seminar, announcing "it's working!" This gave Kusch and Rabi an opportunity to dine on humble pie. Paraphrasing Arthur C. Clarke, Townes remarked,

> People go through four stages before any revolutionary development:
>
> (1) It's nonsense, don't waste my time.
> (2) It's interesting, but not important.
> (3) I always said it was a good idea.
> (4) I thought of it first.

Interestingly, even then the inventors were not thinking of a maser *amplifier* – to them it was a 24 GHz signal source of excellent spectral purity.[14] But by the following year they were fully on-board, with a publication titled "The Maser –

13. ibid., 1640.

14. Which they later measured, by heterodyning the signals from a pair of masers, to be of order 10^{-11} (1s averaging) or 10^{-10} (1 hour). There's a nice photograph of Townes and colleagues, with his hand cupped to his ear, listening to the ~100 Hz beat note produced by the maser pair (see page 40 in the Gordon article cited in footnote 15).



Energy levels of Cr^{+3} in a ruby as a function of magnetic field for an angle of 60° between the crystal axis of symmetry and the dc magnetic field.

Fig. 5: The pump signal saturates the 1 and 3 levels; the latter is metastable, thus an inverted population (and amplification) relative to level 2. [From Giordmaine et al., "A Maser Amplifier for Radio Astronomy at X-Band," *The Proceedings of the IRE*, (1959): 1062; color annotations added.]

New Type of Microwave Amplifier, Frequency Standard, and Spectrometer."[15]

A couple of technical points: (1) The Townes–Gordon maser exploited a collimated molecular beam of ammonia, in which population inversion was achieved by passage through an electric quadrupole (Fig. 3 and 4); the latter selectively focused molecules in the higher energy state (of the so-called 3–3 molecular inversion[16]), and defocused molecules in the lower state. So molecules entering the cavity through a small entrance hole were mostly in the upper state – the desired population inversion! The cavity was tuned to the molecular resonance at 23,870 MHz. (2) The maser could not be tuned; you were stuck with the hand that nature dealt.

Both points have a stunningly different analog in Bloembergen's solid-state maser.

A *SOLID-STATE* MASER: NICO'S GREAT INSIGHT

Enter Nicolaas Bloembergen, at the time an associate professor at Harvard and an expert in NMR and paramagnetic relaxation (his 1948 "BPP" paper with Pound and Purcell, "Relaxation Effects in Nuclear Magnetic Resonance Absorption," was for many years the most cited paper in physics). He was aware of the Pound/Purcell negative temperature experiment, and he had heard Gordon's talk at the APS in New York describing the ammonia maser; but he hadn't really thought about using population inversion in condensed matter. Then, in a conversation with MIT microwave expert Woody Strandberg, Nico asked why it would be interesting to create a population inversion in paramagnetic salts; as related in his 1983 oral history,[17]

> "Why try to invert this magnetization? It can be done. Nuclear spins, we already have. Why do you want to do it at microwave? There's no new science." He [Strandberg] said, "Well, but I want to build a low noise receiver." I said, "Aha! Now that is an important new application." And then, clearly solid materials, especially ones of low temperature, would have some advantages. The problem then is clearly that you want a device that works CW [continuously] rather than pulsed [as in Pound/Purcell negative temperature]. Just flip it over and you get...that's no good. Then, within weeks I came up with the three level pumping scheme.

The *scheme* was to use a microwave "pump" to saturate a pair of energy levels in a spin system in which there is an intermediate state, and in which one of the upper two states

15. Oral history of the origin of the term maser, as related by Jim Gordon, "Reflections on the First Maser," *Optics & Photonics News* (May 2010): "In April 1954, when five of us were having lunch in the Columbia teacher's college cafeteria, Charles Townes proposed that we name the coherent oscillator that we had just created. He vetoed any name that ended in '-tron.' Before we left, we had created the name maser, an acronym for 'microwave amplification by stimulated emission of radiation.' Before long, Arthur Schawlow had re-imagined the maser acronym to mean 'money acquisition schemes for expensive research.' Back then, none of us could have imagined how critical the maser would be in shaping optical technology in the 20th century and beyond."

16. You can think of this as the nitrogen atom having two locations relative to the plane of the three hydrogen atoms; that is, it's a geometric inversion, not to be confused with a population inversion. Owing to quantum mechanical effects there are two energy states, the difference (~10^{-4} eV) corresponding to the 24 GHz resonance frequency.

17. AIP oral history, available at https://repository.aip.org/node/127787 or https://doi.org/10.1063/nbla.mfxw.wdcj.



THE NEW YORK TIMES, FRIDAY, DECEMBER 13, 1957.

DEVICE WILL AID RADIO TELESCOPE

MASER Amplifier Developed at Harvard to Extend the Range in Space Tenfold

By JOHN H. FENTON
Special to The New York Times

CAMBRIDGE, Mass., Dec. 12 —Harvard University scientists have developed a new amplifier they believe will extend the range of radio telescopes tenfold.

The device was operated for the first time Dec. 7 at the Gordon McKay Laboratory of Applied Science, it was announced today.

The amplifier is known as a three-level solid state MASER. The core of the device is a single crystal of potassium cobalticyanide about the size of the outer joint of a man's thumb. The name stands for microwave amplification by stimulated emission of radiation.

In operation, a radio telescope picks up radiation impulses from hydrogen clouds in galaxies of outer space. The MASER amplifies the range beyond that of any known radio telescope.

The amplifier's potential applications include radar systems as well as research in radio astronomy. A MASER-equipped telescope should provide a test of cosmological theories, such as the theory that the universe is expanding, according to Prof. Thomas Gold, Harvard astronomer and authority on radio astronomy.

Professor Gold also said that use of the device should be able to confirm or deny the existance of hydrogen gases between the galaxies, now only suspected.

The Harvard MASER was developed by a group of Harvard scientists, Dr. Nicholaas Bloembergen, McKay Professor of Applied Physics, who proposed the device in 1956; Dr. J. O. Artman, research fellow in applied physics, and Sidney Shapiro, a graduate student. Funds were provided under a contract with the Army, Navy and Air Force and the Harvard Division of Engineering and Applied Physics.

To Use Device in Telescope

Professor Gold said that the college observatory hoped with the assistance of the Division of Engineering and Applied Physics to apply the MASER to its sixty-foot radio telescope at the Agassiz Station at Harvard, Mass., soon. He said that the complicated and experimental nature of the device would prevent its immediate use.

The Harvard MASER is the first to run successfully on the twenty-one-centimeter band, the frequency of emission of radiation from interstellar hydrogen.

The term MASER was coined by Prof. C. H. Townes of Columbia University, who first successfully constructed amplifiers of this type at least in the free world. He used gas instead of a crystal as an operating medium.

The Russians are known to have written papers on MASERS. But there was no information available at Harvard as to whether they have any in operation.

The first operating solid-state MASER of the Harvard type invented by Professor Bloembergen was built at the Bell Telephone Laboratories a year ago.

Similar ones have been successfully built at the Massachusetts Institute of Technology Lincoln Laboratory, which deals with problems of continental defense. None of these operates at twenty-one centimeters.

The Harvard MASER is made up of potassium cobalticyanide and an intentionally introduced impurity of one-half of 1 per cent of potassium chromicyanide. The crystal is kept cold by a bath of liquid helium at 2 degrees Kelvin, a temperature only slightly above absolute zero. (minus 459.6 degrees Fahrenheit).

Electrons of the impurity in three energy levels are used. Amplification is gained by shifting electrons from level to level within the crystal.

Electrons Shift Levels

Whenever an electron falls from one level to another, as a marble on a staircase, it gives off energy at a specific wavelegnth. But if radiation of the same wave-length comes in from the outside and strikes the electron at the lower level it is kicked back upstairs.

By measuring the amount of radiation created by the electrons bouncing back and forth on the "staircase" scientists are able to interpret the signals that have come from outer space.

Radio astronomy in the twenty-one-centimeter wave band began at Harvard. The radiation from the clouds of hydrogen in space was first recorded in 1951 by two Harvard physicists, Dr. Harold I. Ewen and Prof. Edward M. Purcell, a Nobel Prize winner.

The Harvard College Observatory initiated radio research on the hydrogen cloud in the Milky Way (our own galaxy) in 1953, with a twenty-four-foot radio telescope.

Fig. 6: *The New York Times* reports the first maser amplifier for use at the 21-cm wavelength of galactic neutral hydrogen, which had been discovered by Ewen and Purcell six years earlier (see the 2020 Newsletter article "Radioastronomy's first Spectral Line: 'A Glimpse of the Handiwork of Creation'").

is metastable (forbidden transition), see Figure 5. The pump saturates the pair of levels (1 & 3, in the figure), generating equal populations (~ "infinite temperature"); the upper level is then overpopulated relative to level 2, which, by Boltzmann, is less populated than level 1. So the transition has an inverted population, ready to amplify (or oscillate) by stimulated emission.

Bloembergen was persuaded by his radioastronomy colleagues to build a maser for the 21 cm line of neutral



Fig. 7: The world's first hydrogen-line maser deployed on a radiotelescope, rescued from oblivion by Prof. Jim Moran (pictured). All the action happens at the very top (see Fig. 9). It now resides in Harvard's Collection of Historic Scientific Instruments. Sadly, the cryogenic dewar, magnet assembly, and other accoutrements are lost to history.

hydrogen, which had been discovered by Harold Ewen and Purcell just four years earlier. As Nico put it, in his oral history,

> ...the ones who had been thinking about that were of course the people here at Harvard who discovered the 21 centimeter line, and all the astronomers were ape about interstellar hydrogen and 21 centimeters, and clearly there is where you wanted the most sensitivity. So it was a very good goal to aim for in academia, and of course the Harvard Radiotelescope then eventually had a 21 centimeter maser receiver. But in retrospect it was unfortunate, that choice, because it turned out that the maser at 21 centimeters was much harder to build than a maser at X-band. And that's one of the reasons why we didn't build the first maser. The first maser was built at Bell Labs.

The Harvard 21 cm maser was working by the end of 1957, with a *Physical Review* paper submitted in December (Artman, Bloembergen, and Shapiro, "Operation of a Three-Level Solid-State Maser at 21 cm"), but, as Nico ruefully observed, the Bell Labs group (Scovil, Feher, and Seidel) beat them by a year ("Operation of a Solid State Maser"), submitted to *Physical Review* in December, 1956. Harvard's, though later, earned a place in *The New York Times* (Fig. 6).

But neither of these masers was able to operate on a radio-telescope – they were laboratory versions, followed within a few years by fully fieldable masers. The Harvard maser (Fig. 7), complete with cryogenic dewar, was operated on the 60' telescope at Harvard, Massachusetts (Fig. 8), where, even as reported in its initial publication,[18] it demonstrated a tenfold improvement in signal-to-noise ratio in observations of neutral hydrogen in the nebula M33.[19]

We finish the narrative about the invention of masers – both Townes' ammonia maser and Bloembergen's solid-state maser – by comparing them in two aspects. The ammonia maser operates at a fixed frequency (the ammonia inversion frequency, around 24 GHz), whereas the solid-state maser can be tuned by varying the magnetic field, as can be seen in the energy level diagram of Figure 5 (the arrows indicate the operating conditions of Giordmaine et al.). Additionally, the solid-state maser (as with most things solid-state) is delightfully compact, see Figure 9.

Solid-state maser amplifiers were used for many years at radiotelescopes and deep-space communications facilities worldwide, owing to their low noise properties. They were ultimately superseded by low-noise amplifiers built with transistors (HEMT – high electron mobility transistors), which provided almost comparable noise performance with simple trouble-free operation, see Figure 10. We describe these, briefly, in the Epilogue.

18. J. V. Jelley and B. F. C. Cooper, "An Operational Ruby Maser for Observations at 21 Centimeters with a 60-Foot Radio Telescope," *Review of Scientific Instruments* 32, no. 2, (1961): 166. But, once again, the shorter wavelength (X-band) maser was fielded first, see caption to Fig. 5.

19. The 33rd object in Charles Messier's Catalog of Nebulae and Star Clusters. Amusingly, he cataloged objects he was not interested in, because what he wanted to find were comets, and he didn't want to waste his time on fixed objects! Although Messier wasn't interested in the listed objects, his catalog is a favorite of amateur astronomers, and (as in this case) their "Messier numbers" are referenced in professional publications as well.



Fig. 8: Dedication of Harvard's 60' radiotelescope on April 28, 1956 (where, evidently, not enough chairs were provided). Bloembergen proposed the 3-level maser a few months later, and by 1960 it had been deployed at the prime focus of the telescope (up where the legs of the tripod meet). You can see (barely) Prof. Donald Menzel (director of the Harvard College Observatory, seated) at the platform; also pictured is a Chevrolet Styleline Deluxe of unknown ownership. [Image courtesy of the Harvard University Archives.]

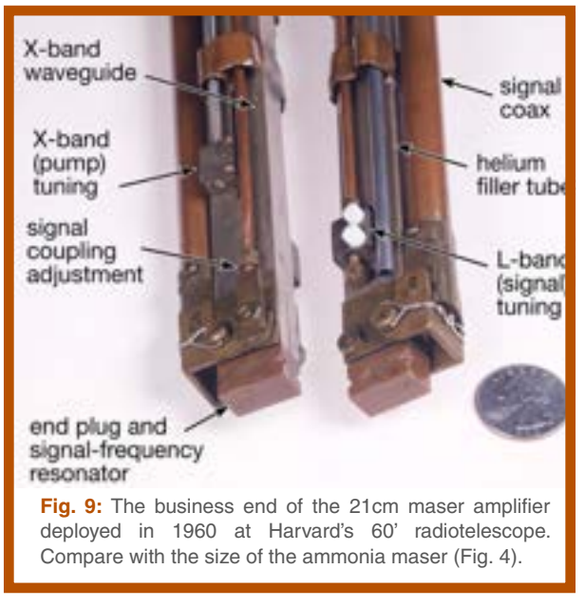


Fig. 9: The business end of the 21cm maser amplifier deployed in 1960 at Harvard's 60' radiotelescope. Compare with the size of the ammonia maser (Fig. 4).

Maser *oscillators*, by contrast, continue[20] to provide precise timing at radio observatories, see "'Unprecedented Spectral Purity': The Invention of the Hydrogen Maser" in the 2022 *Newsletter*. And diode- or flashlamp-pumped solid-state *lasers* – with Bloembergen's 3-level pumping scheme – are here to stay: they are used for all manner of applications, both industrial and scientific. Even the humble green (532 nm) laser pointer is the beneficiary of Nico's invention: a typical model uses an 808 nm pump to create a 1064 nm IR beam from a neodymium-doped yttrium orthovanadate crystal, which is then converted to 532 nm green in a $KTiOPO_4$ nonlinear frequency-doubling crystal. By some estimates, 10 million or more diode-pumped green lasers are produced annually.

LATER WORK WITH LASERS: NONLINEARITIES

One might have guessed that Nico, having created the solid-state maser, would have made the next move, to the shorter wavelengths of the laser. But not so. As Nico relates in his oral history,

> I realized that this pumping scheme would apply at other wavelengths, but I ...lacked the far-sightedness of Townes and Schawlow... to really take it seriously and try to build a device that would work at optical frequencies.

But, once the laser was a reality (thanks to Townes, Schawlow, and Maiman) Nico jumped in with both feet. Motivated by the 1961 observation (by Franken et al.) that a sample of quartz, when irradiated with an intense pulse of light, generated light at half the wavelength (second harmonic generation), Nico and colleagues got into the game, building their own ruby laser, and, of greater importance, working out the theory of nonlinear effects produced by intense laser pulses in their classic 1962 paper "Interactions between Light Waves in a Nonlinear Dielectric."[21]

Where does this nonlinearity come from? As Nico noted in his 1981 Nobel lecture, a small (1 cm) ruby laser can generate a pulsed flux of 10 terawatts/cm^2 at its focused beam,[22] which corresponds to an electric field of some 100 megavolts/cm, comparable to the internal fields of atoms and molecules. So the electrons are "pulled out of their orbits," creating a dense plasma, and with it an optical response that is anything but linear; and such nonlinearities are present even at far less extreme incident fluxes.

In the years following, Bloembergen became the leader in the field of nonlinear optics, with experimental and theoretical contributions in nonlinear optical susceptibility, second- and third-harmonic generation, optical rectification, parametric amplification, nonlinear stimulated Raman and Brillouin scattering, nonlinear optics at surfaces, and nonlinear spectroscopy. This work had the greatest impact, eclipsing even his impressive accomplishments in NMR and his invention of the solid-state maser. The Nobel committee specifically cited this (without even a mention of his maser invention) in the award ceremony speech:

> Nicolaas Bloembergen has contributed to the development of laser spectroscopy in a different way [compared with previous Nobelists Townes, Basov, and Prokhorov]. Laser light is sometimes so intense that, when it is shone on to matter, the response of the system could not be described by existing theories. Bloembergen and his collaborators have formulated a more general theory to describe these effects and

20. Perhaps not for long: optical lattice clocks and trapped ion clocks are doing very well, with stabilities in the 10^{-18} territory; and the demonstration of optical excitation of an extraordinarily low energy nuclear transition (8.4 eV!) in thorium-229 may presage even better clocks. See, for example, X.Tong, L. Hua, X. Hua, and X. Liu, "The ticking of thorium nuclear optical clocks: a developmental perspective," *National Science Review* 12, no. 8 (2025), https://doi.org/10.1093/nsr/nwaf083. At the commercial level, you can buy an iodine-based optical clock from Vector Atomic that claims performance (1000 s Allan Deviation) comparable to a hydrogen maser, in a compact (3U: 5.2" high) turnkey package, transportable and suitable for field use (it was even tested at sea, see J.D. Roslund et al., "Optical clocks at sea," *Nature* 628 (2024): 736).

21. J. A. Armstrong, N. Bloembergen, J. Ducuing, and P. S. Pershan, *Physical Review* 127, no. 6 (1962): 1918.

22. To put that amount of power in context, he noted that the total electric power generated on Earth was about one terawatt. Always eager to educate, he noted also that "the affix 'terra' is derived from the Greek τέρας = monstrosity, not from the Latin 'terra'!"

> founded a new field of science we now call non-linear optics. Several laser spectroscopy methods are based upon this phenomenon, particularly such methods where two or more beams of laser light are mixed in order to produce laser light of a different wave length. Such methods can be applied in many fields, for instance, for studying combustion processes. Furthermore, it has been possible in this way to generate laser light of shorter as well as longer wave lengths, which has extended the field of application for laser spectroscopy quite appreciably.

EPILOGUE

Circling back to Nico's low-noise solid-state maser, stunning progress in solid-state electronics during the intervening years has resulted in contemporary amplifiers with remarkably low self-noise, even when operated at ambient temperatures. For example, a recent HEMT design[23] (Fig. 10) achieves a noise temperature $T_N \leq 7$K over the band 1.2–1.6 GHz at room temperature, in a package roughly 9×5×2 cm – no cryogenics, no pump oscillators, and no fussy tuning. Chill it to 0°C and T_N is around 5K over most of that band, and drops another 2K when operated at -40°C. When fitted with such amplifiers, contemporary radiotelescopes routinely achieve system temperatures of 15–30K; when installed at the Caltech Radio Observatory, for example, the system noise temperature with this particular amplifier measured 22K. Quite an improvement, with this simple amplifier, over the 85K figure obtained with the complicated and fussy maser of Figure 7 at the focus of the dish in Figure 8!

Contemporary state-of-the-art radiotelescopes exploit such performance, covering bands all the way up to 100 GHz. A fine example is the ALMA array in Chile (Fig. 11), where chilled HEMT amplifiers achieve noise temperatures of 30K up to 50 GHz, and 45K to 100 GHz. At higher frequencies ALMA uses cryogenic SIS[24] mixers, followed by HEMT amplifiers; typical noise temperatures are in the range of 100K (to 200 GHz), rising to 350K (to 950 GHz). At the highest frequencies the ALMA receivers are just a few times noisier than the quantum limit.

and, before we get too cocky...

Nature got there first! In 1965 a group of Berkeley radioastronomers were mystified by "Observations of a Strong Unidentified Microwave Line and of Emission from the OH Molecule,"[25] reporting:

> There is no known identification of the strong emission line at 1,665 Mc/s shown in Fig. 1. In what follows, for brevity in writing and to emphasize the surprising nature of the observation just presented, we shall speak of this unidentified line as arising from 'mysterium.'



Fig. 10: The contemporary L-band low-noise amplifier of Weinreb and Shi achieves a noise temperature of 7K when operated at ambient temperature. (Permission for enhanced publication of photo in IEEE MTT, April 2021 article, granted by author S. Weinreb.)

23. S. Weinreb and J. Shi,"Low Noise Amplifier With 7-K Noise at 1.4 GHz and 25°C," *IEEE Transactions on Microwave Theory and Techniques* 69, no. 4 (2021): 2345.

24. Superconductor–Insulator–Superconductor quantum tunneling devices; see, for example, J. R. Tucker, "The Birth of SIS Mixers," in *Submillimeter Astrophysics and Technology: A Symposium Honoring Thomas G. Phillips*, ASP Conference Series 417 (2009).

25. H. Weaver, D. R. W. Williams, N. H. Dieter, and W. T. Lum, *Nature*, 208, 29.

They found mysterium in several other galactic regions, and they noted, "…they are also unusual because the intensity ratios of the emission lines appear to depart greatly from the theoretical OH intensity ratios predicted for normal thermal emission or absorption." They remarked, also, on the "extreme narrowness" of the emission features ("this is the narrowest line so far observed in the interstellar medium"[26]), and they speculated that it may emanate from a point source.

Readers are likely jumping out of their seats, shouting "it's a *maser*, for heaven's sake!" And it is: in quick succession several groups published papers with "maser" in the title: "Maser Action in Interstellar OH"[27] and "Maser Model for Interstellar OH Microwave Emission."[28] From the first of these "These properties strongly suggest that an emission process is at work which, like a maser, involves pumping of the medium by some mechanism at one frequency and a discharge by stimulated emission at the observed radio frequencies" and from the second "We will present a maser amplifier model, based on ultraviolet continuum pumping from nearby stars, which seems capable of explaining most of the observations, including those of anomalous absorption."

A year later an interferometer formed by the 60' Harvard radiotelescope (with Bloembergen's maser amplifier!), in combination with the 84' Millstone antenna some 13 km away, limited the source size of the OH maser W3 to less than two arc-seconds.[29] If the source were of thermal emission, the observed spectral brightness in the small source region would correspond to a temperature >10^9K (which would, of course, dissociate the OH molecules), whereas the spectral line Doppler broadening of <1 km/s suggested that the emitting gas had a kinetic temperature of just a few hundred degrees; this observation added impressive support to the maser model.

In an interesting historical connection to Harvard radioastronomy, thirty years earlier Prof. Donald Menzel had written,[30] in the first of his series "Physical Processes in Gaseous Nebulae,"

> Outside of thermodynamic equilibrium, the condition may conceivably arise when the value of the integral turns out to be negative [an inverted population]. The physical significance of such a result is that energy is emitted rather than absorbed. This energy must be distinguished, however, from that arising in random emissions. The process merely puts energy back into the original beam, as if the atmosphere had a negative opacity. This extreme will probably never occur in practice.

SOURCES AND REFERENCES

In addition to the references cited in the text and footnotes, the following were used in the preparation of this short history:

- G. Holton, P. Pershan, and E. Mazur, "Nicolaas Bloembergen," *Memorial Minute*. Faculty of Arts and Sciences, Harvard University, Nov. 6, 2018;
- E. Mazur, "Nicolaas Bloembergen," *Biographical Memoir*. National Academy of Sciences, 2024;
- Obituaries in *The Boston Globe*, in *The New York Times*, in *Physics Today*, and in *Nature*;
- C.H. Townes, *How the Laser Happened*. Oxford University Press, 1999;
- C.H. Townes, "The Laser and How It Happened," in *The Scientific Legacy of the 20th Century*, Pontificiae Academiae Scientiarum Acta 21. Vatican City, 2011;
- J. Moran, "The Quantum Electronics Assembly of the Bloembergen Maser Used to Amplify Signals from Cosmic Radio Sources of Natural Origin at the 60-foot Agassiz Radio Telescope," draft of document prepared for the Harvard Collection of Historic Scientific Instruments, 17 April 2026;
- AIP Oral History transcripts (Niels Bohr Library & Archives) of interviews with Bloembergen, Scovil, and Townes;
- and conversations with Jim Moran and with Eric Mazur.

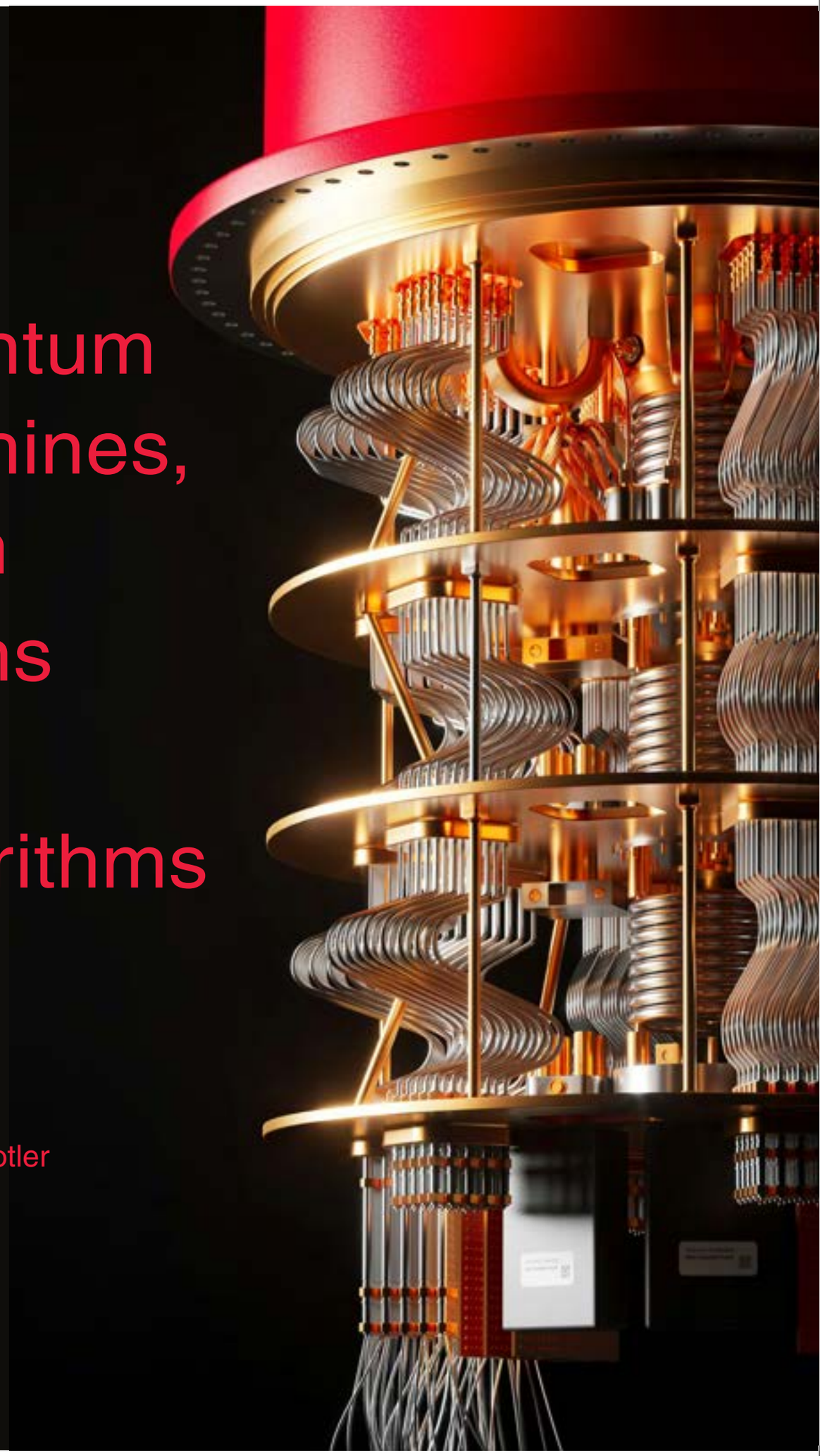
26. The narrowest observed galactic OH lines are ≤1 kHz, their width caused mostly from Doppler broadening in the turbulent gas medium; estimates of their intrinsic line width are in the range of 0.01–0.1 Hz.
27. F. Perkins, T. Gold, and E. E. Salpeter, *The Astrophysical Journal* 145 (1966): 361.
28. M. M. Litvak, A. L. McWhorter, M. L. Meeks, and H. J. Zeiger, *Physical Review Letters* 17, no. 15, (1966): 821.
29. J. Moran et al., "Observations of OH Emission in the H II Region W3 with a 74400λ Interferometer," *The Astrophysical Journal* 148 (1967): L69.
30. D. H. Menzel, "Physical Processes in Gaseous Nebulae," *The Astrophysical Journal* 85 (1937): 330.



Fig. 11: A portion of the 66-telescope ALMA array, in the high Atacama desert of Chile, photographed by the gasping author at its elevation of 16,400 ft.

No text was created or derived, in any form, with the use of artificial intelligence.

Quantum Machines, From Atoms to Algorithms



By Jordan Cotler

Across the Harvard Department of Physics, theorists and experimentalists are learning how to compute, simulate, communicate, and sense with quantum systems.

Quantum computing promises to harness the power of quantum mechanics to process information and perform computation in ways fundamentally different from ordinary, classical computers. It holds the potential to enable algorithms vastly more powerful than those accessible to today's best supercomputers, reveal the mysteries of quantum matter, and probe natural systems with unprecedented precision in the laboratory. Developing such quantum computers has been an international scientific effort, and the Harvard Physics Department has positioned itself at the forefront of this endeavor.

To understand the different facets of quantum computing, it helps to begin with what makes a quantum computer different from a classical computer. An ordinary classical bit can be either 0 or 1. A quantum bit, or qubit, can instead exist in a quantum superposition of 0 and 1, for example a state that yields 0 with 37% probability when measured and 1 with 63% probability. The real power of quantum computing emerges when many qubits are combined. Two qubits can exist in a superposition of 00, 01, 10, and 11; three qubits in a superposition of eight possibilities, from 000 to 111. With each additional qubit, the number of possibilities doubles, growing exponentially with the number of qubits.

This might appear to suggest that quantum computers are automatically exponentially more powerful than classical ones, but the story is more complicated. When a quantum state is measured, its superposition disappears and the measurement produces only a single outcome. The art of a quantum algorithm is therefore to manipulate the superposition so that different computational possibilities interfere: desirable answers reinforce one another, while undesirable ones cancel. In this way, the wavelike nature of quantum mechanics can be cleverly harnessed to draw useful answers from an exponentially large space of possibilities.

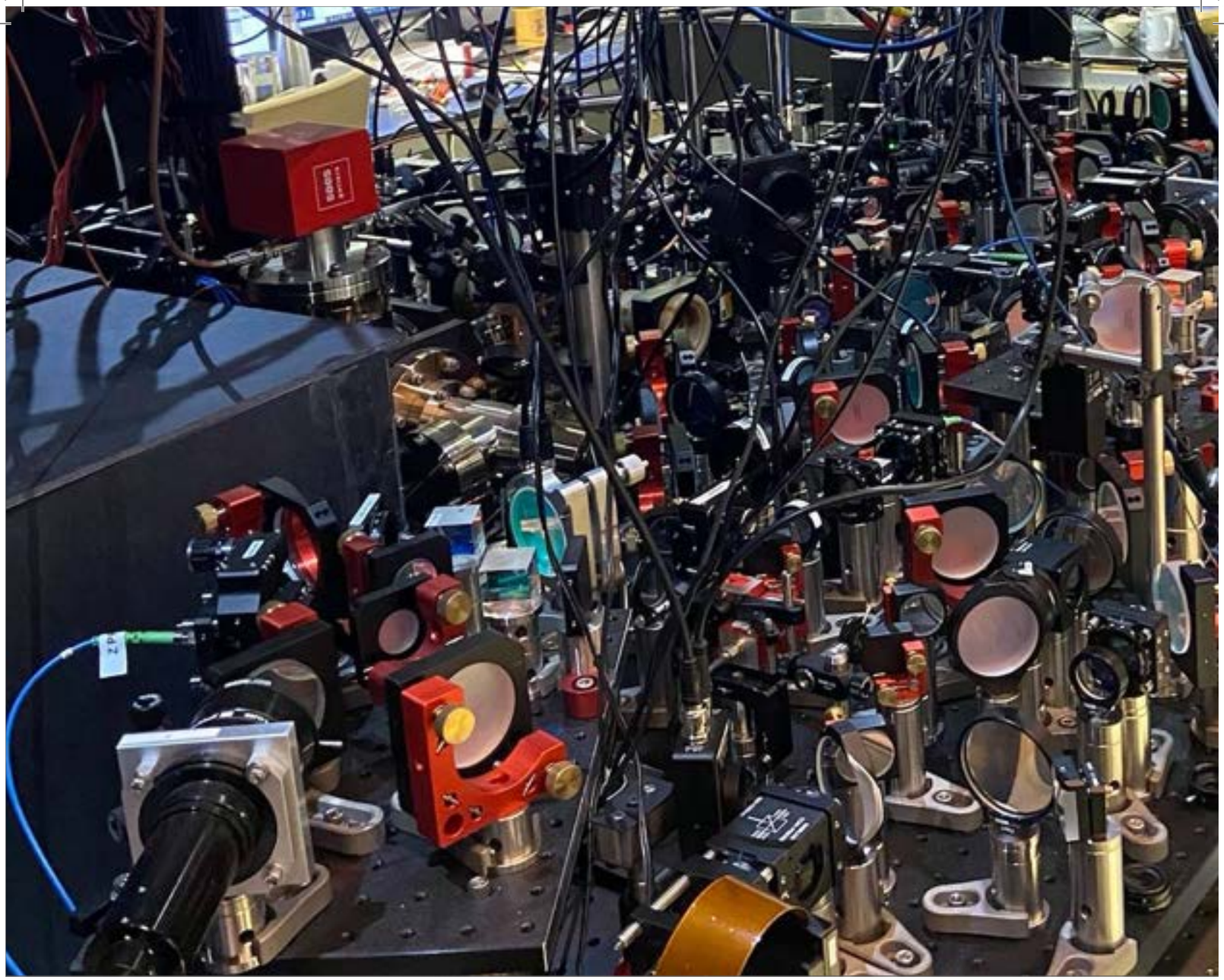
While a quantum computer can be very useful in theory, the practicalities of building one are formidable. For example, one must figure out the physical substrate from which to build stable and controllable qubits. One novel approach is to use individual atoms as qubits, and Joshua and Beth Friedman University Professor Mikhail Lukin has done just that. In the work carried out in Lukin's laboratory, in close collaboration with George Vasmer Leverett Professor of Physics Markus Greiner at Harvard and Lester Wolfe Professor of Physics Vladan Vuletic at MIT, individual rubidium atoms are trapped and arranged using tightly focused laser beams called optical tweezers. The atoms can then be excited into special, highly energetic states known as Rydberg states, in which they behave as qubits and interact strongly with one another. By controlling these interactions with lasers, scientists can make large arrays of atoms behave as programmable quantum computers, using them to perform quantum computations.

Neutral atoms are just one way to realize a qubit. Henry B. Silsbee Professor of Physics John Doyle's group is pursuing a complementary approach based on ultracold polyatomic molecules, whose rich internal structure provides a resource for quantum computation, simulation, and precision measurement. The group has recently demonstrated long-lived qubits in laser-cooled CaOH molecules and controlled interactions between molecular states, which could support quantum information processing and enable new detection methods for physics beyond the Standard Model.

The same precise control that makes atoms and molecules useful as qubits also allows one quantum system to be used to simulate another. This is the idea of quantum simulation, and it is central to the work of Prof. Greiner. His group uses ultracold fermionic lithium atoms trapped in an optical lattice, an artificial crystal created by intersecting laser beams. In this setting, the atoms can mimic the behavior of strongly interacting electrons moving through a solid. Using a quantum gas microscope, the Greiner group can image and manipulate the atoms individually, providing an extraordinarily detailed view of quantum matter. In particular, their experiments realize the Fermi-Hubbard model, an important model for understanding how interactions between electrons give rise to phenomena such as magnetism and potentially high-temperature superconductivity.

Regardless of the physical platform, quantum information remains inherently vulnerable to errors. This creates an apparent paradox: how can we detect and correct an error without measuring the qubits and destroying the quantum state we are trying to protect? The idea is to encode each piece of quantum information across several qubits in a carefully designed entangled state called a quantum error correction code, so that errors can be detected and corrected without revealing the information itself. This method is what makes reliable large-scale quantum computation possible.

Left: An artist's representation of a quantum computer [Courtesy of Planet Volumes on Unsplash]



Making quantum error correction work in practice is itself a challenging problem. Each round of error correction produces a pattern of measurements containing clues about which errors have occurred, and these clues must be interpreted quickly and accurately. Professor of Physics in Residence Susanne Yelin and her collaborators have been devising machine learning methods for this task, using neural networks as decoders that infer which errors have occurred and how best to correct them. In joint work with Lukin and others, she has also helped develop fault-tolerant schemes for neutral-atom quantum computers, in which errors can be detected and repaired repeatedly as a computation proceeds.

Correcting errors, however, is only part of the challenge. Some quantum operations are much easier than others to perform while keeping the information protected, and those operations alone are not enough to realize the full power of quantum computation. One way to overcome this limitation is through special quantum states known as magic states. These states provide an additional resource that allows an error-corrected quantum computer to perform a much broader class of computations. Landon T. Clay Professor of Mathematics and Theoretical Science Arthur Jaffe and his collaborators have developed a mathematical theory of this "magic," studying how it can be quantified, how it appears in complicated quantum states, and how it is related to the difficulty of simulating quantum systems on ordinary computers. Their work helps illuminate what makes certain quantum states especially powerful computational resources.

One particularly elegant form of quantum error correction uses topology. In an ordinary error-correcting code,



Atom array experiment, featuring optical layout, vacuum setup, and classical control electronics for the reconfigurable atom array quantum computing architecture in Mikhail Lukin's laboratory. [Photo courtesy of QuEra]

quantum information is protected by spreading it across many qubits; in a topological code, those qubits are arranged so that the encoded information is stored in large-scale features of the system. A few local errors can distort these features without changing them, and only a sufficiently long chain of coordinated errors can corrupt the information.

George Vasmer Leverett Professor of Physics Ashvin Vishwanath and his collaborators have explored this idea by creating topologically ordered states on programmable quantum computers and manipulating exotic quantum excitations known as anyons. By moving, exchanging, and combining these anyons in carefully controlled ways, one can perform protected quantum operations. This work also creates an interesting bridge back to quantum simulation. Much as the Greiner group uses ultracold atoms to build controllable models of strongly interacting electrons, Vishwanath and his collaborators use quantum processors themselves as laboratories for creating and probing exotic phases of quantum matter. In this manner, the same topological phenomena can both protect quantum information and reveal forms of matter with no ordinary classical counterpart.

The search for topological protection also extends from programmable processors to the materials used to build qubits themselves. Mallinckrodt Professor of Physics and of Applied Physics Amir Yacoby and Professor of Physics and of Applied Physics Philip Kim are exploring two-dimensional van der Waals systems, including transition-metal dichalcogenides, as platforms for topological states that could ultimately support topologically protected qubits. Their interdisciplinary work combines materials engineering, quantum transport, and sensitive probes.

A useful quantum computer also needs a way to move quantum information between processors. The Lukin group, working closely with Tiantsai Lin Professor of Electrical Engineering and Applied Physics Marko Lončar and Mark Hyman Jr. Professor of Chemistry and Professor of Physics Hongkun Park, is building quantum networks in which distant qubits are connected by photons. Using silicon-vacancy color centers in diamond as quantum memories, the teams have entangled two network nodes over a roughly 35-kilometer loop of fiber optic cables in the Boston area. Quantum networks may also need to connect very different kinds of hardware. Doing so requires quantum transduction, the conversion of quantum information from one physical form to another. John L. Loeb Associate Professor of the Natural Sciences and of Engineering and Applied Sciences Julia Mundy, together with Assistant Professor of Electrical Engineering Kiyoul Yang in SEAS, is developing new materials and devices for these conversions.

Once qubits can be built, protected, and connected, there is still the question of what to do with them. Much of quantum computing research is devoted to finding algorithms that would allow quantum computers to succeed when classical computers cannot.

Since systems in nature produce quantum data, a natural question is how we can process and learn from that data using quantum machine learning. This is one focus of my research group, and my collaborators and I have developed quantum machine learning algorithms that can learn properties of complex quantum systems exponentially more efficiently than classical machine learning methods. More broadly, this work is part of an effort to build a quantum version of machine learning theory, asking what can be learned when both the data and the computer processing

them obey the laws of quantum mechanics. Yelin also works on how quantum computers can learn from quantum data, and she recently proposed a theory for learning the dynamics of quantum systems directly from quantum measurements. This past year, I co-taught a new Harvard course on the subject, Quantum Learning Theory, with Prof. Sitan Chen in the Department of Computer Science, introducing students from both physics and computer science to this rapidly evolving field.

Quantum computers may also offer new ways to tackle difficult optimization problems, where the goal is to find the best solution among an enormous number of possibilities. Lukin and collaborators have used Rydberg-atom arrays to study such problems. The interactions between the atoms can be engineered so that favorable configurations of the quantum system correspond to good solutions of the original problem. A related theoretical question is where, more generally, the boundary between classical and quantum computational power lies. Professor of Physics Norman Yao and his collaborators have devised methods to verify quantum computational advantages and, more recently, have shown how noise can make otherwise complex quantum computations efficiently simulable on classical computers.

Another important use of quantum computers is to simulate quantum systems that are difficult to understand by classical calculation alone. As mentioned above, the Greiner group has performed such simulations with ultracold atoms. Herchel Smith Professor of Physics Subir Sachdev has developed theories of strongly interacting quantum matter, including quantum spin liquids, that can now be explored using programmable quantum simulators. These simulations, done by Sachdev, Vishwanath, Lukin, and other collaborators, have connected theoretical ideas about these unusual states of matter with experiments using Rydberg-atom arrays.

The relationship between quantum information and quantum matter also runs in the other direction: quantum-information concepts can become diagnostic tools for real materials. Associate Professor of Physics Matteo Mitrano and collaborators are developing spectroscopic methods to detect many-body entanglement directly in quantum materials. In recent work, an international team led by Mitrano used resonant inelastic X-ray scattering to observe the entanglement of quantum spins in a cuprate material.

With my research group, I have been developing ways of simulating quantum gravity on a quantum computer. In collaboration with Lukin and graduate student Rahul Sahay, we devised a quantum system in which patterns of entanglement give rise to effective particles and interactions that reproduce quantum gravity in a curved spacetime. With Lukin's experimental group, we are leveraging our collective expertise to bring this quantum gravity simulation to life in the lab.

A different use of quantum computation is called quantum sensing: by incorporating quantum computation directly into the sensors or measurement apparatuses, even a few qubits can sometimes extract information from a signal that would be much harder to access with conventional measurements. I have been building a theory of quantum computation-enhanced sensing with graduate student Ishaan Kannan, and we recently collaborated with the group of Associate Professor Peter McMahon at Cornell to realize new kinds of quantum sensors in the lab. Together, we showed that adding even a single controllable qubit to an otherwise conventional sensor can, for certain tasks, exponentially reduce the number of measurements needed to learn properties of a classical signal. We demonstrated this experimentally by using a superconducting microwave cavity coupled to a qubit, finding improvements as large as ten million-fold for particular signal-learning tasks. Remarkably, such advantages do not necessarily require a large quantum computer; in some cases, a single well-controlled qubit can make a dramatic difference.

Quantum sensing is also opening new ways to study matter under conditions that are difficult to access with conventional probes. Norman Yao and his collaborators have developed quantum sensing techniques for studying materials under extreme pressures. One important platform uses nitrogen-vacancy centers (or NV centers): tiny defects in diamond whose quantum states are extremely sensitive to magnetic fields. By incorporating these sensors into diamond anvil cells, the Yao group can map magnetism and superconductivity in materials compressed to enormous pressures, where many conventional probes become difficult to use. In parallel, Yao's and Lukin's groups are also exploring the use of quantum correlations and entanglement to improve such sensors and make them even more accurate with applications to materials science, chemistry, and biology.

Yacoby and his collaborators have used NV centers in a different way, turning individual qubits into nanoscale probes of quantum materials. In recent work, they used carefully controlled microwave pulses to make an NV center act as a magnetic spectrum analyzer, revealing spin dynamics over a wide range of frequencies. These experiments

illustrate that even a single quantum sensor, precisely controlled and measured, can reveal properties of matter that are otherwise extraordinarily difficult to access.

The work described here is only a cross-section of the quantum computing research underway at Harvard. One of the many strengths of our community is its collaborative nature, with projects bringing together researchers from several Harvard groups across Physics, SEAS, Chemistry, and Computer Science, often in partnership with colleagues at other universities.

The Harvard Quantum Initiative has helped make many of these connections possible, bringing researchers and students together and providing a common home for quantum science across the University. As quantum computers become more capable, and as new ways of using even small quantum systems continue to develop, the questions we can ask of nature will expand in scope. The coming years promise not only better quantum computers, but new scientific frontiers that we are only beginning to imagine.



Portrait of Jordan Cotler by Paul Horowitz

New Institute to Strengthen Fundamental Physics Research, Collaboration



The Jefferson Physical Laboratory at Harvard. [Harvard file photo]

Leinweber Institute for Theoretical Physics made possible by $20 million gift from the Leinweber Foundation

Harvard University on Thursday announced the creation of the Leinweber Institute for Theoretical Physics at Harvard, a new initiative focused on strengthening fundamental physics research and connecting physicists across the United States.

Made possible by a $20 million gift from the Leinweber Foundation, the institute, housed in the Department of Physics in the Faculty of Arts and Sciences' Division of Science, will be a hub uniting researchers across the University with those at other leading research institutions to explore the theoretical principles of the physical world.

"Expanding opportunities for collaboration accelerates scientific progress," said Harvard President Alan Garber. "This new institute will strengthen relationships among researchers within our community and across institutions who are working to deepen our understanding of the universe. We eagerly anticipate their discoveries, and we are grateful to Larry Leinweber and the Leinweber Foundation for their support of fundamental research."

A GROWING NETWORK

With the creation of the Leinweber Institute, Harvard joins a growing national network of theoretical physics centers supported by a total investment of more than $150 million by the Leinweber Foundation. The institute will collaborate closely with peers working at California Institute

of Technology; the Institute for Advanced Study; the Massachusetts Institute of Technology; Stanford University; the University of California, Berkeley; the University of Chicago; and the University of Michigan, with each site contributing complementary strengths and shared research fellowship programs.

Underpinning the effort is the idea that theoretical physics progresses most rapidly when scholars from diverse specialties share ideas, tools, and perspectives. The institute's programs will support scholar visits, thematic workshops, and collaborative projects, creating new opportunities for partnership between Harvard theorists and visitors from around the world.

"The foundation's vision is to build a national ecosystem to support theoretical physics — a network of institutes that support one another, challenge one another, and accelerate discovery in ways no single institution could do alone," said Larry Leinweber, founder and president of the Leinweber Foundation. "Harvard is an essential part of that vision. Its history of excellence and its culture of rigorous, creative inquiry make it an ideal participant in the vision. I am especially proud that this gift will help launch and sustain young scientists whose ideas will shape the future of the field."

INVESTING IN THE FUTURE

The gift also establishes the Leinweber Physics Fellows program to support emerging scholars in theoretical physics. A postdoctoral fellowship will enable fellows to pursue independent research under the general supervision of Harvard faculty affiliated with the institute, while faculty and graduate student research will be aided by awards for institute faculty and fellowships to Ph.D. students, attracting top scientists to the field and building a pipeline for innovation and discovery.

"Investing in science is an investment in people — students, postdocs, and faculty whose curiosity and dedication drive every breakthrough," said Hopi Hoekstra, Edgerley Family Dean of the FAS. "This remarkable gift strengthens our ability to support scholars at every stage of their careers and gives them the resources and freedom to pursue bold ideas. We are deeply thankful to the Leinweber Foundation."

The Leinweber Institute's work will span high energy theory — including particle physics, string theory, and quantum gravity — cosmology, and aspects of condensed matter theory that illuminate basic laws of nature. The institute will also support theoretical studies that propose or analyze novel experiments or observations aimed at revealing new facets of fundamental physics.

The institute will be led by incoming faculty director Matthew Reece, a professor of physics in the FAS whose work in particle physics, cosmology, and quantum gravity seeks to uncover physics beyond the Standard Model by connecting fundamental theory to observations and experiments. He has developed new ideas about dark matter, the early universe, and the unexplained features of the Standard Model, and has worked extensively on how data from the Large Hadron Collider, future colliders, and astrophysical measurements can test these ideas.

"It is a great privilege to help launch an institute dedicated to fundamental theoretical physics, at a time when the central questions of the field are as profound and challenging as ever," said Reece. "The Leinweber Foundation's generous gift will sustain and strengthen Harvard's long tradition of training and mentoring great theoretical physicists. I'm delighted by this new opportunity to bring some of the world's best young theorists to Harvard and to give them complete freedom to pursue their scientific interests. I'm excited to see the new ideas and discoveries that will emerge from collaborations fostered within our institute and with the broader Leinweber Network."

BUILDING ON STRENGTH

Harvard's theoretical physicists have long been central to many of the field's most influential advances. Drawing on close collaborations across physics, astronomy, mathematics, and engineering, researchers at Harvard have helped deepen our understanding of the most fundamental laws of nature — ranging from particle physics and cosmology to quantum field theory and gravity — and continue to shape the direction of theoretical research worldwide.

"Harvard's Department of Physics has pushed the boundaries of knowledge in many directions over many decades," said Cumrun Vafa, the Timken University Professor and Physics Department chair. "The generous gift from the Leinweber Foundation enables us not only to enhance our efforts in undertaking theoretical research in fundamental physics at a critical time when there are tremendous financial pressures, but also to better connect us with a network of peer institutions to promote a young cohort of students and researchers, which will impact the future of the field for decades to come."

This article is republished, with permission, from The Harvard Gazette, Dec 22, 2025.



Friends of the Harvard Physics Department

by Marina Werbeloff

A new initiative is taking shape among alumni/ae and friends of the Harvard Physics Department. It doesn't yet have a board or an official membership list, but only a handful of enthusiastic supporters and an idea on how to connect (or reconnect) people with the department while creating a practical and rewarding way to support it.

The group's first chair, Ronald Bradford ("Brad") Malt, notes that the group does not currently have plans to seek affiliation with the Harvard Alumni Association, but rather sees itself as a standalone, department-focused effort, akin to long-running "friends of" communities in other Harvard departments. "It's also different in that it has a real element of collaboration, in person, among professors, students, postdocs, and alums," he says. "It has, so far, taken the form of two in-person meetings, with presentations by physics professors, lab tours, and a chance to share meals together and sit down and talk and ask questions."

The initiative was sparked by an unlikely connection. Malt, a retired lawyer and Harvard applied math alumnus, got to know Landon T. Clay Professor of Mathematics and Theoretical Science Arthur Jaffe through a common love of Bordeaux wine. Jaffe,



who founded the long-running Friends of the Harvard Mathematics Department, suggested to Malt that a similar model could support the Physics Department as it navigates modern budgetary constraints. Through Jaffe, Malt was introduced to Timken University Professor Cumrun Vafa, and the concept for a physics-focused alumni group began to take shape.

The initial, proof-of-concept meeting took place on November 16, 2025, in Jefferson Lab and showcased the range and ambition of today's research at Harvard. The program opened with breakfast and a welcome introduction to the department from Vafa, who at the time served as Chair of the Harvard Physics Department. A series of 20-minute talks by some of Harvard's preeminent physicists followed, highlighting some of the hottest topics in modern physics, from the Rubin Observatory to the Large Hadron Collider, the study of black holes, and the quest to achieve superconductivity outside of extreme cryogenic temperatures.

Malt views the follow-up event on May 3, 2026, also in Jefferson Lab, as the first official meeting of the group. As before, it included lively communal meals and presentations by distinguished Harvard Physics faculty that reflected the department's intellectual breadth and its growing overlap with neighboring fields: on using artificial neural networks to map real neural networks, by Professor of Physics and the current Chair of the department Aravinthan Samuel, and about high-pressure quantum sensing, by Professor of Physics Norman Yao.

A tour then took participants into three experimental research spaces: Professor of Physics Matteo Mitrano's lab, which uses ultrafast lasers to study and control quantum materials; Yao's lab, which studies entanglement in solid-state color centers and quantum sensing, among other topics; and Samuel's lab, which works on imaging whole-brain circuits that drive animal behavior. The late morning concluded with Professor of Physics Matthew Schwartz's talk on AI and the future of theoretical physics, and with Herchel Smith Professor of Physics Subir Sachdev's presentation on superconductivity, black holes, and quantum matter, with Malt delivering the closing remarks.

Lunch followed, with time built in for group discussion, which Malt sees as central to the initiative's appeal. For him, it's as much about the people as the topics: returning to Harvard campus to hear what faculty are working on, to see where the research happens, and to have the kind of informal conversations that rarely fit into a formal lecture or a typical alumni event.

While Malt emphasizes the importance of the in-person element (the informal interactions with the Harvard community that make the experience so worthwhile), he says the group is also considering the possibility of remote participation, to accommodate the alumni who cannot travel to Cambridge.

Malt points out that, because the initiative is still so young, many questions about its future shape and span are yet to be answered, depending on the interests of the future participants. "It's really still a nascent operation that is a kernel of something very helpful, but how it fully flowers and develops, is TBD," he says.

So far, the group has not yet sent its first formal solicitation (even though the department has already received some unsolicited support from individuals who learned about the Friends of Harvard Physics initiative and wanted to help). Malt's near-term vision is to communicate more clearly how gifts can be directed to the Physics Department, and to begin outlining examples of needs that might resonate with different donors. Over time, he expects the group to be able to offer a "menu" of ways to contribute, ranging from discretionary funds the department chair can deploy for immediate priorities to larger philanthropic investments for those who want to fund something more substantial.

Asked about who he thinks might be interested in participating in the Friends of Harvard Physics initiative, Malt says it's anyone, "regardless of whether they were classics majors or physics majors, who have ended up with an interest in physics.... It doesn't have to be their profession: There are a lot of people for whom topics like quantum computing, and the grand unified theory, and AI have just grabbed their imaginations, so we'd love to have people who are interested in getting closer to the department, from anywhere!"

The aim, in other words, is to create a community that makes it genuinely rewarding to stay close to the department: the science, the labs, the faculty and students and postdocs, and the network of fellow alumni who share the same sense of intellectual excitement.

To learn more or to be added to the Friends of the Harvard Physics Department mailing list, please contact Brad Malt (brad.malt@ropesgray.com) or Academic Programs Specialist Jolanta Davis (jmdavis@fas.harvard.edu).



ACADEMIC PROGRAMS

Undergraduate Program

By Dionne Clarke

In May 2026, we proudly graduated 47 outstanding seniors with bachelor's degrees in Physics or Chemistry & Physics. Approximately 60% of our graduates are pursuing advanced degrees in science or medicine at Cambridge, Caltech, Oxford, Stanford, MIT, Yale, Cornell, Columbia, NYU, and right back here at Harvard. Notably, recent graduate Miller MacDonald won a Fulbright grant and will be taking classes at the Niels Bohr Institute for a year before returning to Harvard for his Ph.D. studies. Of the roughly 35% of students pursuing roles in industry, 10% are joining companies focused on the development of artificial intelligence, a higher percentage than we have seen in recent years. Two students are even developing companies of their own. The remaining 5% are pursuing other paths, including law and music. We look forward to catching up with our graduates down the line and learning more about their professional journeys.

Among our graduating seniors, an unprecedented number received departmental prizes: Lucy Nathwani, Christopher Prainito, and Daniel Salkinder won the Sanderson Prize for highest GPA, while Mary Cipperman, Loralei Cook, and Callie Garcia were awarded the Carol Davis Prize for exceptional service to the Physics community.

Mary served as a co-president of our Society of Physics Students and worked tirelessly to keep SPS organized and running efficiently. Callie co-chaired the Events & Panels committee, helping to organize high-visibility department events such as the Pumpkin Drop and Exploring Fields of Study. Loralei Cook gave four years of exceptional service to the department, diligently supporting our daily community coffee breaks, managing technology for the weekly colloquia, and mentoring new student workers.

We are honored to acknowledge Lucy Nathwani, who, in addition to winning the Sanderson Prize, received the American Physical Society's LeRoy Apker Award. Established in 1978 in

Above: Physics alumni/ae reunion, June 6, 2026. [photo by Paul Horowitz]

Next page: Festive dinner for graduating seniors, May 19, 2026 [photo by Dionne Clarke]



honor of experimental physicist LeRoy Apker, this award is the highest national honor given for undergraduate research in physics in the United States. Only two awards are given each year.

Finally, we'd like to recognize the 2026 winners of the Hertz Foundation Fellowships in applied sciences, engineering, and mathematics. Congratulations to Andrew Chu, Miller MacDonald, and Nikhil Seshadri. The Hertz Foundation is the nation's preeminent nonprofit organization dedicated to advancing American scientific and technological leadership.

We would like to thank all those who participated in the Physics Alumni/ae Reception for the 5th through 25th reunion classes! On June 6, 2026, we welcomed over 100 alums and their families back to the Physics Department to reconnect with old friends, tour labs, and even enjoy science demonstrations for the kids. Professors Jennifer Hoffman, Stefan Knirck, and Matteo Mitrano opened their laboratory spaces and gave tours to over 40 participants. We hope to expand the event in the coming years to include even more alumni/ae.

The Society of Physics Students has had another productive year. We've witnessed an explosion of interest in the Directed Reading Program (DRP) with over 30 mentors and mentees participating each semester. Similar to the POLARIS committee's mentorship structure, DRP pairs graduate students with undergraduates for a semester-long independent reading or research project. This program allows graduate students to share some of their favorite physics topics with an undergraduate peer or explore something new together. We are so proud to see DRP grow.

This year's Chilloquium committee hosted Prof. David Mattingly, a theorist at the University of New Hampshire; Dr. Morgan Dwyer, Head of Policy Operations at OpenAI; and Prof. Tatiana Erukhimova, YouTube star and Chair of Physics Outreach at Texas A&M. Prof. Erukhimova gave a rousing virtual presentation on August 6. Here's Chilloquium co-chair Dominic Lehane's take on the experience:



College physics is full of tears. Problem sets, exams, and the heat death of the universe are enough to make any student weep. However, physics also brings forth tears of joy. During last summer's final Chilloquium, several students became misty-eyed when listening to Tatiana Erukhimova discuss her journey into physics and her physics pedagogy research. Professor Erukhimova, Chair of Physics Outreach at Texas A&M, is world-renowned for advancing physics education through innovative pedagogy, large-scale science festivals, and popular physics demonstrations. Besides her contributions to physics education, Professor Erukhimova is a talented lecturer, whose ability to captivate an audience is lightning in a bottle. Presenting via Zoom, Professor Erukhimova demonstrated the principle of inertia by embedding the tip of a massive knife into a potato, holding the knife and potato in the air, and then sharply striking the knife's butt, driving the rest of the blade through the potato while the spud itself appeared motionless.

Although everyone is welcome, the Chilloquium Committee directly invites other Boston-area physics students to attend our talks. After each presentation, time is reserved for students to ask questions.



Rachel Fields '27

Student Spotlight

Rachel Fields ‘27

Rachel has spent all three of her college summers doing physics research. Currently, Rachel is working with Professor Tziperman studying variations in the Atlantic Meridional Overturning Circulation (AMOC), the system of ocean currents that circulates water within the Atlantic Ocean and likely causes the observed sea surface temperature variability known as the Atlantic multidecadal oscillation. Recently, multiple studies have suggested a weakening of the AMOC which would have catastrophic effects on sea level rise, global temperatures, and precipitation levels. Rachel’s ongoing project uses particle Markov-chain Monte Carlo algorithms to identify the key drivers of AMOC variability by fitting self-sustained and damped oscillation models to AMOC variability simulated by state-of-the-art CMIP6 models.

A damped model of AMOC oscillates in response to weather variability while a self-sustained AMOC would exist and oscillate even without external forcing. Attributing AMOC variability to either of these models would guide our understanding of how AMOC will respond to climate change and allow us to make better predictions about future AMOC behavior.

Aside from her work in physical oceanography, Rachel also spent time working with Professor Argüelles-Delgado to analyze neutrino dimuon data from the IceCube collaboration. Neutrino dimuons refer to the creation of two high-energy muons by a neutrino interaction. Rachel’s project used Monte Carlo simulations to scan for the angle between the pair of dimuons. Understanding the angle dependence between the two produced muons is important to differentiating dimuons from other particle events that hit the sensors and confirming that dimuon data is accurately labelled as such.

Prior to her work with Monte Carlo simulations, Rachel worked in Professor Doyle’s lab where she built external cavity diode lasers (ECDLs) in support of searches for beyond the Standard Model physics, particularly focused on finding ultralight dark matter. The two ECDLs she built improved the magneto-optical trap of strontium monohydroxide (SrOH) molecules by increasing the photon cycling by up to a factor of two, which allows for more precise measurements of SrOH properties.

In addition to physics, Rachel is pursuing a secondary in Government and a citation in Spanish. She also spends a significant portion of her time supporting other students as a Course Assistant, Peer Tutor, and Peer Advising Fellow for first years. Outside of academics, Rachel has served on the board of several clubs, including the Harvard Undergraduate Association, Harvard Hillel, and Club Swim. Following college, Rachel plans to pursue a Ph.D. in Physical Oceanography. To advance that goal, she supported Professor Langmuir’s geophysics work on a research cruise in the Pacific Ocean for two weeks in August.

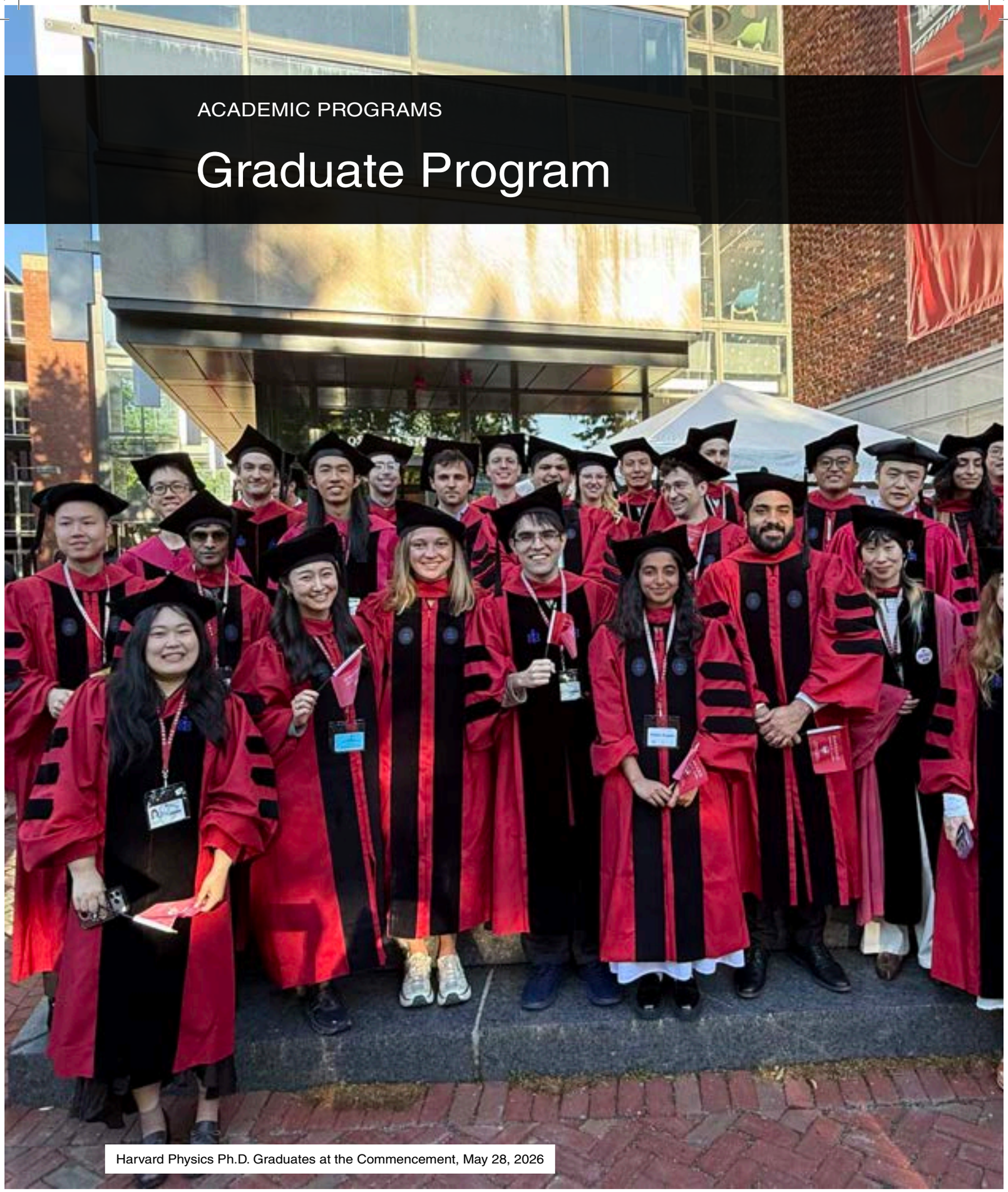
Rafael Jacobsen ‘27



Rafael found out about Professor Aravi Samuel’s lab through a Physics Night Seminar, where he was immediately interested in how a physicist approaches fundamental questions in neuroscience. For the past few years, Rafael has investigated the neural activity of small worms, called C. elegans, as they move freely in response to temperature. These simple worms only have 302 neurons in their entire nervous system, allowing tractable analysis to be done on their neural data. Rafael’s work in the lab involves designing and performing experiments, creating pipelines for image analysis of complex videos, and interpreting the behavior and neural activity of these small worms. This past summer, he did theoretical research at the Flatiron Institute on the same neural circuit in C. elegans. The opportunity to work in Professor Samuel’s lab cemented his interest in experimental neuroscience with a physicist’s approach, and he plans to apply for graduate school in physics in the fall. In his free time, Rafael rock climbs, bikes long-distance, does homeless outreach, and plays cello.

ACADEMIC PROGRAMS

Graduate Program



Harvard Physics Ph.D. Graduates at the Commencement, May 28, 2026



The incoming G1 cohort includes students from eight countries (the United States, China, South Korea, Canada, Germany, Portugal, Spain, and Taiwan) and represents the full breadth of physics research, spanning atomic, molecular, and optical physics, astrophysics, biophysics, condensed-matter physics, high energy physics, machine learning and artificial intelligence, mathematical physics, neuroscience, statistical physics, quantum foundations, and quantum gravity. Among these incoming students, 7 are primarily interested in experimental physics, 10 in theory, and 6 in work across both domains. Beyond their scientific pursuits, these students bring a rich array of interests and talents from outside physics — with hobbies ranging from blacksmithing to dance to pottery — underscoring the diverse experiences and perspectives this cohort will contribute to the department.

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.

J. Pablo Bonilla Ataides: 2026 GOLDHABER PRIZE WINNER (theory)



J. Pablo Bonilla Ataides received his Bachelor of Science and Bachelor of Advanced Studies in Physics and Mathematics from the University of Sydney, graduating with First Class Honours and the University Medal. He subsequently worked as a research assistant at UNSW and as a quantum scientist at PsiQuantum before coming to Harvard, where he completed an M.A. and is now finishing his Ph.D. in Physics in Professor Mikhail Lukin's group. During his graduate studies, Pablo has published numerous papers in leading scientific journals, including Nature and Science, and has been invited to present his work at conferences around the world, including the APS Global Physics Summit.

Pablo's research focuses on fault-tolerant quantum computation and, in particular, quantum error correction. Quantum computers have the potential to solve important scientific problems beyond the reach of conventional computers, but their fundamental building blocks (qubits) are extraordinarily sensitive to noise and errors. Pablo develops new quantum error-correcting codes, architectures, and fault-tolerant protocols aimed at making large-scale quantum computers practical. His work has helped establish high-rate quantum error-correcting codes as a promising route toward reducing the enormous hardware overheads traditionally associated with fault-tolerant quantum computing. By combining theoretical ideas with experimental efforts in neutral-atom quantum computing in the Lukin group, his research aims to bridge the gap between abstract error-correction theory and what can be implemented on real quantum hardware.

Goldhaber Prize (continued)



Anasuya Lyons: 2026 GOLDHABER PRIZE WINNER (theory)

Ana Lyons is a fifth-year Ph.D. student in the Vishwanath group. Before joining the physics department at Harvard, she completed her undergraduate studies at UC Berkeley, where she graduated with highest honors. She grew up in Washington DC, where her love of physics was cultivated during her time as a museum guide at the Smithsonian Air and Space Museum.

During her Ph.D., Ana has worked at the intersection of condensed matter theory and quantum computing. In particular, she studies non-Abelian topological order, a phase of matter containing exotic particles known as "anyons." These particles can be braided around each other to perform quantum computation—a particularly elegant way to build a quantum computer. Ana has contributed to both the theory of computing with non-Abelian anyons, and to the first experimental realization of a "universal" non-Abelian model in a quantum device. Her research has also explored the connections between statistical mechanics and quantum error correction. In all her work, she is motivated by a desire to understand the physics of computation and the ways in which many-body systems process information.



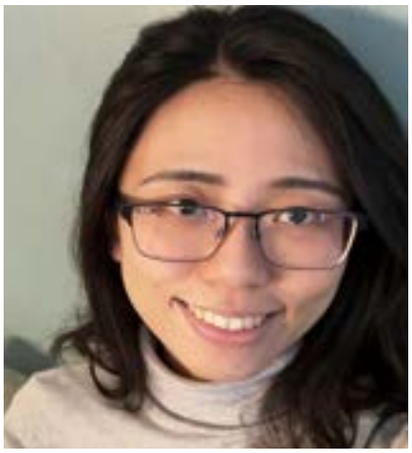
Nik Gjonbalaj: 2026 GOLDHABER PRIZE WINNER (theory)

Nik O. Gjonbalaj studied as an undergrad at Boston University, where he received a Goldwater Scholarship and a B.A./M.A. in physics. During that time, he did research on applying methods from quantum control to classical many-body systems and also on deriving bounds on what kinds of conformal field theories are possible.

Nik is now a rising fifth-year Ph.D. student in the group of Prof. Susanne Yelin. His research focuses broadly on quantum simulation and ways to prepare, evolve, and characterize quantum states. He has worked on understanding collective decay in disordered atomic arrays, preparing non-equilibrium quantum spin liquids, measuring chaos using Hamiltonian learning, and developing new algorithms for quantum chemistry.

Looking forward, Nik wants to find new ways to use emerging fault-tolerant quantum computers to understand quantum many-body physics.

Outside of physics, Nik enjoys bouldering with friends and attending experimental rap concerts.



Grace Li: 2026 GOLDHABER PRIZE WINNER (experiment)

Grace Li completed her undergraduate studies in physics and computer science at the University of Toronto, where she developed an interest in atomic, molecular, and optical (AMO) physics. She is now a Ph.D. student at Harvard University in Professor John Doyle's research group, where she investigates pathways toward achieving quantum control of polyatomic molecules using laser cooling techniques.

Over the past several years, Grace has contributed to the development of a new molecular laser-cooling technique, the "conveyor-belt MOT," which greatly enhances molecular-cloud compression and enables access to higher molecular densities. She now leads an experiment focused on bringing calcium monoamide ($CaNH_2$), a tetra-atomic asymmetric-top molecule, into the ultracold regime and under quantum control.

The Cutting Prize

The prize was established by bequest of W. Bayard Cutting, Jr., 1900, and is awarded to students "of the very highest intellectual attainments." Winners are chosen by the faculty of the Physics Department.



Zihni Kaan Baykara: 2026 THE CUTTING PRIZE WINNER

Kaan Baykara completed his undergraduate studies at the University of Chicago, earning a B.A. in Physics and a B.S. in Mathematics. He is currently a fifth-year Ph.D. student at Harvard working with Prof. Cumrun Vafa. His research explores quantum geometry and duality, seeking a common origin for apparently different string theories.

Recently, Kaan and his collaborators proposed $S^1 \vee S^1$, two circles joined at a point, as a new quantum geometry for M-theory. They showed that M-theory on this geometry gives rise to Type 0A string theory. In subsequent work, Kaan and his collaborators showed that variants of this geometry describe all the other non-supersymmetric strings. Taken together, these works complete the unification of string theory by placing all string theories, supersymmetric and non-supersymmetric alike, within a single geometric framework.



Xiaomeng Alex Cui: 2026 THE CUTTING PRIZE WINNER

Xiaomeng Alex Cui grew up in Singapore and China and attended the University of California, Santa Barbara for his undergraduate studies. At UCSB, he conducted research in experimental condensed matter physics with Professor Andrea Young, exploring proximity effects between two-dimensional materials and demonstrating how spin-orbit coupling can be induced in bilayer graphene simply by placing it in contact with WSe_2. This work contributed to a study published in *Nature* and sparked his broader interest in studying quantum phenomena in van der Waals heterostructures.

At Harvard, Alex pursues his doctoral research under the guidance of Professor Philip Kim. Building on pioneering work by former members of the Kim group, he developed new techniques to integrate cuprates—a family of high-temperature superconductors—into functional van der Waals heterostructures. These advances enabled the creation and study of unconventional superconductors assembled with atomic-scale precision. In particular, by twisting van der Waals cuprates relative to one another, Alex and his collaborators discovered new interfacial phases that spontaneously break time-reversal symmetry. Through collaborations with researchers at Harvard and other institutions, his work has helped establish van der Waals cuprates as a promising platform for engineering and uncovering new physics in high-temperature superconductors.



Srinivas Mandyam: 2026 THE CUTTING PRIZE WINNER

Srinivas received his B.A. and M.S. from the University of Pennsylvania and his M.Phil. in Physics from the University of Cambridge, where he was a Churchill Scholar.

Srinivas is currently a fifth-year Ph.D. student working with Profs. Norman Yao and Chris Laumann, using quantum sensors to study quantum materials under high pressure. He enjoys developing novel measurement techniques to extract hidden physics from these exotic systems. Outside of the lab, he runs volunteer initiatives to teach grade-school students public speaking skills.

More Graduate Student Awards and Fellowships*

KEMPNER GRADUATE FELLOWSHIP:
Jorin Overwienig

NDSEG FELLOWSHIP 2025:
Matthew Bilotta
Harald Putterman

NSA-LPS QUBIT COLLABORATORY NATIONAL QUANTUM FELLOWSHIP:
Nicholas Poniatowski

NSF FELLOWSHIP:
Santiago Cane
Samuel Christian
Luen Clingerman

ARTHUR SACHS SCHOLARSHIP FALL:
Alexandre Polo

FREDERICK SHELDON TRAVELING FELLOWSHIP:
Aidan Chambers

WHITE PRIZE:
Anjolaoluwa Bamtefa
Julia Book Motzkin
Grace Bramlage
Kiara Carloni
Pangaea Finn
Felipe Gomez
Danielle Grey-Stewart
Christian Hallas
Thomas Hillman
Kellianne Kornick
Annika Lunstad
Abdullah Nasir
Khanh Pham
Sanjay Raman
Yoshihiro Saito
Jaroslav Scheinpflug
Huy Tran
Alex Wen
Weijie Wu

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

AY 2025-2026 Graduates

Maggie Anderson
Thesis: "Synthesis and Characterization of Frustrated Magnets as Thin Films"
Advisor: Julia Mundy

Kees Benkendorfer
Thesis: "Wayfinding: Searching For Hints of New Physics Using a Weakly-Supervised Anomaly Search and a Measurement of High-pT ttZ Production with the ATLAS Experiment"
Advisor: Masahiro Morii

Marcus Bintz
Thesis: "Quantum Magnetism in Dipolar Rydberg Atom Arrays"
Advisor: Norman Yao

Laura Bruce
Thesis: "The Long Game: Searches for Massive, Long-lived Particles at 13.6 TeV with the ATLAS Experiment"
Advisor: Masahiro Morii

Helena Casademunt
Thesis: "Brain-Wide Representations of Olfactory Behavior in C. elegans"
Advisor: Aravinthan Samuel

Shu-Fan Chen
Thesis: "Tracing the Origins: Cosmological Information in the Large-Scale Structure of the Universe"
Advisor: Cora Dvorkin

Neng-Chun Chiu
Thesis: "Continuous Coherent Operation in a Large-Scale Neutral Atom Array Quantum Architecture"
Advisor: Mikhail Lukin

Aaron Coe
Thesis: "Determining the Surface Ground State in YbB_6 and Developing Ultra-Sensitive Nanoscale Dissipation Measurements In Scanning Probe Microscopy"
Advisor: Jenny Hoffman

Aurelien Dersy
Thesis: "Learning Simplicity and Structure in Quantum Field Theory"
Advisor: Matthew Schwartz

Pavel Dolgirev
Thesis: "Design and Control of Strongly Correlated Quantum Matter: From Materials to Programmable Quantum Hardware"
Advisors: Mikhail Lukin, Eugene Demler

Junkai Dong
Thesis: "Two Silhouettes of Strongly Correlated Topological Phases: Fractionalization and Crystallization"
Advisor: Ashvin Vishwanath

Simon Evered
Thesis: "Digital Quantum Simulation and Error Correction with Atomic Processors"
Advisor: Mikhail Lukin

Dan Ferenc Segedin
Thesis: "Redox Engineering of Ruddlesden–Popper Nickelates: Pathways to Unconventional Superconductivity and New Materials Discovery"
Advisor: Julia Mundy

Daniel Fernandez
Thesis: "Probing Short-Wavelength Magnon Scattering with Scanning NV Magnetometry"
Advisor: Amir Yacoby

Haoyang Gao
Thesis: "Interaction-Enhanced Sensing in Solid-State Spin Ensembles"
Advisor: Mikhail Lukin

Felipe Gomez
Thesis: “Advances in Information-Theoretic Differential Privacy: Composition and Calibration”
Advisors: Flavio Calmon, Efthimios Kaxiras

Jinen Guo
Thesis: “Advancing the Scalability Frontier of Neutral Atom Quantum Processors”
Advisor: Mikhail Lukin

Christian Hallas
Thesis: “Laser Cooling of Polyatomic Molecules for Quantum Science”
Advisor: John Doyle

Kevin Hauser
Thesis: “Extending STM Capabilities: Multi-Frequency Lock-In Amplification for Closed-Cycle STM and Tip-Controller Lattice Distortions in WTe_2”
Advisor: Jenny Hoffman

Yan Qi Huan
Thesis: “Nuclear Spin Memories for Silicon-Vacancy Quantum Network Nodes”
Advisor: Mikhail Lukin

Rabia Husain
Thesis: “Understanding the Standard Model and Beyond Using Computational Tools”
Advisor: Matthew Reece

Marcin Kalinowski
Thesis: “Towards Useful Computation with Neutral-Atom Quantum Processors”
Advisor: Mikhail Lukin

Gustavs Kehris
Thesis: “Probing Muon + b-Jet Resonances in pp Collisions with the ATLAS Detector”
Advisor: John Huth

Lev Kendrick
Thesis: “Low-temperature Physics in the Fermi-Hubbard Model”
Advisor: Markus Greiner

Shion Kubota
Thesis: “Studies of Neutrinos in High Definition with LArTPC”
Advisors: Roxanne Guenette, John Doyle

Ted Liu
Thesis: “Probing Quantum Geometric Effects in the Antiferromagnetic Topological Insulator $MnBi_2Te_4$”
Advisors: Suyang Xu, Julia Mundy

Xiaoling Liu
Thesis: “Optical Probe of Electronically Correlated States in Atomically Thin Semiconductors”
Advisor: Mikhail Lukin

Benjamin Mazel
Thesis: “String Field Theory for Nontrivial Backgrounds”
Advisor: Xi Yin

Abigail McClain Gomez
Thesis: “Near-Term Stepping Stones on the Path to Useful Quantum Computing”
Advisor: Susanne Yelin

Nayantara Mudur
Thesis: “Statistical and Generative Models for Inference and Reasoning in Astrophysics and Beyond”
Advisor: Douglas Finkbeiner

Abdullah Nasir
Thesis: “Improved Optical Trapping of SrOH to Probe Ultralight Dark Matter”
Advisor: John Doyle

Saran Prembabu
Thesis: “Symmetry and Topology in Correlated and Gapless Quantum Matter”
Advisor: Ashvin Vishwanath

Shivam Raval
Thesis: “Methods for Transparency and Control in Embedding Visualizations”
Advisors: Martin Wattenberg, Michael Brenner

Pieter-Jan Stas
Thesis: “Distributed Applications of a Solid State Qubit Quantum Network”
Advisor: Mikhail Lukin

Pavel Stroganov
Thesis: “Control Infrastructure for a Continuously Operating Neutral Atom Array”
Advisor: Mikhail Lukin

Neeraj Tata
Thesis: “Parables of Quantum Gravity”
Advisor: Daniel Jafferis

Tianli Wang
Thesis: “Flat-Space Holograms from the Bottom-Up and the Top-Down”
Advisor: Andrew Strominger

Weijie Wu
Thesis: “Quantum Enhanced Metrology with Nitrogen-Vacancy Centers in Diamond”
Advisor: Norman Yao

Katherine Xiang
Thesis: “Optical Perturbation-Response Measurements of Molecular Biophysics”
Advisor: Adam Cohen





ACADEMIC PROGRAMS

Research Scholars

By Bonnie Currier,
Assistant Director of
Research Scholar Affairs

On February 27, 2026, the Department of Physics organized a panel on transitioning from academia to start-ups. The panel was composed of former research scholars in our department who are now in area start-ups and was moderated by two members of our Research Scholar Advisory Committee.

On April 3, 2026, some of our current post-doctoral fellows presented a panel on getting a post-doctoral appointment. This panel was moderated by two of our own graduate students, and we offered it in order to give graduate students first-hand information on the full process of searching for and applying to post-doc positions.

On April 24, 2026, we had a panel on getting a faculty position. The panel was composed of junior faculty from Harvard, MIT, BU and Wellesley and was moderated by two members of our Research Scholar Advisory Committee. This panel provided valuable advice and experiences from a junior faculty viewpoint.

Our 13th annual Research Scholar Retreat was held on September 23, 2026, at the Connors Center in Dover, MA. The Retreat is a full day away from campus for scholars to relax with new and returning colleagues. Our plenary speaker was Eric S. Lander, Founding Director and Core Institute Member of The Eli and Edythe L. Broad Institute of MIT and Harvard.

Our current scholars come from 42 nations!

Above and next page: Scenes from the 13th Annual Research Scholar Retreat.

Bottom photo: Postdoc Stella Schindler, Bonnie Currier, and Executive Director Despina Bokios.





Dear Physics Community:

This will be my last report on research scholar affairs. FAS has a new administrative services model and many staff positions were either reconfigured or ended. My position was ended.

I am sad about leaving because I have worked at Harvard for many years, but my positions in Physics have always included supporting the research scholars.

I know that our precious scholars will continue to receive the respect and attention they so richly deserve. After all, they are part of the great Harvard mission that educates and nurtures the individual.

I am honored to have served our faculty, students, staff and my charges, the scholars, these many years.

Be well, all!

Bonnie Currier

Alumni/ae Notes

1967

Andrew Zucker (A.B. '67; Ed.D. '78): I am still working to improve K-12 science education. Did you know that learning to evaluate "scientific" claims—e.g., that climate change is a hoax—is not a priority in science classrooms? There is some progress, as two dozen states are advancing media literacy education. However, with science under sustained federal attack, students need a better understanding of how government science agencies help protect air, water, food, pharmaceuticals, and the environment, and how to make informed science-related choices, like getting vaccinated. Science classes need to help students learn science for citizenship, not only prepare them for college and careers. https://improvethengss.org/blog/

Joseph Seale (B.A.): In our 45th year of marriage, my wife and I have two sons, a daughter, and two great grandkids, all doing well. I continue to sing semi-professionally in ChoralArt.org of Portland, Maine. Over my career I have done audio and video electronics and applied physics in support of engineering R&D, concluding with 16 years as Principal Physicist for Eclipse Product Development Corp. I've authored about 33 issued patents in biomedical devices, automotive engines, wind energy, and thermal energy, including an ongoing invention development in thermal energy.

1970

Anthony Zee (Ph.D.): My book Top Ten Ideas of Physics was published by Princeton University Press in June 2025. This is the 8th book I have published with PUP, and as long as its director and editor urge me to keep writing, I will continue. Meanwhile, my 4th grandchild, Arthur, was born to my 2nd son Peter Zee and his wife. I intended to retire from the University of California at the end of academic year 2025-26, but its rules are such that it is a bit to my advantage to continue teaching till the end of 2026-27.

1972

Brian Salzberg (Ph.D.): In 2024 I retired as Professor of Neuroscience and Physiology at the University of Pennsylvania's Perelman School of Medicine. In June of 2025, I was elected to the Council of the Oriental Ceramic Society of London, beginning a three-year term.

1975

George Gollin (A.B.): I retired last May, after 42 years of teaching and research, mostly in particle physics, but more recently in designing simple medical devices that attack unaddressed clinical problems in the poorer parts of the world. (I'm still doing the medical stuff in retirement.) My textbook, *A Problem-Based Introduction to Special and General Relativity,* was published by World Scientific a few months ago. I won a Guggenheim in 2009 but haven't yet found a publisher for the book that came from that, titled *On Destroying an Evil Thing: Confronting Higher Education's Criminal Fringe*. That was a wild ride!

Daniel Prober (Ph.D.): I graduated PhD from Physics, Harvard in 1975, and started teaching at Yale 51 years ago. Still working.

1977

Laurie McNeil (A.B. Chemistry and Physics; A.M. Physics): In January 2025 I was presented with the J.D. Jackson Award for Excellence in Graduate Education by the American Association of Physics Teachers (AAPT). (You may read my address, "There is more to graduate education than is found in Jackson's book," in American Journal of Physics vol. 93(3), pgs. 210-214 (2025)). This crowned my career as a physics educator, complementing the George B. Pegram award for "Excellence in Physics Education in the Southeast" presented to me by the Southeastern Section of the American Physical Society (APS) in 2019. After 41 years on the faculty of the University of North Carolina at Chapel Hill, I retired in July 2025 as the Bernard Gray Distinguished Professor Emerita. I continue my professional activities as a Deputy Editor at the *Journal of Applied Physics* and on the Editorial Board of the Effective Practices for Physics Programs (EP3) Guide (a joint effort of APS and AAPT).

1979

David A. Van Baak (Ph.D.) has been named CEO of TeachSpin, Inc., a leading designer and supplier of equipment intended for upper-level undergraduate laboratory instruction in physics.

1980

Hamish Norton (A.B.): I did my Ph.D. thesis at U. of Chicago on data from E617 at Fermilab (collaborators included Jim Cronin, Bruce Winstein, Mel Schwartz, René Turlay) and went immediately into banking, initially at Lazard Frères & Co. From banking I got into ocean shipping, currently as president of Star Bulk. Shipping, as ever, profits from chaos. Happy to speak with any students thinking about taking a divergent track.

1981

Bill Rose (A.B.): I am retired from University of Delaware. I still review manuscripts for journals and write recommendations when asked. Son Bill, Harvard Physics A.B. 2011, Ph.D. physics University of Illinois, works as a senior systems engineer for Onto Corp. He welcomed a son, my second grandchild, in 2025.

1985

Kirk B. Goodall (A.B.): I lead a team of NASA engineers who foresaw the potential of the Internet before funding was available. My efforts enabled JPL to partner with commercial firms and acquire the necessary bandwidth. Wrote and operated the software which enabled the public to see Mars Pathfinder images before cache networks were commercially available. This event received worldwide press coverage and was hailed by The New York Times as the "Defining Moment" that established the Internet as a new communications medium. Currently living in Silicon Valley, where I am active in the startup company network of entrepreneurs and investors.

1986

Scott Milner (Ph.D.; advisor: Paul C. Martin): I hold the Joyce Chair in chemical engineering at Penn State, where I have been since 2008, when I moved from ExxonMobil Corporate Research. In spring 2025, I received the APS Polymer Physics prize "For insightful contributions to the theory of polymer brushes, copolymers, molecular entanglement rheology, interaction parameter estimation, and polymer crystallization." This fall, my forthcoming book, Writing and Presenting for Scientists and Engineers: Getting Your Story Straight, will be published by MIT Press.

Eric B. Sirota (Ph.D.): I joined Exxon's Corporate Research lab in Clinton, NJ, as a post-doc in 1986, and I never left; continuing to do fundamental soft condensed-matter physics, studying crystallization, phase-separation, and viscosity, in simple and complex hydrocarbon systems; working at the interface of chemistry and engineering, and applying my work across a broad industry. When the lab closes next year, I'll have to continue my research somewhere else. Meanwhile, I've been writing musical theatre, with my musical, Frankenstein, playing Off-Broadway, and now a movie; and my musical A Good Day, about music and Alzheimer's, in development. https://EricSirota.com.

1987

Stephen Barrow (A.B.): After graduating from Harvard College, I received a Ph.D. in Physics from the University of Pennsylvania. I then spent several years working at particle accelerators located in North America and Europe, during which time I was the lead author on five physics papers, all published in Physical Review C. I eventually settled down and spent almost 20 years living in Maryland and working on three of NASA's space telescopes. The vast majority of that time was spent working on the James Webb Space Telescope (JWST). In September of 2024 my family and I moved to Massachusetts and I currently work for a subsea robotics company.

1988

Dan Kammen (Ph.D): Bloomberg Distinguished Professor of Energy & Climate Justice, Johns Hopkins University, Dan was elected to the US National Academy of Sciences in 2025, and to the American Academy of Arts & Sciences in 2020. Since 1999, Dan has been a Coordinating Lead Author for the Intergovernmental Panel on Climate Change (IPCC). The IPCC shared the 2007 Nobel Peace Prize.

1990

Mark Alford (Ph.D.; advisor: Sidney Coleman): I recently completed 10 years as chair of the physics department at Washington University in St. Louis, and now I am taking a sabbatical. Thanks to a research award from the Humboldt Foundation, I am spending most of 2026 at the Goethe University in Frankfurt, interacting with several groups that share my research interest in predicting the properties of ultra-dense matter found inside neutron stars.

Seth Weisberg (A.B.) retired from his career as a technology and regulatory lawyer, including many years as the Chief Legal Officer of Stamps.com, a company he helped lead from a startup to an eventual sale to a private equity firm for $6.6 billion. He lives in Los Angeles and spends his time with his wife Nicola and four children, learning languages, studying Yiddish language and culture, Scottish Country dancing, and playing bridge and chess.

1991

Christian Ryan (A.B.): In 2020 I co-founded Silverquicken Education, which provides hands-on enrichment programs for 3rd-8th graders across the country, with a growing niche in gifted education. We use puzzles and games within a story-based fantasy world to teach authentic problem-solving, creativity, and teamwork. Silverquicken leads with fun, which draws kids in, lowers their guard, and motivates them to solve tough challenges collaboratively. Gifted kids especially can struggle with struggle itself (much as the department's own Louis Deslauriers, Logan McCarty, et al. found in "Measuring actual learning…" in 2018 https://doi.org/10.1073/pnas.1821936116). We're here to address the issue upstream, at younger ages. Please check out silverquicken.com!

1992

Christopher Ball (A.B.): Since 2023, I have been serving as the Interim Director of the ElectroScience Laboratory at The Ohio State University, in addition to being a staff research scientist. My recent research has focused on a variety of sensing and communications technologies, including an infrared spectroscopic sensor for food and agriculture, an X-ray communications system for space platforms, infrared detector development for earth science and space domain awareness, optical sensing for permafrost research, and wearable sensors for chemical detection. I am also part of an improv comedy group called the Bunsen Burnouts, performing regularly around Columbus, Ohio.

Vineer Bhansali (Ph.D.): Vineer is the Founder and CIO of LongTail Alpha, a firm specializing in Risk Mitigation Strategies and Tail Risk Hedging in Financial Markets. His 6th book, a compilation of his Forbes.com pieces, titled *Expecting The Unexpected: Investing in a World of Economic Turmoil*, is available for free download on the company's website: https://www.longtailalpha.com/expecting-the-unexpected/ He is currently serving on the Investment Committees of the American Physical Society and the Simons-Laufer (SLMATH) Mathematical Sciences Institute.

1994

Daniel W. Savin (Ph.D.) has been recognized recently as a 2024 Fellow of the American Association for the Advancement of Science and as the 2026 Recipient of the Laboratory Astrophysics Prize of the Laboratory Astrophysics Division of the American Astronomical Society (AAS). He continues to work at Columbia University as a Senior Research Scientist in the Astrophysics Laboratory and to serve as a Science Editor for the journals of the AAS.

Chris Carone (Ph.D.) is a Professor of Physics at William & Mary, where he has been a faculty member since 1997. He currently has a half-time appointment as the Vice Dean for Research and Graduate Studies in William & Mary's School of Computing, Data Sciences, and Physics. This school, which was launched in July 2025, is the first new school created at William & Mary in the past half century. In addition to his involvement in academic leadership, Carone remains an active researcher in elementary particle theory. He lives in Williamsburg, Virginia, with his wife and two kids.

1996

Zachary Doyle Walton (A.B.): Since leaving Harvard, I have had two eureka moments. The first was during my Ph.D. in quantum cryptography at Boston University. I realized that a particular way of understanding quantum entanglement led to a new method for implementing quantum cryptography over noisy channels (*PRL* 91.8 (2003): 087901). The second was when I realized that a particular way of addressing the problem of time led to a new derivation of quantum mechanics (https://thequantumexplained.com/). After my Ph.D., I went to medical school and became an anesthesiologist. In my part time, I work on medical devices (https://biplanemedical.com/).

1997

Martin Z. Bazant (Ph.D. in Physics; advisor: Tim Kaxiras): Martin Z. Bazant, Chevron Professor of Chemical Engineering and Mathematics at the Massachusetts Institute of Technology, was elected to the National Academy of Engineering, Class of 2025.

1998

Shine May Hung (A.B. Chemistry & Physics): I've been teaching mathematics and recently high school AP Computer Science in the Seattle area. Also, I've been dabbling in amateur astronomy and astrophotography—please enjoy the eclipse pictures I took from 2017 and 2024* and feel free to reach out!

Lisa Lapidus (Ph.D.): Lisa is a professor at Michigan State University, Department of Physics and Astronomy, with a research focus in biophysics. She recently published a textbook, *University Physics for Life Sciences: A Cellular Approach* (MIT Press), based on a curriculum that she developed at MSU. The book is a significant departure from the traditional introductory physics curriculum, focusing on physics topics and applications relevant to modern biology and integrating Python coding and other types of simulation.

Dean Lee (A.B., 1992, and Ph.D.): I am currently a Professor of Physics and Head of the Theoretical Nuclear Science Department at the Facility for Rare Isotope Beams at Michigan State University. My research group works on quantum many-body theory with applications to nuclear physics and beyond. The tools we use include Monte Carlo lattice simulations, machine learning algorithms, and quantum computing. I live with my wife, Young Hyun Cho, who is a member of the piano faculty at the Michigan State University College of Music.

Joel Sawady (A.B., Harvard Medical School 2005): My wife Rebecca '98 and I live in Cambridge. Our daughter Ember works at Draper Labs, our son Alex studies astrophysics at Ursinus College in Philadelphia. Rebecca teaches math at the Amigos School. I'm on the faculty at Harvard Medical School and practice primary care at Cambridge Health Alliance. We've been involved with community health work in rural El Salvador for 20+ years. I lead efforts to treat diabetes and high blood pressure there, and recently started an oral health program. More information at cdhelsalvador.org. I welcome any contacts from fellow Physics alums!

Sameer Sheth (A.B. Physics & Astronomy) is professor of Neurosurgery at Baylor College of Medicine and adjunct professor of Electrical and Computer Engineering at Rice University. His clinical practice consists of functional neurosurgery (epilepsy, movement disorders, psychiatric disorders), and his research focuses on understanding the neurophysiology of higher order cognitive processes. He and his brother Sunil Sheth (see 2004 listing, below), along with a Rice engineer, co-founded Motif Neurotech to create more effective and less invasive "electroceutical" therapies for neuropsychiatric disorders. Sameer and his wife Sarita are bringing up and releasing to the world Ronak (20, sophomore at UT Austin) and Naina (16, HS sophomore).

* see back cover

2002

Mikhail Lipatov (A.B.): In 2009 I received a Ph.D. in biology from Stanford, with a dissertation in evolutionary biology. I then completed a postdoc in cultural evolution with my doctoral advisor, and a postdoc at Stony Brook University in human evolutionary genetics. I then got a Ph.D. in physics at the University of California at Santa Barbara, with a dissertation in astrophysics. Subsequently, after completing a 3-year postdoc on the cultural evolution of social media networks at the University of Tennessee, I am back in evolutionary genetics, as a postdoc at the department of Ecology and Genetics at Uppsala University in Sweden.

2003

Jean Nahrae Lee (A.B. cum laude with departmental honors): After graduating from Harvard College I completed a Ph.D. in Economics at Harvard, advised by Nobel Laureate Michael Kremer – but not before publishing my first and only physics paper on seismic anisotropy beneath the Kaapvaal Craton in southern Africa. I have traveled to 40+ countries for work and with friends and family. My husband Andrew and I have a joyful family life and are enthusiastic supporters of local causes supporting federal and military retirees, serving the homeless, and our Methodist church. We work in climate and at the World Bank, respectively, and have shared interests in energy and energy finance.

2004

Matthew Eisaman (Ph.D.) passed away in 2025. Please see the obituary in Yale News: https://news.yale.edu/2025/03/06/eisaman-pioneer-field-marine-carbon-removal-and-valued-colleague.

Rahul Sheth (A.B. Chemistry & Physics and M.D. 2009) has moved back home to Houston, where he is an associate professor of Radiology at MD Anderson. His clinical practice and research focus center around the use of energy to eradicate cancers throughout the body. This area of work explores interesting intersections between energy, biophysical properties of tumors, and tumor biology. Rahul and his wife Bina are raising their children Sajan (13) and Radha (11).

Sunil Sheth (A.B. Chemistry & Physics and M.D. 2009) has moved back home to Houston and is currently an associate professor of Neurology at UTHealth Houston, where he directs the Vascular and Interventional Neurology division. His research lab focuses on machine learning tools to improve neuro-imaging interpretation and treatments for acute stroke. He is also proud to be educating the next generation of stroke doctors and interventionalists. He and his wife Shreya are also plenty busy with their two kids Sandhya (14) and Dhruv (13).

2005

Yannis Paulus (A.B.): I am a retina surgeon, clinician scientist, and the Jonas Friedenwald Professor and Associate Professor at Johns Hopkins University Wilmer Eye Institute with a joint appointment in biomedical engineering, where I direct a lab developing new treatments for eye diseases like macular degeneration and diabetes, and started up multiple companies to commercialize this research. My lab develops new laser technologies, nanotechnology, and imaging systems for early detection and personalized, precision medicine. My wife Penelope and I have 5 boys, with our oldest having passed me in height.

2006

Melike Lakadamyali (Ph.D.): In 2024, Dr. Lakadamyali was promoted to Professor with tenure in the Department of Physiology at the Perelman School of Medicine, University of Pennsylvania. Her research focuses on the spatial logic of cell function using advanced microscopy methods including super-resolution imaging. Her lab discovered that human DNA is folded into nanoscale domains that dynamically remodel in response to physiological and pathological cues. More recently, her group developed methods to extract multiscale spatial features from DNA images and showed that these features can distinguish disease cell states. In 2025, she received a sabbatical fellowship to spend a year at EMBL Heidelberg, developing multiplexed imaging approaches.

2007

Christopher Slowe (A.B./A.M. Physics & Math '00, and Ph.D.): Over the last two years, Chris has helped lead Reddit through major technical and organizational change, including its IPO and the industry's shift toward AI and LLMs. After nine years as CTO, he's stepping into a new role as Reddit's first Senior Technical Fellow. As he was also Reddit's founding engineer, the move feels less like leaving leadership than returning to the technical center of the company. Grad school to him was a kind of "nerd finishing school": in hindsight, it taught him habits of thought that later proved useful as a startup founder and senior executive.

2011

Joshua Goldman (Ph.D.): I founded KoBold Metals (https://koboldmetals.com/), the leading independent mineral exploration company and largest exploration technology developer worldwide, with over $1 billion of venture capital raised and over 300 employees in 12 countries. Here is some press from *The Wall Street Journal* (https://www.wsj.com/tech/ai/kobold-metals-ai-copper-lithium-caad58da) and *The Financial Times* (https://giftarticle.ft.com/giftarticle/actions/redeem/6ª e4da19-6777-443b-9e6f-01dfef55c4ª a). I've hired several other Harvard physics Ph.D. graduates, and my co-founder is also a Harvard Ph.D. alum, though not in physics.

Lester Kim (A.B.): The biggest news is that I got married this year in NYC. Besides that, I was the founding engineer/ Head of Engineering at Balcony Technology Group, working at the intersection of U.S. real estate data and govtech. Now, I am an AI engineer focused on automated testing and evaluation metrics for B2B AI applications. I am interested in how AI can create better software sustainably, so that more people can use AI to build software to solve problems. If you're interested, reach out via email (lester.c.kim@gmail.com), LinkedIn (https://www.linkedin.com/in/lester-kim), or X (https://x.com/LesterCKim).

Maham Siddiqi (A.B. Astrophysics and Physics): I am currently a Lecturer in the Department of Space Science at the Institute of Space Technology (IST), which is a government-sector university in Islamabad, Pakistan. I am also enrolled in a Ph.D. Program in Physics at the National University of Sciences and Technology (NUST) in Islamabad, Pakistan. In my doctorate research, I work on quantum optics and quantum sensing, focusing on photon catalysis, with a particular interest in non-classical state engineering and entanglement, as a means to harness quantum advantage in precision measurements. In the coming years, I hope to complete my Ph.D. in this field and to make some lasting contributions in the field of physics, particularly in the domains of quantum optics and quantum metrology.

2013

Joanna Behrman (A.B. 2013): Joanna won the 2024 Early Career Prize in the History of Physics from the International Union of Pure and Applied Physics. The award was given in recognition of "pioneering research in the history of women in physics, alongside her extensive work communicating the history of physics to public audiences and extensive service and institution building on behalf of the history of physics community." Joanna is currently a postdoc in the Department of Science Education at the University of Copenhagen, where she studies the networks of historical women in physics and works on her book project: A New History of American Women in Physics.

Sujit Datta (Ph.D.): Datta started his faculty career at Princeton in 2017, and was promoted to Associate Professor in 2023. He was recruited to Caltech in 2024 as Professor of Chemical Engineering, Bioengineering, and Biophysics, where his lab studies the physics of soft and living matter. He became the chief editor of Reviews of Modern Physics in 2025. His scholarship has been recognized by awards from the American Physical Society, American Chemical Society, American Institute of Chemical Engineers, and Society of Rheology, among others.

Takuya Kitagawa (A.B. 2008; Ph.D. 2013): After ~10 years in Japan as Chief Data Officer and Head of AI at Rakuten, I moved back to Boston with my family — including a three-year-old son who loves running around — to serve as President and Board Director of QuEra Computing, the neutral-atom quantum computing company founded by Misha Lukin, Vladan Vuletić, and Markus Greiner. QuEra has delivered quantum computers to AWS Cloud (2022) and AIST Japan (2025), and raised $230M+ from Google, SoftBank Vision Fund, NVIDIA, among many others. I also co-founded Topologic, another deep-tech venture focused on topological materials, and am passionate about translating impactful research into industry. I'd love to hear from alumni interested in QuEra, deep tech entrepreneurship, or playdates!

Christian Yoo (A.B.): My wife Sharon, also Harvard '13, and I are proud parents of our three-year-old daughter and are happily expecting a baby boy this summer. I recently completed my Ph.D. in Nuclear Science and Engineering at MIT and am enjoying post-doctoral work in fusion energy research at the MIT Plasma Science and Fusion Center.

2014

Nick Hutzler (Ph.D.): Nick is a Professor of Physics at Caltech studying molecules for fundamental physics. He lives in Pasadena, CA, with his wife Mary and kids Isaac (7) and Lydia (4). Come visit if you are in the area!

Mariel Pettee (A.B., Physics & Mathematics): In Fall 2025 I started a new position as an assistant professor of Physics at the University of Wisconsin—Madison, where I've started a research group specializing in interdisciplinary machine learning methods for fundamental physics.

Laszlo Seress (A.B. Chemistry and Physics, A.M. Chemistry): Laszlo Seress and Shuting Yan are delighted to announce their marriage. Laszlo is a Vice President of Corporate Development at the D. E. Shaw Group. Shuting is a Post-Doctoral Researcher in Systems and Computational Biomedicine at Weill Cornell Medical School. The couple are based in New York City.

2015

Ben Burns (A.B.; MBA 2015): After grad school I spent 10 years as a product manager at Bose, launching smart speakers, noise cancelling earbuds, and my favorite, the Ultra Open Earbuds (check them out!). I wasn't doing any math, but a physics background was invaluable in applying and communicating the physics of sound and making the right tradeoffs across the many disciplines involved in the high-wire act of consumer hardware. Now I've moved into robotics, joining a Boston-area start-up called Familiar Machines and Magic, from the previous founder of iRobot (of Roomba fame). We're building something delightful in physical AI -- we'll be out of stealth mode by the time this note is published. If anyone is interested in catching up about robotics or consumer hardware more broadly, reach out at benjamin.burns.10@gmail.com.

Roman Berens (A.B. Physics & Classics): Since 2023 I have been a postdoctoral fellow at Vanderbilt University studying various aspects of black hole perturbation theory. I recently accepted a position to join the new Simons Collaboration on Black Holes and Strong Gravity as the inaugural collaborative postdoctoral fellow. I will begin this position at the University of Illinois later this year. I am excited to expand my collaborations and to keep studying black holes!

Michael Zimet (A.B. Chemistry and Physics): Since January of 2026, Michael is a Postdoctoral Associate in Biomedical Engineering at Duke University interested in computational and mathematical modeling of deep brain stimulation (DBS) neurosurgery. He worked in quantitative macroeconomic research at Bridgewater Associates for a few years before completing his Ph.D. in Dynamical Neuroscience at the University of California, Santa Barbara, in the fall of 2025. Currently he is working on electrostatic modeling of DBS electrodes and neural signal processing of local field potential recordings from Parkinson's disease patients with DBS implants. His graduate research applied methods from optimal control to inform the design of phase-specific DBS protocols and applied linear system identification to characterize the habituation effect in cardiac physiology and pupillometry time series recordings.

2017

Eric Anschuetz (A.B. & A.M.): I am wrapping up my time as a Burke Fellow at Caltech and will be starting a faculty job at the National University of Singapore in Fall 2026.

2019

Cameron Krulewski (A.B. Mathematics & Physics): I graduated with my Ph.D. in Mathematics from MIT in May 2025. Last year, I began my first postdoctoral appointment at Dalhousie University in Nova Scotia, working with Prof. Theo Johnson-Freyd on topics related to topological quantum field theory. In September 2026, I will begin a postdoc at the Perimeter Institute for Theoretical Physics, supported by an NSF Mathematical Sciences Postdoctoral Research Fellowship.

Lily Shi-Naseer (Ph.D.): My second child, Sunna, was born half a year ago. My novel The Cry of the Silkworm, a coming-of-age and revenge story set in turn-of-the-century China, was published by Atlantic Books/Allen&Unwin in 2024/25 and explores the lasting consequences of China's one-child policy. It has since been translated into Italian (Più forte della seta) and Bulgarian (Вопълът на копринената буба), and I was also featured in *The Guardian*: https://www.theguardian.com/lifeandstyle/2024/nov/27/a-moment-that-changed-me-at-seven-i-saw-the-truth-of-chinas-one-child-policy-and-felt-my-parents-pain.

2020

Piroz Bahar (A.B.): I recently graduated from medical school at the University of Michigan and will still be staying at the University of Michigan for my urology residency.

2022

Taylor Lee Patti (Ph.D.): It's been a busy few years here in sunny Southern California! My husband, Julius van den Broek, and I have welcomed two daughters, Cecelia (Cealy), 2.5 years, and Paula (Auli), 11 months. I was also recently promoted to Research Manager at NVIDIA and am now the head of my own growing research group, the Quantum Simulation and AI (QSAI), which focuses on GPU-accelerated simulations and approximations of quantum systems, as well as deploying AI methods to design and optimize quantum devices and protocols. Much love to Harvard, especially to my dear advisor Susanne Yelin.

Hengyun (Harry) Zhou (Ph.D.): After a few exciting years at local quantum computing startup QuEra, Harry recently moved back to academia as an assistant professor of EECS at MIT. Harry's research focuses on novel quantum error correction schemes and associated architectures, which can reduce the cost of building large-scale quantum computers. He recently started a quantum error correction group meeting at MIT that people are welcome to attend!

2024

Santiago Giner (A.B.): After graduating from Harvard, I came back to my home country of Venezuela. I started teaching physics at the college level here in Caracas to engineering students. This year, I started working as a data analyst at Farmatodo, one of the largest pharmacy and convenience store chains in Venezuela and Colombia. My daily job revolves around applying AI/ML models to customize product recommendations for customers. After graduating, I also completed my first marathon, where I ran a time of 2 hours, 56 minutes!

Lauren Kwee (A.B.): Last year, I completed my Master's in Education at the Harvard Graduate School of Education, and I'm continuing to teach AP Physics at Chelsea High School just outside of Boston. In summer 2026, I'll be visiting CERN as part of their two-week-long international high school teacher program, where I'm excited to learn more about particle physics and connect with educators from around the world!

Staff News: VIRGINIA DAVIS





Above: winter bud (top); kayak;

Next page: Nahant Bay

[photographs by Virginia Davis]

Virginia Davis joined the department of physics as Associate Director of Finance and Research Administration in January 2026. We sat down with Davis to talk about her new job, her circuitous path to finance, and how she spends her time when she's not balancing budgets. The interview has been slightly edited for length and clarity.

Tell us a bit about where you grew up and what brought you to Massachusetts.

V.D.: I'm a transplant. I grew up in a very small town in New York State by the name of Red Hook, about an hour and a half north of Manhattan, an hour south of Albany: a little development that was surrounded by corn and cow pastures. So, I grew up a country girl, but never really felt like I fit there. I went to Penn State for my college degree and then I got my master's degree from Keller School of Management. I moved to Massachusetts in 2013, after being downsized from an investment bank during the recession. I'd already been thinking about relocating, so it felt like the right moment.

What did you study?

V.D.: I was pre-med and I loved it. Some of the classes loved me back, but organic chemistry and I had a very love-hate relationship: I loved it, it hated me. So, we ended up breaking up shortly after that since, you know, you kind of need organic chemistry to study medicine. So I switched majors.

After college, I waited tables for a little while as I looked for a full-time job, and then I ended up working at a small broker-dealer in regulatory compliance, near my hometown, and from there went to an investment bank in Manhattan, on a healthcare and biopharma team. From there I moved to Watertown, MA, to a nonprofit for sexual and reproductive health and human rights in developing countries, then spent time as an analyst for the Commonwealth towards the tail end of the Patrick administration. After the Patrick administration, the unit that I was working in was disbanded, and none of us were reabsorbed into the Baker administration. So, I ended up at Boston Children's Hospital as a grant administrator and, from there, I went to Northeastern University for 9 years.

Did you ever regret leaving medicine?

V.D.: Not really, since it never really left me: healthcare investment banking, a reproductive health nonprofit, a hospital, the College of Science. And honestly, my hours are better now than what they would have been - I work Monday through Friday, and I get holidays.

What drew you to the Harvard Physics job?

V.D.: I'd been casually looking for a while, and this came up. It was a step away from research administration, which is a fairly narrow niche, and more solidly into a broader financial and administrative role. It also happened to be a step up. Best of both worlds!

What does an Associate Director of Finance do in an academic department?

V.D.: I manage the department's operating expenses, oversee gift and endowment funding, and supervise the team that handles procurement and corporate card reporting, reimbursements, and purchase compliance. I also build the department's budget, which I did for the first time just a few weeks after starting.

What are your priorities for the next year or two?

V.D.: My biggest priority is changing the way that we monitor our accounts and transactions throughout the fiscal year, so that we don't go through a large exercise at year-end close that adds a lot of stress and extra work to the finance team. The goal at the end of this is just for it to be checking boxes and minor tasks, not to be doing it all at once to make sure that things are round and settled.

What do you like to do outside of work?

V.D.: I'm an amateur photographer. I was classically trained on film in college, including the Ansel Adams method of black-and-white photography. I do a lot of landscapes, but I like texture, and I like grit. My photography tends to be darker. I do have a camera, but these days I mostly do a lot of it on my phone, because carrying a big camera case around gets a little cumbersome.

I'm also an amateur baker - and everything I bake is gluten free. In the cooler months, I spend a fair amount of time in the kitchen, with my daughter Emma, baking cookies, cupcakes, and cheesecakes. We have plans to attempt our very first homemade bread.

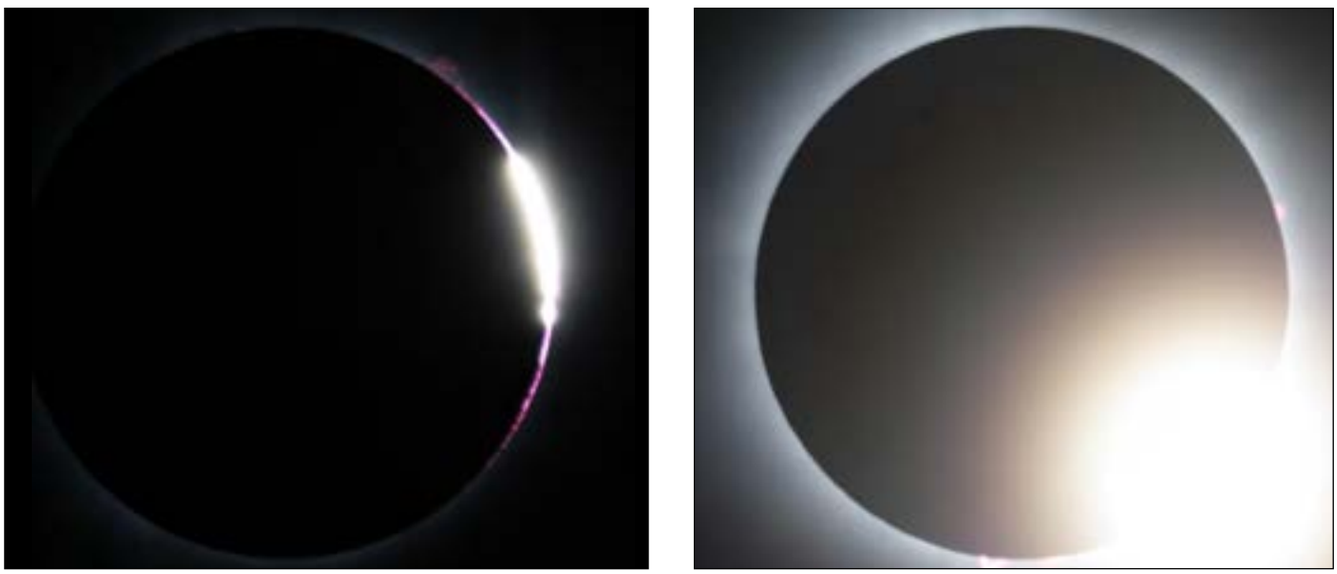
I read a lot, mostly fantasy and historical fiction. I have a special affection for the World War II era. And I like spending as much time as I can with my husband.

Anything else we should know about you?

V.D.: Just that I'm a quiet, book-reading, baking, finance nerd. That about sums it up.



HARVARD UNIVERSITY
Department of Physics



Solar eclipse 2017 (left) and 2024. [Photographs courtesy of Shine May Hung '98]

Departmental Events

For details on upcoming colloquia, lectures, and other events, please consult our Calendar of Events: https://www.physics.harvard.edu/events/gencal.

Many Morris Loeb Lectures, Lee Historical Lectures, and other departmental events are available on video: https://www.youtube.com/harvardphysics.

For questions about Monday Colloquia, please email: physics_colloquium@fas.harvard.edu.

Stay Connected

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

Check out our website: https://www.physics.harvard.edu and view previous issues of the Newsletter.

Follow us on X: https://x.com/harvardphysics.

Support the department: https://community.alumni.harvard.edu/give/51717765.