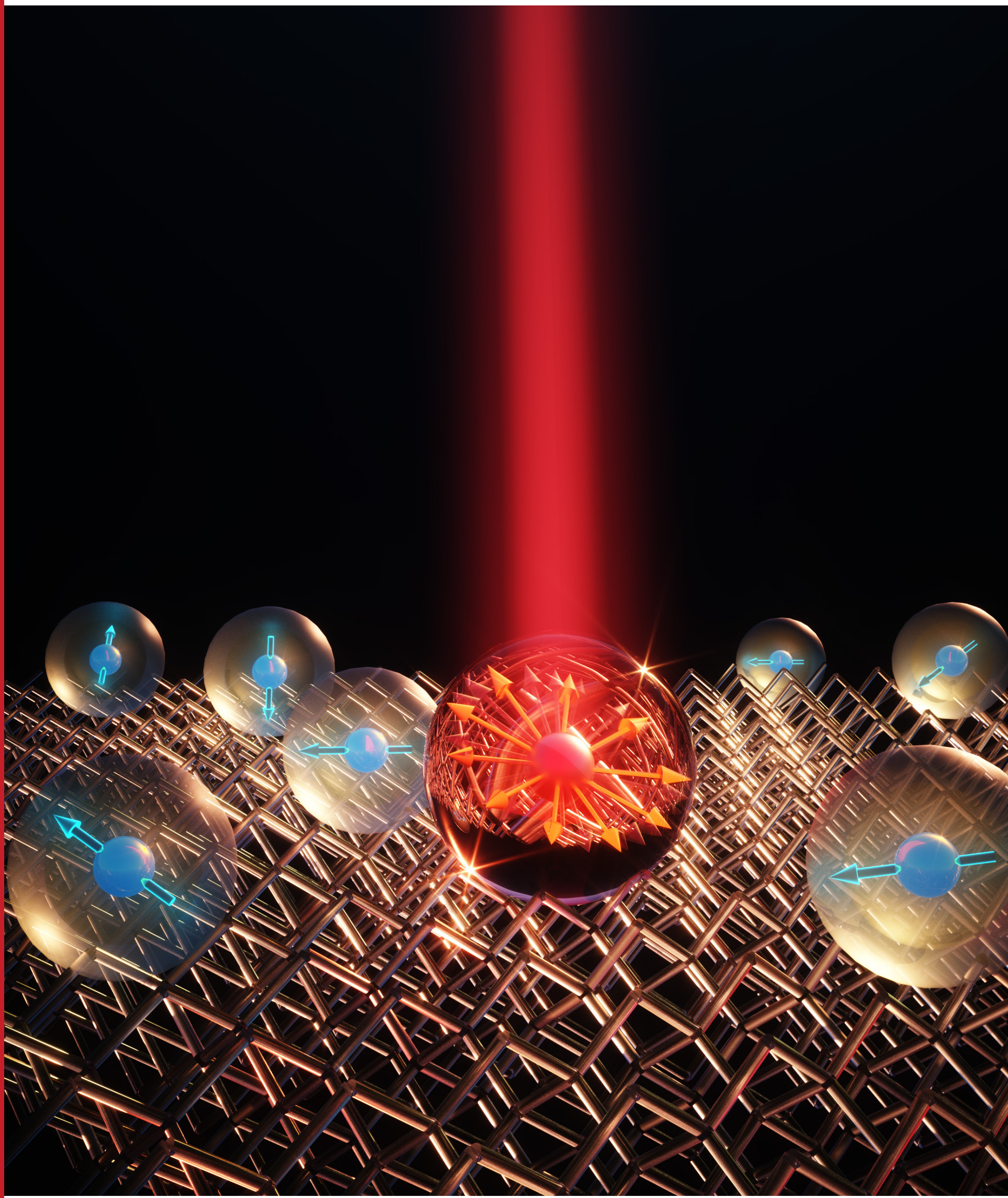
PHYSICS

Harvard University Department of Physics Newsletter

FALL 2023

NORMAN YAO: Carrying Quantum Weirdness to Its Logical Extreme



also in this issue:

Wallace Sabine and the Founding of Architectural Acoustics,

New Faculty,

Mitrano Lab,

Bert Halperin,

and much more

HARVARD UNIVERSITY
Department of Physics

The Department Today:

206
Undergraduate concentrators

244
Graduate students

89
Postdoctoral fellows

185
Other research scholars

47
Tenured faculty members

4
Tenure-track faculty members

6
Non-ladder faculty members

9
Preceptors

35
Staff members

ON THE COVER:

An artist's representation of a two-dimensional layer of quantum spins interacting with one another via their magnetic dipole moments. Understanding and characterizing the dynamics driven by such interactions remains an important question, with wide-ranging impacts in quantum sensing and simulation. By optically interrogating a subset of these spins, the Yao group studies how decoherence—normally considered a detriment—can actually encode a substantial amount of information about the underlying many-body dynamics of these spins. (See "Norman Yao:Carrying Quantum Weirdness to Its Logical Extreme" in this issue, page 8.)

ACKNOWLEDGMENTS

Newsletter Committee:

Professor Cumrun Vafa (Chair)
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Professor Paul Horowitz
Professor Matteo Mitrano
Professor David Nelson
Professor Mara Prentiss
Professor Norman Yao

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Letter from the Chair

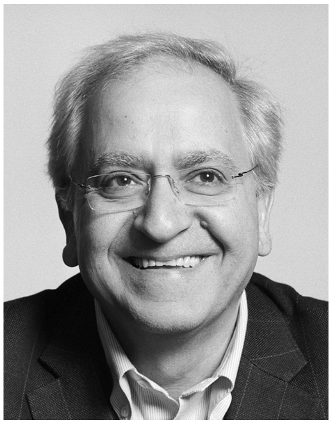


photo by Brigitte Lacombe

Dear friends of Harvard Physics,

I assumed the role of the Department of Physics chair last summer, during an historic moment in Harvard's history: the appointment of Harvard's 30th President Claudine Gay, the first African American and only the second woman ever to lead our university.

It is my great pleasure to welcome you to this, the tenth anniversary edition of the Harvard Physics Newsletter, which includes reminiscences from our rich history, some of the remarkable achievements of the recent years, and the latest departmental news. Among the latter, I'm delighted to announce the appointment of Mallinckrodt Professor of Physics Mara Prentiss to a Harvard College Professorship, in recognition of her excellence in undergraduate teaching, and of Joshua and Beth Friedman University Professor Mikhail Lukin to a University Professorship: the highest honor for Harvard faculty.

Our cover story this year is dedicated to Professor of Physics Norman Yao and his research group. Norm graduated from our program with a Ph.D. in physics ten years ago (see an article about the Lukin group Norm co-wrote for the first issue of this Newsletter[1]). Now he's leading his own group, which conducts cutting-edge research at the intersection between AMO physics, condensed matter, and quantum information science (pp. 8–15).

Many of us look forward every year to wonderful historical essays written for this Newsletter by our colleague Paul Horowitz, Professor of Physics and of Electrical Engineering, Emeritus. This year's essay, about the founder of the field of architectural acoustics Wallace Sabine, will be a treat for anyone interested in the history of the Harvard physics department and of American physics in general (pp. 16–27).

The two feature articles in this issue of the Newsletter are a profile of Assistant Professor of Physics Matteo Mitrano's research group, which studies quantum-mechanical properties of materials (pp. 28–35), and of Bertrand Halperin, Hollis Professor of Mathematicks and Natural Philosophy, Emeritus (p. 36–39).

Pages 40–51 are dedicated to reports from our academic department—undergraduate, graduate, and postgraduate—and include many fascinating profiles of our students, while our biennial Alumni Notes are found on pages 52–56. I hope you will enjoy catching up on the news from your old friends and former classmates as much as we do.

As always, a "Celebrating Staff" feature rounds up the Newsletter (pp. 57–59), including a fond tribute to Stan Cotreau, who retired last summer after 39 years of running the Harvard Physics Machine Shop.

As I'm writing these words, our department is hosting its first Loeb lecturer this year: Collège de France Professor Jean Dalibard. To find out more about this and other events, lectures, and colloquia, please check the events calendar on our website. And, as always, please stop by and say hello if you happen to be in the area: nothing delights us more than checking in with old friends.

Warmly,

Cumrun Vafa,

Department of Physics Chair &
Hollis Professor of Mathematicks
and Natural Philosophy

[1] See Peter Maurer, Jeff Thompson, and Norman Yao, "Quantum Optics," *Harvard Physics Newsletter* (2014)

Promotions: Cora Dvorkin

photo by Paul Horowitz

The Department of Physics is delighted to announce the promotion of Cora Dvorkin to Professor of Physics with tenure.

Prof. Dvorkin is a theoretical cosmologist who sees advancing the frontiers of fundamental physics with the help of astrophysical observations, rigorous theoretical modeling, and novel statistical methods as the overarching goal of her research. The main questions that guide her work are: What is the nature of dark matter? Are there new light particles beyond the Standard Model (SM)? What is the physics of the early universe?

Dvorkin has made significant contributions to the study of dark matter, light relics, and the physics of the early universe, focusing on a broad range of observational probes, such as the Cosmic Microwave Background, the large-scale structure of the universe, and strong gravitational lensing. She has pushed the frontiers of sub-GeV dark matter-baryon scattering using cosmological observables, which provide complementary constraints to current direct-detection experiments. This scenario became one of the main drivers for the dark matter science of CMB-S4: the next-generation ground-based cosmic microwave background experiment.

Dvorkin's research group has developed a general formalism aimed at probing dark matter at small cosmological scales using gravitational lensing, by means of a statistical measurement of dark matter substructure. Using high-resolution simulations, the group has demonstrated the ability of such a measurement to discern between different dark matter scenarios. It has also quantified the contribution from line-of-sight halos and subhalos and found the former to be dominant for many of the strong lensing systems studied in the literature.

Inspired by this, Dvorkin and her group reanalyzed a substructure in the JVAS B1938+666 lens (previously claimed to be a subhalo) and showed, with decisive evidence, that it is instead a halo along the line of sight. This constitutes the first dark perturber shown to be a line-of-sight halo with a gravitational lensing method. It also has shown, for the first time in the literature, that machine-learning techniques can accelerate direct detection of dark matter perturbers in lensing systems by many orders of magnitude.

In collaboration with particle physicists, Dvorkin identified a new production channel for dark matter via the freeze-in mechanism: the decay of photons that acquire an in-medium plasma mass. This turned out to be a dominant channel for sub-MeV dark matter production. Her group has also proposed and conducted a systematic search for Light (but Massive) Relics, using the latest cosmological data sets. Light Relics are a generic prediction of a broad range of beyond-SM scenarios and could compose (part of) the dark matter.

Recently, Dvorkin's group performed the first field-level analysis of a galaxy data set. Using the wavelet scattering transform—originally proposed by mathematicians 10 years ago—the group analyzed galaxy-clustering data and found significant improvements in the constraints on cosmological parameters over those coming from the standard power-spectrum analysis. The wavelet scattering transform presents several advantages over traditional estimators (in that it is more efficient) and over "black box" machine-learning methods (in that it is interpretable).

In the early universe arena, Dvorkin has pioneered a model-independent formalism for probing the shape of the inflationary potential, known as "Generalized Slow Roll." This formalism has been widely used in the literature for primordial features studies and it has been applied to the data by several members of the community, including the Planck collaboration. The next-generation CMB-S4 collaboration plans to use this approach as its main way of reconstructing the shape of the inflationary potential.

Dvorkin has also constructed new theoretical templates for higher-order correlation functions of the initial curvature perturbations that could shed light on the physical properties of particles with non-zero spin during inflation as well as possible phase transitions during the early universe. She developed statistical tools to look for these correlation functions in cosmological data measured by current and future surveys.

In 2014, she participated in the joint analysis of BICEP2, the Keck array, and Planck collaboration results. She worked on the likelihood analysis of a multi-component model that included Galactic foregrounds and a possible contribution from inflationary gravity waves. The code that she wrote was made publicly available, and it has been extensively used by the community. No statistically significant evidence for primordial gravitational waves and strong evidence for galactic dust were reported in this work.

While studying the observational imprints of inflation on the CMB, Dvorkin became interested in the period of reionization. She developed a new statistical technique for extracting the inhomogeneous reionization signal from measurements of the Cosmic Microwave Background polarization. This technique has been tested in actual data and implemented by several members of the community. She further showed that existing calculations of the Cosmic Microwave Background B-mode polarization power spectrum from reionization were incomplete by finding an additional signal of the same order of magnitude as the one that had been previously calculated. These B-modes have been sought for and seen in simulations by several groups.

Prof. Dvorkin is the Harvard Representative at the NSF-funded Institute for Artificial Intelligence and Fundamental Interactions (IAIFI)'s Board. This is a joint effort with colleagues at Harvard, MIT, Tufts, and Northeastern. She was the co-leader of the Inflation analysis group for the next-generation CMB-S4 experiment. Prior to this, she was the leader of the Dark Matter analysis group.

In 2022, Dvorkin was voted "favorite professor" by the Harvard senior Class of 2023. She has been awarded the 2019 DOE Early Career award and has been named the "2018 Scientist of the Year" by the Harvard Foundation (with support from Harvard students) for "salient contributions to physics, cosmology and STEM education." She has also been awarded a Radcliffe Institute Fellowship for 2018-2019 and a Shutzer Professorship at the Radcliffe Institute for the period 2015-2019. In 2018, she was awarded a Star Family Challenge prize for Promising Scientific Research, which supports high-risk, high-impact scientific research at Harvard. In 2012, she was awarded the Martin and Beate Block scholarship, which is conferred on the most promising young physicists by the Aspen Center for Physics. She has given more than 100 invited talks at conferences and workshops around the world.

Born and raised in Buenos Aires, Argentina, Dvorkin received her Diploma, with honors, in Physics from the University of Buenos Aires. She earned her Ph.D. in the Department of Physics at the University of Chicago in 2011, where she won the Sydney Bloomenthal Fellowship for "outstanding performance in research." She has conducted postdoctoral research at the School of Natural Sciences at the Institute for Advanced Study in Princeton (from 2011 to 2014) and at the Institute for Theory and Computation at the Center for Astrophysics at Harvard University (from 2014 to 2015), where she was both a Hubble Fellow (awarded by NASA) and an ITC fellow, before joining Harvard Physics faculty in 2015.

Introducing New Faculty: Eslam Khalaf

Eslam Khalaf joined the ranks of the Harvard Physics faculty in July 2023 as an assistant professor of Physics.

Eslam grew up in Cairo, Egypt, where he studied electronics engineering in college. He switched to physics in his graduate studies, earning a master and then a Ph.D. degree from the Max Planck Institute for Solid State Research in Stuttgart, Germany. During his doctoral studies, Eslam theoretically investigated the effect of disorder on electronic transport in topological insulators and semimetals by deriving an exact solution for the field theory describing transport in a disordered wire with topologically-protected channels. His Ph.D. work was awarded the Otto Hahn medal by the Max Planck Society for outstanding scientific achievements by a junior scientist.

For his postdoctoral fellowship, Eslam joined the group of Prof. Ashvin Vishwanath at Harvard, where he addressed several key questions in the physics of topological phases and moiré heterostructures.

In his early postdoctoral work, he formulated a unified theory of surface states of topological insulators and superconductors protected by crystalline symmetries, and he developed tools for their diagnosis.[1]

His more recent work on twisted bilayer graphene has helped elucidate the nature of the correlated insulating states, in addition to proposing a novel topological mechanism for superconductivity.[2] He also proposed a new class of moiré heterostructures predicted to exhibit very interesting properties, including superconductivity,[3] which were later experimentally realized.

At Harvard, Eslam plans to build on his past expertise in the fields of topological phases, moiré heterostructures, and field theories of localization to pursue several directions: (i) to explore new qualitative phenomena in quasicrystals, both on the interacting and non-interacting levels, motivated by their possible realization in multilayer incommensurate moiré systems; (ii) to employ insights from moiré materials to predict novel platforms for correlation and topology with more tunability or higher energy scales; and (iii) to extend the application of field theoretic methods for disorder to new systems, particularly in disordered non-Hermitian systems.

Having already spent several years as a postdoctoral fellow at Harvard, Eslam has collaborative relationships with several Harvard Physics faculty members, including Professors Ashvin Vishwanath, Philip Kim, Amir Yacoby, and Efthimios Kaxiras. He anticipates further collaboration opportunities with Professors Jenny Hoffman, Julia Mundy, Matteo Mitrano, and Subir Sachdev on areas of common interest.

[1] Khalaf et al., "Symmetry indicators and anomalous surface states of topological crystalline insulators," *Phys. Rev. X* 8, 031070 (2018).

[2] Khalaf et al., "Charged Skyrmions and Topological Origin of Superconductivity in Magic Angle Graphene," *Science Advances*, 7(19):eabf5299 (2021).

[3] Khalaf et al., "Magic Angle Hierarchy in Twisted Graphene Multilayers," *Phys. Rev. B* 100, 085109 (2019).

Introducing New Faculty: Sonia Paban

Sonia Paban is a theoretical physicist who joined Harvard Physics Department in July 2023 as Senior Lecturer on Physics and Senior Research Scientist in Physics.

Dr. Paban earned her Ph.D. in physics from the University of Barcelona, Spain (Advisor: Rolf Tarrach) and did her post-doctoral studies at the University of Minnesota and the University of Texas at Austin as a Fullbright Fellow. She was appointed Assistant Professor at UT Austin in 2000 and Associate Professor in 2006.

First in her family to graduate from high school, let alone college or graduate program, Dr. Paban credits her success and her passion for teaching to a handful of teachers and college professors who inspired and encouraged her, showed her the beauty of science and the power of the scientific method, and taught her the skills to become a scientist. At UT Austin, her teaching was recognized by the College of Natural Sciences Teaching Excellence Award, the Regents' Outstanding Teaching Award, and election to the UT Academy of Distinguished Teachers.

Over the years, Dr. Paban has worked on phenomenology, formal fundamental physics, and cosmology. One goal of her phenomenology research was to derive constraints on physics beyond the standard model using precision measurements of the atomic and molecular electric dipole moments. In another direction, she investigated the possible consequences for baryogenesis of the then-recently measured neutrino masses.

Paban's most notable formal fundamental physics papers explore a variety of subjects, ranging from the difficulty of embedding de Sitter space in string theory to formal aspects of supersymmetry and string theory. In cosmology, her focus has been on the initial conditions of inflation, both at the classical and quantum levels, as well as their phenomenological consequences.

Inflation explains the isotropy and homogeneity of the cosmic microwave background while predicting that the large-scale structure originates in the inflaton quantum fluctuations. However, the original papers on inflation begin with the FLRW metric, which is already isotropic and homogeneous. In her recent work, Paban and collaborators tested the robustness of inflation to inhomogeneous initial conditions. The result of these numerical simulations strengthens the argument for inflation. Namely, they have shown that after a few e-folds, a highly inhomogeneous universe with a cosmological constant becomes essentially homogeneous and isotropic, with perhaps one black hole per horizon.

Inflation also requires that the inflation potential be highly flat. This feature arises naturally in some models, such as the Starobinsky model. Still, it would be desirable to determine the existence or non-existence of a broader class of potentials that support inflation, which is the direction of Paban's current research on multi-field inflation models. Though the most recent cosmological observations are consistent with the simplest inflationary scenario, theoretical and phenomenological constraints motivate multifield inflation models with strongly non-geodesic trajectories. Paban's current work focuses on the observational implications of multifield models, such as breaking the single-field consistency relations between observables, leaving signature features in the primordial power spectrum, producing primordial black holes, and sourcing a stochastic background of gravitational waves.

Faculty Prizes, Awards, and Acknowledgments[1]

AMERICAN ACADEMY OF ARTS AND SCIENCES:
L. Mahadevan

AMERICAN PHILOSOPHICAL SOCIETY:
Lene Hau

2024 OLIVER E. BUCKLEY CONDENSED MATTER PHYSICS PRIZE:
Ashvin Vishwanath

CLARIVATE ANALYTICS HIGHLY CITED RESEARCHERS 2022:
Michael Brenner
Markus Greiner
Efthimios Kaxiras
Philip Kim
Mikhail Lukin
Hongkun Park
Ashvin Vishwanath
David Weitz
Su-Yang Xu
Norman Yao
Xiaowei Zhuang

2024 IUPAP C10 EARLY CAREER SCIENTIST PRIZE IN STRUCTURE AND DYNAMICS OF CONDENSED MATTER:
Matteo Mitrano

THE FRANKLIN INSTITUTE ANNUAL AWARD IN THE SCIENCES AND BUSINESS:
Philip Kim

FRONTIERS OF SCIENCE AWARD (INTERNATIONAL CONGRESS FOR BASIC SCIENCE):
Matthew Reece

HARVARD COLLEGE PROFESSORSHIP:
Mara Prentiss

HARVARD UNIVERSITY PROFESSORSHIP:
Mikhail Lukin

HARVARD YEARBOOK'S FAVORITE PROFESSOR OF THE CLASS OF 2023:
Jacob Barandes
Cora Dvorkin

INTERNATIONAL INSTITUTE OF SCIENCE DISTINGUISHED LECTURER, BANGALORE:
David Nelson

U.S. NATIONAL ACADEMY OF SCIENCES (INTERNATIONAL MEMBER):
Philip Kim

NATIONAL SCIENCE FOUNDATION CAREER AWARD:
Carlos Argüelles-Delgado

2023 PACKARD FELLOWSHIP:
Carlos Argüelles-Delgado

NORMAN F. RAMSEY PRIZE IN ATOMIC, MOLECULAR AND OPTICAL PHYSICS, AND IN PRECISION TESTS OF FUNDAMENTAL LAWS AND SYMMETRIES:
John Doyle

SIR C.V. RAMAN MEMORIAL LECTURER, INDIAN INSTITUTE OF SCIENCE:
David Nelson

ROYAL SOCIETY (UK) FOREIGN MEMBER:
Subir Sachdev

THE RAYMOND AND BEVERLY SACKLER INTERNATIONAL PRIZE IN CHEMISTRY:
Adam Cohen

2023 SIMONS INVESTIGATOR IN PHYSICS:
Daniel Jafferis
Norman Yao

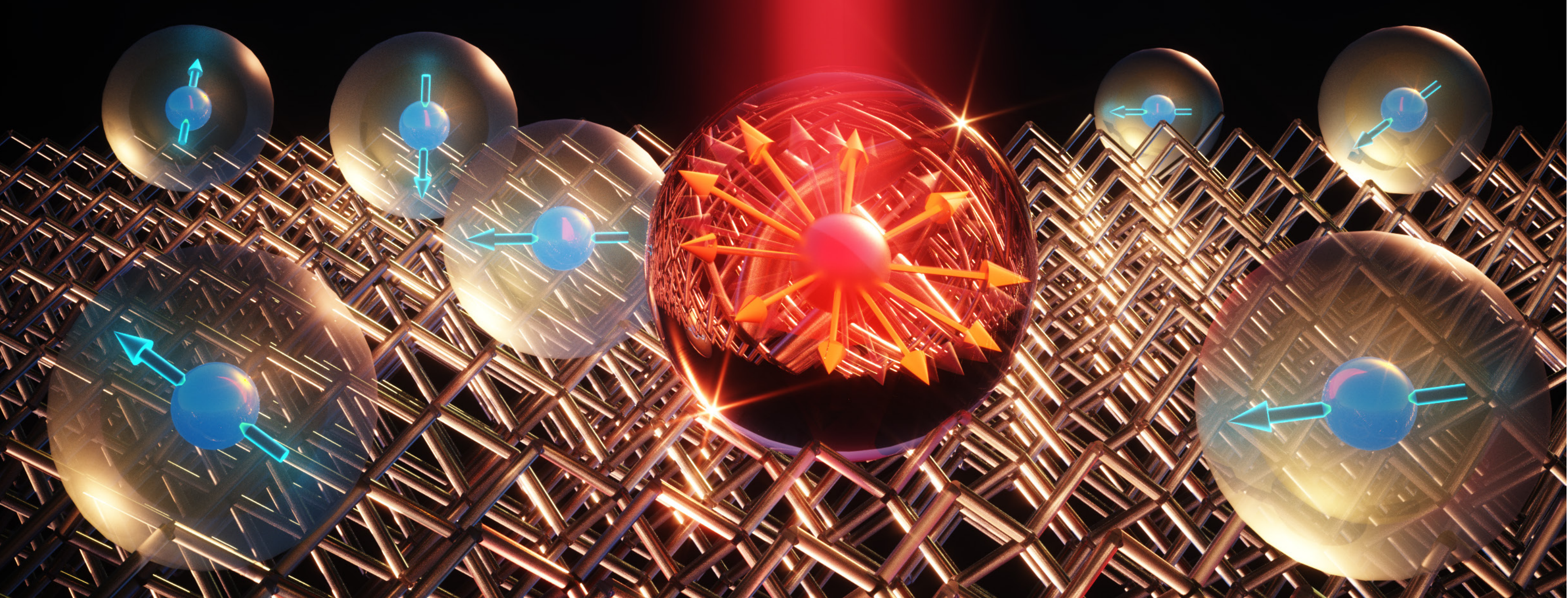
2023 JACQUES SOLVAY INTERNATIONAL CHAIR IN PHYSICS:
Subir Sachdev

2023 STAR-FRIEDMAN CHALLENGE FOR PROMISING SCIENTIFIC RESEARCH:
Vinothan Manoharan
Matteo Mitrano
Julia Mundy

[1] Includes awards received since the publication of last year's newsletter.

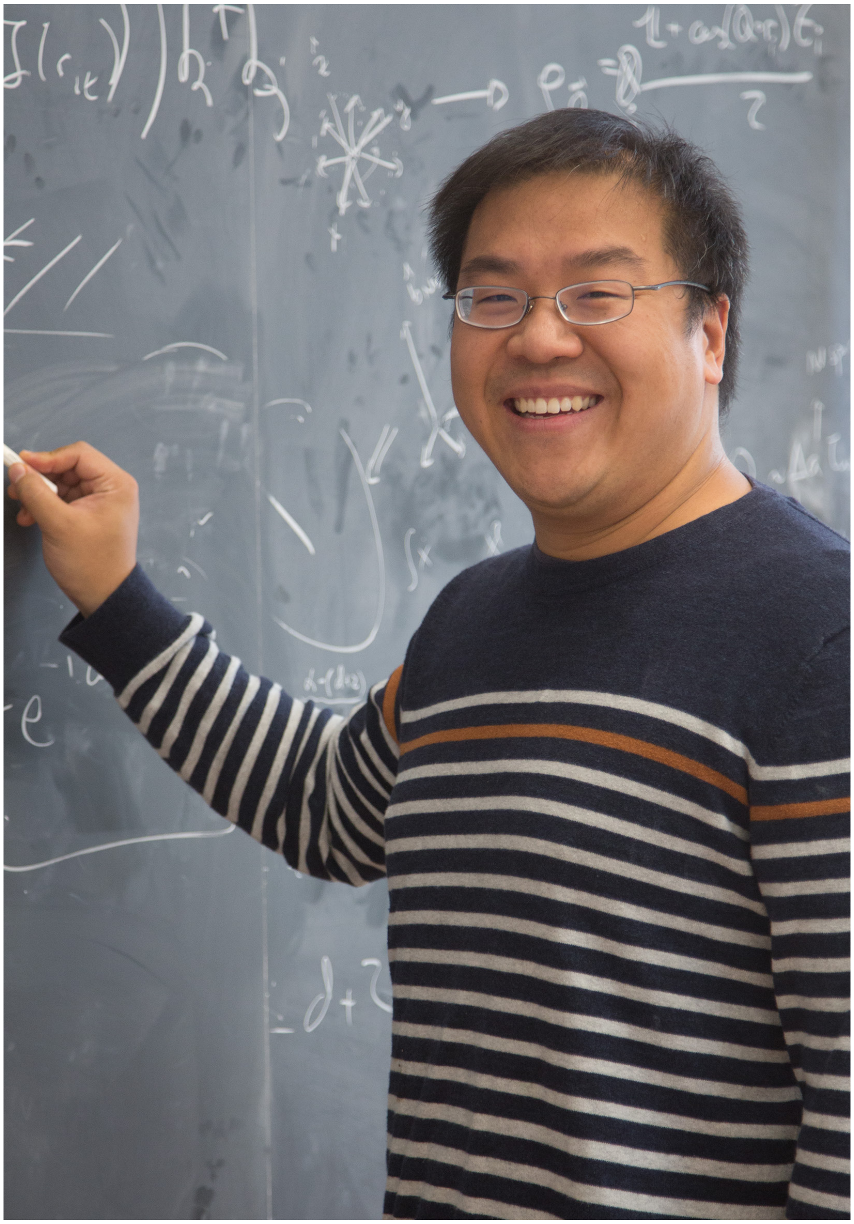
NORMAN YAO: Carrying Quantum Weirdness to Its Logical Extreme

by Steve Nadis



The most widely known feature of quantum mechanics may be the fact that it's notoriously strange. Particles, according to the theory, can have fractional charges and can literally be in two places at the same time. The mere act of observing a process inevitably changes it. All that's been understood for many decades. But the more we probe and the closer we look, the weirder things get—to which Norman Yao's attitude is "Bring it on!"

Yao—a Professor of Physics who joined the Harvard faculty last year—pokes and prods nature in the hopes of eliciting new phases of matter that only manifest themselves, fleetingly, under extraordinary circumstances. He studies systems that are intentionally thrown out of whack by administering intermittent kicks that keep them from ever settling down. And he creates conditions within miniature diamond anvils that cause the orientations of tiny magnets residing inside to flipflop like gymnasts during floor exercise routines. Yao will go to great lengths, and also to absurdly tiny lengths—as well as to extremely low temperatures (a few thousandths of a degree above absolute zero)—to take us as far from the familiar, humdrum everyday world as one can get within the confines of Jefferson Laboratory.



Prof. Yao photo by Paul Horowitz.

Yao was exposed to physics early in life. His father, an electrical engineer and statistician who emigrated to the United States from China after the Cultural Revolution, introduced young Norm to the subject through little experiments they carried out in their garage. An inspirational high school teacher, the late Michael Gilmore, reinforced Yao's interest in physics, showing him that the discipline involved much more than just solving equations. "It was all about developing a good intuition as to what nature wants to do," Yao says. And the Physics 16 course taught by Mallinckrodt Professor of Physics Howard Georgi, which Yao took as a freshman, sealed the deal. "Howard taught us that physics is a human enterprise," he recalls. "It's more fun, and you learn more, when you do it with other people." That message has clearly rubbed off on Yao, who exudes joy when talking about or doing physics. Nevertheless, he came close to ending up in an entirely different area of study—that of biophysics rather than the quantum world he currently lives and breathes.

As a Harvard undergraduate from 2005 to 2009, he spent four years doing biophysics research under the guidance of his then-advisor, Mallinckrodt Professor of Physics and Applied Physics David Weitz, a person Yao regarded as "the best possible mentor—someone who taught me that the hardest thing in science is figuring out the right questions to ask."

Opposite page: An artist's representation of a two-dimensional layer of quantum spins interacting with one another via their magnetic dipole moments. Understanding and characterizing the dynamics driven by such interactions remains an important question, with wide-ranging impacts in quantum sensing and simulation. By optically interrogating a subset of these spins, the Yao group studies how decoherence—normally considered a detriment—can actually encode a substantial amount of information about the underlying many-body dynamics of these spins.

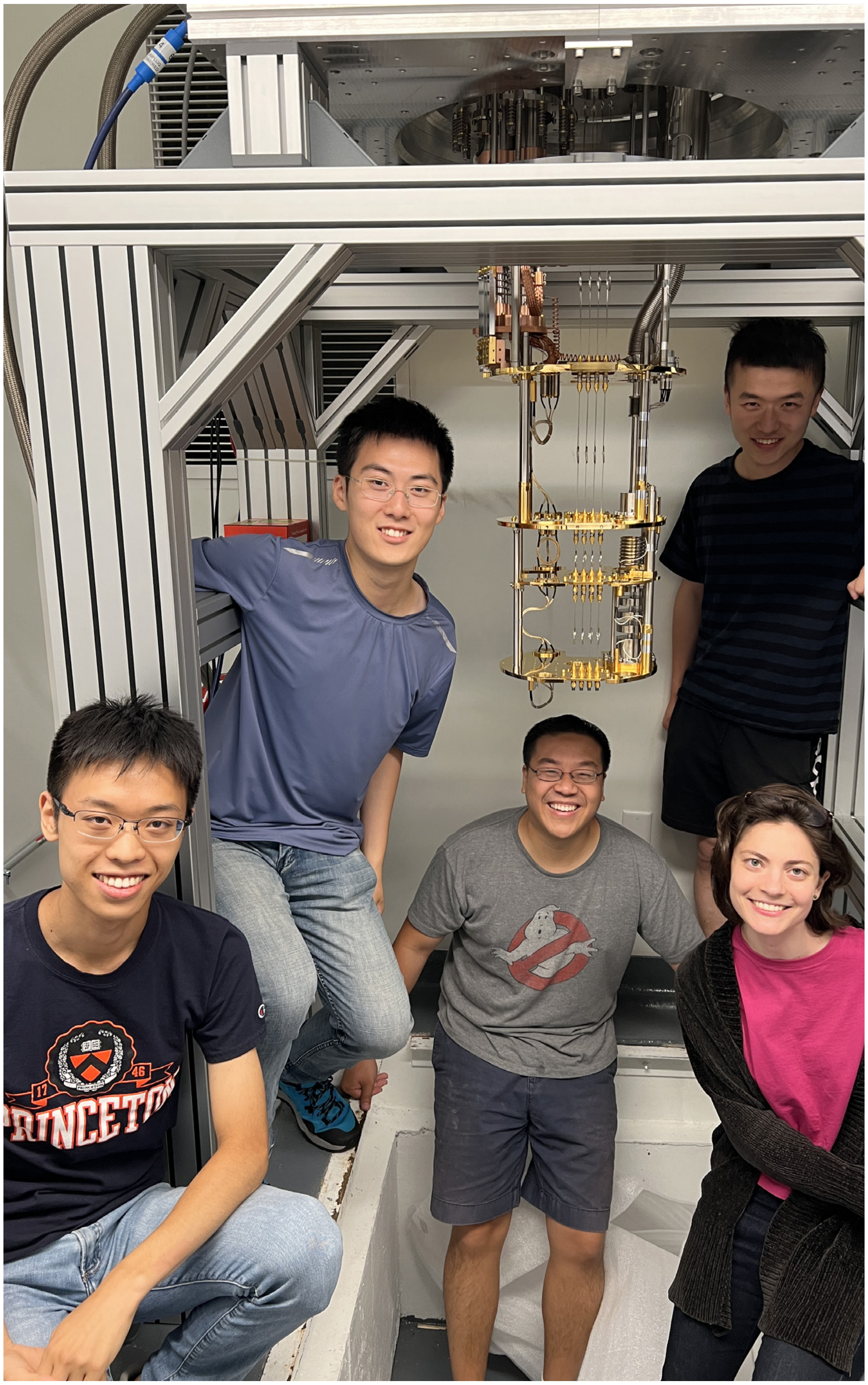
Marcus Bintz: Building Unusual Magnets in Unusual Ways

"I've always had a wide range of interests in physics, and I am especially drawn to physics at the boundaries between different disciplines," says Marcus Bintz, a theoretical physics Ph.D. student. "While physics has traditionally been divided into different subfields—for historical or sociological reasons—we are not constrained by those definitions in Norm's lab. Crossing boundaries is something we do every day"—a fact that greatly appeals to Bintz's sensibility.

He works in a number of areas, like many in Yao's group, and a big focus of his research is on "building unusual magnets, atom-by-atom." A physical setting that Bintz has given a lot of thought to involves the use of atomic tweezer arrays. There are about 100 atoms in such an array. Each atom is trapped by a separate, tightly-focused laser beam so that its magnetic, electrical, and optical properties can be studied. A lot of this work revolves around antiferromagnetic materials—materials whose microscopic properties anti-align with those of their nearest neighbors.

"Some people think about these materials in the context of quantum computation," Bintz says, "but that is not my principal motivation. My goal is to understand both the basic and complex features of these systems—strongly interacting quantum many-body systems."

A related thrust of his research is the study of phases of matter where quantum mechanics is fundamentally important at the macroscopic scale. In particular, he is investigating topological phases of matter called spin liquids. Curiously, there are rocks in the ground we don't understand well (including a mineral called Herbertsmithite), which appear to have similarities to spin liquids, Bintz says. "It would be great if our experiments into synthetic phases of matter could shed light on this naturally-occurring material. I think that would be beautiful."



Installing a dilution refrigerator in Jefferson Lab in order to take spin dynamics experiments down to milli-Kelvin temperatures: Norman Yao (center) with undergraduate student Tasuku Ono, graduate students Che Liu and Weijie Wu, and postdoctoral scholar Emily Davis.
[photo by Paul Horowitz]

Yao planned to continue his work in that area when he began his graduate studies in 2009, also at Harvard, but Weitz urged him to broaden his perspective and try something different. "If you later decide that biophysics is your true calling," Weitz told him, "so be it." As a PhD student, Yao worked with his graduate advisor, Joshua and Beth Friedman University Professor Mikhail (Misha) Lukin, whom he called "one of the most creative and intuitive scientists I've ever met." Under Lukin's tutelage, Yao "caught the quantum bug"—and never looked back.

As to how he "got hooked on the quantum stuff," Yao explains, "I love puzzles. I can be interested in anything, so long as there are questions that feel deep and important to me." And within the related fields of quantum information science, condensed matter physics, and atomic, molecular, and optical physics, he adds, "there've always been more than enough interesting things to keep me going. And it hasn't let up yet."

Because he is reluctant to turn his back on a good problem, Yao presently works on multiple fronts—as both a theorist and an experimentalist—supervising more than two dozen students and postdocs. There are 15 people in his group on the theory side and 11 on the experimental side, with five separate experiments now underway. Having a nearly 50-50 split between theory and experiment is uncommon in his discipline, and it makes for a pretty hectic schedule. "There's a lot going on, and it is at the limit of what I can handle," Yao admits. But when it comes to physics, he likes going to the limit—and then pushing a bit further.

By the time he arrived at Harvard in January 2022—after having spent the previous seven years at the University of California, Berkeley, first as a Miller postdoctoral fellow and then a faculty member—Yao had already gained some recognition in the field. He is perhaps best known for his work on "time crystals," which grew out of his joint interests in periodically shaken (so-called Floquet) systems and novel ways to elude ergodicity—the tendency of a physical system to forget its initial conditions as it evolves. Putting those two interests together, he discovered, was "a combination that can give rise to the full complexity of out-of-equilibrium physics."

Time crystals were originally proposed in 2012 by the Nobel Prize-winning physicist Frank Wilczek. A few years later, it was shown that time crystals could not exist in thermal equilibrium, but the phase might be attainable in Floquet systems that never reach stasis. Whereas ordinary crystals have a lattice structure made up of building blocks that repeat in space, time crystals—as the name suggests—have a structure that repeats in time. In a 2017 paper published in *Physical Review Letters,* Yao and three colleagues (including George Vasmer Leverett Professor of Physics Ashvin Vishwanath) laid out a procedure for making a time crystal and measuring its properties, detailing the range of conditions under which it could exist and be elicited through laboratory experiments. A crystal of this sort has an odd quirk: It can only emerge if it is regularly shaken, but the time crystal itself oscillates at a slower (sub-harmonic) frequency than that at which it is shaken.

Yao then collaborated with two teams of experimentalists—one headed by

Prabudhya Bhattacharyya: Upping the Pressure in Quantum Sensing

When Prabudhya Bhattacharyya first joined Norman Yao's group in 2017 as a University of California, Berkeley, graduate student, Yao proposed an idea that sounded quite intriguing: to take quantum defects in a piece of diamond that is, itself, part of an anvil cell and use those defects—called nitrogen-vacancy or NV centers—to measure magnetism in high-pressure superconductors. (At an NV center, a nitrogen atom substituting for carbon sits next to a vacant lattice site.) The idea of using an NV center to perform such a measurement "seemed so practical," recalls Bhattacharyya, "that I was surprised it hadn't been attempted before."

In 2018, the team obtained NV center measurements at pressures of 50 gigapascals (GPa). "However, we found that the signal intensity degraded rapidly as we pushed to higher pressures," Bhattacharyya says, casting doubt on their hopes of carrying out these measurements at 100 GPa—the pressure at which many interesting high-pressure superconductors are synthesized. But they discovered a work-around: By using a different face of the diamond crystal in the anvil cell, they changed the orientation of the NV center. As a result, signal intensity did not degrade as the pressure increased. In 2021, they conducted successful measurements at 140 GPa. Bhattacharyya believes "it's definitely worth pushing up to 200 GPa, and I feel optimistic that our approach would still work."

He finished his research in Yao's group in July 2023 after earning his Ph.D. in late 2022, and he's just started a postdoctoral fellowship at Berkeley. Since then, his work has shifted to a different experimental platform called cavity atom interferometers, which he's investigating with Professor Holger Mueller. But Bhattacharyya plans to keep track of research on high-pressure NV sensing, saying that he "expects to see some very nice applications coming from it!"

Emily Davis: Untangling the Mystery of Squeezed States

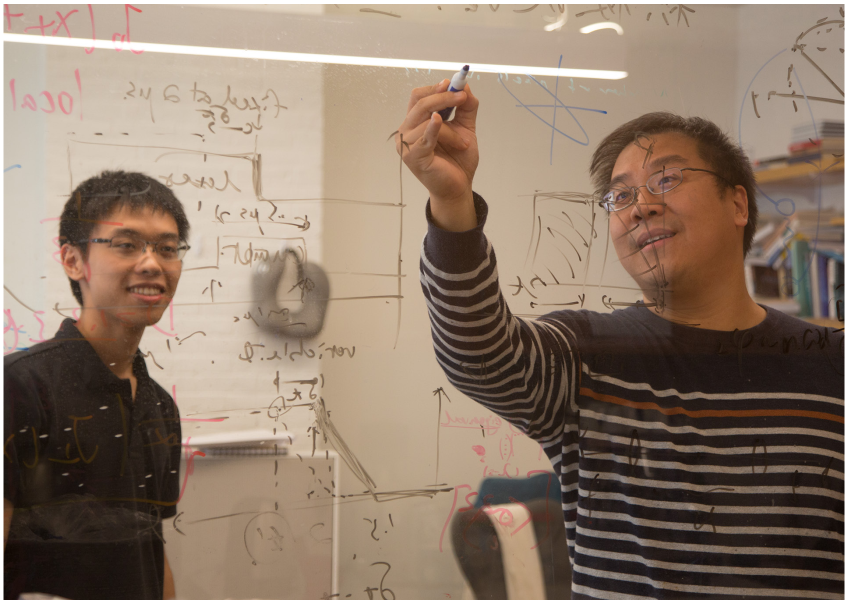
Emily Davis, a postdoctoral scholar in the Yao lab, joined the group in the summer of 2020 after getting her Ph.D. at Stanford earlier that year. She liked the fact that the theorists and experimentalists in the group worked closely together, which she says is pretty unusual in physics. That mix makes sense to Davis, an experimentalist, because she did a fair amount of theory in graduate school.

Her first project was to show that all the nitrogen-vacancy (NV) centers in a specially-grown diamond sample were confined to a thin, two-dimensional layer. This effort proved successful, and Davis was first author on a paper discussing these results in a March 2023 issue of *Nature Physics*.*

Her next goal was to entangle the NV centers in order to create a squeezed state. "We're not talking about physical squeezing," she explains. "Squeezing here refers to a specific form of entanglement that is useful for making very precise measurements." After working closely with students Weijie Wu and Zilin Wang for just over a year, Davis says, "we have some tantalizing hints that we are seeing this special form of entanglement [squeezing] for the first time in an NV system." Those indications are exciting, she notes, "but still preliminary."

If this work pans out, Davis says, "and we are able to create a very large entangled state, NV centers could potentially be used to detect dark matter particles through their magnetic signatures." That's a direction she hopes to pursue in the future, though that will mostly likely take place at New York University, where she is starting as an assistant professor in January 2024.

* E.J. Davis, B. Ye, F. Machado, S. A. Meynell, et al. "Probing many-body dynamics in a two-dimensional dipolar spin ensemble," *Nat. Phys.* 19, 836–844 (2023).



Norman Yao and undergraduate Tasuku Ono discuss spin squeezing, a type of entanglement that allows for quantum-enhanced measurements. The sensitivity of such measurements scales fundamentally better than what would be possible using only classically correlated spins. [photo by Paul Horowitz]

Duke University professor Christopher Monroe, and the other headed by Lukin at Harvard—to observe the first experimental signatures of time-crystalline behavior, which they reported in 2017. Monroe's group accomplished this by stringing together a chain of trapped ytterbium ions, whereas Lukin's group created a time crystal within a small piece of diamond that had millions of atomic-sized impurities called nitrogen-vacancy (NV) centers—sporadically-placed defects within diamond's otherwise uniform carbon lattice.

"Such similar results achieved in two wildly disparate systems underscore that time crystals are a broad new phase of matter, not simply a curiosity relegated to small or narrowly specific systems," commented Indiana University physicist Phil Richerme. Time crystals, according to Yao, may be the simplest example of the new phases of matter that can arise in a nonequilibrium, many-body system.

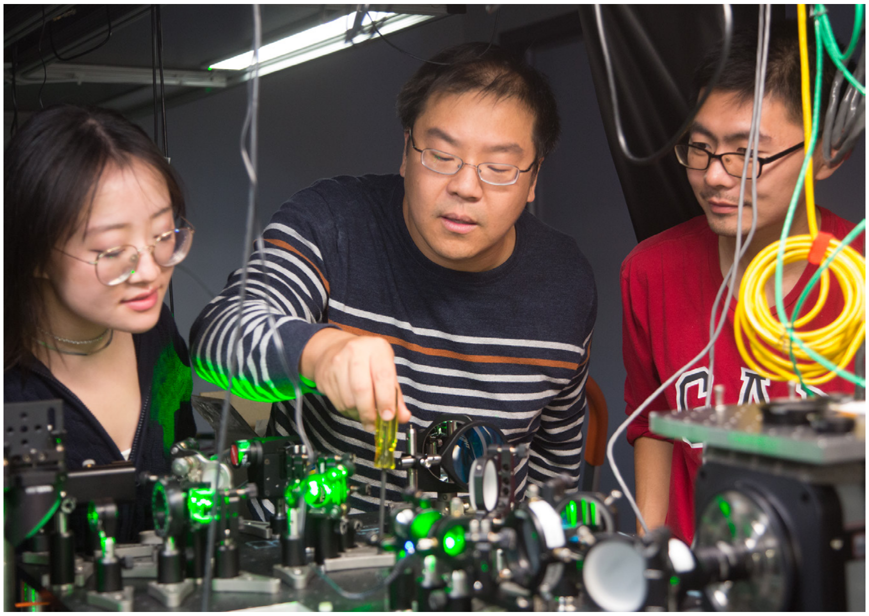
It was around this time that Yao, who had been trained as a theorist and had always viewed physics through that lens, decided he should also get involved in the experimental side of things. "I've always loved theory," he says, "but I realized that—at the end of the day—physics is an experimental science, and there is nothing like seeing real data." But he first had to figure out what he could do that would be new and interesting.

He consulted an old friend, Christopher Laumann, currently an Associate Professor of Physics at Boston University, who had been a postdoctoral fellow at Harvard while Yao was a graduate student. He and Laumann had worked together closely during that time and have since written about a dozen-and-a-half joint papers. Laumann, who is also a theorist, suggested an intriguing research direction: Diamond had already served as the host material for the aforementioned NV centers, and it was also a prime workhorse for performing table-top, high-pressure experiments. What if these two functions were put together?

In addition to being used for simulations of time crystals, NV centers can also serve as "quantum sensors" to measure, for example, local magnetic and electric fields—both their strength and orientation. With regard to the "workhorse" role, millimeter chunks of diamond had long been assembled into an apparatus called a diamond anvil cell, which could achieve high pressures (up to millions of "atmospheres") by compressing a material between two opposing diamond faces. Laumann and Yao realized that one might be able to integrate NV centers directly into the surface of the diamond pieces that are applying the pressure.

"People had studied NV centers under pressure before," Yao said, "but no one had considered inserting a layer of NV sensors directly into a diamond anvil cell." His Harvard group is currently using this technique to make local measurements of high-pressure superconductors, and they've made significant progress on this front. About ten research groups in the world have since adopted this approach, which is proving to be quite useful—an outcome that Yao finds tremendously satisfying.

While the microscopic nature of NV centers makes them ideal quantum sensors, Yao emphasizes that "we're not yet taking advantage of the most quantum mechanical feature of a many-particle system—that being entanglement." His group is now



Graduate student Esther Wang, postdoctoral scholar Zepp Wang, and Norman Yao adjust a confocal microscope used to image quantum materials at high pressures. The Yao lab has pioneered a novel technique capable of imaging the physics that occurs inside a diamond anvil cell. This has led to the first local measurements of the so-called Meissner effect in superconducting superhydride materials. [photo by Paul Horowitz]

Bingtian Ye: Forging Progress in Quantum Metrology

Bingtian Ye, a Harvard Physics Ph.D. candidate, joined the Yao group in 2017, soon after starting graduate school at Berkeley. When trying to choose an advisor, Ye found "Norm's energy and great enthusiasm for doing physics" hard to resist.

Ye moved to Harvard last year. His current research interest is spin squeezing, which he calls "one of the main directions people are pursuing these days to achieve better sensitivity in quantum measurements, or metrology." One way to measure a magnetic field, he explains, is to put a particle with a magnetic dipole in that field and see how the particle's spin direction changes. "The change in that angle over time," Ye says, "basically tells you the magnetic field strength." The precision of your measurement goes up with the number of experiments you can do and the number of particles—and hence the copies of "spins" in each experiment—but there are practical limits for the precision given a fixed number of spins. One way to alleviate that limitation and thereby boost the precision, Ye says, "is to manipulate the spins so they are entangled, which will allow you to do better at quantum sensing." And if the entanglement has just the right structure, he adds, a spin squeezed state can be generated.

Ye and fellow graduate student Maxwell Block were the lead authors on a paper posted on the Physics arXiv in January 2023, "A Universal Theory of Spin Squeezing," which lays out the necessary and sufficient conditions for creating a spin squeezed state via quantum evolution. In quantum mechanics, measurement error is unavoidable, Ye says, "but our theory sets limits for the precision of spin measurements. We're now looking for ways to reduce that error even further, and we have ideas on how to get there."

Greg Kahanamoku-Meyer:
Applying Quantum Physics to Computing and Computing to Quantum Physics

Greg Kahanamoku-Meyer got his PhD earlier this year after starting at Berkeley in the Yao lab in 2016—first in a postbaccalaureate position and then as a graduate student. A big part of his work has been on numerical studies of many-body quantum systems. "Although we basically understand how individual atoms and particles move around and behave quantum mechanically, things get more complicated when you put a lot of them together," Kahanamoku-Meyer says. "The number of variables grows exponentially with the number of particles, and you soon need to use supercomputers." And even supercomputers can get quickly overwhelmed.

Kahanamoku-Meyer carried out simulations of time crystals that were described in papers in 2018 and 2019. His simulations were consistent with the experiments led by University of Maryland physicist Chris Monroe, which made the first observations of time crystals—a phase of matter that had been hypothetical until that time. Time crystals are periodically driven systems to which energy is repeatedly added, and Kahanamoku-Meyer's simulations provided clues as to what prevents that energy from instantly heating up the system and melting any crystal as soon as it forms. Simulations of this sort can be instructive for a number of reasons, Kahanamoku-Meyer says, including the fact that "observing a real quantum system changes it, potentially affecting the results of later observations. But in a simulation, you can do whatever you want without affecting anything."

Over the course of his Ph.D. work, Meyer has veered into computational applications of many-body quantum physics, "straying further and further into quantum computing." He is grateful that "Norm has always encouraged me in this direction, rather than trying to pull me back." That lenient and open-minded attitude on the part of his advisor owes to a simple fact, Kahanamoku-Meyer says: "Norm is basically interested in everything."

carrying out additional work in this direction, trying to generate what's called a "spin-squeezed state" among the numerous NV centers randomly scattered throughout a diamond crystal. (See accompanying sidebar, "Emily Davis: Untangling the Mystery of Squeezed States.") "You can think of each NV center as a little magnet or dipole endowed with a characteristic spin," Yao explains. The trick is to get these different spins entangled in a certain way.

Entanglement, a distinctive property of quantum mechanics, is a strong form of correlation. A simple example of an entangled state would involve two NV centers whose spins are aligned in the same direction. If one is up, the other is up; if one is down, the other is down. Entanglement of this type can be a boon to quantum sensing. In classical mechanics, if you're using 100 sensors rather than just one, the precision of your measurements increases by a factor of 10 (the square root of 100). But in the quantum realm, going from 1 to 100 sensors can increase your precision a hundredfold. "The main goal would be to perform more sensitive measurements of an external magnetic field, though there could be other applications," Yao says. But achieving the desired spin-squeezed condition in a solid-state material is proving to be a difficult challenge that neither he and his colleagues, nor anyone else, has yet solved

Meanwhile, Yao has many projects underway of a theoretical bent. A major thrust of his research, for example, revolves around a single question: What are the emergent phases of matter of many-body systems—systems that must be analyzed *en masse*, as a collection of strongly-interacting particles, where the interactions give rise to qualitatively new phenomena not present in systems that have few particles. And within this area, his group has recently been investigating quantum spin liquids—a topological phase of matter proposed 50 years ago by the physicist Philip Anderson (also a Nobel Prize winner). "Topology refers to the shape of the space in which the particles reside, and the defining feature of a topological phase is that its physics depends on that shape," Yao says.

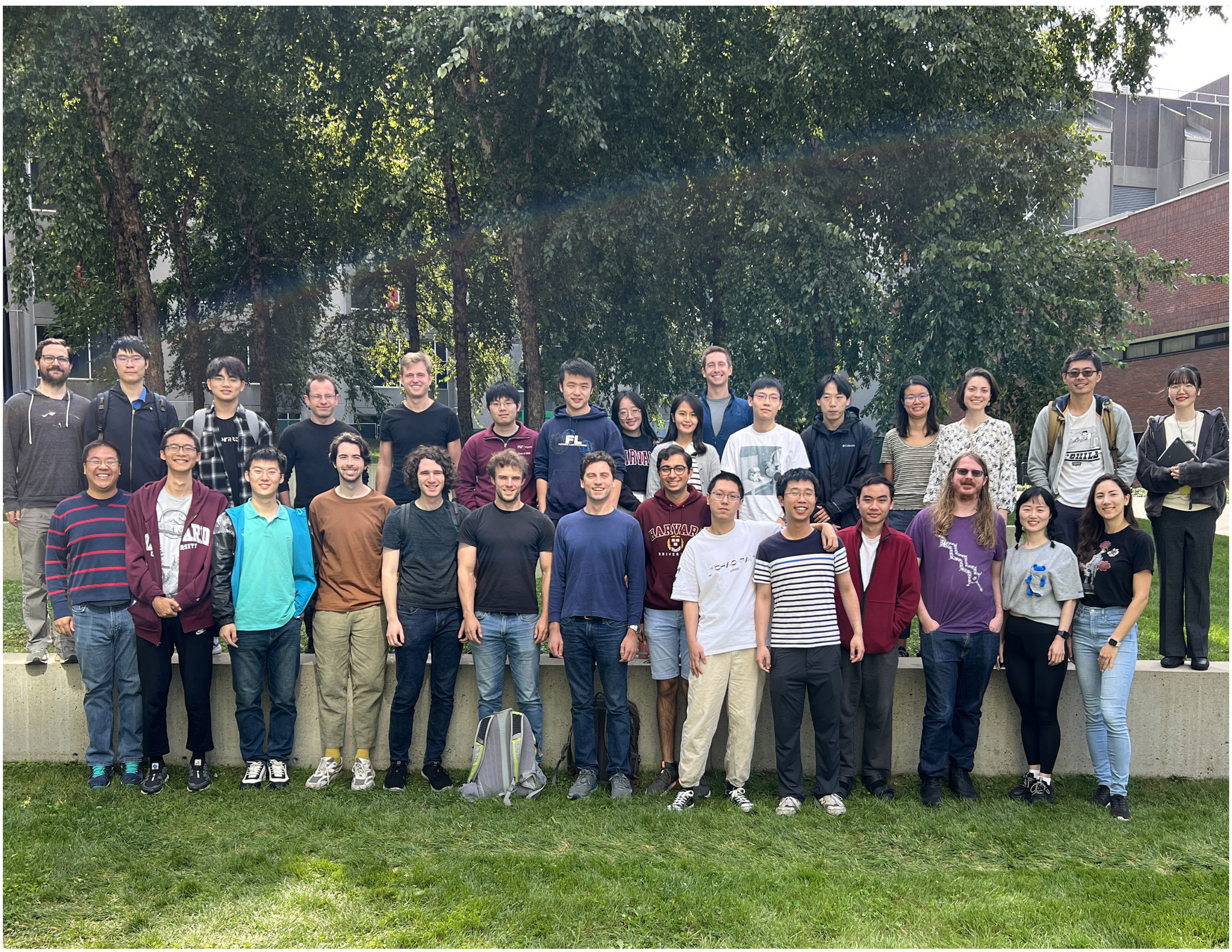
To give a sense of what a spin liquid is, imagine a two-dimensional array of tiny magnets whose spins are indicated by arrows. If the spins are all aligned, that material is called a ferromagnet. If neighboring spins are anti-aligned—with one pointing in one direction and an adjacent one pointing in the opposite direction—the material is an antiferromagnet. And if the spins point in random directions, it's a paramagnet. "If you take little measurements locally, a spin liquid looks just like a paramagnet," Yao explains. "But there are actually hidden correlations that are secretly spread out across the entire system. These non-local correlations can be used to encode and manipulate quantum information in ways that are particularly resilient to external noise."

The search for spin liquids is still on, as there is no clear-cut evidence that a spin liquid exists in any natural material. But it remains the object of great attention, because many people believe that certain types of spin liquids can host excitations called anyons, which could be important for quantum computing—useful, Yao says, "for storing information for relatively long times or for processing information more robustly."

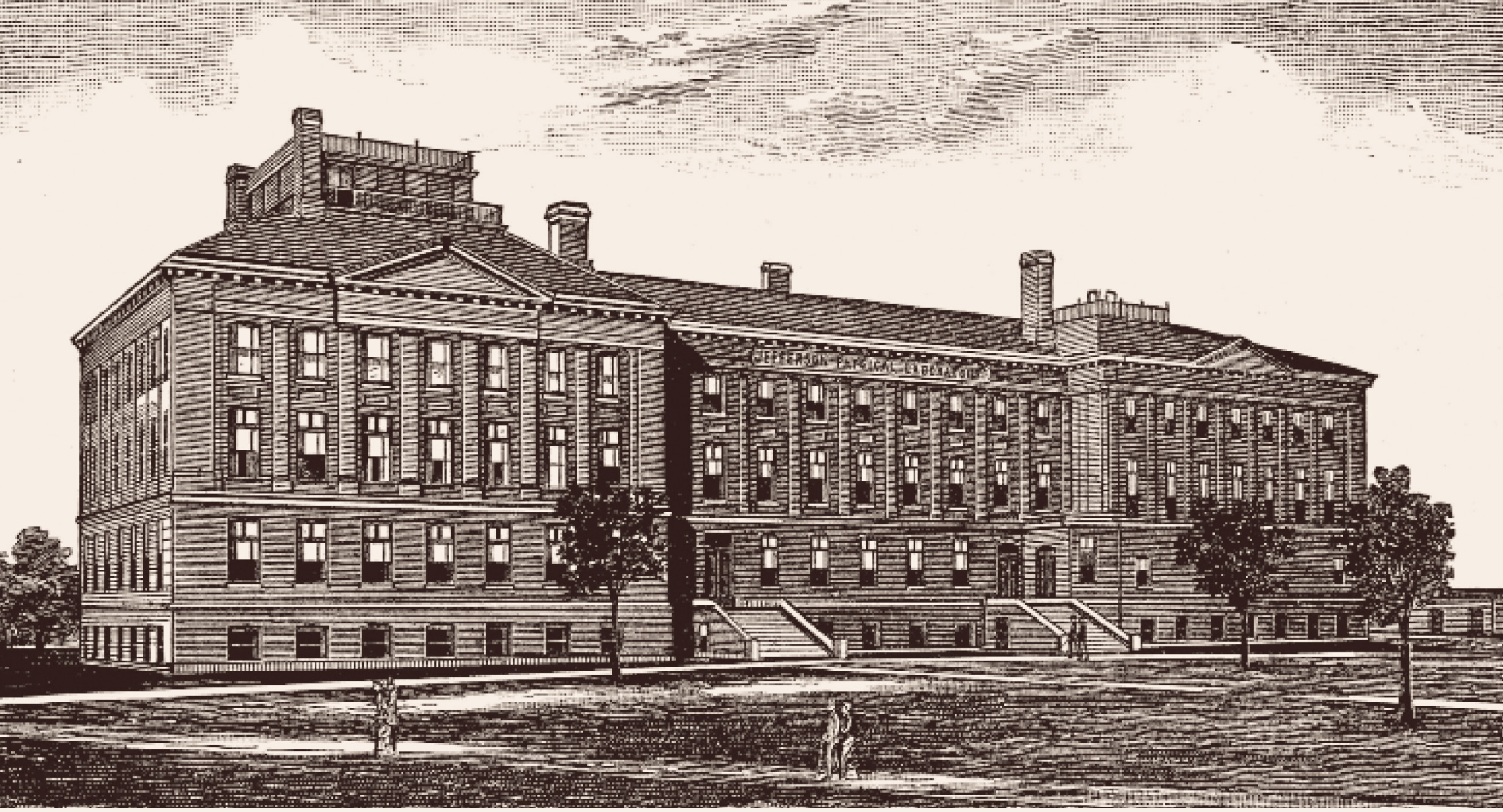
On a related vein, he is now exploring questions that lie at the intersection of quantum computing and atomic physics. In particular, a big focus in his group is to find new ways of demonstrating that a quantum device can hold a clear "quantum advantage," capable of performing a calculation that would take a conventional supercomputer a ridiculously long time to complete.

Yao is pursuing many other projects—more than can be discussed here—the combination of which is keeping him plenty busy. Nevertheless, in moments of relative calm, he tries to look into the future to catch a glimpse of where he may be headed and to consider what he ultimately hopes to accomplish. During introspective times like this, he is reminded of something his graduate advisor Lukin used to ask whenever he was about to embark on a new undertaking. "'Norm,' Misha would say, 'how would this help mankind?' He asked it all the time, and it became sort of a running joke," Yao reflects. "I used to give that idea short shrift, but as I've become older, I've come to appreciate its importance.

"I do physics, and sometimes there's a lot of abstraction in this work. It can be easy to get lost in that abstraction and get carried away by how beautiful the question is," Yao adds. "But when I look back at my career in 20 years, I hope I can answer Misha's question in some kind of affirmation—seeing that the threads of my research, when taken as a whole, are truly pointing to something. And that, yes, there was some benefit to mankind."



Yao group (2023)



"AS IMMOVABLE AS A HIGH MOUNTAIN":

Wallace Sabine and the Founding of Architectural Acoustics

by Paul Horowitz

Fig. 1: Wallace Clement Sabine

"It was entirely due to Sabine's encouragement and it was under his direction that I undertook in the autumn of `97 [1897] the investigation of the extreme ultraviolet. From that time on with but two short interruptions I was in constant contact with him, first as a student and later as a colleague." Who was it that was thus encouraged? None other than Theodore Lyman,[1] to whom we owe the eponymous series, optical spectra produced by transitions to the electron's ground state.

[1] Lyman, T., "An Appreciation of Professor Sabine," *J. Acoust. Soc. Am.*, 7 (1936): 241. In his warm introduction, Lyman remarked "Professor Sabine combined virtues and talents very rarely found in a single individual. He was above all things the very personification of unselfishness. Gentle and retiring to a fault, he always avoided publicity and cared little for fame and nothing for rewards. Yet where the right was concerned he was as immovable as a high mountain."

Few are aware of Sabine's role in Lyman's career, but in the field of acoustics he stands as a giant, for he founded – and developed to a remarkable degree, especially given the equipment of the time – the science of architectural acoustics. As Winston Churchill remarked, "never let a good crisis go to waste." And indeed, it was a crisis that sparked a revolution in the design and construction of lecture halls and theaters.

Our story begins in 1895 with the unexpectedly awful acoustics in the newly built Fogg lecture hall (Figure 2, the current site of Canaday Hall), for which President Eliot[2] sought help from the young Sabine. In the words of Sabine's cousin Paul Sabine:[3]

This building had just been completed and this room was intended to be used to accommodate large lecture courses and for lectures open to the public. Its plan is one which from the tradition of the Greek amphitheater might be expected to be acoustically satisfactory. Moreover, in plan it is not markedly different from Sanders Theater, a much larger room which both for music and speaking is acoustically quite acceptable, so that the designers had no reason to expect prior to the event the acoustical calamity which was to reward their efforts. The lecture room of the Fogg Art Museum should in the light of all available knowledge of the subject, have been acoustically excellent. As a matter of grim fact it was extremely bad.[4]

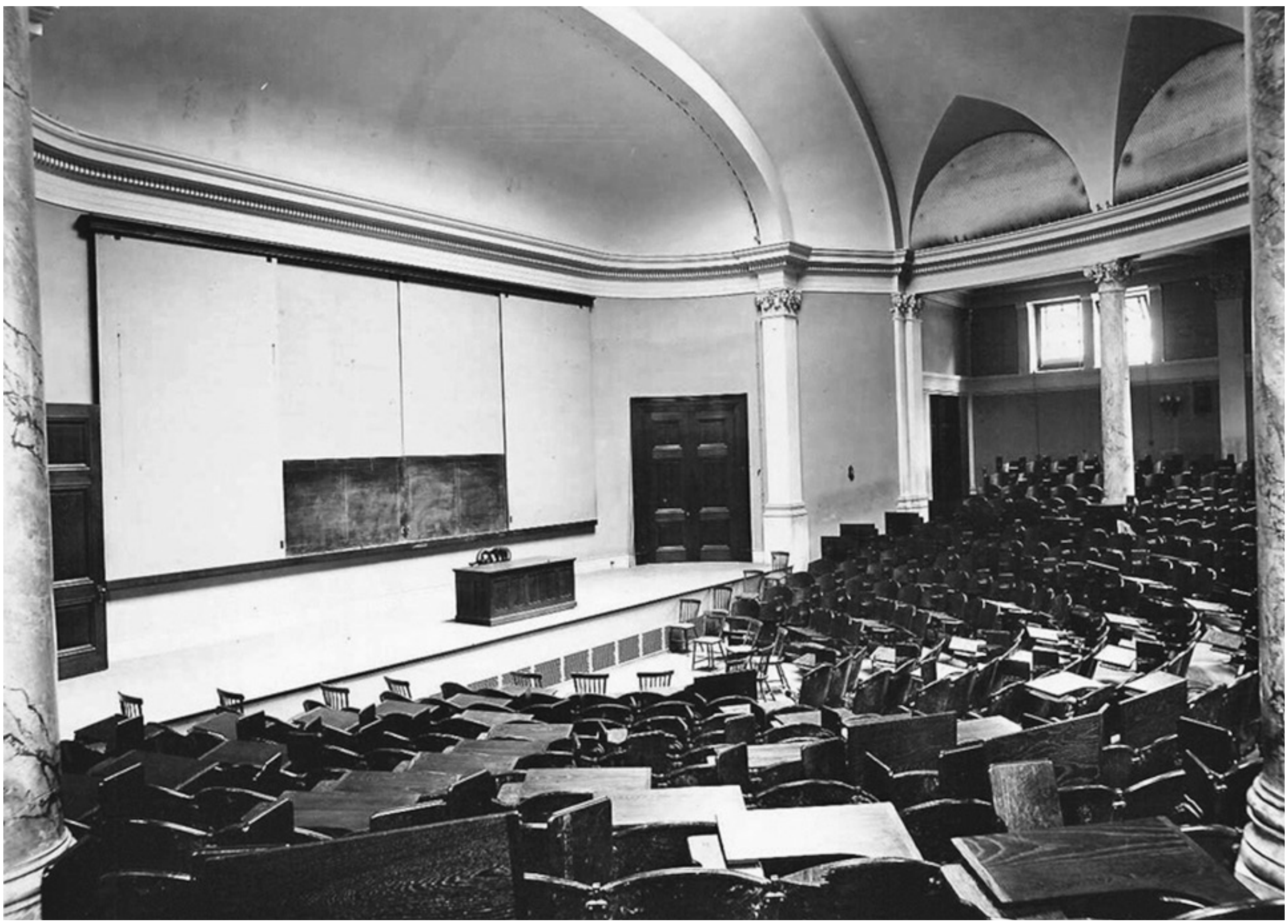


Fig. 2: The new Fogg lecture hall, circa 1895, where lectures were unintelligible. Note the hard surfaces, such as plaster walls and ceiling, and hard-surface student desks and seats; evidently it occurred to no one to equip the latter with cushions.

[2] Prodded by a complaint from his cousin and lecturer in fine arts Charles Eliot Norton.

[3] About the choice of whom Paul Sabine had this to say: "What to do? The college authorities did what I suspect college authorities are prone to do in all such cases, referred the problem to the Physics Department – and the Physics Department in turn placed the wailing infant on the doorstep of the youngest professor in the department." (Sabine, P.E., "The Beginnings of Architectural Acoustics," *J. Acoust. Soc. Am.*, 7 (1936): 242.)

[4] ibid.

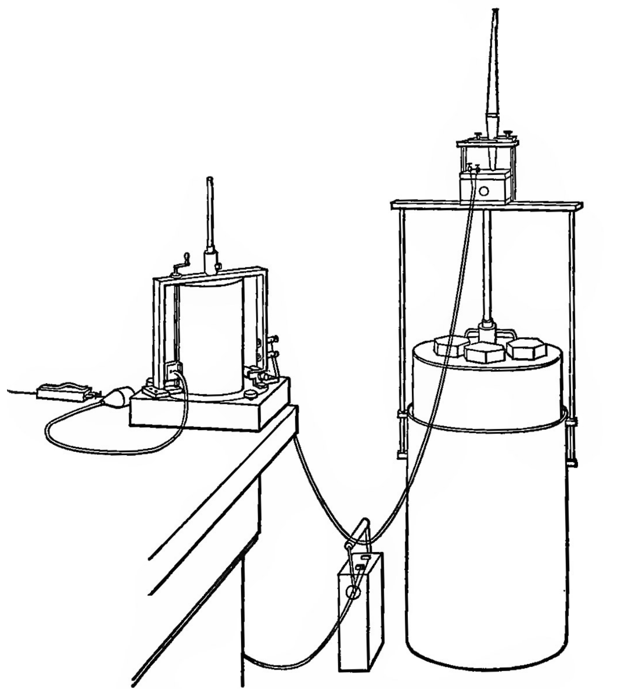


Fig. 3: Sabine's apparatus: air from a reservoir is released into an organ pipe by an electric valve; the listener pressed a key when the reverberant sound became inaudible. (Figure 1 of Sabine, W.C., "Reverberation," *The American Architect*, 1900.)

REVERBERATION

Sabine suspected that the hall's excessive reverberation time was largely responsible, and set to work with simple apparatus (Figure 3, an air-tank-driven organ pipe and a mechanical chronometer: 1895 was firmly in the pre-electronic era) and with dogged determination to make quantitative measurements of the flawed hall's reverberation time; the idea was that you can't tune it up if you can't measure it. The procedure he finally settled on (having abandoned his "preliminary gropings" involving optical observations of gas flames) was to mark the time from the end of the organ-pipe sound to the moment when the residual sound was inaudible.[5]

One might worry that a subjective method like this would be both imprecise and unrepeatable, but a set of measurements taken over multiple days, and with different observers (see an example in Figure 4), established to Sabine's satisfaction that it was adequate to the task – that task being to determine the acoustic "absorbing power" of different kinds and quantities of various materials.

Having established a procedure to quantify reverberation time, Sabine proceeded to measure the effect of various quantities of absorber in reducing the reverberation time. For this he chose the nearby supply of seat cushions from Sanders Theater (Figure 5). Here we let him tell the story:

> *With an organ pipe as a constant source of sound, and a suitable chronograph for recording, the duration of audibility of a sound after the source had ceased in this room when empty was found to be 5.6 seconds. All the cushions from the seats in Sanders Theatre were then brought over[!] and stored in the lobby. On bringing into the lecture-room a number of cushions having a total length of 8.2 meters, the duration of audibility fell to 5.33 seconds.*
>
> *Little by little the cushions were brought into the room, and each time the duration of audibility was measured. When all the seats (486 in number) were covered, the sound was audible for 2.03 seconds. Then the aisles were covered, and then the platform. Still there were more cushions – almost half as many more. These were brought into the room, a few at a time, as before, and draped on a scaffolding that had been erected around the room, the duration of the sound being recorded each time. Finally, when all the cushions from a theatre seating nearly fifteen hundred persons were placed in the room – covering the seats, the aisles, the platform, the rear wall to the ceiling – the duration of audibility of the residual sound was 1.14 seconds.*

That was just the beginning. Sabine then investigated the placement of the cushions, finding that it mattered little how they were arrayed, as long as their total area was exposed – in his words "the measurements of the cushions should be, not in running meters of cushion, but in square meters of exposed surface." He then tried other materials:

> *Curtains of chenille, 1.1 meters wide and 17 meters in total length, were draped in the room. The duration of audibility was then 4.51 seconds. Turning to the data that had just been collected it appeared that this amount of chenille was equivalent to 30 meters of Sanders Theatre cushions. Oriental rugs, Herez, Demirjik, and Hindoostanee, were tested in a similar manner; as were also cretonne cloth, canvas, and hair felt. Similar experiments, but in a smaller room, determined the absorbing power of a man and of a woman, always by determining the number of running meters of Sanders Theatre cushions that would produce the same effect.*

[5] In contemporary terms, Sabine's "reverberation time" amounts to a decay of 60dB (energy reduction of 10^6).

	Observer	Total Absorbing Power	Absorbing Power per Person
First night, whole audience	W. C. S.	123.0	.42
" " " "	G. LeC.	113.0	.39
" " half "	W. C. S.	58.3	.41
" " " "	G. LeC.	58.3	.41
Second " whole "	W. C. S.	66.2	.40
" " " "	E. D. D.	64.6	.39
			.40 (3)

Fig. 4: Measurements of the absorbing power (fraction of sound absorbed) in the "large lecture-room of the Jefferson Physical Laboratory" (J250), as a function of audience size, carried out by three observers over two successive nights in 1899. In Sabine's words "In view of the difficulties of the experiment the consistency of the determination is gratifying. The average result of the six determinations is probably correct within two per cent."]

For many weeks of nights Sabine and his helpers transported those now-historic cushions, doing their experiments between 2 and 6AM, and returning them before the next day's classes. A useful result was the finding that the ideal reverberation time for a lecture hall is 1.0 seconds, and for a concert hall 2–2.25 seconds. Along the way, Sabine established a reproducible unit of absorption, the square foot of open window. In his charming prose:

> *It is obvious, however, that if both cushions and windows are to be classed as absorbents, the open window, because the more universally accessible and the more permanent, is the better unit. The cushions, on the other hand, are by far the more convenient in practice, for it is possible only on very rare occasions to work accurately with the windows open, not at all in summer on account of night noises – the noise of crickets and other insects – and in the winter only when there is but the slightest wind; and further, but few rooms have sufficient window surface to produce the desired absorption. It is necessary, therefore, to work with cushions, but to express the results in open-window units.*

And the contemporary unit of sound absorption is the sabin (one square foot of open window), and the metric sabin (one square meter); the absorption of Sabine's cushions (at 512 Hz) were equivalent to 0.8 that of an open-window of the same area.

Having established optimal reverberation times, Sabine proceeded to "fix" the Fogg lecture hall, by installing wall panels of felt. In his words: "the room was rendered not excellent, but entirely serviceable, and it has been used for the past three years without serious complaint." But he was only getting started. Already he had a sophisticated appreciation of room acoustics and remedies; here is a sample (from the *Proc. Am. Inst. Architects*, 1898):

> *There is no simple treatment that can cure all cases. There may be inadequate absorption and prolonged residual sound; in this case absorbing material should be added in the proper places. On the other hand, there may be excessive absorption by the nearer parts of the hall and by the nearer audience and the sound may not penetrate to the greater distances. Obviously the treatment should not be the same. There is such a room belonging to the University, known locally as Sever 35. It is low and long. Across its ceiling are now stretched hundreds of wires [a traditional pre-Sabine remedy] and many yards of cloth. The former has the merit of being*

Fig. 5: A Sanders Theatre historic seat cushion, approximately 52" x 18" and 5" thick, of "wiry vegetable fiber covered with canvas ticking and a thin cloth."

harmless, the latter is like bleeding a patient suffering from a chill. In general, should the sound seem smothered or too faint, it is because the sound is either imperfectly distributed to the audience, or is lost in waste places. The first may occur in a very low and long room, the second in one with a very high ceiling. The first can be remedied only slightly at best, the latter can be improved by the use of reflectors behind and above the speaker. On the other hand, should the sound be loud but confused, due to a perceptible prolongation, the difficulty arises from there being reflecting surfaces either too far distant or improperly inclined.

Sabine proceeded to extend his measurements to cover the audible frequencies, and to include the effect of the audience. Here is an example of his descriptive prose:

In the very nature of the problem the most important data is the absorption coefficient of an audience, and the determination of this was the first task undertaken. By means of a lecture on one of the recent developments of physics, an audience was enveigled into attending, and at the end of the lecture requested to remain for the experiment. In this attempt the effort was made to determine the coefficients for the five octaves from C_2 *128 to* C_6 *2048, including notes E and G in each octave. For several reasons the experiment was not a success. A threatening thunderstorm made the audience a small one, and the sultriness of the atmosphere made open windows necessary, while the attempt to cover so many notes, thirteen in all, prolonged the experiment beyond the endurance of the audience.*

Sabine repeated the experiment successfully the following summer ("Moreover, bearing in mind the experiences of the previous summer, it was recognized that even seven notes would come dangerously near over-taxing the patience of the audience").

Sabine turned his attention to the absorbing properties of pretty much anything he could find. In his 1900 paper, he includes tables of the absorption coefficient (relative to an open window) of various wall surfaces ("plaster on wood lath, plaster on wire lath, plaster on tile," etc.), of various "settees, chairs, and cushions," of audiences ("audience per square meter, audience per person, isolated woman, isolated man"), and, most charmingly, of "Miscellaneous" (Figure 6).

As Sabine accumulated reverberation-time data from rooms of different sizes, trying to make sense of things, he noticed that, when plotting measurements of reverberation time T versus total absorbing area a, the data fell on nested hyperbolas. In other words, for any given hall the product $T \times a$ was approximately constant as the amount of absorber was changed. He called this the "hyperbolic law." And he further realized that the product $T \times a$ was proportional to the hall's volume. Put another way, he found

$$T_{reverb} = kV/a \qquad (1)$$

where V is the volume of the hall, a is the total absorbing area, and k is a constant whose value he found to be 0.171 when a is in units of square meters of open window.[6] As he wrote to President Eliot in 1898, upon this realization:

Miscellaneous

Oil paintings, inclusive of frames	.28
House plants	.11
Carpet rugs	.20
Oriental rugs, extra heavy	.29
Cheesecloth	.019
Cretonne cloth	.15
Shelia curtains	.23
Hairfelt, 2.5 cm. thick, 8 cm. from wall	.78
Cork, 2.5 cm. thick, loose on floor	.16
Linoleum, loose on floor	.12

Fig. 6: Absorption coefficient of miscellaneous materials, from Sabine's 1900 paper. He explains, helpfully "the values are per square meter, except in the case of plants, where the coefficient is per cubic meter."

[6] This is the famous Sabine formula for reverberation time, which allows calculation of the required total absorbing power when the hall volume and desired reverberation time are known. He gives a derivation in his 1900 paper (in a section called "Exact Solution") based on physical concepts like absorption at each of a sound wave's multiple reflections.

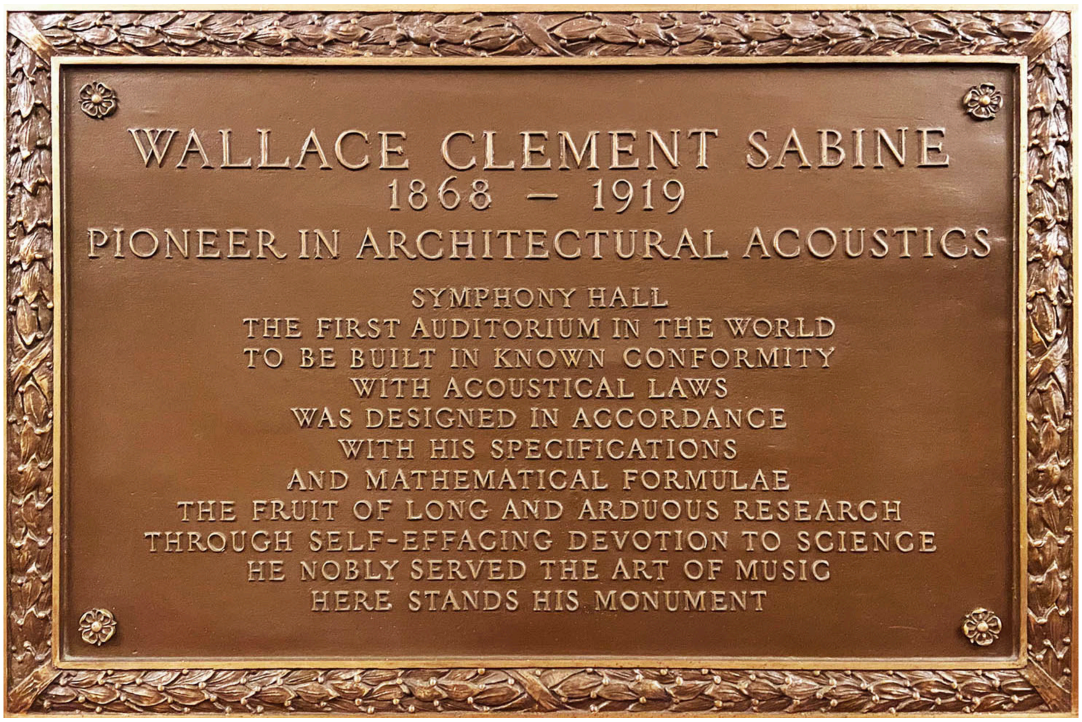


Fig. 7: This plaque stands in the main corridor of Boston's Symphony Hall. (Photo by Bridget Carr, used with permission)

> *Last night the confusion of observations and results in which I was floundering resolved themselves in the clearest manner. Now it is only necessary to collect further data in order to predict the character of any room that may be planned at least as respects reverberation.*

BOSTON SYMPHONY HALL

By this time Sabine's reputation had spread, and, with superb timing, he was called in to advise on the "New Boston Music Hall" (now Symphony Hall) – a "room being planned." Sabine already had considerable knowledge of other halls (for example the Leipzig Gewandhaus, the Old Boston Music Hall, Sayles Hall in Providence, and the Boston Public Library).

The original concept in 1893, favored by New York architect Charles Follen McKim, was to create a gleaming semi-circular hall in the style of ancient Greek amphitheaters. This would be a departure from the rectangular box-like halls that were admired for their excellent acoustics, the best of which was probably the Neue Gewandhaus in Leipzig. Happily, a serious financial crisis put this plan on hold, allowing our physicist time to do his research and thus intervene with some acoustical sanity. The amphitheater plan was abandoned, partly with the realization (conveyed in a letter to the architect from Henry Lee Higginson, chairman of the building committee and the founder of the BSO) that

> *While we hanker for the Greek theater plan, we think the risk too great as regards results, so we have definitely abandoned that idea. We shall therefore turn to the general plan of our Music Hall and of the halls in Vienna and Leipsic* [sic], *the latter being the best of them all…*[7]

President Eliot, already aware of Sabine's success with the Fogg Lecture Hall, connected him with his friend Higginson. Sabine, initially hesitant to become involved, bore down on his collection of reverberation data, and, after two weeks of intense study, came up with his hyperbolic epiphany (Equation 1): "I have found it at last!" he said. As his mother, who happened to be with him at the time, recounted, "His whole face smiles, though he is very tired."

[7] Letter from Higginson to McKim, 10/27/1898.

A DISASTER PREVENTED

The new Music Hall was intended to seat somewhat more than the hall it was to replace (2,600 vs 2,391). But the Leipzig hall was far smaller (it seated 1,560); so the initial plan, before Sabine intervened, was simply to scale up the dimensions of the Gewandhaus by a linear factor of 1.30. But a linear scaling, from Sabine's formula, would increase the ratio V/a (and therefore the reverberation time) by that same factor, thus a reverberation time of about 3 seconds (in the words of Leo Beranek, it would have been "an acoustical disaster"). Sabine worked with the architect and committees to address this problem, nicely solved by reducing the ceiling height, adding balconies, reducing seat spacing, and other measures. The result is a hall that was (and continues to be) among the best in the world.[8] In 1946, the plaque shown in Figure 7 was placed in Symphony Hall.

LATER WORK

Sabine's success with Boston's new hall led to a lifetime of consultation on hundreds of churches, cathedrals, auditoriums, and theaters. In some cases, the damage had already been done (as with the Fogg), and, as he succinctly put it, "in repair work for bad acoustical conditions it is generally impracticable to change the shape, and only variations in materials and furnishings are allowable." One example was the New Theatre in New York City, which opened in 1909, and which, according to Wikipedia, was "noted for its fine architecture" but had "a serious defect in the acoustics." Sabine used Schlieren photography on a model of the hall (illuminating it "by the light of a very fine and somewhat distant electric spark") while ensonifying it with "a proportionally scaled sound-wave." The Schlieren photographs show nicely the propagation of echoes throughout the hall. Sabine concludes:

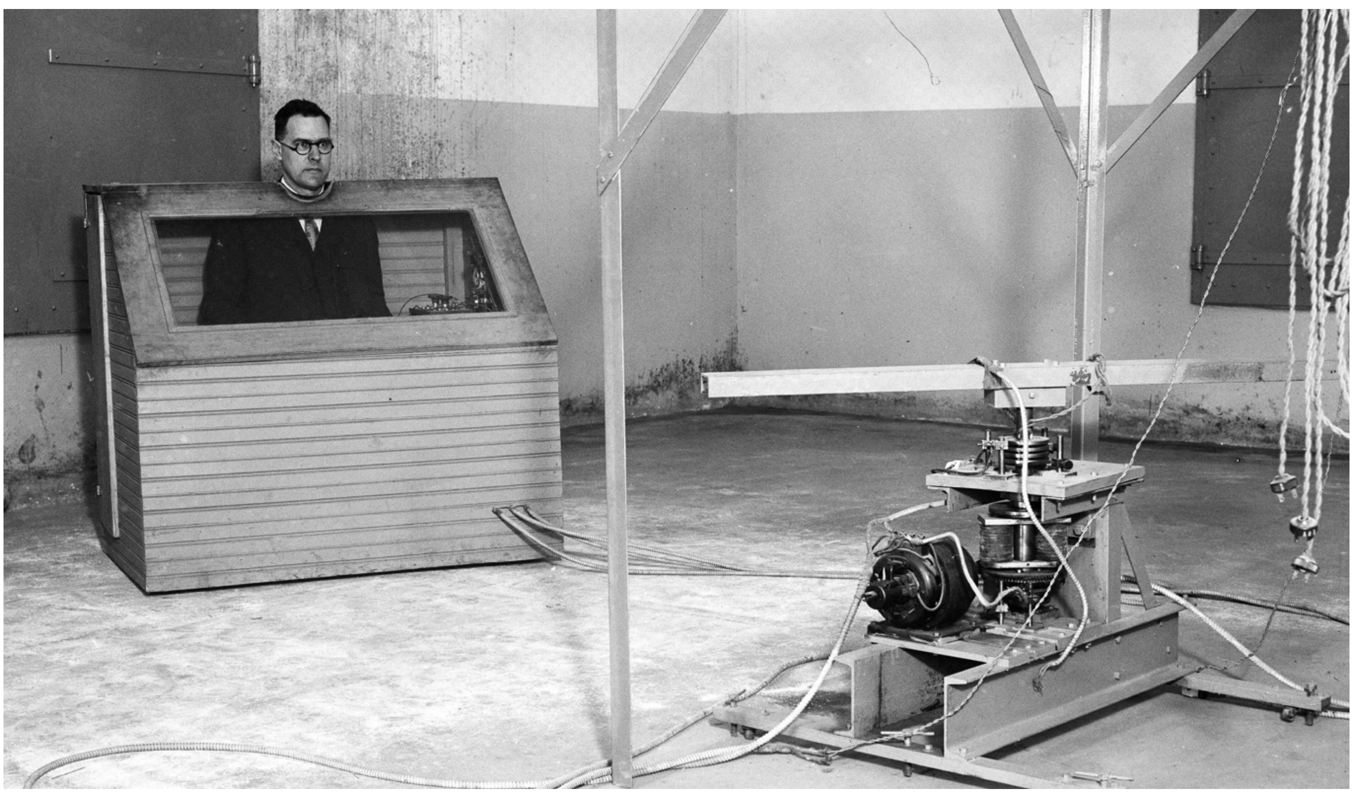


Fig. 8: To gauge intelligibility in a highly reverberant environment, Sabine used this box (shown without the front closure) in his reverberation chamber to eliminate absorption from the clothed body.

[8] In Beranek's admittedly subjective "Rank-Orderings of Acoustical Quality of 58 Concert Halls, Developed From Questionnaires and Interviews" (reference of footnote 12) the top ten, in order, are: 1. Grosser Musikvereinssaal, Vienna; 2. Symphony Hall, Boston; 3. Teatro Colón, Buenos Aires; 4. Konzerthaus, Berlin; 5. Concertgebouw, Amsterdam; 6. Tokyo Opera City Concert Hall, Tokyo; 7. Grosser Tonhallesaal, Zurich; 8. Carnegie Hall, New York; 9. Stadt-Casino, Basel; and 10. St. David's Hall, Cardiff.

> *The photographs… show the echoes produced in the horizontal plane passing through the marble parapet in front of the box.*
> . . .
>
> *While these several factors, reverberation, interference, and echo, in an auditorium at all complicated are themselves complicated, nevertheless they are capable of an exact solution, or, at least, of a solution as accurate as are the architect's plans in actual construction. And it is entirely possible to calculate in advance of construction whether or not an auditorium will be good, and, if not, to determine the factors contributing to its poor acoustics and a method for their correction.*

Quite apart from halls and churches, Sabine did some consulting for the Remington Typewriter Company, who wished to reduce their products' noises. With typical thoroughness, Sabine worked out a theory of the initial production of vibrations: "In percussion typewriting machines, the principal sources of vibration are in ascending order of importance (1) the space bar; (2) the recovery of typebars and keys; (3) the typeshift; (4) the carriage (a) release and (b) check; (5) the striking of the type." He then details each of these, followed by a consideration of the sound propagation mechanisms: "No portion of the noise of the typewriter is communicated to the air in any considerable measure at the actual point of impact. The sound we hear comes to us (1) from the extended surfaces of the machine, and (2) to a surprisingly great extent, from the table on which the typewriter rests and from which it has never been insulated in any effective manner."

This and other investigations led Sabine to study sound transmission through walls, starting with "measurements of the decrease in intensity (loudness) of the sound transmitted between two rooms when (1) one to six layers of half-inch felt intervened between them, or (2) when one to six layers of sheet iron, each separated from the other by one inch of airspace intervened, or (3) when two to six layers of sheet iron separated by half-inch layers of felt and one inch of airspace intervened. An original concept introduced in that paper was the plotting of the transmitted intensity on a logarithmic scale – the forerunner of the decibel!"[9] For some of these experiments Sabine used the "constant temperature room" in the sub-basement of Jefferson (Figures 8 and 9), used much later as the bottom site for the Pound-Rebka experiment.[10]

Fig. 9: From his 1900 paper in The American Architect: "There is a room in the Jefferson Physical Laboratory, known as the constant-temperature room, that has been of the utmost service throughout these experiments." This contemporary photograph shows the entrance down the Sabine's reverberation chamber, one level below grade at the west end of Jefferson Laboratory. (inset: plaque placed by Prof. Richard Wilson)

Even in his early work on the Fogg, Sabine had studied wall materials, for example plaster over tile or brick, compared with plaster on lath laid over studding. His interest at that time was primarily in their absorption of reflected sound. But by 1915 he had a full understanding of the attenuation of transmitted sound produced by what we now call acoustic impedance mismatch. In his article that year in *The Brickbuilder*,[11] he described how "any discontinuity diminishes the transmission of sound; and the transition from masonry to air is a discontinuity of an extreme degree. Two solid masonry walls entirely separated by an air space furnish a vastly better sound insulation than either wall alone."

[9] Quotation from Beranek, L. and Kopec, J., "Wallace C. Sabine, acoustical consultant," *J. Acoust. Soc. Am.* 69 (1981): 1.

[10] And Sabine's former student Lyman had his spectroscopy lab in the other sub-basement, just a few steps away; see P. Horowitz, "Testing Einstein's Prediction: the Pound-Rebka Experiment," *Harvard Physics Newsletter* (2021): 12.

[11] "The Insulation of Sound," *The Brickbuilder* 24, no. 2 (1915): 31.

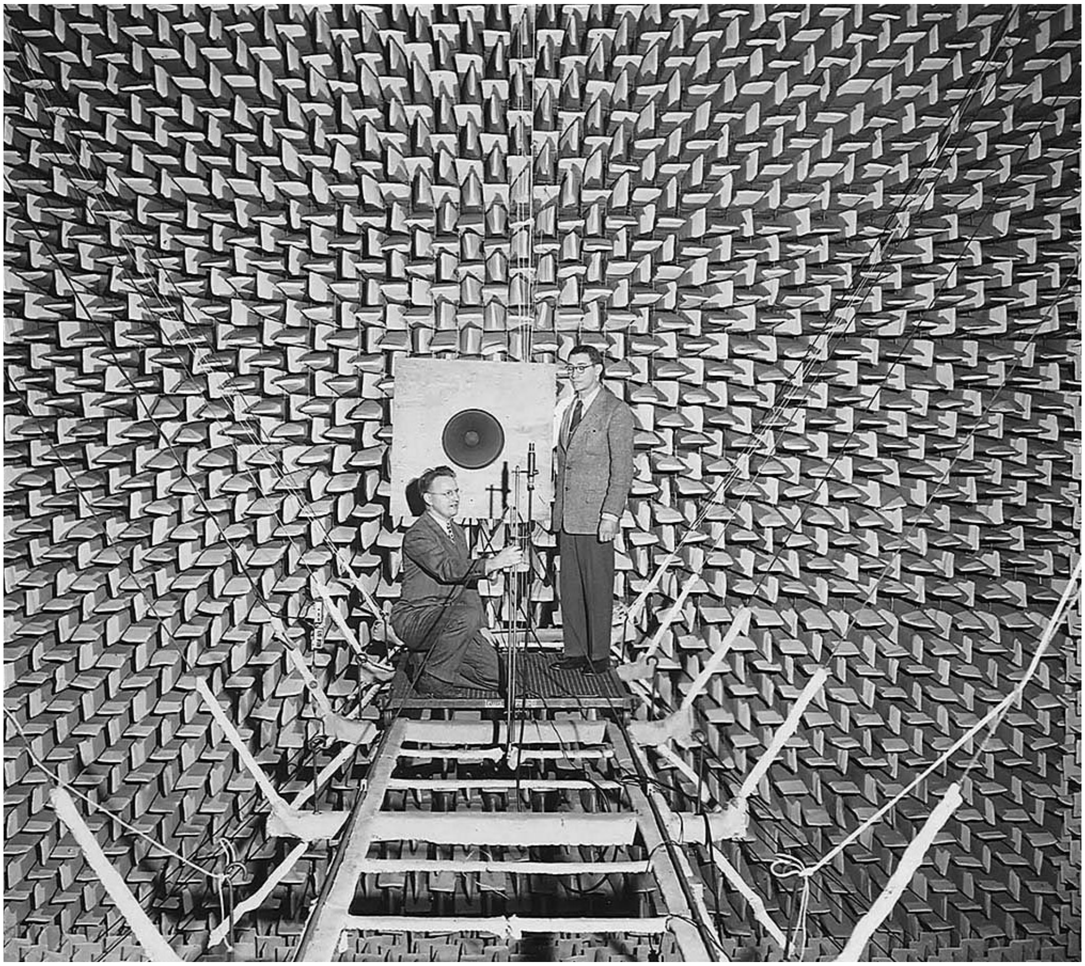


Fig. 10: "Beranek's Box" -- Harvard's anechoic chamber in 1948. (Harvard University Archives)

Sabine has some lovely descriptions of building construction gone wrong. He observes, wryly, that "it is always easier to explain why a method does not work than to know in advance whether it will or will not. It is especially easy to explain why it does not work when not under the immediate necessity of correcting it or of supplying a better." Then he proceeds to find the flaws in a home that was painstakingly built for good sound isolation:

> *The house in New York presented a problem even more interesting. It was practically a double house, one of the most imperative conditions of the building being the exclusion of sounds in the main part of the house from the part to the left of a great partition wall. This wall of solid masonry supported only one beam of the main house, was pierced by as few doors as possible – two – and by no steam or water pipes. The rooms were heated by independent fireplaces, The water pipes connected independently to the main. It had been regarded as of particular importance to exclude sounds from the two bedrooms on the second floor. The ceilings of the rooms below were, therefore, made of concrete arch; on top of this was spread three inches of sand, and on top of this three inches of lignolith blocks; on this was laid a hardwood floor; and finally, when the room was occupied, this floor was covered by very heavy and heavily padded carpets. From the complex floor thus constructed arose interior walls of plaster on wire lath on independent studding, supported only at the top where they were held from the masonry walls by iron brackets set in lignolith blocks. Each room was, therefore, practically a room within a room, separated below by three inches of sand and three inches of lignolith and on all sides and above by an air space.*

And, surprise of surprises, "In the rear bedroom, from which the best results were expected, one could hear not merely the shutting of doors in the main part of the house, but the working of the feed pump, the raking of the furnace, and the coaling of the kitchen range." And "rapping with the knuckles on the wall of [a basement] room produced in the bedroom, two stories up and on the other side of the great partition wall, a sound which, although hardly, as the architect expressed it, magnified, yet of astonishing loudness and clearness. In this case, the telephone-like nature of the process was even more clearly defined than in the other cases, for the distances concerned were much greater." Sabine used this example, which he said had "many interesting aspects," to teach about airborne versus conducted sound, the conversion between longitudinal and transverse waves, and mitigating measures to address the problem.

A CENTURY OF PROGRESS IN ARCHITECTURAL ACOUSTICS

With twentieth-century electronics – microphones, amplifiers, and accurate measuring instruments – and with the basis provided by Sabine's initial discoveries and careful measurements of sound absorption and reverberation time, architectural acoustics matured to the science it is today. The importance of many subtle factors was elucidated; these include effects such as "early sound," reverberant sound, diffusion, and a host of other parameters.[12]

"Beranek's Box" – An Anti-Reverberation Chamber

Among the leading figures in architectural acoustics was Leo Beranek (PhD, Harvard, 1940), whose measurements of dozens of concert halls worldwide established a solid foundation for concert-hall design.[13] Among his many accomplishments, in 1943 he built the first anechoic (echo-free) chamber in the US, needed for acoustic measurements in support of the war effort. A painstaking set of measurements on sub-scale anechoic chambers informed the final product, whose interior space of 38 x 50 x 38 feet was covered with 19,000 Fiberglas wedges (Fig. 10). The performance was excellent – only fractional dB's of departure from perfect inverse-square falloff from an acoustic source[14] over the range of 70 Hz to 10 kHz.

This author, having measured home-built microphones in Beranek's Box, can attest that the silence experienced in it is highly disorienting. A better testament comes from composer John Cage, whose experience in 1951 in the box[15] is said to have inspired his best-known composition *4'33"* (four minutes and 33 seconds of silence).

An Era of Sophistication

With the science of reverberation firmly in hand, research in concert-hall acoustics has focused on the subjective intangibles: what makes a hall have favorable characteristics, characterized as a sense of "proximity," or of feeling "warm," or "lively," or "rich," or "intimate"? Or, on the other side of the coin, "dull," or "flat," or "monophonic," or "shrill," or "brittle"? And, quite apart from the audience experience, what about the performers' ability to hear each other clearly?

It's fair to say that contemporary architectural acoustics has succeeded in its primary goal: to ensure, ahead of construction, that a new hall will not disappoint. Some of the more interesting questions relate to the ability of an audience member to image the separate instruments on stage. Recent work by a physics department graduate (Fig. 11) has provided hints: good "spatial hearing" appears to exploit phase coherence in the acoustic overtones, which is degraded by early reflections; this can be experimentally demonstrated by scrambling overtone phases with an all-pass network (which otherwise preserves the spectrum).

[12] Here are some from the authoritative *Concert Halls and Opera Houses – Music, Acoustics, and Architecture*, 2nd ed. by Leo Beranek (Springer, 2004): early decay time, binaural quality index, bass ratio, initial-time-delay gap, lateral fraction, acoustical glare and surface diffusivity, brilliance, balance, blend, and immediacy of response.

[13] He consulted on the design of Philharmonic Hall in New York, but, sadly, most of his recommendations were ignored or overruled by the architects and committees. In the words of acoustician Christopher Brooks, "he ought to have resigned on the spot." When the hall was completed in 1964, the result was unsatisfactory. Happily, Beranek found a receptive client 30 years later – for the Tokyo Opera City (TOC) Concert Hall, which utilized all of his findings. It opened in 1997, to overwhelmingly positive reviews. According to cellist Yo-Yo Ma (Harvard, AB `76), "This hall simply has some of the best acoustics in which I have ever had the privilege to play… What has been accomplished is a miracle!"

[14] Thus demonstrating an absence of reflected sound.

[15] "It was after I got to Boston that I went into the anechoic chamber at Harvard University… Anyway, in that silent room, I heard two sounds, one high and one low. Afterward I asked the engineer in charge why, if the room was so silent, I had heard two sounds. He said, 'Describe them.' I did. He said, 'The high one was your nervous system in operation. The low one was your blood in circulation.'" (Cage, J., "A Year from Monday," *Wesleyan* (2010: 134.)

WALLACE CLEMENT SABINE AWARD OF THE ACOUSTICAL SOCIETY OF AMERICA

David Griesinger
2017

The Wallace Clement Sabine Award is presented to an individual of any nationality who has furthered the knowledge of architectural acoustics, as evidenced by contributions to professional journals and periodicals or by other accomplishments in the field of architectural acoustics

PREVIOUS RECIPIENTS

Vern O. Knudsen	1957	Richard V. Waterhouse	1990
Floyd R. Watson	1959	A. Harold Marshall	1995
Leo L. Beranek	1961	Russell Johnson	1997
Erwin Meyer	1964	Alfred C. C. Warnock	2002
Hale J. Sabine	1968	William J. Cavanaugh	2006
Lothar W. Cremer	1974	John S. Bradley	2008
Cyril M. Harris	1979	J. Christopher Jaffe	2011
Thomas D. Northwood	1982	Ning Xiang	2014

Fig. 11: The tradition lives on: among other awards (including the gold medal of the German Tonmeister Society) Robert Pound's student David Griesinger (PhD 1978) received the Sabine Award, whose citation concludes "The implications of this research [into the neural mechanisms of aural perception] for acoustic design of spaces built for music and speech is substantial. It represents an equivalent paradigm shift in the field of architectural acoustics to similar paradigm shifts that David has instigated throughout his career. His enduring interest in the human perception of sound is manifested by the ongoing research, continued writing and publishing of technical papers, and true inventions in the field to which he has contributed so much."

Another development, which would have made Sabine jealous, is the use of active measures (electronic enhancement) to improve concert hall sound. An example is the LARES system,[16] which uses sophisticated digital processing and an array of distributed loudspeakers to subtly compensate for acoustic deficiencies. When done well, such enhancement sounds completely natural, and listeners usually do not even realize that it is in use. One of these systems was installed in the Jay Pritzker Pavilion in Chicago, an outdoor venue designed in part by Frank Gehry, and accommodating up to 11,000 people; a sense of naturalness is preserved by sophisticated processing and time-aligning the multiple spaced radiators to convincingly enhance the (degraded) direct sound. According to one listener,[17] "I have never in my life heard sound projected so faithfully and beautifully over such a great distance. It was an ethereal experience." And, quite apart from improving the sound reaching an audience, well devised experiments with enhancement can help illuminate the factors that are important in human sound perception.

IT ALL STARTED WITH SABINE

Sabine's pioneering work continues to stand as a monument to careful scientific study, uncolored by one's preconceptions. His attention to detail, ability to learn so much from so little information, simplicity of conception and execution, and clear love of the subject are characteristics of a great scientist. His name, and his 1898 "eureka" formula (equation 1), appear in nearly every publication and every study on architectural acoustics.

SOURCES AND REFERENCES

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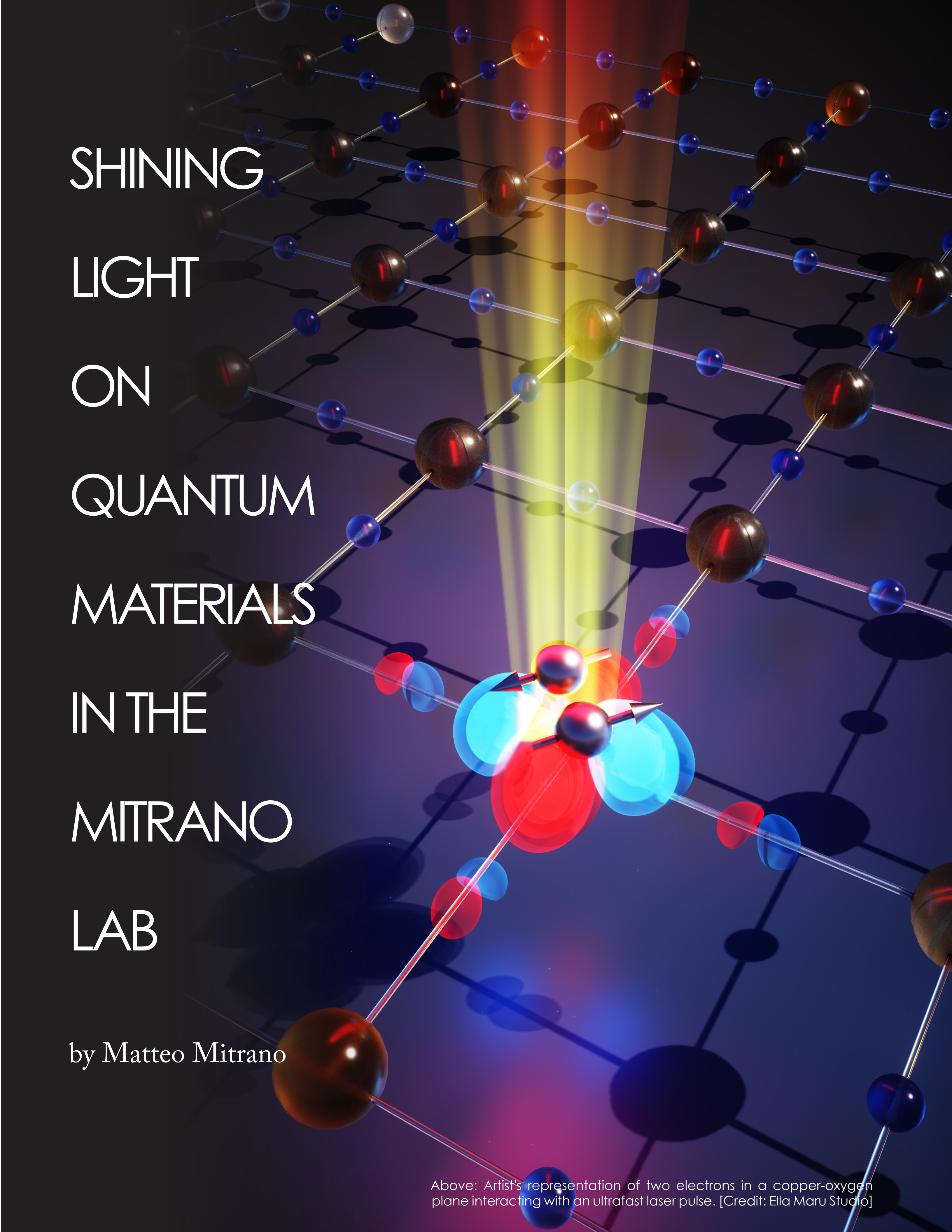
- The Harvard University Archives;
- Sabine, Wallace C., *Collected Papers on Acoustics*, Harvard University Press, 1922;
- Stebbins, Richard P., *The Making of Symphony Hall*, published by Boston Symphony Orchestra, Inc., 2000;
- miscellaneous journal articles and other online sources;
- and helpful conversations and communications with David Griesinger and Michael Sammut.

[16] Lexicon Acoustic Reinforcement and Enhancement System, invented by Griesinger and Steve Barbar in 1988 while at Lexicon, Inc. Hundreds have been installed worldwide, in concert halls, opera houses, conference rooms, churches, sound stages, and outdoor music venues.

[17] Steve Robinson, senior vice president of WFMT radio.

SHINING LIGHT ON QUANTUM MATERIALS IN THE MITRANO LAB

by Matteo Mitrano



Above: Artist's representation of two electrons in a copper-oxygen plane interacting with an ultrafast laser pulse. [Credit: Ella Maru Studio]

The technological progress of our society is intimately related to our capability to manipulate materials. A major focus of modern research efforts is the study of quantum materials, in which quantum mechanical properties manifest themselves over a wide range of energy and length scales. Achieving reliable control of these materials is essential to producing significant advances in energy applications and transportation, as well as information technology.

Throughout much of the past century, physicists have employed external stimuli (pressure, electric and magnetic fields) or devised growth methods to create and tune new states of matter. The recent introduction of intense laser fields has enabled entirely new control pathways, grounded in the concept of driving quantum materials out of equilibrium. This development presents intriguing questions: can we induce novel states of matter with light? Can we stabilize them? How do we probe quantum materials far from equilibrium?

Professor Matteo Mitrano's lab is focused on answering these questions and understanding how light can induce extraordinary effects in ordinary materials. We use the light-matter interaction as a tuning knob to dynamically induce and manipulate emergent phenomena in quantum materials, such as superconductivity, quantum magnetism, and other strongly correlated phases. Our condensed matter physics experiments leverage advanced experimental techniques (ranging from optical spectroscopy to x-ray scattering methods), as well as sophisticated theoretical modeling, to capture the richness and complexity of light-driven quantum materials. The ultimate goal of our research is to produce light-matter hybrid states in which materials exhibit novel, hitherto unobserved properties.

MANIPULATING MATTER WITH LIGHT

The key ingredient in all our experiments is the light-matter interaction. At the simplest level, laser fields interact with a material by coupling to its electric dipoles, but the way this coupling translates into photoinduced physical effects is highly dependent upon the microscopic details of each system. Following photoexcitation with an intense laser pulse ("pump"), a material will generally absorb photons, increasing its energy. If the pumping process is adiabatic, i.e., slow with respect to the natural electronic timescales, it may bring the material into an excited state with a generally higher effective temperature. However, when the external perturbation is much faster than the material's natural timescales ("nonadiabatic regime"), the same material might exhibit unique – and otherwise inaccessible – electronic and structural properties.

The world opened by these flashes of light is vast and yet largely unexplored. Short and intense laser pulses can induce phase transitions by switching a material between degenerate ground states or driving it into a long-lived (metastable) excited state. Further, they can completely reshape the free energy of a quantum system or transiently move atoms by resonantly exciting vibrations of the crystal structure. Finally, they can coherently hybridize with (or "dress") the electronic wavefunction, thus altering the effective energy scales of electronic motion inside a crystal. The net result of these microscopic processes is a plethora of photoinduced phase transitions and emergent quantum states of matter, such as light-induced superconductivity and topological phases.

A natural question at this point is how it is possible to stabilize delicate quantum phases in an excited state. This brings us to another important ingredient of ultrafast experiments, which is dissipation. Ultimately, any physical system needs to efficiently dissipate energy to avoid runaway heating from the pump laser, and one of the frontiers of our research consists of studying and engineering dissipation processes to keep driven systems in a metastable state. The subtle balance between incoming and outgoing energy in a system out of equilibrium is at the heart of many dynamical phenomena, including life itself, which, as Schrodinger writes in his 1944 lectures[1] is "partly based on existing order that is kept up."

Once a material is driven out of equilibrium, one needs to interrogate its properties at the natural timescales of its electron, lattice, and spin degrees of freedom. These are typically measured in femtoseconds (10^{-15} s) and, thus, require specialized spectroscopic methods. Our spectroscopy experiments make use of two femtosecond laser pulses (an intense "pump" and a weaker "probe" beam). The relative delay between these pulses can then be varied by tuning the path length traveled by one of the pulses to follow the resulting nonequilibrium dynamics. Our experiments (typically

[1] Erwin Schrodinger, *What is life?* and *Mind and Matter.* Cambridge, c1967.

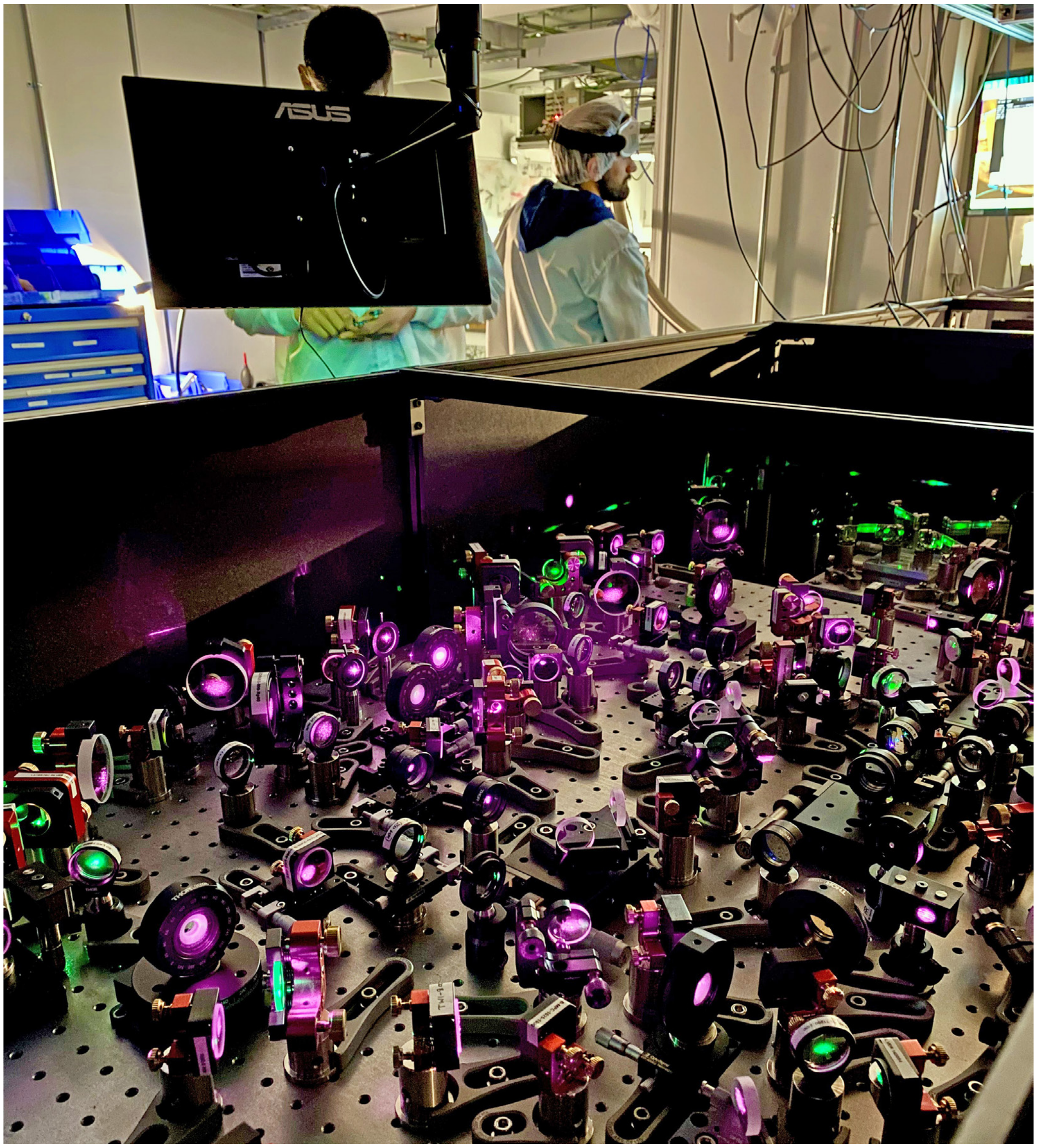


Fig. 1: Detail of an optical setup producing tunable light at midinfrared wavelengths to excite lattice vibrations in quantum materials.

concerned with phenomena at picosecond or sub-picosecond timescales) usually require optical path differences of a few millimeters. Pump-probe experiments are either performed in a single-shot mode, where the pump induces irreversible changes on a given system, or in a stroboscopic mode, in which the experiment is repeated multiple times at the repetition rate of the laser. Our group focuses on reversible optical control experiments, primarily making use of the latter approach. Each dataset involves repeating each experiment over several million pump-probe interactions at any given pump-probe time delay.

Our group specializes in optically exciting lattice vibrations and in probing quantum materials at meV energies (the natural energy scale for many collective phenomena). These experiments require ultrafast laser pulses in the far infrared or terahertz (THz) region of the electromagnetic spectrum. At these frequencies (approaching the laboratory blackbody radiation), the laser beams are invisible to the eye, and light generation and detection requires advanced optical techniques (Figure 1).

Filippo Glerean, one of the postdocs working in the Mitrano Lab, has developed a sophisticated spectrometer to measure the low-energy optical properties of quantum materials in THz pump-probe experiments (see Figure 2). According to Filippo,

> "Unlike visible light, THz photons are not easily detectable. In our experiments, we overcome this challenge by using nonlinear optical processes and imaging methods that allow us to measure the complex electric field of each single THz pulse. This approach amplifies our ability to observe small changes in the behavior of a solid excited by light, helping us explore and understand new light-driven phenomena in various materials."

PROBING DRIVEN MATTER WITH ULTRAFAST X-RAYS

Optical spectroscopy is a great method to identify fingerprints of quantum phases in and out of equilibrium, but understanding their emergence at a more fundamental level requires some sort of microscope. By having much shorter photon wavelengths (e.g., comparable to the atomic spacing in materials) and carrying substantial momentum, x-rays can interrogate quantum materials at the atomic level and provide complementary information to optics. On the one hand, x-ray diffraction is routinely used to determine crystallographic structures. On the other hand, the scattering of x-rays at resonance with certain atomic transitions provides unprecedented access to low-energy excitations and to microscopic ordering phenomena.

Our group is at the forefront of the development of two powerful techniques to investigate light-driven phenomena in quantum materials: time-resolved x-ray absorption spectroscopy (trXAS) and time-resolved resonant inelastic x-ray scattering (trRIXS). The former is a momentum-integrated probe of unoccupied electronic states, while the latter accesses collective modes of electrons and spins with momentum and energy resolution. Together these experimental methods provide a comprehensive picture of the microscopic changes happening in a material excited far from equilibrium.

Both of these techniques require extremely intense femtosecond x-ray pulses, which are beyond the capabilities of a university laboratory and need to be generated at mile-long linear accelerators called "x-ray free electron lasers," (XFELs). These machines produce relativistic electrons which are then wiggled through a long (~100 m) undulator to extract x-ray light. Each x-ray pulse is tagged, precisely synchronized

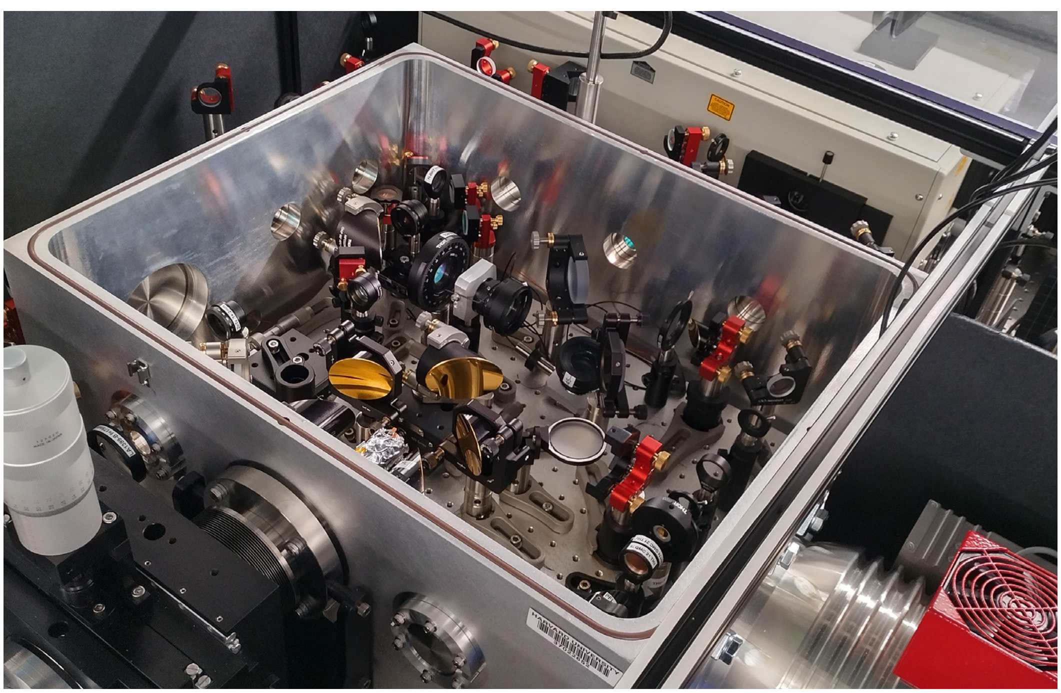


Fig. 2: THz spectrometer used to measure the low-energy properties of light-driven quantum materials.

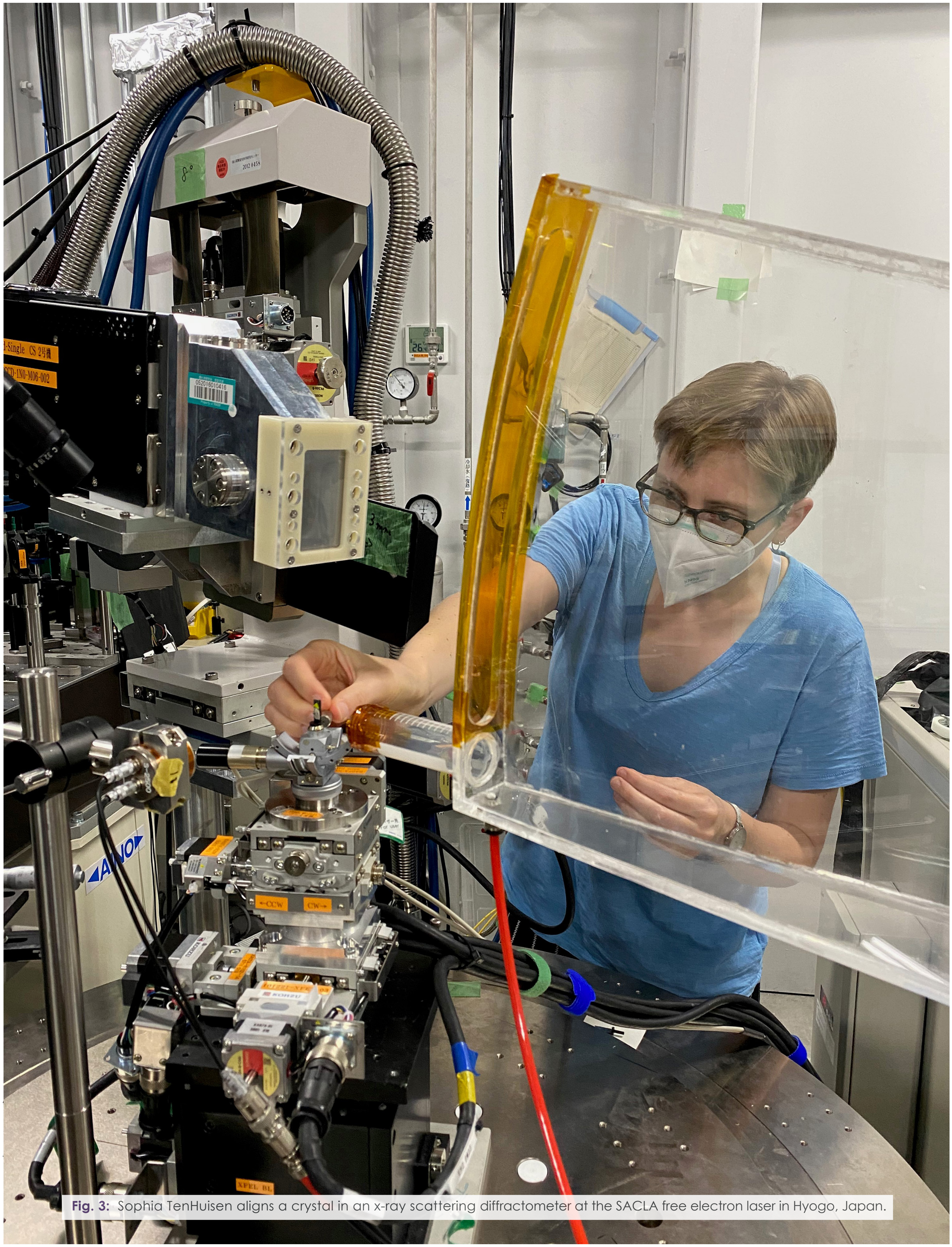


Fig. 3: Sophia TenHuisen aligns a crystal in an x-ray scattering diffractometer at the SACLA free electron laser in Hyogo, Japan.

with an optical laser, and mechanically delayed, so as to enable pump-probe experiments like the ones we perform in our lab. Our group routinely travels to XFELs around the world, such as the LCLS in California, the SACLA XFEL in Japan, the Pohang XFEL in South Korea, the SwissFEL in Switzerland, and the European XFEL in Germany (see Figure 3).

Thanks to the use of ultrafast x-rays, we have been able to observe how ultrafast lasers dynamically renormalized the electron-electron interactions in a strongly correlated oxide. In a study led by one of our postdocs, Denitsa Baykusheva, we used time-resolved x-ray absorption spectroscopy to accurately measure shifts of the electronic states in the high-temperature superconductor $La_{2-x}Ba_xCuO_4$ and discovered an unprecedented reduction of the Coulomb repulsion (also known as Hubbard *U*) between electrons in the copper orbitals in response to optical pumping. This experiment challenges the notion that the effective Coulomb repulsion in these inorganic materials is a constant quantity, insensitive to doping or other perturbations. It also indicates that the spin fluctuations – dictated by the exchange energy scale – must undergo light-induced changes which could be detected in future trRIXS experiments. Denitsa notes:

> "Since the Hubbard *U* plays such an important role in strongly correlated materials, these findings open novel possibilities for their manipulation in ways previously unattainable at equilibrium. Precisely tuning the Hubbard *U* allows us to explain phenomena such as transient superconductivity, and to selectively induce nonlinear responses of correlated electron ensembles."

By combining trXAS and trRIXS, one can go further and fully reconstruct the microscopic distribution of charge during a photoinduced phase transition. By carefully orienting the x-ray polarization along different high-symmetry directions of a crystal, one can interrogate different orbitals and distinct components of the electronic wavefunctions. The resulting x-ray spectra contain both local and nonlocal processes and can be modeled via theoretical calculations to yield an accurate time- and orbital-resolved picture of electronic and spin motion. By collaborating with theorists and performing our own cluster calculations, our group aims to integrate time-resolved x-ray spectroscopy and theoretical modeling (ranging from exact diagonalization methods to time-dependent density functional theory and quantum chemistry calculations) to produce an electronic movie of photoinduced processes in quantum materials.

ULTRAFAST DYNAMICS OF ONE-DIMENSIONAL SUPERCONDUCTORS

Achieving and stabilizing superconductivity at ambient pressure and temperature is a major research focus of modern condensed matter physics and a fundamental step towards lossless electrical power transmission, next-generation quantum sensing technologies, and controlled nuclear fusion. Superconductivity is normally observed at cryogenic temperatures and/or at extremely high pressures, thus hampering its widespread application outside of a research laboratory. Progress toward superconductivity at ambient conditions requires either completely new experimental approaches (e.g., the synthesis of new materials) or the simultaneous application of multiple tuning knobs.

Can we induce or enhance superconductivity at higher temperatures with light? Our laboratory aims to answer this question by using specifically tailored laser pulses. Our goal is to dynamically stimulate more robust superconducting states which could then be stabilized or used as a template to design novel superconductors at equilibrium. Over the years, it has been shown that superconductivity can indeed be induced or enhanced by pumping specific lattice vibrations in a variety of materials ranging from copper oxides to organic molecular solids. Whether the appearance of this phenomenon in such a diverse class of materials is due to the same microscopic mechanism is not yet understood, and gaining insight into the microscopic physics of this phenomenon could enable more efficient light-control strategies.

A promising class of systems to probe the microscopic physics of light-driven superconductivity are one-dimensional (1D) systems, which are theoretically simpler to describe. Effective 1D electronic properties in a three-dimensional crystal occur when the atoms are arranged in a way that effectively confines electrons along a single spatial direction, and a suitable class of 1D systems for our studies are copper oxides like Sr_2CuO_3 and $Sr_{14}Cu_{24}O_{41}$. These materials are almost perfect realizations of 1D electronic models and could, in principle, be used as a Rosetta stone for studying light-driven superconductivity.

Hari Padma, another postdoctoral researcher in our group, is focused on this goal. In his own words:

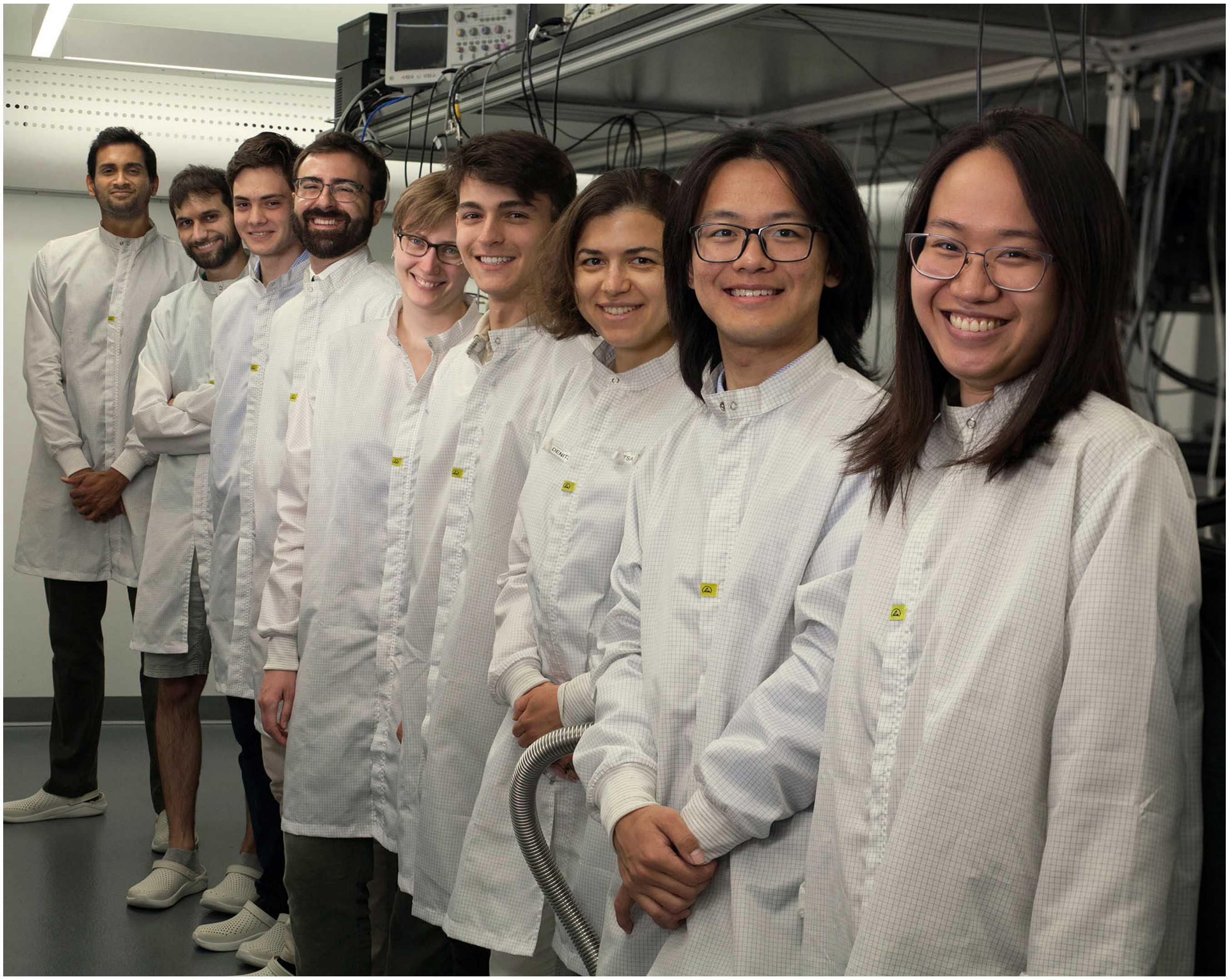


Fig. 4: Group photo of the Mitrano Lab in the Harvard ultrafast optics laboratory. [Photo by Paul Horowitz]

"One thing that makes copper oxides such an interesting experimental system is that so many of the key electronic energy scales are close together, allowing many different phases of matter to emerge from only small changes to the material composition or structure. Time-resolved x-ray spectroscopies like trRIXS and trXAS give us a direct window into these energy scales, how they can be modified by optical excitation, and how the material properties directly respond to that excitation. We're also working to expand these tools to extract information about many-body entanglement from RIXS measurements, as demonstrating the possibility to directly interrogate entanglement would give us an entirely different view of how superconducting coherence emerges in correlated electron systems driven far from equilibrium."

TOWARD A QUANTUM SPIN LIQUID PHASE

Light-induced superconductivity is only one of the possible forms of emergent quantum phases that can be induced through light-matter interactions. In the last few years, it has been theorized that ultrafast lasers with linear or circular polarization can be used to achieve driven quantum spin liquidity. In a nutshell, a quantum spin liquid is a state of matter characterized by the absence of magnetic order and by the presence of entangled spin excitations. As these excitations might have applications for fault-tolerant quantum computing, the discovery of quantum spin liquidity in real material has a tangible applicative dimension beyond the fundamental interest in a novel quantum phase of matter.

Identifying a quantum spin liquid in real materials requires both a material platform that eludes magnetic ordering at low temperatures and adequate experimental observables. Organic molecular solids, such as the κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$, are prime candidates for the search of quantum spin liquidity, as their triangular structure and electronic interactions do not allow spins to find an easy way to order. Further, they exhibit characteristic excitations in the optical conductivity that likely originate from spin fluctuations.

However, the coupling between structure and electron spins introduces low-temperature ordering even in these systems, which means that the conditions for quantum spin liquidity are not fully met at equilibrium. Our idea is to use light pulses to selectively suppress the ordered phase and nudge the systems toward a dynamic spin-liquid instability. We take advantage of the fact that light deforms the molecular orbitals via the excitation of molecular vibrations and systematically tunes the electronic interactions of the system in a reversible fashion. Changes in the spin fluctuations are then probed by interrogating the behavior of the system in the THz range.

Glerean and graduate student Tepie Meng have demonstrated the presence of a resonant excitation effect in κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$ and are now evaluating the pump-induced changes to the optical spectrum of this material. The spectral fingerprints of a quantum spin liquid are already subtle for a material at equilibrium, and nonequilibrium conditions require extra care. Tepie recalls:

> "The first step for us was to prove that midinfrared light changes the molecules of κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$. It was surprising to confirm that the molecules in this material respond to the midinfrared pump by undergoing motions with a period of 1 ps. Even more surprising was seeing that these molecular displacements are accompanied by a large change of the THz conductivity, thus implying changes to the spin fluctuations. Our next step is to confirm that these changes are actually due to emergent quantum spin liquidity, and I am looking forward to tackling this question in the near future."

Achieving dynamical spin liquidity in organic systems would be a significant milestone in the study of light-induced long-range order and would provide fresh opportunities for the discovery of other forms of nonequilibrium quantum coherence.

BERTRAND HALPERIN: Shaping Our Knowledge of Condensed Matter for Sixty Years—and Still Going Strong

by Steve Nadis

[photo by Paul Horowitz]

"My first encounter with Bert Halperin was quite dramatic for me, though perhaps less so for him," Robert Birgeneau said. A physicist and chancellor emeritus at the University of California, Berkeley, Birgeneau started at Bell Labs in April 1968 at the age of 26. One day, he was in his office, talking with some colleagues about an experiment he'd just completed that explored the properties of a crystal that appeared to be a two-dimensional realization of the so-called "Heisenberg model."

Halperin, who was also 26 at the time, overhead the discussion while walking down the hallway and joined the conversation. Birgeneau explained what he had accomplished, "and Bert sort of stared off into space and didn't say anything for a while," Birgeneau recalled. "In less than a minute—though it seemed longer—Bert replied in his nice, quiet way: 'I don't think your interpretation is quite right.'" The system in question, Halperin suggested, would not remain in a two-dimensional Heisenberg state but must, at some point, experience a crossover to a three-dimensional "Ising model." During this transition, the magnetic properties of the material would dramatically change.

"The phenomenon Halperin described hadn't been in the scientific literature before," Birgeneau said. "It was something that he had figured out in real time, and I instantly knew he was right." Birgenau called his coauthor and said they had to modify the conclusions of their paper, which had already been submitted to Physical Review Letters. A few months later, he presented this work at a major physics meeting where their findings were attacked by leaders in the field, including some Nobel laureates. Birgeneau stuck to his guns—deciding that "Bert Halperin is smarter than any of these people"—and his position, which also happened to be Halperin's position, ultimately proved correct.

The Harvard physicist Amir Yacoby has a similar respect for his colleague's intellectual prowess. "If you have something you don't know, most people would Google it. When l have something I don't know, I 'Bert it.' I'll ask Bert the question, knowing that he will have the answer."

Halperin, who is approaching his 82nd birthday, has spent 60 years in the field of condensed matter physics (though it was called solid-state physics when he started out)—and he knows a thing or two about this subject.
"I view him as the wise man in our department—an infinite source of knowledge and advice," said his Harvard Physics colleague Philip Kim.

"Bert is a towering figure," agreed the physicist David Nelson, a long-time colleague in the department. "He's had a magnificent career in science" with a long list of awards—including the Lars Onsager Prize, the Wolf Prize, the Dannie Heineman Prize, and the American Physical Society Medal for Exceptional Achievement in Research—to show for it.

Although Halperin is now in the later stages of career, he has vivid memories as to how he got started on his current path. His father was an amateur mathematician, serving as a customs inspector in his day job. Halperin did well in math as a youth but found it too abstract for his tastes. When he entered Harvard as a 16-year-old in 1958, he didn't know whether to go into physics or become a doctor. He took both organic chemistry and physics in his first year. While he did not care for the former, he liked physics very much, deciding early on that he would have to go into theory because he couldn't see himself ever becoming a competent experimentalist.

After graduating in 1961, Halperin took a summer job at Los Alamos. He had asked to work on a project in plasma physics, because he thought it "sounded romantic," but he was assigned, instead, to a group using neutron scattering to measure the vibration spectrum of an aluminum crystal. When he arrived at the New Mexico lab, his bosses asked him to read a book by Leon Brillouin, Wave Propagation in Periodic Structures, which provided his first introduction to solid-state physics. He was immediately captivated by the idea of exploiting the symmetry of a crystal—in which atoms are arranged in unit cells that repeat over and over again like a checkerboard—in order to tackle what might otherwise be intractable problems. By taking advantage of symmetry, he said, one could reduce a problem involving billions of equations and billions of unknowns to one involving just three equations and three unknowns.

Halperin found Brillouin's insights to be "both surprising and beautiful," asserting that "this book really did change my life." After his summer gig ended, he decided to study solid-state physics at Berkeley, which he chose for its "very good reputation for physics. I also wanted to go someplace where I thought the climate would be better than Boston's. I was ready for something tropical—and, if not exactly tropical, at least a bit warmer in the winter." However, his advisor left Berkeley for Princeton in June 1964, and after a summer working at Bell Laboratories, Halperin went with him. He obtained his Ph.D. in 1965 and then spent a year as a postdoctoral fellow in France before returning to Bell, where he stayed for a decade. "It was an exciting place to be for anyone doing solid-state and condensed matter physics," he said. "At that time, it really was the preeminent place in the world for that kind of physics."

He quickly got involved in many disparate areas of research, but the work he did with Pierre Hohenberg on dynamical critical phenomena—a field they largely invented—helped make his reputation. "Basically, we were trying to understand the properties of a material near a critical point—perhaps the best example of a critical point being the temperature at which a ferromagnetic material loses its magnetization," Halperin said. The magnetization doesn't just jump to zero. It decreases in a continuous way, dropping off according to a power law that is difficult to predict. One of the problems he worked on at Bell Labs—and continued to pursue upon joining the Harvard faculty in 1976—was to figure out the precise details of how that magnetization behaves and, in particular, how it fluctuates in time close to the transition temperature. He also explored liquid-gas phase transitions, which occur at a critical point of both temperature and pressure, playing a key role in understanding the dynamic, time-dependent properties of those systems.

Early in his career at Harvard, Halperin collaborated with Nelson on a series of papers—the first of which was published in 1978—on the "Theory of Two-Dimensional Melting." As Nelson explained, "In grade school you may have learned that are three phases of matter—solid, liquid, and gas—but in two-dimensional systems we discovered that there is actually a fourth phase, the 'hexatic' phase." What they found is that in certain materials—such as crystals that have a hexagonal lattice (sometimes called a triangular lattice)—melting and freezing can occur in two stages. The hexatic phase is an intermediate, liquid-crystal phase that lies somewhere between melting and freezing.

This same behavior, Nelson noted, has not been observed for simple molecules in three-dimensional systems; it is special to the two-dimensional realm. The emergence of this phenomenon, moreover, has to do with the structure of a crystalline lattice—not only the distance between atoms but also the angles between them. Simply put, Halperin said, "two-dimensional settings are weirder than three-dimensional settings, and further from classical systems, due to the fact that fluctuations near the critical point become more important." The transition from solid to liquid in three dimensions can occur in a big jump, he added, whereas in two dimensions, "you can more easily have these intermediate phases."

Halperin didn't know about the quantum Hall effect until 1981, when he was contacted by the editor of Physics Today, Gloria Lubkin, who was writing an article and wanted his thoughts on this subject. "Never heard of it," was his first reply. But his curiosity was piqued and quickly heightened when he read the May 1981 paper by Robert Laughlin of Bell Labs, which offered an explanation for some of the puzzling observations made by Klaus von Klitzing in 1980.

In the 1870s, Edwin Hall (who became a Harvard professor) showed that for a metal in a magnetic field, there could be a voltage drop perpendicular to an electrical current flow, whose ratio is termed the Hall resistance. Von Klitzing's experiments on a silicon semiconductor surface, carried out more than a century later, found that for a two-dimensional electron system at low temperatures, the Hall resistance could be quantized, taking on a discrete set of values given by the formula h/ne^2, where h is Planck's constant, e is the electron charge, and n is an integer—hence the name "integer quantum Hall effect." Later experiments found additional plateaus where n is a simple rational fraction, like 1/3 or 2/5—manifestations of the so-called "fractional quantum hall effect."

"The Hall resistance remains constant over a certain range of magnetic fields before jumping to a different plateau," Halperin explained. "And at low temperatures, the value of that constant can be determined to a precision of $1/10^8$." He wrote a paper in 1981 that helped explain the integer quantum Hall effect and why it was so precisely quantized, despite the presence of impurities in the semiconductor.

At low temperatures, Halperin deduced, there will be no mobile carriers (electrons) moving in the direction of the electric field. "But there will always be low-energy electrons that could move along the edges of the sample," he said, "and these edge states could be important for a lot of things."

Edge states of this sort do occur, for example, in a topological insulator—a material that insulates on the inside but can conduct on the outside. This type of material, however, was not discovered for another two decades.

"The quantum Hall effect should be called the quantum Hall effects, plural, because there are many different effects that can arise with regard to the behavior of electrons in two-dimensional systems at low temperatures and very strong magnetic fields," Halperin said. He's even uncovered a kind of anomalous behavior in single-layer systems that he calls the "unquantized quantum Hall effect."

He continues to work in this area, noting that "almost half of what I've done since the 1980s relates to the quantum Hall effect, because there are so many variations that can occur in so many different systems." In recent years, he has collaborated with Kim and Yacoby, who are studying these phenomena in single layers of graphene and in multi-layered systems.

In 2019, Halperin coauthored a Nature Physics paper with Kim and others on the fractional quantum Hall effect in bilayer graphene. That paper owes its origins, to some extent, to a Physics Department social gathering at which Kim's graduate student talked to Halperin about a recent experiment. "The next morning, Bert sent me all these amazing calculations he had worked out the night before," Kim said, and their joint paper came out shortly thereafter. "Bert's a theorist, yet he can pore over all the details of an experiment without ever losing sight of the big picture," Kim added. "It's that ability that makes him such a rare figure in condensed matter physics. He can take our data and weave it into the foundational theories that he builds."

Yacoby, who has collaborated with Halperin on about two dozen papers since 2000, has had similar experiences. Whenever he suggests an idea to his colleague, Yacoby said, "Bert almost always comes back with some deep theory that captures the essence of what is going on in a way that has all kinds of internal beauty. That's something I haven't seen with anybody else."

What Birgeneau admires about Halperin, perhaps most of all, is the fact that "he's a very deep thinker and a very modest person—someone who thinks so clearly and logically that he is never carried away by fashion. He just draws his own conclusions." And over the years, Birgeneau said, "he has helped a long line of experimentalists, in all kinds of different fields, to understand their experiments (mine included), both after the fact and in advance."

Although Halperin stopped teaching classes or taking on graduate students about a decade ago, he is still quite active and productive—with four papers that came out in the first half of 2023. He continues to work on a regular basis with several professors in the department, as well as with their students and postdocs. "I'm interested in all kinds of physics, especially condensed matter physics," he said. "I follow the latest developments in the field as best I can, trying to see where I can make a contribution."

As to what problem preoccupies him the most, Halperin said there is no single overriding question in condensed matter physics—comparable to, say, the dark matter and dark energy problems in particle physics—such that if someone could solve it, it would completely change everything. "Instead, we face a many-headed problem. And I'm interested in all of it."

Undergraduate Program

by Dionne Clarke

Above: Undergrads at the Physics as a Liberal Art workshop (left to right): Jorge Ponce Garcia, Qijia Zhou, and Jing-Jing Shen

The Harvard Physics Undergraduate Program comprises 206 concentrators, with 50 new students who signed up this fall. Throughout the year, students were actively engaged in research projects, served on various Society of Physics Students (SPS) committees, and collaborated on problem sets (always accompanied by cookies!) during the weekly Wednesday Physics nights. The community continued to thrive with fun traditions as well as essential academic programming.

We celebrated the fall with the Annual Pumpkin Drop: a festive tradition of testing Newton's Law of universal gravitation on various types of frozen produce. More than 100 community members watched as pudding-filled pumpkins created a huge splash after undergoing projectile motion with a longer than anticipated range.

Last March marked the return of the weekly lunches with the Monday Colloquia speakers, after a two-year hiatus. These lunches provide students with an exciting opportunity to share casual meals with the Monday Colloquia speakers. Over 45 students have participated in just two months, earning a "seat at the table" with Physics experts from various subfields, industry leaders, and even Nobel Prize winners!

Visitas (the visiting weekend for accepted high school seniors), which brought over 100 prospective students to Jefferson Laboratory on April 23rd and

24th, featured three major events: lunch with Physics faculty, a boba tea meet-and-greet with Primus (an SPS group for first-generation/low-income students), and a massive liquid Nitrogen ice cream event hosted by SPS. At the end of the year, SPS welcomed two new presidents: Elizabeth Kozlov and Jorge Garcia Ponce, who will oversee six SPS subcommittees and two affiliate groups.

Last summer, 47 students conducted research through the Joint Physics/Harvard College Research Fellowship Program. Thanks to contributions from Harvard College, the Dean of Science, Physics Faculty, and internal department funds, students received research stipends and supplementary funding based on financial need. In addition to research, an ambitious group of Harvard and MIT students revived the Chilloqium seminar series (for more information, please see below).

Summer concluded with significant leadership transitions across the Harvard Community. With a new Department Chair, the College welcoming a new Dean of FAS, and a historical first in the University Presidency, the upcoming year promises a lasting impact on the Physics community!

I was appointed the Undergraduate Program Administrator in January of 2023, after six years of administrative experience in the Physics Department. I sincerely enjoy working directly with students: encouraging them to use their unique gifts, helping navigate administrative hurdles, and creating new opportunities to enhance their undergraduate experience.

Student Profile: Kaylie Hausknecht

Kaylie Hausknecht '24 is grateful to have had the opportunity to explore physics at all length scales through her undergraduate research projects. Currently, she works in Michael Brenner's lab developing fully differentiable simulations of fluids to solve inverse design problems in fluid mechanics. In her work, she models complex fluid systems in such a way that she can compute exact gradients through every step of the simulation. This allows her to choose a flow property, like the efficiency of mixing, and solve multi-parameter optimization problems to identify flow set-ups and geometries that maximize the desired property. She believes these methods provide exciting new ways to approach open problems in fluid mechanics, and she hopes to continue exploring applications of differentiable physics simulations in the future.

Her first research project at Harvard was in Jenny Hoffman's lab, where she designed a new type of machine learning (ML) model to study data from scanning tunneling microscopes. Kaylie took a gap year between her freshman and sophomore years of college when classes were fully remote and worked as a NASA intern. At NASA, she contributed to the development of new models of laminar-turbulent transition on aerospace vehicles to improve NASA's industry flow solvers. For her next project, she joined the "ExoMiner" team at NASA Ames where she worked on building complex ML models to do exoplanet detection. Ultimately, her team identified 301 new planets in old Kepler Space Telescope data with their models, and NASA announced the discovery in a press release. She enjoyed her work there so much that she continued to intern part-time at NASA during the following school year. After that, she wrote a junior thesis in astrophysics, under the direction of Avi Loeb, that explored high redshift galaxies in James Webb Space Telescope data. She has presented at seven academic conferences so far and enjoys talking about her research to anyone who will listen!

Throughout her time at Harvard, Kaylie has also enjoyed teaching. She has been a course assistant for classes in the mathematics, applied mathematics, and physics departments. She is the Co-President of Harvard's chapter of Science Club for Girls, an organization that aims to help girls from underrepresented communities embrace and pursue STEM. She also served as the Undergraduate Representative to the Harvard Physics Department's Equity and Inclusion Committee. After graduation, Kaylie hopes to go on for a Ph.D. in physics and to ultimately pursue a career that will allow her to both teach and do research. She will greatly miss the camaraderie of the students in the physics concentration, the lively nights-turned-mornings spent psetting with friends, and the loft in Jefferson Lab where she loves to work and watch sunsets.

Chilloquium

by Mincheol Park,
Harvard College Senior and Physics Concentrator

Chilloquium, short for "Chill Colloquium," is a weekly hour-long Zoom speaker series featuring established physicists from diverse research backgrounds. Each session includes a presentation by the speaker, touching on their research and personal journey, followed by an open "ask-me-anything" Q&A session where students engage with the speaker.

Harvard SPS co-presidents Sambuddha Chattopadhyay and Chris Fechisin founded this series during the COVID-19 pandemic in the summer of 2020. Today, Chilloquium is organized by four Harvard SPS officers (Mincheol Park, Tasuku Ono, Jennifer Song, and Claire Swadling) and three MIT SPS officers (Tung X. Tran, Quan M. Nguyen, and Chirag Falor). Each event attracts 20-50 attendees, including undergraduates, professors from Harvard/MIT, and international students from Japan and Vietnam. The series prioritizes diversity, inviting speakers from various countries, affiliations (universities, institutes, private companies), and research fields.

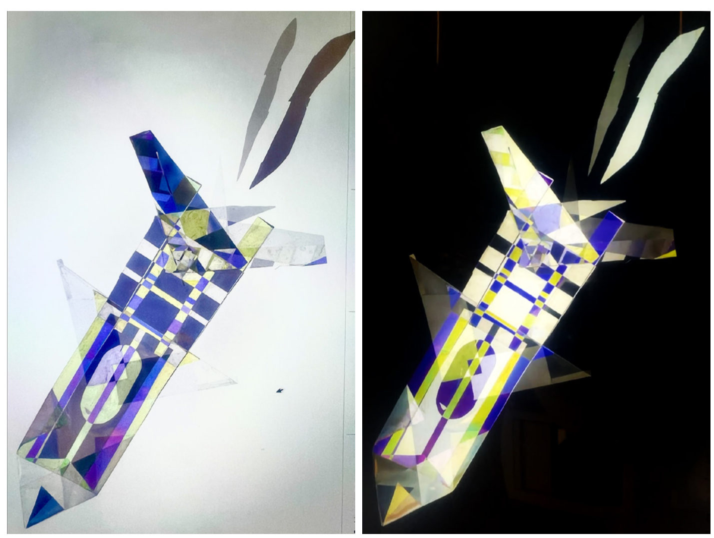
Chilloquium's impact stems from the informal conversations it cultivates, offering insights into the journey from being an undergraduate to an established researcher. By attending these talks, I was deeply motivated to become a physicist. I hope students can learn from it and follow their own dreams to be physicists as well.

Physics as a Liberal Art

Last winter, "Physics as a Liberal Art," an event sponsored jointly by the Office of Fine Arts and Physics Department, exposed students to the intersectionality of the physical sciences and visual arts. The event consisted of two parts: an interactive workshop and a showcase. At the workshop, participants were encouraged, with the help of volunteers, to create "physically interesting" art, such as polarized film manipulations, spirographs, and origami, accompanied by handouts that explained the science behind each craft. At the showcase, students and faculty viewed the submitted art and voted on their favorites.

Katherrin Billordo, a sophomore studying Economics and Art and Visual Studies, won the "People's Choice" award, and Jennifer Song's artwork was deemed the "Most Scientifically Interesting."

This event was made possible by the Office of Fine Arts' annual Project Fund, which supports interdisciplinary art initiatives that impact Harvard College students. Claire Swadling, a sophomore studying physics who participated in the First-Year Arts Program, conceptualized the event while taking Prof. Howard Georgi's freshman seminar "Beautiful Physics." In this class Claire first learned of using polarized film for making art objects. Shortly thereafter, she applied for a grant with the support of Prof. Georgi, who gave the event its name.



Above: Rocket ship made of cellophane tape by Jennifer Song. When the rocket is placed between a bright computer screen, which is polarized, and a polarizing film, one can observe the rocket change colors as the film rotates.

ACADEMIC PROGRAMS

Graduate Program

Last spring, we welcomed prospective Ph.D. students to our first in-person open house since 2019! The incoming graduate cohort, split 57/43 percent between men and women, is as diverse as ever: it represents countries from around the world, including Singapore, France, the United States, Brazil, Canada, Taiwan, India, Iran, the United Kingdom, Jamaica, Germany, China, Greece, and Vietnam.

Above: Commencement 2023

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.

Sepehr Ebadi

2023 GOLDHABER PRIZE WINNER (experiment)

Sepehr obtained his Bachelor in Engineering Science (Physics Option) from the University of Toronto in 2017. During his undergraduate studies he was on a team working toward creation of ultracold molecules for studies of chemical reactions and quantum chemistry.

He is currently a sixth year graduate student in Prof. Greiner's groups, where he uses arrays of optically trapped neutral atoms for quantum simulation and computation. Notably, his group has used atom arrays for the study of Ising quantum phase transitions, and for solving maximum independent set, an NP-hard problem, using a quantum machine.

Barbara (Basia) Skrzypek

2023 GOLDHABER PRIZE WINNER (experiment)

Born and raised in Chicago, Basia Skrzypek is the daughter of immigrants who moved to the United States from Poland in their early twenties in search of better opportunities for their children. She became a first generation college graduate when she received her B.S. from Loyola University Chicago, where she majored in physics and mathematics and worked on Chern-Simons modified gravity with her advisor, Robert McNees. She was also at the Large Hadron Collider for two summers, working on particle reconstruction in the ATLAS experiment. It was this experience that gave her a sense of what it was like working in a large scientific collaboration, particularly because those opportunities were lacking at her liberal arts college, which had no physics graduate program.

After undergraduate school, McNees encouraged Basia to pursue a master's at the Perimeter Institute for Theoretical Physics. She wrote her master's thesis based on her work with Sebastian Mizera and Freddy Cachazo on scattering amplitudes for effective field theories. She then came to Harvard, where she now works with Carlos Argüelles-Delgado as a part of the IceCube Collaboration. Her work focuses on searching for high-energy signatures of physics beyond the Planck scale and studying the question of the origin of astrophysical neutrinos through multimessenger astrophysics. After Harvard, Basia plans to continue working on neutrino physics as a postdoc at the Lawrence Berkeley National Laboratory.

Outside of her academic interests, she is passionate about drawing physics comics, helping her little brothers with their homework, building Legos with her partner, and spending time with her rescue cat, Pearl.

Goldhaber Prize *(continued)*

Rodrigo Araiza Bravo

2023 GOLDHABER PRIZE WINNER (theory)

Rodrigo graduated from the University of Illinois at Urbana-Champaign in 2018 with bachelor's degrees in Applied Mathematics and Engineering Physics. While at UIUC, Rodrigo participated in experimental research in quantum optics and theoretical research in quantum information science and many-body quantum physics. After working for a year at UIUC as a researcher, he entered the Physics Ph.D. program at Harvard University in 2019 and joined Prof. Susanne Yelin's group, where he now studies how to use many-body physics and ideas from quantum simulation for quantum machine learning applications. He is particularly interested in using atomic arrays for creating quantum versions of recurrent neural networks, a simple but powerful neural network architecture in machine learning.

Rodrigo is also heavily involved in the Harvard community outside his scientific research. He has been recognized as an excellent teaching fellow by GSAS, as well as for his efforts in recruiting minority students to Harvard Physics. He served as the Physics Department Steward for the Harvard Graduate Student Union.

Rodrigo is currently pursuing a secondary field in Science, Technology, and Society at the Harvard Kennedy School where he is conducting research on the sociology and political aspects of quantum technologies' funding and instituted research directions in the US. He recently completed an internship at IBM Quantum working on Responsible Quantum Computing research. Rodrigo is a co-founder of the Quantum Ethics Project, an organization supporting young researchers who want to develop a richer scientific scholarship by incorporating ethical questions into their training, and an officer for the GSAS Quantum Science and Society student group.

Maine Christos

2023 GOLDHABER PRIZE WINNER (theory)

Maine Christos completed her undergraduate degree at Rutgers University, New Brunswick, double majoring in physics and math. She conducted research under Prof. Sunil Somalwar in the Rutgers high energy experiment group, with a focus on applying various machine learning techniques to optimize searches for new physics in multilepton data taken at the CMS detector at CERN.

Maine is currently a fourth year Ph.D. student at Harvard working under Prof. Subir Sachdev in condensed matter theory. Her research broadly focuses on the study of phases in systems with strong electron correlations. She has worked on theoretical models of different phases observed in high temperature superconductors, including spin glasses, strange metals, and a theory of confinement transitions of the pseudogap phase to superconductivity and charge order. She has also worked on theories for the correlated insulators and superconductivity observed in twisted magic-angle graphene.

GSAS Merit Fellowship

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

Erin Crawley

2023 MERIT SCHOLARSHIP WINNER

Erin completed her B.S. in Mathematical Physics at Queen's University in Ontario, Canada. As an undergraduate, she conducted research on black hole evaporation with Prof. Mark Van Raamsdonk at the University of British Columbia and on aspects of general relativity with Prof. Kayll Lake at Queen's. She was a Chancellor's scholar at Queen's and graduated with the Governor General's medal for the highest academic record of the graduating class.

At Harvard, Erin works with Prof. Andrew Strominger on aspects of black holes and flat space holography. Flat space holography is a research program that aims to develop a theory of quantum gravity (that is, a theoretical framework that combines the effects of both gravity and quantum mechanics) in physically-relevant spacetimes. This correspondence posits that 4D gravity observables can be recast as quantities in a 2D conformal field theory, and Erin's research has extended the correspondence to understand the connection between the spaces of states in both theories, and how to realize black holes in the 2D theory. Erin is excited about the ability of this direction to extend the successes of the AdS/CFT correspondence to spacetimes which are good approximations to our universe on astrophysical scales. Outside of physics, Erin enjoys singing and playing piano and guitar.

Katie Fraser

2023 MERIT SCHOLARSHIP WINNER

Katherine Fraser is a sixth-year Ph.D. student working with Prof. Matthew Reece on beyond-the-standard-model (BSM) phenomenology. She has worked on a variety of topics in BSM physics, including dark matter, flavor, and axion physics. In particular, much of her recent work has focused on understanding the interaction of axions with topological defects and on applications of machine learning (ML) to particle physics.

Prior to starting her Ph.D., Katherine also did her undergraduate work here at Harvard. After working with the ATLAS group, she became excited by theoretical high energy physics and began her research on applications of ML to particle physics in collaboration with Prof. Matthew Schwartz, which she continues to pursue.

More Graduate Student Awards and Fellowships[1]

DOE Computational Science Graduate Fellowship:
Alexander Johnson

Frederick Sheldon Traveling Fellowship:
Gustavs Kehris

Jack T. Sanderson Memorial Prize in Physics: Avery Parr

Natural Sciences and Engineering Research Council of Canada Scholarship:
Joshua Sandor
Erin Crawley

NSF Graduate Research Fellowship:
Kiara Carloni
Sarah Hoback
Leo (Chiu Fan Bowen) Lo
Ana (Anasuya) Lyons
Srinivas Mandyam
Terry (Yoong) Phang
Anant Kale

Paul & Daisy Soros Fellowship for New Americans:
Tan Dao

White Prize:
Nathan Agmon
Ananya Bansal
Kees Benkendorfer
Maine Christos
Aurelien Dersy
Katie Fraser
Roy Garcia
Miaochen (Andy) Jin
Elise Koskelo
Jerry Ling
Tianli Wang

Recent Graduates

Laurel Anderson
Thesis: "Electrical and Thermoelectric Transport in Mixed-Dimensional Graphitic Mesoscopic Systems"
Advisor: Philip Kim

Dan Borgnia
Thesis: "The Measure of a Phase"
Advisor: Ashvin Vishwanath

Abdulkadir Canatar
Thesis: "Statistical Mechanics of Generalization in Kernel Regression and Wide Neural Networks"
Advisor: Cengiz Pehelvan

Michelle Chalupnik
Thesis: "Quantum and Photonic Information Processing with Non-Von Neumann Architectures"
Advisor: Marko Lončar

Will Conway
Thesis: "Biophysics of Kinetochore Microtubules in Human Mitotic Spindles"
Advisor: Daniel Needleman

Xing Fan
Thesis: "An Improved Measurement of the Electron Magnetic Moment"
Advisor: Gerald Gabrielse

Nicolò Foppiani
Thesis: "Testing Explanations of Short Baseline Neutrino Anomalies"
Advisor: Roxanne Guenette

Andrei Gheorghe
Thesis: "Methods for Inferring Dynamical Systems from Biological Data with Applications to HIV Latency and Genetic Drivers of Aging"
Advisor: Alison Hill

Jonathan Haefner
Thesis: "Improving Kr-83m Calibration and Energy Resolution in NEXT Neutrinoless Double Beta Decay Detectors"
Advisor: Roxanne Guenette

Andrey Sushko
Thesis: "Structural Imaging and Electro-optical Control of Two-Dimensional Semiconductors"
Advisor: Mikhail Lukin

Iris Cong
Thesis: "Quantum Machine Learning, Error Correction, and Topological Phases of Matter"
Advisor: Mikhail Lukin

[1] Includes awards received since the publication of last year's newsletter.

Recent Graduates *(continued)*

Ryan Gelly

Thesis: "Engineering the Excitonic and Photonic Properties of Atomically Thin Semiconductors"

Advisor: Hongkun Park

Emil Khabiboulline

Thesis: "Quantum Communication and Thermalization, From Theory to Practice"

Advisor: Mikhail Lukin

Douglas Mendoza

Thesis: "Optimization Algorithms for Quantum and Digital Annealers"

Advisor: Alan Aspuru-Guzik

Lauren Niu

Thesis: "Patterns and Singularities in Elastic Shells"

Advisor: L. Mahadevan

Chi Shu

Thesis: "Quantum Enhanced Metrology in the Optical Lattice Clock"

Advisor: Vladan Vuletic

Nathan Agmon

Thesis: "D-instantons and String Field Theory"

Advisor: Xi Yin

Daniel Ang

Thesis: "Progress towards an Improved Measurement of the Electric Dipole Moment of the Electron"

Advisor: Gerald Gabrielse

Alek Bedroya

Thesis: "The Swampland: From Macro to Micro"

Advisor: Cumrun Vafa

Sean Burchesky

Thesis: "Engineered Collisions, Molecular Qubits, and Laser Cooling of Asymmetric Top Molecules"

Advisor: John Doyle

Ian Davenport

Thesis: "Optimal Control and Reinforcement Learning in Simple Physical Systems"

Advisor: L. Mahadevan

Nick DePorzio

Thesis: "Dark Begets Light: Exploring Physics Beyond the Standard Model with Cosmology"

Advisor: Cora Dvorkin, Lisa Randall

Ruihua Fan

Thesis: "Quantum Entanglement and Dynamics in Low-Dimensional Quantum Many-Body Systems"

Advisor: Ashvin Vishwanath

Anne Fortman

Thesis: "Searching for Heavy, Charged, Long-Lived Particles via Ionization Energy Loss and Time-of-Flight in the ATLAS Detector Using 140.1 fb-1 of √s = 13 TeV Proton-Proton Collision Data"

Advisor: Melissa Franklin

Barak Gabai

Thesis: "From the S-Matrix to the Lattice: Bootstrapping QFTs"

Advisor: Xi Yin

Haoyu Guo

Thesis: "Novel Transport Phenomena in Quantum Matter"

Advisor: Subir Sachdev

Mina Himwich

Thesis: "Aspects of Symmetry in Classical and Quantum Gravity"

Advisor: Andy Strominger

Yaowen Hu

Thesis: "Coupled-Resonators on Thin-Film Lithium Niobate: Photonic Multi-level System with Electro-optic Transition"

Advisor: Marko Lončar

Sooshin Kim

Thesis: "Quantum Gas Microscopy of Strongly Correlated Bosons"

Advisor: Markus Greiner

Ella King

Thesis: "Frankenstein's Tiniest Monsters: Inverse Design of Bio-Inspired Function in Self-Assembling Materials"

Advisor: Michael Brenner

Robert Lin

Thesis: "Finding and Building Algebraic Structures in Finite-Dimensional Hilbert Spaces for Quantum Computation and Quantum Information"

Advisor: Arthur Jaffe

Qianshu Lu

Thesis: "Cosmic Laboratory of Particle Physics"

Advisor: Matthew Reece

continues on the next page...

Recent Graduates *(continued)*

Cole Meisenhelder

Thesis: "Advances in the Measurement of the Electron Electric Dipole Moment"

Advisor: Gerald Gabrielse

Olivia Miller

Thesis: "Measuring and Assessing Introductory Students' Physics Problem-Solving Ability"

Advisor: Eric Mazur

Tharon Morrison

Thesis: "Towards Antihydrogen Spectroscopy and CW Lyman-Alpha via Four-Wave Mixing in Mercury"

Advisor: Gerald Gabrielse

Sruthi Narayanan

Thesis: "Soft Travels to the Celestial Sphere"

Advisor: Andy Strominger

Paloma Ocola

Thesis: "A Nanophotonic Device as a Quantum Network Node for Atoms in Optical Tweezers"

Advisor: Mikhail Lukin

Atinc Çağan Şengül

Thesis: "Studying Dark Matter at Sub-Galactic Scales with Strong Gravitational Lensing"

Advisor: Cora Dvorkin

Alyson Spitzig

Thesis: "Using Non-Contact AFM to Study the Local Doping and Damping through the Transition in an Ultrathin VO2 Film"

Advisor: Jenny Hoffman

Houri Tarazi

Thesis: "UV Completeness: From Quantum Field Theory to Quantum Gravity"

Advisor: Cumrun Vafa

LaNell Williams

Thesis: "What Goes right and Wrong During Virus Self Assembly?"

Advisor: Vinnothan Manoharan

Jeremy Yodh

Thesis: "Flow of Colloidal and Living Suspensions in Confined Geometries"

Advisor: L. Mahadevan

Grace Zhang

Thesis: "Fluctuations, Disorder, and Geometry in Soft Matter"

Advisor: David Nelson

ACADEMIC PROGRAMS

Research Scholars

by Bonnie Currier

Above: photo by Shannon Haggerty

On October 11, 2022, senior faculty from inside and outside Harvard gave a panel on getting a junior faculty appointment for Harvard postdoctoral fellows and other scholars. Graduate students were also invited. This panel was moderated by two members of the department's research scholar advisory committee.

On February 7, 2023, we had a panel on careers in entrepreneurship and venture capital. The panel included representatives from America's Frontier Fund, Satori Capital, Activate, QuEra Computing, and Harvard Grid. Two members of the research scholar advisory committee moderated the panel.

The third panel, on April 14, 2023, was moderated by two physics graduate students and features current physics post-docs as panelists. Its topic was how to get a postdoctoral scholarship, and all graduate students were invited.

The 10th annual Research Scholar Retreat took place on September 20, 2023, at MIT-Endicott House in Dedham, MA. This was a full day away from campus just for research scholars to relax and share their research with their colleagues. Our plenary speaker was Peter Galison, Pellegrino University Professor of the History of Science and of Physics, Harvard.

Alumni/ae Notes

1959

Sheldon Lee Glashow (Ph.D.): I take this opportunity to coin the word "leucippity," honoring the elder of the two Greek scholars who devised the atomic hypothesis millenia before its confirmation. Leucippity refers to conjectures that wait many years for acceptance: like atoms, gravitational waves, continental drift, neutrinos, or Higgs bosons. Vela satellites, deployed in the 1960s to search for Soviet violations of the nuclear test ban treaty, saw instead bursts of radiation from above. When secrecy was lifted in 1973, the discovery of cosmic gamma ray bursts was announced, a rare instance of both serendipity and leucippity.

Robert Kolenkow (Ph.D.): As a graduate student in physics at Harvard I took Van Vleck's course in group theory. I didn't really understand it and I vowed to make introductory group theory available to juniors and seniors. Based on the undergraduate course I developed at MIT, my text *An Introduction to Groups and Their Matrices* was published by Cambridge U. Press in June 2022. I have always felt that groups and their matrix representations are so important they should be part of the undergraduate curriculum.

1960

Frances Mautner-Markhof (A.M.): In 2021, I was the Executive Editor in the startup of a new online news platform, iGlobenews, which brings news and global views on and for the international community. In April, 2023, I was appointed to the Austrian Fulbright Alum Advisory Panel and am a member of the Austrian Physical and Chemical Society & the Austrian Journalists Club. Some of my recent publications include:

- www.iglobenews.org/iaea-safeguards-a-model-for-international-ai-regulation/;
- www.iglobenews.org/quantum-entanglement-schrodingers-nobel-heirs/;
- www.iglobenews.org/nuclear-sharing-why-us-nuclear-weapons-are-in-europe-2/;
- www.iglobenews.org/nuclear-sharing-and-other-challenges-for-the-2022-npt-review-conference/;
- www.iglobenews.org/osce-a-model-for-comprehensive-and-cooperative-security/;
- and "Nuclear Sharing in Europe and the NPT: Relevance for the Korean Peninsula," *Rinsa Forum* (Research Institute for National Security Affairs), Korea National Defense University, 72 (2021).

1962

Peter Bond (A.B. *cum laude*): I co-authored with Robert Crease a book published in 2022 entitled The Leak: Politics, Activists and Loss of Trust at Brookhaven National Laboratory. It recounts the events and impacts of a harmless leak of tritium from the spent fuel pool of a research reactor in 1997 and presages events of today with fake news and outsized influence of celebrities. The leak resulted in the firing of the operating contractor of the Lab and the termination of a premier research reactor, and it threatened closure of the Laboratory itself. Politicians from both parties, media headlines, and anti-nuclear activists, including Alec Baldwin and Christie Brinkley, played significant roles.

1964

Richard A. Holt (A.B.; A.M. 1966; Ph.D. 1973, Thesis Advisor: Frank Pipkin) Research I did in 1969 as a graduate student was acknowledged by the Nobel prize committee in the description of the 2022 Nobel Prize in Physics (https://www.nobelprize.org/uploads/2022/10/advanced-physicsprize2022-3.pdf). John Clauser, at Columbia, and Abner Shimony and Mike Horne, at BU, independently realized that entangled photon pairs could provide an experimentally feasible test of Bell's Inequality; however, they didn't know how to calculate the QM prediction for photon pairs emitted in arbitrary directions. I did the calculation, and thus became a co-author of the famous "CHSH" paper. John Clauser invited my wife and me to be his guests in Stockholm last December, where we had a delightful time at the Nobel lectures, concert, several receptions, and of course the Prize Ceremony and banquet.

Norman Horing (Ph.D.): Shortly after finishing my Ph.D. at Harvard, I settled into a professorship in theoretical physics at Stevens Institute of Technology. I have authored or co-authored six science books, in addition to regular publications in scholarly journals. The books are: F*undamentals of Semiconductor Physics and Devices* with R. Enderlein (World Scientific, 1997), *Introduction to Complex Plasmas*, with M. Bonitz and P. Ludwig (Springer, 2010); *Low Dimensional Semiconductor Structures: Characterization, Modeling and Applications*, with H. Unlu (Springer, 2013); *Low Dimensional Semiconductor Structures and Devices,* with H. Unlu (Springer, 2015), *Quantum Statistical Field Theory: Schwinger's Variational Method with Applications to Nanostructures, Graphene and Superconductivity* (Oxford, 2017); and *Progress in Nanoscale and Low-Dimensional Materials and Devices,* with H. Unlu (Springer, 2022). In 2016, I retired after 50 years at the Institute but continue to be active in research and guide graduate physics students as Professor Emeritus. I am now preparing another book on the physics of Dirac materials and their nanostructures.

Richard N. Zare (Ph.D. Chemical Physics): I am pleased to report that I joined Prof. Philip Kim on stage on April 27, 2023, to receive the Benjamin Franklin Medal in Chemistry from the Franklin Institute in Philadelphia. It was a thrilling event.

1966

Andrew J. Hanson (A.B. Chemistry & Physics *cum laude*): I retired from Indiana University as a Professor of Computer Science in 2012, having written my last major Physics paper (Eguchi-Gilkey-Hanson, *Physics Reports* 66[6]) in 1980 and moved on to Artificial Intelligence at SRI and then Scientific Visualization at IU since 1989. Later this year I will publish the sequel to my first book *Visualizing Quaternions* (2006), called of course *Visualizing More Quaternions*. This spring, I installed a 4-foot steel sculpture of the Calabi-Yau Quintic (hidden dimensions of String Theory) at IU. I am in frequent touch with HR'66 classmates such as fellow Harvard Bandsman Henry Frisch in Physics at Chicago. My wife Patricia Foster (Harvard M.A. Biology '70) and I spent the 2022-23 holiday season touring New Zealand and Australia, and I have a new one-year-old granddaughter to enjoy. So, I am as yet far from actually retired!

1967

James Dakin (A.B.): I published *Wrestling with Light – History, Science and Applications* through AIP publishing in 2021. Topics range from astronomy to arcs, architecture, atoms, and art. In fall 2023 I will be teaching a sophomore honors seminar based on this textbook at Appalachian State University in Boone, NC. Emphasis will be on students researching individual topics more deeply and presenting these to their classmates. Meantime I have just completed a project to find museum homes for artifacts accumulated at GE Lighting's Nela Park campus in Cleveland, OH. Some items went back to the Edison years around 1880.

Andy Zucker (A.B.): I received an Ed.D. in science education in '78. The government's actions to combat climate change were greatly slowed, and hundreds of thousands of lives were lost during the pandemic, because of mis- and dis-information. With funding from the Howard Hughes Medical Institute, my colleagues and I will tackle scientific misinformation in schools at a local nonprofit Media Literacy Now. We will work with experts to identify skills and knowledge K-12 students need to learn in science classes to better evaluate sources of science-related information. Science teachers need more tools to address this serious problem, and policymakers need to acknowledge that learning about misinformation is a high priority.

1968

Matthew Miller (A.B.): Last year I co-founded Princeton Stellarators, Inc. , a spin-out from Princeton University and the Princeton Plasma Physics Labs, commercializing recent advances in stellarator physics and engineering. Our objective is to get fusion on the grid soon enough to make a difference. Practical commercial fusion finally is within grasp as the holy grail of energy production. Ours is just one of a number of private companies pursuing this objective. With so many shots on goal, one or more is bound to succeed. I hope ours is one of them.

1971

Chester M. Boltwood, Jr. (A.M.): I left physics, but stayed on at Harvard for pre-med studies. I received an M.D. at UC Davis (a letter from P.C. Martin helped). I trained in Internal Medicine and Cardiology in the greater UCLA system, staying on as a junior faculty at the affiliated VA Hospital for 7 years. I continue full-time practice including interventional cardiology, and my interests include cardiac physiology and hypertrophic cardiomyopathy. Physicists gravitate to cardiology, including Scott Yang, PhD '95, who is also a Kaiser cardiologist. He specializes in cardiac MRI (perhaps apropos the original report of NMR by Bloch and Purcell).

Walter Patrick ("Pat") Hays, III (A.B.): I've recently published *Silicon Planet: My Life in Computer Chips* (Amazon). *Silicon Planet* tells the story of the rise of the computer chip - the people, the dramas, the inflection points - through the lens of my 40-year career as a designer and entrepreneur. After Harvard, I earned a Ph.D. in particle theory from M.I.T. during the golden age of quantum field theory. Several years later, my career took a major turn when I fell in love with chip design.

1972

Brian M. Salzberg (Ph.D.): I have been a Professor at the University of Pennsylvania since 1975. At the moment, I am Professor of Neuroscience and of Physiology in the Perelman School of Medicine at the University of Pennsylvania, where my laboratory continues to study, by a variety of optical means (fluorescence, absorption, light scattering) the exocytosis of peptides from mammalian nerve terminals. I became a Fellow of the American Physical Society some 35 years ago, but since then I've become much more of a biophysicist.

1975

Jacquelyn A. Weiss (Ph.D.): I have moved to the greater Boston area; luckily I am able to continue doing neurological consultations with my multi-specialty group in the Bay area via telemedicine. Unfortunately, I cannot practice in my subspecialty as clinical neurophysiology testing cannot be performed remotely.

1976

Alan J. Cohen (Ph.D. Chemical Physics): Alan is now a Program Director at the United States National Science Foundation in the Technology/Innovation/Partnerships Division and is on a team reviewing major proposals from academia and industry as part of the new NSF Engines Program.

1978

Edward Farhi (Ph.D.): I graduated under the supervision of Howard Georgi. I worked on theoretical particle physics and was the director of theoretical physics at MIT for 12 years. In the late '90s, I switched my interest to quantum computing and I still work in that area. I joined Google's quantum team in 2017. I am actively researching quantum algorithms.

1979

Eric Dunn (A.B. *summa cum laude*): Most of my working life has been in the computer software industry. After being employee #4 at Intuit and the CFO who took it public in 1993, I held several other jobs there, including CTO, and then worked in venture capital. Since 2016 I have been the CEO of Quicken personal finance software, a private company spun off from Intuit. I have been married to Susan Dunn, my Harvard classmate, for 40 years; we have lived in Palo Alto, CA, the entire time. We have two children in their twenties who are gainfully employed and have found great partners!

Edward Hayworth (A.B.): After dividing my time between living in California, Switzerland, and China for several years, the pandemic caused me to return to California full-time. I am happily retired from a career in investment banking and strategic planning. I now enjoy pursuing my lifelong interest in the history and philosophy of science and keeping up with the latest developments in physics. Like so many others, I am enjoying once again being able to travel and to experience the incredible wonders firsthand that the world has to offer. I wish everyone health and peace.

1984

Daniel Raftery (A.B.): In 2012, I moved to the medical school at the University of Washington in the pursuit of 1000's of clinical samples to analyze. My lab works is in the field of metabolomics, the advanced measure of metabolism using mass spectrometry and nuclear magnetic resonance. We developed new analytical methods and use a variety of machine learning approaches to identify disease biomarkers and drug targets. While early cancer detection has been a goal, we've had more success in applying this approach to detecting infectious diseases. A couple of colleagues and I have now launched a new startup company with this focus. We are also using machine learning methods to model metabolism, for both our cellular work and our measurements of human blood, which is providing some interesting surprises.

1986

Jim Crimmins (A.M.): I'm currently the owner and CEO of CFV Labs, a Solar Photovoltaic research and development lab in Albuquerque, New Mexico. We work with people like NREL and Sandia on developing and characterizing new solar technologies like Perovskites as well as with manufacturers to optimize mainstream crystalline silicon (c-Si) and cadmium telluride (CdTe) solar products. If anyone is interested in discussing current or emerging commercial solar technologies, please feel free to contact me at jim.crimmins@cfvlabs.com.

Eric B. Sirota (Ph.D.): I am still doing physics research at ExxonMobil's research laboratory in New Jersey, where I've been since I graduated in 1986. I have been doing fundamental physics impacting chemical engineering challenges, and continue to work in areas of phase behavior, thermodynamics, and viscosity, on materials including waxes, lubricants, polymers, and asphalt. I'm currently studying the behavior of molecules present in renewable feeds. I also write musical theater. Most exciting, my musical, *Frankenstein*, which played Off-Broadway for three years, has been adapted for screen and released as a movie (TheFrankensteinMusical.com). I'm currently developing a musical that touches on Alzheimer's. This year I was honored to be included in the GSAS 150th website: gsas.harvard.edu/news/alkanes-and-altos.

1991

Michael A. Burstein (A.B.): For the past few years, I've been an editorial manager at Savvas Learning Company, overseeing the creation of our Next Generation Science Standards program for high school students, Experience Physics. I'm also a writer and editor of science fiction stories, and my anthology *Jewish Futures* was published by Fantastic Books in August, 2023.

1992

Christopher Ball (A.B.): In September 2022, Chris was appointed the Interim Director of the ElectroScience Laboratory at The Ohio State University. He began working at ESL in 2016 after a 15-year career at Battelle Memorial Institute. His research focuses on the development of novel sensor and communications technologies, including a handheld optical sensor to characterize nutrients in food and agricultural products, a submillimeter wave sensor to detect trace levels of hazardous gases, a space communications system based on x-rays, and a microwave radiometer recently flown in space aboard a CubeSat.

Vivek Rao (A.B.): In 2023 I started as a data analyst at Solum Partners, in Boston, which invests in real assets within the agriculture and food production industry. Previously I was an equity derivatives and FX analyst at Bain Capital. I am married, with three children. One of them recently graduated from college, and the other two will be starting college soon.

1997

Martin Z. Bazant (Ph.D.) In 2022, Martin co-founded an MIT start-up company, Lithios Inc., developing Advanced Lithium Extraction from brines using electrochemistry. He also co-founded the non-profit International Electrokinetics Society and serves as its first president.

1998

Sameer Sheth (A.B.): Along with collaborators (including my brother Sunil Sheth, A.B. '04), I co-founded a company, Motif Neurotech (motifneuro.tech), through which we are developing minimally invasive neuromodulation therapies for mental health disorders. I was promoted to Professor of Neurosurgery at Baylor

College of Medicine and was named Director of the Cain Foundation Laboratories, a group of labs focused on epilepsy research. My wife continues to love her elementary teaching career. Our son is a junior in HS and will be hitting the college application warpath, and our daughter (7th grade) continues her speech and athletics pursuits.

1999

Shirling Tsai (A.B. Chemistry & Physics): I took the complex analysis class in 1997 with Prof. Kaxiras and it was one of my favorites! I went to med school (Columbia) and then specialized in vascular surgery (trained at Cornell and the MGH) and now I'm section chief of vascular at the Dallas VA and Program Director for the vascular surgery training programs at UT Southwestern.

2000

Martino Poggio (A.B.): Aside from leading my research group at the University of Basel, Switzerland, focusing on nanometer-scale mechanics, magnetism, and imaging (poggiolab.unibas.ch), I concluded two years as Chair of the Physics Department in 2021. The following year, I also took the role of Director of the Swiss Nanoscience Institute (www.nanoscience.ch).

2002

Peter Dong (A.B. Physics & Music): I got the opportunity to work on the book *Collision: Stories from the Science of CERN*, which paired scientists with writers to collaborate on science fiction stories based on particle physics. I got to work with acclaimed screenwriter Steven Moffat on a story based on a bizarre but not impossible reverse causality theory that the universe is deliberately hiding dark matter from us. I think Steven wrote a really good story, and the collection overall is a fun read.

Jeffrey Filippini (A.B. Chemistry & Physics): In 2022 I was promoted to Associate Professor of Physics at the University of Illinois Urbana-Champaign. My research focuses on observational cosmology, particularly cryogenic instrumentation for millimeter and sub-millimeter observations of the early universe. During the 2022-23 austral summer I led the second Antarctic science campaign for SPIDER, a NASA long-duration balloon mission to observe the cosmic microwave background and characterize polarized Galactic dust emission. I'm happy to report a successful flight, and data analysis is just beginning.

2005

Kevin Weil (A.B. Physics & Math): I recently joined Planet as President. Planet builds and operates a fleet of over 200 satellites that image the entire planet every day, with a dataset going back over 2000 days. It's an inspiring company with a business that spans climate & sustainability, agriculture, insurance, forestry, finance, civil government, and defense. Lots of interesting work to do for physics grads! My wife Elizabeth runs Scribble Ventures and we have three fun/crazy kiddos.

2007

Alex Wissner-Gross (Ph.D.): Dr. Wissner-Gross was pleased to announce that a number of his portfolio startup companies raised venture funding. To learn more, visit www.alexwg.org.

2008

Max Chalfin (A.B.): I've had the pleasure of working with Running Tide Technologies to build out their science and engineering capabilities. It's a climate solutions startup focused on developing pathways to perform carbon dioxide removal (CDR) using natural systems in the ocean. Ocean CDR is an emerging, promising, and at times controversial category of technologies to reverse the worst impacts of the climate emergency by moving emitted carbon back into the earth's slow carbon cycle. Along this journey, I've had the opportunity to dig into the field of biogeochemistry (nature-based carbon removal is essentially applied biogeochemistry). It is a fascinating science, which I believe represents a seamless extension of the principles and methods of physics into a characterization of the natural world and the earth system. It is also the language of climate mitigation research. Teach your undergrads biogeochemistry today!

Quentin Sedlacek (A.B.): During the pandemic, I joined the faculty in the School of Education at Southern Methodist University. I also received a research grant from the Spencer Foundation to study how ideologies of language, race, and racism shape the practices of K-12 science teachers. There is already a wealth of valuable research identifying strategies to help K-12 students become better at talking and writing about science; my research complements this literature by asking how universities can help K-12 science teachers become better listeners and readers of their students' work, and how such efforts could advance educational equity.

2009

Aaron Kuan (A.B.; Ap. Phys. Ph.D. 2016) studied with Prof. Jene Golovchenko during his Ph.D., where he also served as the Music Director of the Dudley House Orchestra and met his future wife, Xiuye Chen (MCB Ph.D. '17), whose research inspired him to embark on neuroscience. After graduating, he started a postdoc with Prof. Wei-Chung Lee's lab at Harvard Medical School, where he developed new electron and x-ray imaging techniques to map brain connectivity. This fall, he will join the Neuroscience Department at the Yale School of Medicine as an Assistant Professor, where he will study brain-wide circuits that underlie cognition.

2010

Benjamin Burns (A.B. Physics & Astrophysics): This year I welcomed two new babies into the world. My wife, Lianna Karp '10, delivered our son Julian Orion Burns in January 2023, and our life has been thrown into a new orbit around him ever since. And professionally, in my role as the product lead managing the earbuds category at Bose, I launched the Bose QuietComfort Earbuds II last September, which boast the world's best noise cancellation of any earbud or headphone. These two releases have been complementary: the baby's cries can clock in at over 100dB, so I'm happy the earbuds came first.

2011

Maham Siddiqi (A.B. Physics and Astrophysics): After receiving my degree, I worked as a Research Fellow at the Harvard-Smithsonian Center for Astrophysics for a year before moving on to do my Masters in Physics from Muscat, Oman. After completing my Masters, I joined the Institute of Space Technology (IST) in Islamabad, Pakistan, as a Lecturer in the department of Space Science in 2019. I am currently still working here as a faculty member while also starting my Ph.D. in Quantum physics, as of September 2022, from the National University of Sciences and Technology (NUST) in Islamabad, Pakistan.

2013

Joanna Behrman (A.B.): In the past two years I published two articles on the history of women in physics and astronomy which made the covers of *Physics Today* ("Physics ... is for Girls," August 2022) and *American Journal of Physics* ("Sarah Frances Whiting, Pioneering Laboratory Instruction in Astronomy," June 2023). As of April 2023 I also welcomed a son, Ruben, who is cover-worthy in every way as he makes new discoveries about the universe daily.

Tony Pan (Ph.D.): Tony finally found his better half Alexis, got engaged, and is getting married this summer. They spend their time enjoying nature in Seattle, whether crabbing, fishing, or just growing fruits in the yard. Also, Tony's company Modern Hydrogen raised $63M during this time, helping companies reliant on natural gas to decarbonize and produce clean hydrogen at the point of use.

2014

Nick Hutzler (Ph.D.): Mary and I welcomed our second child, Lydia, in 2021. She and her brother Isaac are doing well, and we all live in Pasadena, CA. Please look us up if you are ever in Southern California!

2016

George David Torres (A.B. Physics & Math): I'd love to include the birth of my son, George Emerson Torres, to the Physics Newsletter. My wife Taylor Torres and I were overjoyed to welcome him on February 1st, 2023.

2017

Alex Lupsasca (Ph.D.): I received my Harvard Ph.D. in Physics under the supervision of Andy Strominger. After two postdocs, I started a faculty position at Vanderbilt University last fall. I very much enjoyed my time at Harvard, both professionally and personally, and I am grateful to the department for setting me up on a path to academic success!

2018

Tansu Daylan (Ph.D.): I am delighted to be starting as an Assistant Professor of Physics at Washington University in St. Louis in Fall 2023. I was a Ph.D. student in the department between 2013 and 2018, working with my advisor Douglas P. Finkbeiner on the astrophysical signatures of dark matter. As I embark on this journey, I look forward to sparking passion and curiosity in my students and inspiring them to make a lasting impact on our field and the broader society. I hope to occasionally visit Jefferson Lab to crash the Puppet Show or catch up with friends and colleagues.

Yasmeen Fakhro (A.B. Chemistry & Physics): I got a new job as an Associate Producer & Consultant at Fablemill. Fablemill is an award-winning boutique production house and advisory firm based out of Bahrain that amplifies underrepresented voices and showcases Arab stories to a global audience.

2018

Lincoln Craven-Brightman (A.B. Physics & Math): Over the last two years, I finished a position as an MRI research engineer at Mass General Brigham. It was a great opportunity to grow and learn, and I'm immensely proud of the projects I was able to take ownership of and see through completion! The job inspired me to further develop my electrical and computer engineering to pursue a passion for research instrument design, and I just completed the first year of my Master of Engineering degree at University of British Columbia, Vancouver.

2019

Vaibhav Mohanty (A.B. Chemistry & Physics): After graduating from Harvard Physics in 2019, Vaibhav went to the University of Oxford on a Marshall Scholarship and received his first Ph.D., in Theoretical Physics, working with Prof. Ard Louis on statistical physics and biological evolution and submitting his dissertation, "Robustness of Evolutionary and Glassy Systems," at age 22. In 2021, he joined the Harvard-MIT MD-PhD program, now pursuing his second PhD at Harvard Chemistry with Prof. Eugene Shakhnovich, using physics-based models to develop mutational "traps" to combat the rapid evolution of proteins in infectious pathogens and in cancer. This year, he was awarded the PD Soros and Hertz fellowships.

Celebrating Staff

by Clea Simon

This past season has been a busy one, with new hires and new activities designed to bring the Physics Department together.

With many new faces in the department and several other staffers taking on new roles, this has been a season of change. This year has also brought about a renewal of pre-pandemic gatherings. For the first time since 2019, the department was able to host an in-person open house. During the March event, more than 70 students enjoyed two full days of catered events and activities, topped off by science demonstrations in the instructional labs. "We got to actually do the same types of experiments that the students get to do, which was really exciting," said Hannah Belcher, who has stepped into a new role as graduate student administrator.

Despina Bokios won the axe-throwing competition at Urban Axes

"There were lots of loud noises and fire," Belcher said, with a laugh. Demonstrations included the depressurization of a steel drum ("we got to see it crush itself") and the lighting on fire of balloons filled with various gases. ("That one got very loud!")

Sometimes bonding is as important as learning. "A big part of my job is community building and creating opportunities for staff to socialize and to professionally develop together, improve our culture, and just generally have a good time," explained undergraduate program administrator Dionne Clarke, who also serves as the chair of the social committee. "Our department has a very friendly community." Her mission, she says, is to continue to foster "that warm and welcoming environment."

Recently, that has meant a series of fun outings, including an afternoon at an axe-throwing club and another at Putt Shack, a high-tech miniature golf park in Boston's Seaport District. In addition to the activities themselves, these outings allowed for informal conversations about everything from staff members' hometowns to what passes for barbecue in Boston.

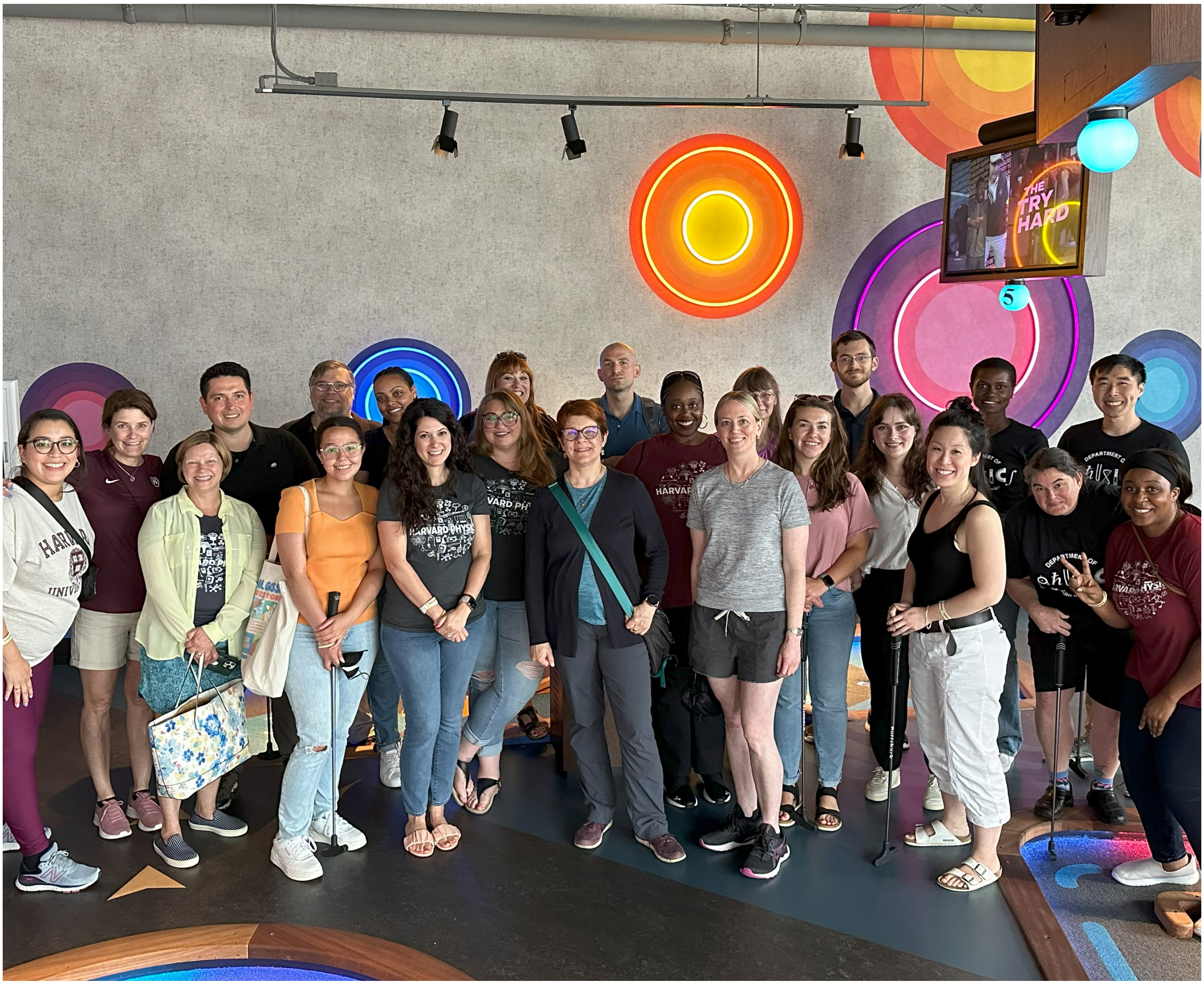
"It's just fun to go somewhere else and not focus on work for a little bit," said Helene Uysal, associate director of administration. "It gets folks out of their offices and gives everyone the opportunity to try a new adventure and hang out with the larger group."

Such activities have particular value in the wake of the pandemic. Said Belcher: "After Covid everything was shaken up. A lot of people have moved on to other jobs. A lot of people retired. The department felt less social than it was before. Since we're back in a hybrid environment, we now have a chance to get to know the new hires and really bring them into the department culture."

This has also meant a renewal of diversity events for graduate students. The department hosted a Pride event this year, and

Belcher looks forward to bringing back the department's diversity dinner series as well. Some of this involves enabling communities within the department to do their own outreach. The LGBTQ-plus community, for example, has a social hour every week, she said. "Organized by and for the community."

Overall, this has been a time of renewal for the department staff. "Between the social committee and what we're doing with the grad students, we're really back in a good groove," said Belcher. "There's been a renewed interest in supporting the staff and making the staff feel supported by the department as a whole. That's really important for morale."



At Putt Shack

A Tribute to Stan Cotreau

by Clea Simon

Making tools, learning how to use them, and guiding generations of students as they manufactured their own specialized equipment: These skills, and many more, have long been the province of Stan Cotreau, manager of the Physics/SEAS Instructional Machine Shop. Cotreau, who retired last June after 39 years at Harvard not only oversaw the expansion and reimagining of the Machine Shop, he turned it into a teaching tool for generations of researchers.

Cotreau originally came to the university for a position as a machinist at the Harvard Observatory. After nine years, he recalled, he was given the opportunity to join the Physics Department, taking over the Machine Shop. What he found was a crowded space "in disarray," he said. The shop was open only two mornings a week and the equipment was "antiquated." He responded by overseeing the purchase of new equipment and developing a teaching curriculum. Along with crafting the specialized tools needed for various research projects, he also guided graduate students and post-docs in how to use the shop to create their own tools.

"It grew to the point where I focused on teaching," he recalled. This proved to be a welcome development. "Teaching and spending time with the students and having the privilege of sharing my trade with the students was probably the high point of my career," said Cotreau.

Cotreau admirably filled both roles, said John Doyle, the Henry B. Silsbee Professor of Physics, acting as both an educator and providing unparalleled technical support for both graduate students and post-docs.

Performing these duties, Cotreau created "a kind of magic," said Doyle. Students, he explained, would be "learning while they're creating new knowledge and new processes and moving the scientific frontier forward. And Stan would interact with those students in a way that educated them both on best practices and what was possible as far as machining was concerned."

Indeed, said Cotreau, much of what he taught ranged far from simply operating the massive and complex collection of tools assembled in the basement machine lab. "I did a lot of listening to a lot of stories and it wasn't all about metal," he recalled. "Students would come in and they would make a mistake on a part, and they would instantly burst into tears or get really frustrated, and you knew that it wasn't the fact that they ruined the part that had them upset." In response, Cotreau explained, he would "just talk to them. You'd find out a parent was sick or they got dumped by their boyfriend, or whatever, and you just lend an ear. I never offered advice, I just listened. That's what they needed."

With such empathy as well as his machine skills, Cotreau left his imprint on generations of students. Now, as he begins his retirement, the teacher and machinist is enjoying time spent with his grandchildren and doing some wood carving.

"It was time," he said about his retirement and of passing the management of the shop along to Alejandro Lopez, who taught with Cotreau for two years. "It's in good hands." said Cotreau.

That doesn't mean his own special gifts won't be missed. "Stan gave the students something that was missing from their past education, which was a practical understanding of what to do to get to that endpoint," said Doyle. Cotreau, he added, not only taught "the hands-on approach, but also the theory behind it."

A crowd gathers in front of Jefferson Lab to watch the traditional Pumpkin Drop organized by the undergraduate Society of Physics Students. [photo by Kane Sjoberg '25]

Departmental Events

For details on upcoming colloquia, lectures, and other events, please consult the Harvard Physics Calendar webpage: https://www.physics.harvard.edu/events/gencal

Watch the videos of various events on YouTube: https://www.youtube.com/user/harvardphysics

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

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