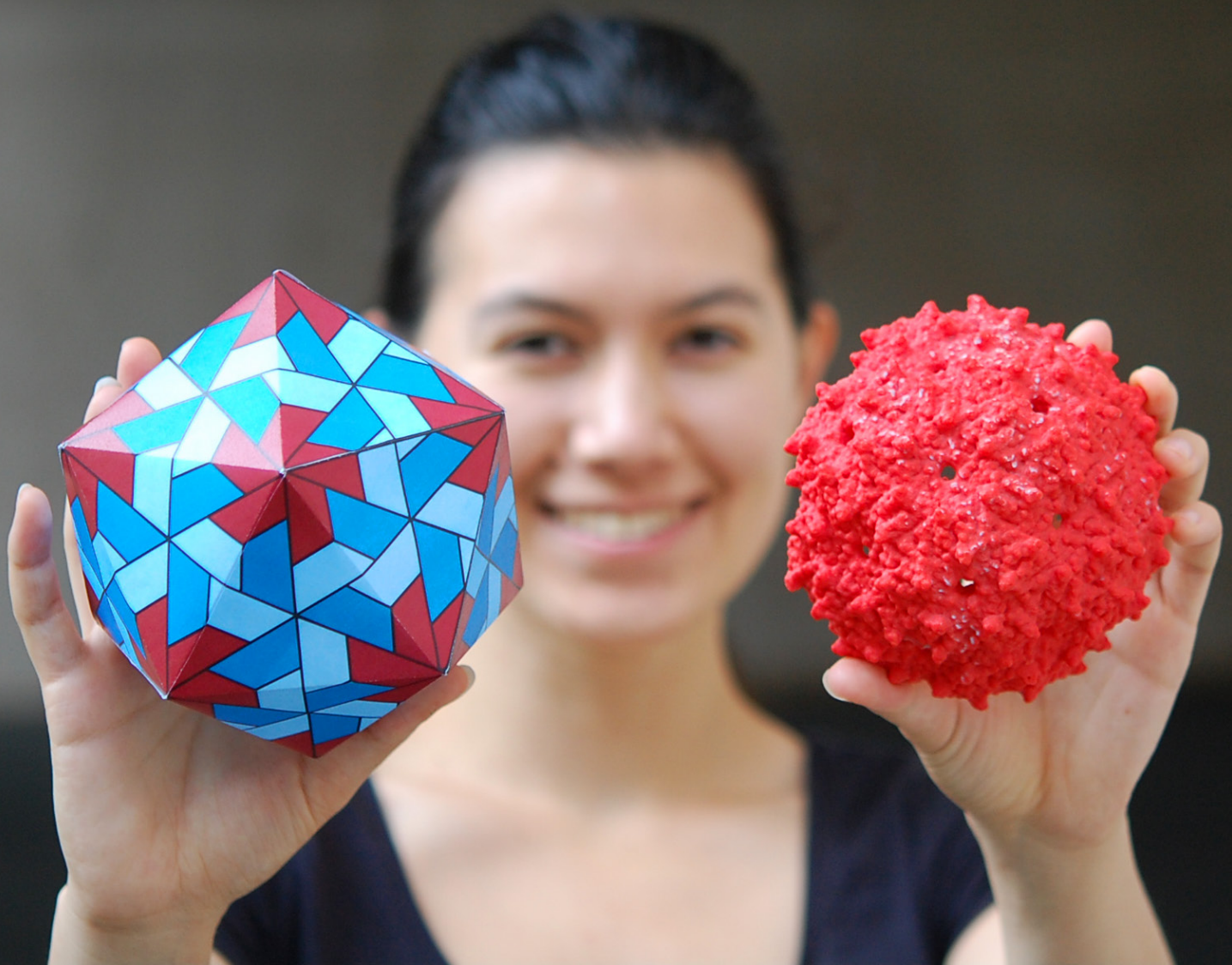


PHYSICS

Harvard University Department of Physics Newsletter

FALL 2021



SOME ASSEMBLY REQUIRED:

Probing the Physics of Order and Disorder
in the Manoharan Lab

also in this issue:

The Pound-Rebka Experiment

An Afternoon with Gerald Holton

Cumrun Vafa: A Career Built on Strings

and much more



HARVARD UNIVERSITY
Department of Physics

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G4 Amelia Paine displays a detailed model of the MS2 protein capsid alongside a simpler one highlighting its icosahedral symmetry. The actual virus is 3,000,000 times smaller. (see p. 6)

ACKNOWLEDGMENTS

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Letter from the Chair



Dear friends of Harvard Physics,

I'm happy to report that in-person classes have resumed this fall. Even though the signs of ongoing pandemic are still everywhere—in the posters exhorting people to follow the safety guidelines, in the outdoor tents, in the safety masks covering the faces of our students and colleagues—the halls and pathways on our campus are once again thrumming with creative energy and scholarly zeal. Our staff are also back on campus on a part-time basis, braving office renovations and the general hubbub of an academic term in full swing.

I hope you will enjoy this ninth issue of our annual newsletter. In it, we honor Steven Weinberg, our former colleague and a friend to many, as well as a towering figure in the field of theoretical particle physics, who passed away at the end of July. Please read Prof. Howard Georgi's reminiscence of Weinberg on page 4.

Our cover story, "Some Assembly Required," written by graduate students Caroline Martin and Amelia Paine, describes several avenues of research being conducted in Prof. Vinodhan Manoharan's group. This research includes the dynamics of virus assembly and the study of colloids, both as a convenient substitute for modeling the behavior of molecules, proteins, and atoms, but also for their own properties which can be harnessed in designing self-assembled materials (p. 6).

This year's historical focus is on the gravitational redshift experiment conducted in 1960 in Jefferson Laboratory by Robert Pound and his graduate student Glen Rebka Jr. You can read this fascinating story, written by Prof. Paul Horowitz, on page 12. Paul has also penned an article on an afternoon spent with Mallinckrodt Professor of Physics and Professor of the History of Science, Emeritus, Gerald Holton, talking about our department and its history (p. 20). A profile of Prof. Cumrun Vafa, written by Steve Nadis, "Cumrun Vafa: A Career Built on Strings," is on page 22. Vafa is a preeminent high-energy theorist and proponent of string theory who, together with Prof. Andrew Strominger, was awarded the 2017 Breakthrough Prize in Fundamental Physics

"for transformative advances in quantum field theory, string theory, and quantum gravity."

In this issue, you will also find a story by Clea Simon about the physics/SEAS machine and electronics shops, which stayed open throughout the worst days of the pandemic (p. 28), and Mary McCarthy's tribute to Anne Trubia, who retired at the end of June from her position as Director of Administration (p. 35). To celebrate the retirements of other notable staff members, Barbara Drauschke, Tom Hayes, and Rob Hart, please turn to page 53.

The reports from our academic programs can be found on pages 37-46. I hope you will enjoy the many profiles of our students you will find on those pages. You may also enjoy perusing the Alumni Notes on pages 47-51 and catching up with what your old friends and fellow physics alumni have been doing lately. On page 52, you will find a memorial tribute to Arianna Wright Rosenbluth, a Harvard Physics alumna and a pioneer in computational science at the very dawn of the computer age. She played a central role in the creation of the Metropolis algorithm, an extremely useful computational tool and the basis of what are now known as the Markov Chain Monte Carlo methods.

This year some events are returning to campus, with livestreaming options on Zoom. Please consult the [calendar of events](#) on our website for more information and write to us at physics_newsletter@fas.harvard.edu with any questions you might have. We are always happy to hear from old friends!

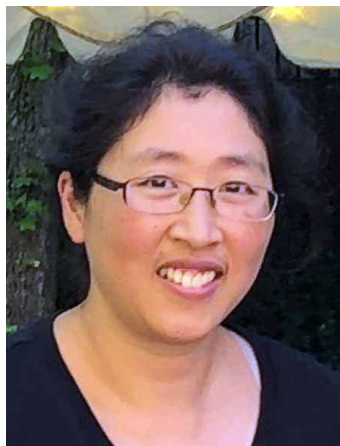
Before I sign off, I have a very exciting news to share: Executive Director Despina Bokios, who has replaced Anne Trubia, has just started her tenure in our department. Despina comes to us from Boston University, where she held a similar position as Director of Operations in the physics department. Look out for Despina's profile and her impressions of her first year in office in our next Newsletter.

Best wishes to you all,

Efthimios Kaxiras,

Department Chair, John Hasbrouck Van Vleck
Professor of Pure and Applied Physics

Faculty Promotions



Kang-Kuen Ni

Congratulations to Kang-Kuen Ni for her promotion to full professor with tenure!

Ni moved from her native Taiwan to the U.S. in 2000 to pursue her study of physics: first a B.S. at the University of California, Santa Barbara, then a Ph.D. at the University of Colorado, Boulder, and later postdoctorate at Boulder and Caltech. Her doctoral dissertation, completed under the supervision of Prof. Deborah Jin and Prof. Jun Ye, describes the first experimental realization of an ultracold, near-quantum-degenerate gas of polar molecules.

Ni's research in molecular physics naturally brought her to work on quantum problems at the interface of physics and chemistry. From the point of view of physics, molecules are more complex than atoms and represent a new frontier in atomic physics; from the point of view of chemistry, this research touches on the most fundamental aspect of chemical reactions: transforming reactants to products. At Harvard since 2013, with an appointment in the Chemistry Department as well as Physics, Ni has a unique opportunity to explore such an interface of the two disciplines.

Her group built a molecule from exactly two atoms using optical tweezers, first as a proof-of-principle demonstration (which was a cover story in *Science* in 2018), and later achieving complete quantum state control of the molecules. This level of

control is unprecedented and forms the basis of the next research direction for the group: using these fully-controlled single molecules as basic building blocks for quantum simulations and computations.

Ni and her group have also studied the coldest chemical reaction that's ever been recorded and tested quantitatively, and their comparison of experiment and calculation, based on statistical theory, revealed unexpected deviations. Explaining such deviations will require major advancement of computational resources or techniques, and this data will serve as a benchmark for future theoretical advancements.

In addition, the group saw reactants transform into products through an intermediate stage, which is typically transient in nature and is very hard to observe directly. In their case, however, the transient intermediate stage lasted a million times longer than normal, thus allowing direct observation as well as influencing the reaction pathway through interaction with light.

Ni's future research directions include establishing coherence in reaction products, observing interferences in reaction pathways, and using chemical reactions as a mechanism to generate quantum entanglement resources.

Faculty Prizes, Awards, and Acknowledgments^[1]

AAAS Fellowship:

Eric Mazur
Christopher Stubbs

BBVA Foundation Frontiers of Knowledge Award:

Gerald Holton

Alfred P. Sloan Research Fellow in Physics:

Carlos Argüelles-Delgado
Roxanne Guenette

American Academy of Arts and Sciences:

Ashvin Vishwanath
Amir Yacoby

Aramont Fellowship:

Matteo Mitrano

Dirac Medal (University of New South Wales & Australian Institute of Physics):

Lene Hau

Charles Hard Townes Medal:

Mikhail Lukin

Clarivate Analytics Highly Cited Researcher 2020:

Eugene Demler
Markus Greiner
Philip Kim
Mikhail Lukin
Hongkun Park
Subir Sachdev
Ashvin Vishwanath
David Weitz
Amir Yacoby
Xiaowei Zhuang

DOE Early Career Research Program Award:

Julia Mundy

Hamburg Prize for Theoretical Physics:

Eugene Demler

Hans A. Bethe Lectureship:

Andrew Strominger

Herbert P. Broida Prize:

John Doyle

IUPAP Young Scientist Prize in Astroparticle Physics:

Carlos Argüelles-Delgado

Lurie Prize in Biomedical Sciences:

Xiaowei Zhuang

The Mustafa Prize in All Areas of Science and Technology:

Cumrun Vafa

Norman F. Ramsey Prize (APS):

Mikhail Lukin

SETI Institute 2021 Drake Award:

Paul Horowitz

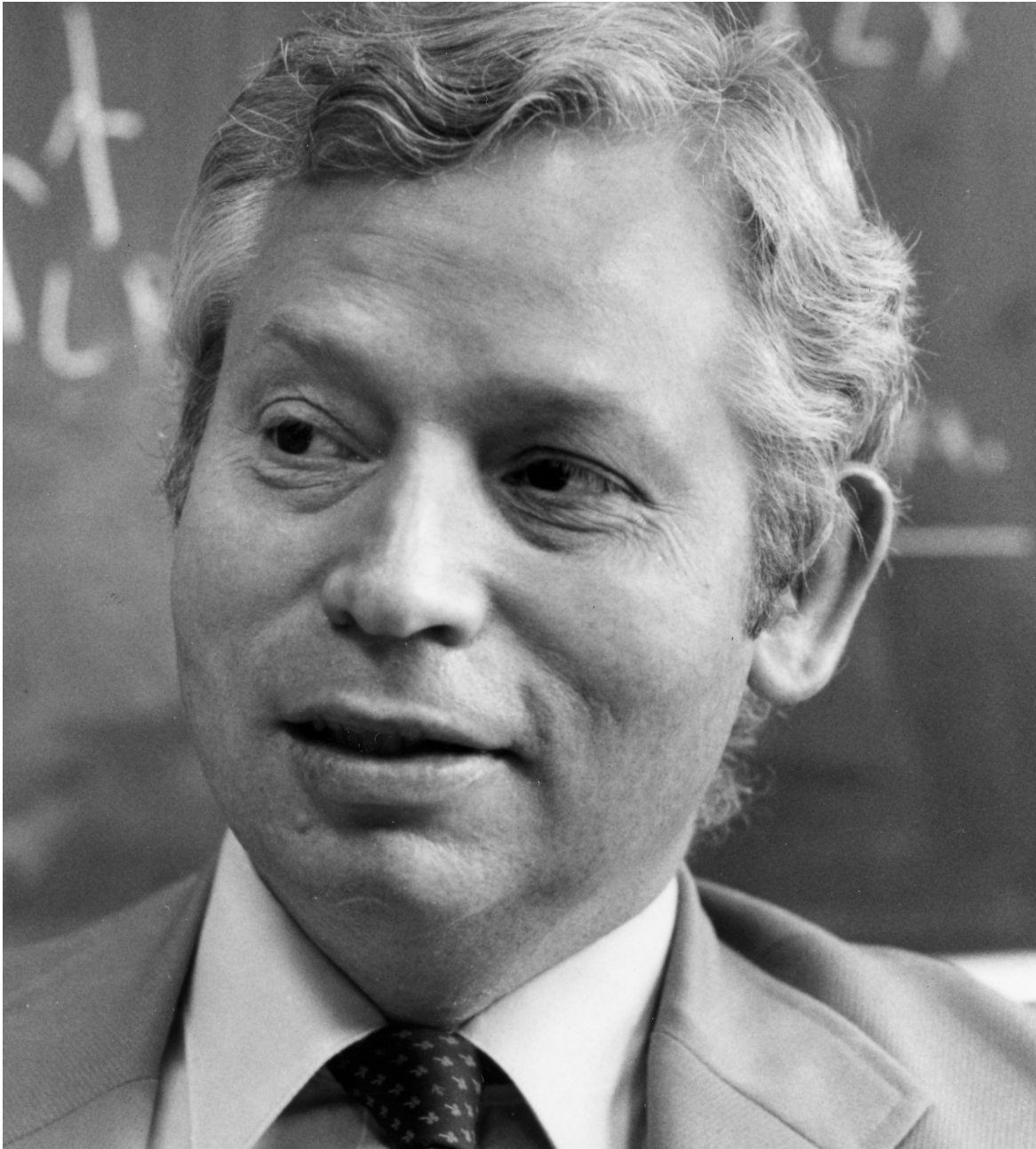
Star-Friedman Challenge for Promising Scientific Research:

Julia Mundy

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

Steven Weinberg – A Reminiscence

by Howard Georgi



Photograph of Steven Weinberg: courtesy of AIP Emilio Segrè Visual Archives

Theoretical physics lost one of its most brilliant, thoughtful, influential and durable practitioners when Steven Weinberg died in July at the age of 88. Steve came to MIT in 1969 after ten very productive years at Berkeley that established him as one of the world's leading quantum field theorists. He joined the Harvard faculty in 1973 as the Higgins Professor of Physics, taking over the chair held by Julian Schwinger and Percy Bridgeman before him.

Legend has it that when Steve moved into Schwinger's elegant wood-paneled office on the third floor of Lyman he found a large pair of shoes. There may never be another Julian Schwinger, but Steve did an admirable job of filling those shoes.

Steve's time in Cambridge from 1969 to 1983 was an exciting period for particle physics during which the standard model was built and largely established. But it didn't start out that way! When Weinberg wrote the paper that is sometimes hailed as the birth of the standard model of particle physics, "A Model of Leptons" in 1967, quantum field theory (QFT) was in the doldrums. While many of the pieces of the standard model were developed in the '60s and even the late '50s, nobody could put them all together. Steve's paper did little to change that. It was not obvious that calculations with the model made sense, and the paper was largely ignored—even by Steve himself. So too was the prediction of the charmed quark at Harvard by Glashow, Iliopoulos, and Maiani.

The situation changed dramatically at the beginning of the '70s because of seismic shifts in both theory and experiment. A Dutch theory student, Gerard 't Hooft, made sense of spontaneously broken non-Abelian gauge QFTs in general and Weinberg's model in particular. And experiments to look inside protons at the great accelerator laboratories using electrons and muons began to see evidence of the underlying QFT. Few were convinced immediately, but Steve and the Harvard group and a few other centers of QFT research realized that the game was afoot and built the standard model. The final pieces of the puzzle emerged after just a few frenetic years with the discovery of asymptotic freedom by David Politzer at Harvard and others and the experimental discovery of states involving the charmed quark.

Eventually, the rest of the world caught up and the Nobel Prize in 1979 to Glashow, Salam, and Weinberg put a suitable crown on the most exciting period in QFT since the work of Feynman, Schwinger, and Tomonaga in the late '40s. In the process, Weinberg, along with Ken Wilson, 't Hooft, and a few others, radically changed our (and his) view of QFT.

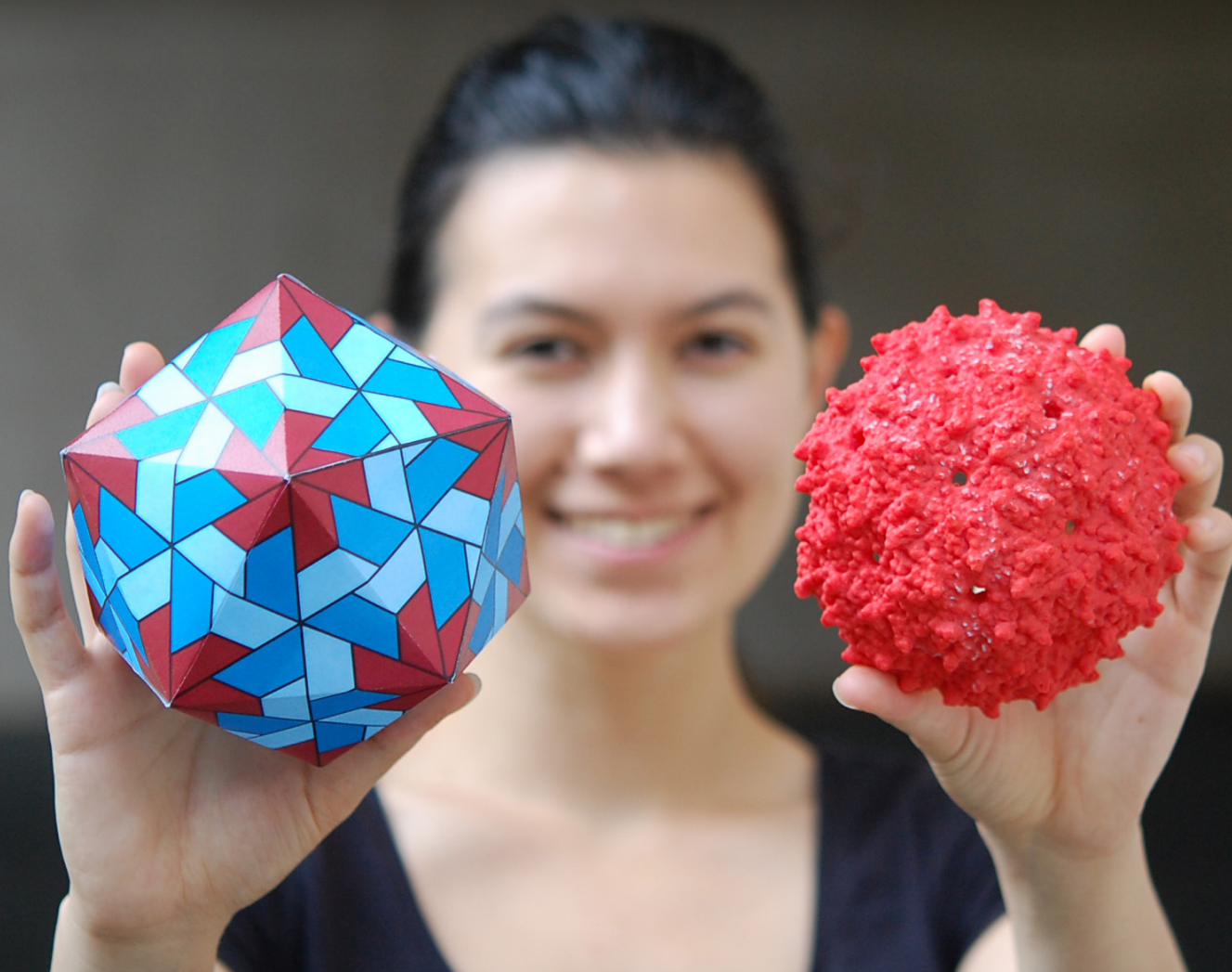
QFT is only a part of Steve's enormous contribution to physics. His breadth and productivity were astonishing. He wrote over twenty books, some learned tomes such as the three-volume *The Quantum Theory of Fields* and *Gravitation and Cosmology*, but also many books for a general audience, both on physics (e.g., *The First Three Minutes*) and on pressing societal issues (e.g., *Glory and Terror: The Growing Nuclear Danger*).

Steve was an unusual character even by the standards of theoretical physicists! I collaborated with him on two papers, one important one with Helen Quinn was one of the two pillars of grand unification. He and I interacted pretty much every day while he was at Harvard because we were interested in all the same issues. He was the only person I ever met who didn't need examples. He almost always started with generalities. One of the great ironies is that he got his Nobel primarily for a specific model.

Perhaps one of Steve's greatest strengths was that he thought deeply, sometimes philosophically, about issues, but didn't let this get in the way of progress. He could change his mind. One of my favorite examples comes from his 1972 text *Gravitation and Cosmology*, where he wrote "At one time it was even hoped that the rest of physics could be brought into a geometric formulation, but this hope has met with disappointment, and the geometric interpretation of the theory of gravitation has dwindled to a mere analogy, which lingers in our language in terms like 'metric,' 'affine connection,' and 'curvature,' but is not otherwise useful. The important thing is to be able to make predictions about images on the astronomers' photographic plates, frequencies of spectral lines, and so on, and it simply doesn't matter whether we ascribe these predictions to the physical effect of gravitational fields on the motion of planets and photons or to a curvature of space and time." Less than 15 years later, he returned to Harvard from Texas as a Loeb Lecturer, giving talks on string theory and the geometry of extra dimensions.

When I think of Steve's long career, what comes to mind are words like *brilliant*, *deep*, *thoughtful*, but even more *noblesse oblige*. He knew he had special talents and was compulsively driven to use them to the fullest. He continued to work hard on his physics almost to the very end. Very few have ever done more.

SOME ASSEMBLY REQUIRED



Probing the Physics of Order and Disorder in the Manoharan Lab

by Caroline Martin and
Amelia Paine

Above: Amelia Paine displays a detailed model of the MS2 protein capsid alongside a simpler one highlighting its icosahedral symmetry. The actual virus is 3,000,000 times smaller.

The past year has fundamentally changed the way we think about the world. In the midst of all the upheavals of the ways we worked, socialized, and lived, there was a new hyper-awareness of the microscopic. Suddenly, questions that scientists had long been trying to answer felt far more urgent: How do micrometer-sized aerosols floating in the air spread through a poorly circulated room?

What are the forces acting on an infectious agent in an evaporating droplet left behind on a doorknob or a package? What drives the runaway assembly of viruses as they hijack a cell?

Professor Vinothan Manoharan's lab has been answering questions about the principles that govern the microscopic world for over a decade. We study the spontaneous emergence of complex, ordered structure from simple, disordered components. Our experiments probe the underlying physics that drives this process of self-assembly. We use this understanding to design new, useful materials, such as vibrant pigments that get their color from their microscopic structure. With our research on the emergence of order, whether in biological systems such as viruses or in model systems such as colloidal suspensions, we are gaining a deeper understanding of the physics that drives organization, assembly, and life itself.

Do viruses understand physics?

Viruses have an unmistakable elegance, despite their potentially disastrous effects on their hosts. Honed by evolution to make do with as small a genome as possible, they take advantage of symmetry to be efficient. The simplest viruses, like the bacteriophage MS2 studied in our lab, consist of a protein shell, or capsid, protecting an RNA genome. MS2 and many other viruses exhibit icosahedral symmetry, with a capsid made from 180 copies of a single protein assembled into a structure that resembles a soccer ball. We can think of viruses as one of the simplest examples of how biological systems create order out of the chaotic soup of the universe.

For many viruses, this assembly into perfect icosahedral capsids can even be reproduced in a test tube. Add some viral RNA to some coat protein and give it a good shake, and you may find yourself with functional viruses, spontaneously formed by the process of self-assembly. It's a frightening thought to some, but in our lab, it's only the viruses' bacterial hosts that are scared. Self-assembly, a term coined specifically to describe the way viral capsids form these ordered structures, is driven by the minimization of free energy—the balance between enthalpy and entropy.

But how does this ordered structure form so reliably? To create a spherical shell, the proteins that make up the capsid must form twelve perfectly placed defects, much like the twelve black pentagons on a traditional soccer ball. There are so many ways for this structure to go wrong, so how is it able to go right? Or, as Manoharan puts it, “how does the virus know where to put

the defects?” For systems with a huge number of degrees of freedom, like a folding protein or an assembling capsid, there are a nearly infinite number of incorrect configurations available, but somehow, these systems find the correct one.

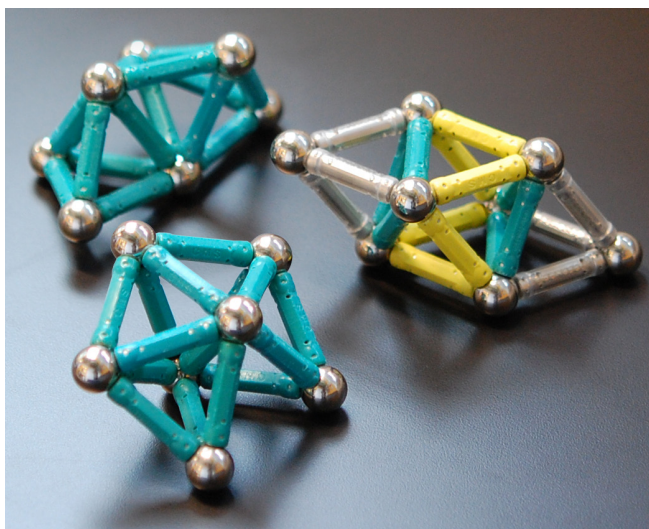
To understand how this happens, we need to observe the capsid as it assembles and rearranges itself in solution. The challenge is the length scale. Because our viruses are much smaller than the wavelength of light, observing them in action is not as simple as putting the components under a microscope and watching as they put themselves together. While it is possible to see the viruses in incredible detail with an electron microscope, we wouldn't be able to see any of their dynamics. They'd be frozen in place.

As small as they are, however, viruses can still scatter light, and as a capsid grows during assembly it will scatter more and more. Using a technique called interferometric scattering microscopy, we look at the interference between this scattered light and a weak reference beam to trace the size of individual viral particles as a function of time. With this method, we've been able to determine how MS2 assembles: very slowly at first, then rapidly after overcoming a nucleation barrier.

The results of these experiments have opened more questions than they have answered. We've found that it only takes a few properly aligned proteins to start rapid growth, and after the capsid reaches that critical size it grows to completion, without backtracking to correct for errors. We still don't know how it avoids errors, but one possibility is that the virus's own RNA guides the assembly process.

That hypothesis raises a related question: how does the virus assemble so reliably around its own RNA, when its host cell is full of other RNA that the cell needs to function? Tim Chiang, a fifth-year graduate student, is working to answer this question. “The virus's task is like finding and isolating needles in a giant haystack,” says Chiang. Understanding how viruses successfully carry out this task could lead to developments in medicine and self-assembling biomaterials further down the road.

In his experiments, Chiang has been able to control the self-assembly of MS2 to selectively package its own RNA, as it does in a cell. He now wants to understand what fundamental characteristics of the coat protein and RNA allow for this selective packaging. MS2 coat protein can form ordered capsids around any RNA molecule of a reasonable size, so how can it reliably encapsulate its own RNA while avoiding cellular competitors? Chiang hypothesizes that the energetic barrier to viral self-assembly could play a role by preventing self-assembly



Attractive colloidal particles form clusters whose structures can be controlled by introducing DNA-mediated specific interactions. These structures can be modeled using the magnetic sticks and balls shown here.

from initiating on random molecules. “This is one example of an intriguing possibility—that biomolecules have evolved according to the rules of fundamental physics to perform increasingly complex tasks,” he says, “to a point where their collective behaviors represent those of living things.”

Colloids: atomic “spherical cows”

Stop us if you’ve heard this one before: When plagued by low milk production, a dairy farmer asks a local university for advice. Failing to get any help from the ecologist or the engineer, he turns to the physicist. Weeks and weeks of calculations later, the physicist returns with a solution! But it can only work for a spherical cow suspended in vacuum.

This joke highlights the tendency of physicists to abstract. When faced with a messy system, we simplify the components until we’re left with a model we can work with. For questions of self-assembly, one such model system is a colloidal suspension. While not in a vacuum, the simplest colloids are indeed spheres, around a micrometer in diameter, suspended in a fluid. Milk, in fact, is a colloidal suspension of blobs of fat, and it is light scattering from these suspended particles that gives milk its white color. Colloidal suspensions are useful model systems because they’re both controllable and large enough to easily image. If we can induce some kind of interaction between these small spheres, we can then study them as though they were big atoms, big proteins, or big molecules, and watch as they put themselves together in interesting ways.

Researchers have gotten creative in devising controllable interactions between colloidal spheres, taking inspiration from biology and using strands of DNA to make the spheres stick together. DNA is famous for its double-stranded helical structure that forms only between complementary sequences. By coating the spheres with complementary strands of DNA, we can make the colloids sticky—when the spheres come close enough, the DNA strands on one surface zip together with the complementary strands on the other, like selective, programmable Velcro. But because these interactions are highly dependent on temperature, the DNA acts like a special kind of Velcro that zips together when it’s cold and melts away if it gets too hot.

DNA-coated particles offer an enormous range of possibilities for bespoke self-assembly. Imagine a system where each particle sticks only to certain other particles. When you mix them together, the particles arrange and rearrange themselves until they finally find the structure you want. Instead of building such a structure up block by block, you can make the particles do the work for you and self-assemble into your desired configuration.

It’s important to remember that the colloidal particles aren’t cleverly coordinating amongst themselves to create the final structure. Rather, they’re lumbering along in random Brownian motion until they manage to find the free energy minimum that we initially design the system to have.

One way to add complexity to the system is by introducing additional strands of DNA to the solution. We can add strands that can disrupt the stickiness between particles by binding to the single strands, or strands that can strengthen the stickiness by forming an additional reinforcing beam between two strands. With control over these additional DNA strands in solution, we could take a system that is predetermined and static and make it more adaptive and more responsive to its environment.

Colloidal particles are not just controllable, though. They are also, in the grand scheme of things, large. Large enough that we can directly image the particles coming together, that is. With a light microscope, we can directly observe every step of the assembly process in three dimensions, which is not so easy to do for atomic crystallization or protein folding. For third-year graduate student Jessica Sun, this feature is crucial for answering a deceptively simple question: how does a crystal change when its substrate isn’t flat, but instead has some curvature? “Almost everything in our world has curvature, either macroscopically or microscopically,” says Sun, “and this curvature can have a huge impact on the formation of structure.”

Consider, for example, trying to gift-wrap a ball. As Sun explains, “the gift wrap always has to crinkle.” That happens because the curvature of the ball is incommensurate with the flat plane of the wrapping, and therefore the wrapping must tear or deform to conform to the surface. “The same thing happens when you have crystallization on a sphere. There are going to be defects,” Sun adds.

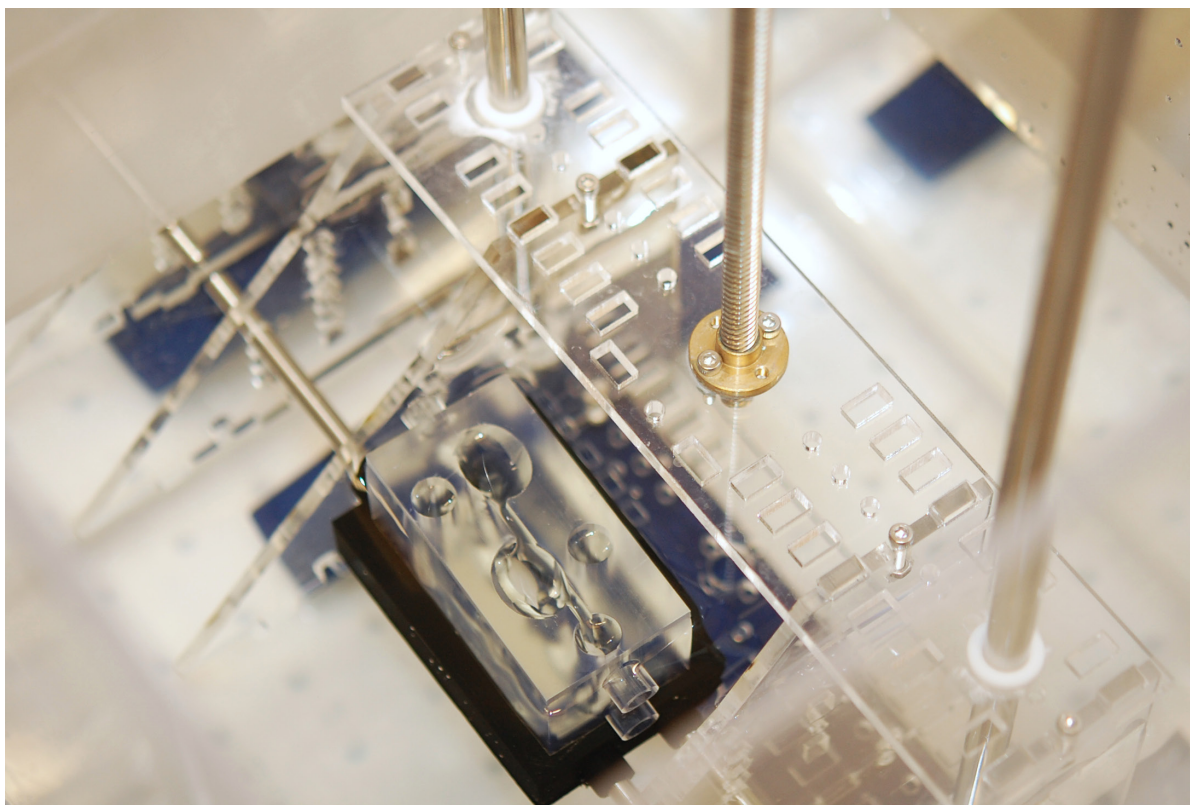
Even when we imagine a different kind of curvature, like a cone or a cylinder, the structure still determines the kinds of defects we observe. When wrapping a cone, for example, the strip of paper may lie flat, but once you bring the two ends together, you’ll see that the pattern on your wrapping paper will not perfectly match up. For crystal growth, this rotation of crystal orientation means that there will be some incompatibility when the growth fronts meet, resulting in interesting regions of defects.

“When I first started working on this project, I was sure it would be a simple one,” Sun remarks. “Cones are one of the basic shapes you learn in elementary school, so how hard could they be, right? But I’m continually surprised by the rich physics in this simple problem.”

Assembly in action

Colloids are more than just a model system. They can also be used as building blocks for designable, self-assembled materials, like Legos that can put themselves together. One such designable feature of these materials is their color. For colloidal systems, color can arise from light scattering and interference, rather than from absorption by chemical dyes. It’s like constructing a house from colorless blocks and realizing that the finished product somehow looks blue.

“Structural color exists in all kinds of biological systems,” says sixth-year graduate student Annie Stephenson, “from beetles to butterflies to bird feathers.” Many of the most vivid colors of nature come from some nanoscale structure rather than from traditional pigment. These nanostructures can be crystalline (which creates an angle-dependent, iridescent effect) or disordered (which creates a color that remains consistent regardless of your viewing angle). In our group, we’ve taken inspiration from the cotinga, a bright blue bird whose color arises from the close, random packing of air pores within the small-scale structure of the feather. The packing of these spherical bubbles can be mimicked with colloidal spheres, resulting in the same angle-independent blue shade.



An apparatus built by Ahmed Sherif to manipulate millimeter-scale objects at the interface between air and water.

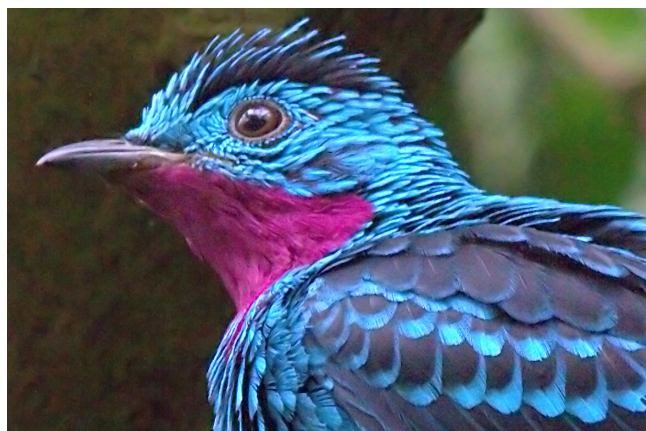
Structural color has far-reaching applications, including cosmetics, paints, and displays, which all require colors that appear the same regardless of the angle you're looking from. To achieve this consistency, our lab focuses on understanding how to use disordered packings of colloids to produce colors. As postdoctoral fellow Ming Xiao explains, "we can control structural colors by tuning how the colloidal particles pack." By altering the volume fraction, we can change the spacing between the spheres, change the way the structure scatters light, and thus change the color of the sample. We can even dynamically change the color by using an external stimulus to stretch or compress the sample and thus change the particle spacing. "It's similar to the way that cephalopods can change their skin color and texture," notes Xiao.

Structural color is particularly appealing because it allows flexibility in our choice of the constituent material. Because the structure itself provides the color, we aren't confined to a particular dye or chemical to provide a pigment. This means we're free to design a material to be biodegradable, biocompatible, or more environmentally friendly. As second-year graduate student Jennifer McGuire explains, "we're inspired by nature for these systems, but we are not confined to what nature does. The goals we have for materials can be very different from how evolution drives things."

An essential tool in this design process is an accurate predictive model for the color of a particular sample. With a Monte Carlo model developed by our group, we can simulate the path of thousands and thousands of photons traveling through the material. We can predict which photons will scatter back to our eyes and determine the color of the sample for a given set of experimental parameters. We can even optimize for a particular color and determine how best to make it. "It's so exciting to be able to accurately and quickly predict the connection between color and structure. That's a really powerful design tool," says Stephenson. "Now that we have such a good model for structural color," adds McGuire, "we're exploring more and more applications, and heading beyond the visible spectrum."

We're also heading beyond the microscopic. One of the newest members of the group, second-year graduate student Ahmed Sherif, is working on ways to assemble much bigger objects. He takes advantage of capillary forces, which arise from the surface tension of a liquid interface.

You may already be familiar with one effect that arises from capillary forces. If you've ever glanced at an almost-empty bowl of Cheerios during your morning breakfast, you might have



The spectacular plumage of a male spangled cotinga. Photo by Greg Hume.

noticed that the remaining pieces of cereal floating in the milk tend to clump together. This phenomenon, called the Cheerio effect, occurs because of surface tension; the cereal deforms the surface of the milk, and that deformation is reduced when the cereal pieces are touching, driving the lone pieces together into bigger clumps.

It turns out that capillary forces can be repulsive too. Sherif likes to demonstrate this by showing a video of a bowl of milk with Cheerios and a (somewhat less appetizing) pushpin floating nearby. The pushpin is repelled from the Cheerios because, as Sherif explains, "it pulls the interface down while the Cheerios bend it upwards." As a result, when the pushpin approaches a Cheerio, the interfacial area must increase, creating a restoring force.

Sherif wants to use the gentle push and pull of these forces to build structures from millimeter-scale objects. He does this by mixing floating objects of different wettabilities, shapes, and weights at a liquid interface. It's not unlike the approach the lab takes with DNA-coated colloids: in both cases, we use a diversity of interactions to drive assembly of complex structures.

However, the physics is different when menisci are involved. "That's both a challenge and an opportunity," says Sherif. Phenomena like contact-line pinning and contact-angle hysteresis complicate the task of assembling objects at a liquid interface, but they also open many possibilities for making new interactions. We're just starting to explore what those possibilities are, and how they might lead to different types of assembly from what's currently possible at the nanometer (virus) scale or micrometer (colloid) scale.

Scientific progress: a random walk?

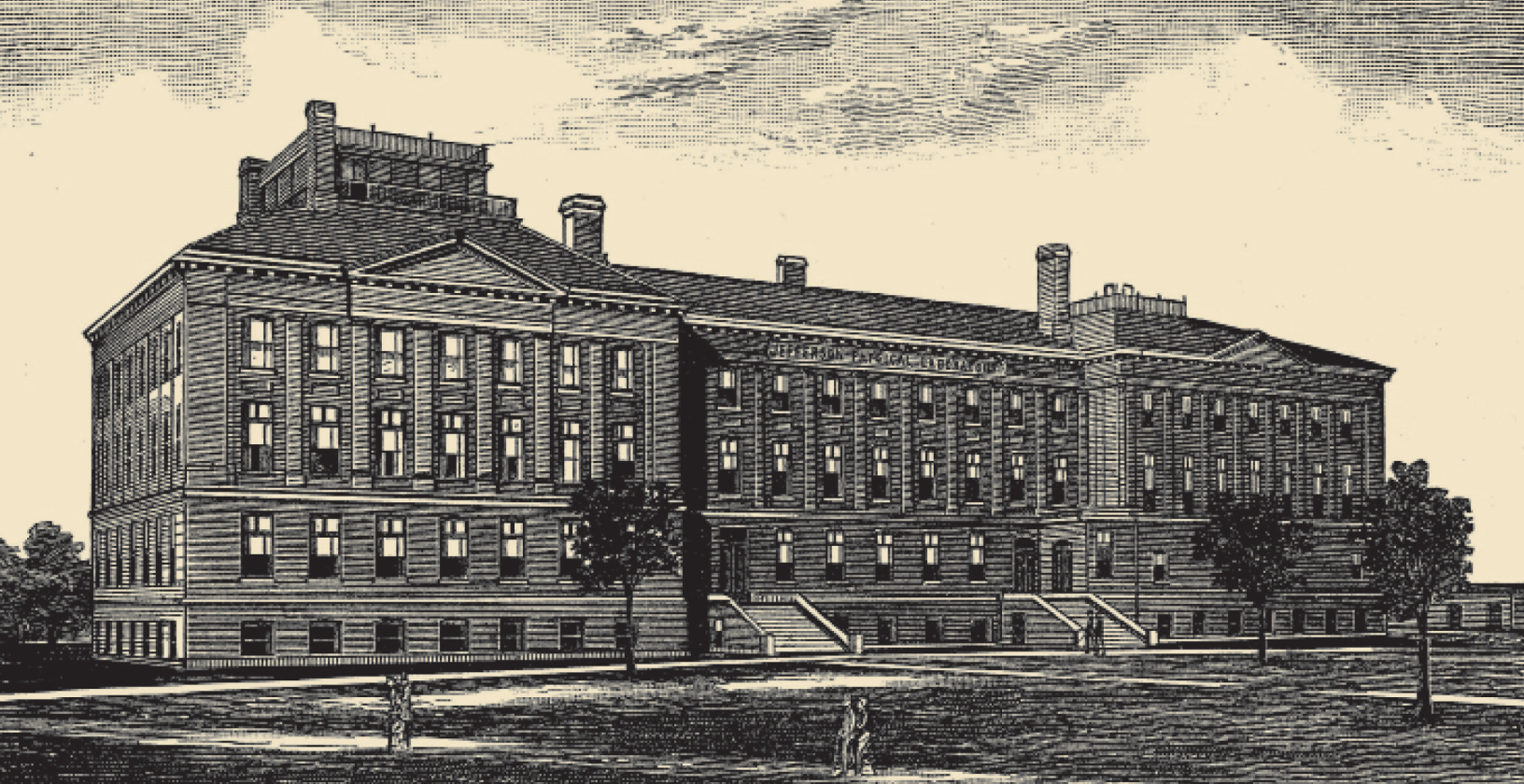
“When I started at Harvard, I never thought my group would be working on systems whose sizes span six orders of magnitude,” says Manoharan. “In those days, we did experiments on colloids. Now we work with viruses, DNA, microfabricated cones, and cereal-sized chunks of matter.” The lab hosts a motley array of tools to study all these systems. A holographic microscope that can detect the nanometer-scale movements of colloidal particles sits not too far from a shaker used to grow bacteria and the viruses that kill them. In the corner sits a 3D printer used to make the aforementioned cereal-sized chunks. And that’s just the hardware. “I guess I’m

more surprised that simulations have become such an integrated part of our research” says Manoharan, “but we go where the science takes us.”

With support from the department, collaborations with other groups, and inspiration from our fellow students, Harvard makes it easy for us to follow the science. The path is a winding one, and at times our exploration may feel like a bit of a random walk. But we aren’t lumbering along in aimless Brownian motion; we’re purposely chasing down the next discovery, wherever the science leads.



Annie Stephenson and Jennifer McGuire design and fabricate structurally colored materials inspired by nature. The vivid blue and green within the test tubes come from the microscopic structure of the sample.



TESTING EINSTEIN'S PREDICTION: The Pound–Rebka Experiment

by Paul Horowitz

Monday, January 24th, 1960: Robert Pound was worried. The previous night's data – the first with the fully configured experimental setup – had seemed to agree with Einstein's prediction, made a half century earlier, the only one of the famous three^[1] that had stubbornly resisted experimental confirmation. But, having worked through the night, the exhausted professor and his student Glen Rebka realized, with chagrin, that the more recent measurements were wandering, that “something not under our control seemed to be interfering with the system, and we had no idea what it could be.”^[2]

[1] These are (1) the precession of the perihelion of Mercury, which deviates from the classical prediction by about 8% (43 arc-sec per century); (2) the bending of light in a gravitational field; and (3) the shift of color of light as it moves toward or away from a gravitating body. The first of these was known when Einstein formulated his theory of general relativity. The second (1.75 arc-sec deflection of starlight grazing the sun) was first tested during a solar eclipse on May 29, 1919, with subsequently improved observations in the decades following; it is responsible for the phenomenon of “gravitational lensing.” The third prediction—the “gravitational red shift”—was long considered beyond the possibility of laboratory measurement, amounting to only one part in 10^{16} per meter of height.

[2] As related in Pound's delightful account “Weighing Photons, I,” *Phys. perspect.* 2, 224—268 (2000).

Setbacks like this are the stuff of experimental science; understanding experimental flaws, and overcoming them, gives joy to scientists.

But Pound was scheduled to give an invited talk one week later, at the annual American Physical Society meeting in New York, at which he hoped to report on this brave experiment. And, as luck would have it, a competing group from England had rushed in with a post-deadline talk to report their experiment's preliminary results. The image of the dispassionate scientist overlooks the reality of human ambitions.

The Gravitational Red Shift

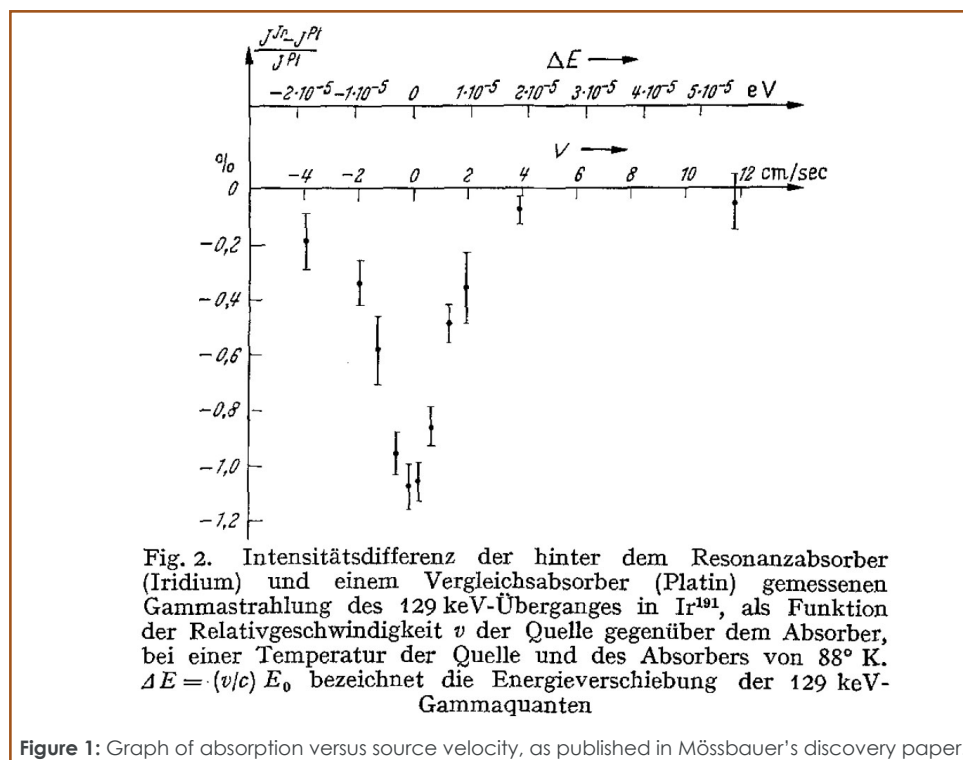
Rewind fifty years: Einstein contributes a lengthy review article titled “On the Relativity Principle and the Conclusions Drawn from It,”^[3] in which he reviews his theory of (special) Relativity, but with an added section introduced this way: “A further question suggesting itself is whether the principle of relativity is limited to nonaccelerated moving systems. I added to the present paper a fifth part that contains a novel

consideration, based on the principle of relativity, on acceleration and gravitation.”

His “novel consideration” begins with the bold assumption of “the complete physical equivalence of a gravitational field and a corresponding acceleration of the reference system.” This is helpful, he tells us, because “it permits the replacement of a homogeneous gravitational field by a uniformly accelerated reference system, the latter case being to some extent accessible to theoretical treatment.”

If you're OK with this “Equivalence Principle,” the rest is clear sailing: imagine a photon of frequency f falling through a height h on Earth; it arrives $t=h/c$ seconds later. Now, following Einstein's recipe, replace gravity with a rocket with acceleration a equal to g . During the photon's time of flight the rocket acquires velocity $v=gt=gh/c$, which causes a first-order (classical) fractional Doppler shift of v/c ; i.e., the frequency of the received photon is $f'=f(1+gh/c^2)$.

That's the gravitational red shift.^[4] It's a really small effect, just 3.5×10^{-14} for a photon scaling the Eiffel Tower. Such precision



[3] *Jahrbuch der Radioaktivität und Elektronik*, 4, 411–462 (1907).

[4] Nicely derived in A. Einstein, “On the Influence of Gravitation on the Propagation of Light,” *Annalen der Physik*, 35, 898–908 (1911). English translation found at <https://einsteinpapers.press.princeton.edu/vol3-trans/393>. Interestingly, in that paper he used only the equivalence principle (i.e., gravity vs. acceleration), which gives the correct result for the redshift, but only half the correct result for starlight deflection. He corrected this error in a 1915 paper.



Figure 2: Pound (center) speaking with J. B. H. Kuper via his cavity-stabilized X-band (10GHz) klystron oscillators, stable enough for frequency-modulated audio communication. Henry Torrey (of the NMR-discovery trio, see the 2019 Physics Newsletter) stands mute at the right. (Photo from “Five Years at the Radiation Laboratory,” M.I.T., 1946).

was considered beyond the realm of possibility – so Einstein calculated instead the reddening of a solar photon,^[5] getting $f' = f(1 - 2 \times 10^{-6})$.

Astronomical attempts to measure solar redshifts were generally unsuccessful, owing to large offsets, line broadening, and Doppler shifts caused by turbulent motion of the emitting regions, along with the effects of pressure and temperature.

As far as the possibility of a terrestrial (laboratory) measurement, the best frequency standards were inadequate by many orders of magnitude. As late as 1955, for example, the first atomic beam apparatus (an “atomic clock”) was built by Zacharias; it had a short-term stability of a part in 10^9 , some five to six orders of magnitude poorer than required to measure, even approximately, the redshift from a structure as tall as the Eiffel Tower.

And thus things stood until 1958.

Enter Rudolf Mössbauer

In a surprising paper,^[6] the German physicist Mössbauer reported a sharply defined resonant absorption of gamma rays, emitted by nuclei in the excited state of iridium-191, by a foil of the same isotope. Resonant absorption was a well-known phenomenon in optical spectroscopy (where photon energies

are around an electron-volt), but at gamma-ray energies (129keV in this case) the recoil of the emitting nucleus reduces the gamma energy (Doppler effect); and the analogous effect in an absorbing atom further separates the lines. The newly-discovered “Mössbauer Effect” circumvented this resonance shift by transferring the recoil momentum to the atomic lattice as a whole, thus the term “recoilless resonant scattering.” Figure 1 reproduces Mössbauer’s measured absorption versus imposed velocity of the emitter, thus tracing out the resonance width; the resonance is sharp, with a full-width to half-maximum of about 10^{-10} .

In the fall of 1959, Pound’s student Glen Rebka learned of Mössbauer’s work, and proposed a program of measurements of possible hyperfine structure. Pound had other ideas – he (along with colleagues like Zacharias at M.I.T.) had been pondering the use of stable atomic clocks to test Einstein’s redshift (Zacharias was thinking of a pair of clocks, on a Swiss mountain and valley; but his cesium-beam clocks were not yet good enough). The quest for stable oscillators had been a persistent theme in Pound’s career: during his wartime radar work at M.I.T. he had developed a cavity-stabilized klystron that allowed FM communication at audio frequencies (see Figure 2); and around this time he devised an NMR-stabilized oscillator.^[7]

[5] For the general case of nonuniform gravitational field, substitute the gravitational potential difference for gh .

[6] R. L. Mössbauer, “Kernresonanzabsorption von Gammastrahlung in Ir^{191} ,” *Die Naturwissenschaften*, 45, 538–39 (1958).

[7] “R. V. Pound and R. Freeman, “Frequency Control of an Oscillator by Nuclear Magnetic Resonance,” *Rev. Sci. Ins.*, 31, 2, 96–102 (1960).

So Pound wanted to exploit the resonance of unprecedented sharpness to test the last unconfirmed prediction of Einstein. Here we let him tell the story:

When I saw Glen that morning, I described what I had read [about using masers to test General Relativity] and again expressed the feeling that one ought to be able to use this new gamma-ray resonance for such tests. As we talked we suddenly realized a test of the “gravitational red shift” couldn’t be simpler, and I think Glen saw it first. By simply separating the source of the gamma rays from the resonant absorber by a vertical path, the gravitational potential difference... should lead to a measurable displacement of the resonance.

The Experiment

Were that “it couldn’t be simpler”! Consider this: exploiting the full height of Jefferson Laboratory’s isolated tower (Figure 3, an architectural feature incorporated seventy five years earlier in anticipation of sensitive physical measurements), the magnitude of the redshift would be just 2×10^{-15} , so you’d need precision of a part in 10^{16} to measure it with just modest confidence. That’s six orders of magnitude smaller than Mössbauer’s measured resonance in iridium!

Pound and Rebka quickly identified the stable isotope Fe^{57} as a better candidate than Mössbauer’s cryogenic iridium – the lifetime of its Co^{57} parent was nearly a thousand times longer ($0.1\mu\text{s}$, versus 0.14ns), thus promising a far narrower (lifetime-limited) resonance; and its gamma energy was an order of magnitude lower (14.4keV , versus 129keV), favorable for improving the fraction of recoilless decays (by depositing more of the recoil energy in the lowest phonon mode, i.e., motion of the lattice as a whole). With luck it could be even used at room temperature.

The duo set to work, and, with help from M.I.T. nuclear physicist Lee Grodzins, they obtained a few millicuries of isotopically pure Co^{57} and a suitable scintillator detector. Glen learned to roll thin foils of iron absorber, and to electroplate the precious cobalt onto an iron substrate, followed by annealing to diffuse it into the lattice. Initial measurements showed a satisfyingly narrow and deep resonance – a line width of a part in 10^{12} (somewhat larger than theoretically possible) and a recoilless fraction of 80%. And this did not require Mössbauer’s cryogenic environment – it was done at room temperature.

The way was now clear to attempt to measure Einstein’s effect. Pound and Rebka published their Fe^{57} results,^[8] with the

comment “We are now confident that we can perform the gravitational experiment inside the laboratory using this γ -ray from Fe^{57} .”

The Hard Work

Confidence is one thing. Designing, building, debugging, and properly interpreting the results is quite another – and there are many ways to do an experiment wrong. The successful execution of the Pound-Rebka experiment is a textbook example of experimental brilliance and attention to detail. Particularly so since their measured Fe^{57} resonance width was

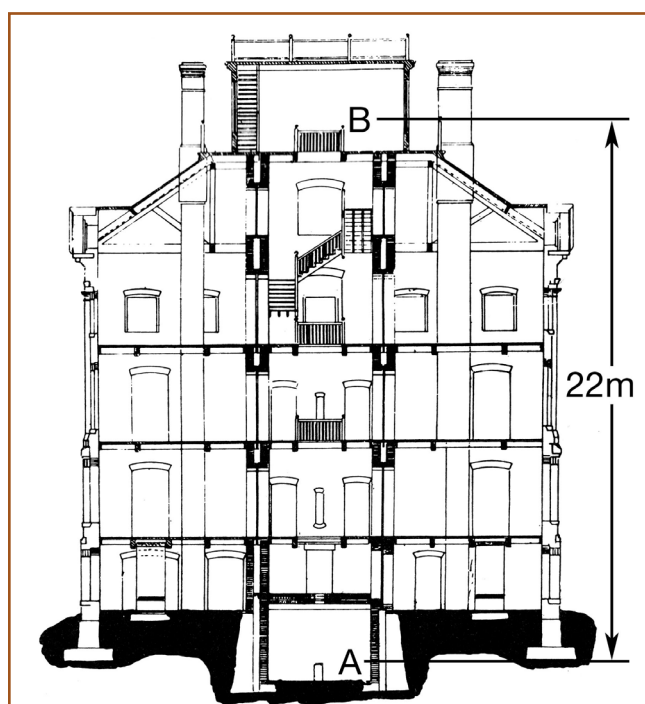


Figure 3: Cutaway diagram of Jefferson Laboratory, showing the approximate location of source/detector pairs (A and B) used in the redshift experiment. The top level is currently a penthouse “thinkatorium” for the 4th-floor theory group. The sub-basement had been the target area for the ball-dropping experiments of Edwin Hall (of Hall-Effect fame), and subsequently became Wallace Sabine’s original reverberation chamber. Sabine was asked by the President and Fellows of Harvard College to fix the poor acoustics of the new Fogg Lecture Hall. He determined, through an exhaustive set of acoustic measurements, the ideal reverberation time for concert halls (he was the acoustical consultant for Boston’s exemplary Symphony Hall) and for lecture halls. The Fogg reverberated for about 5.5-seconds, about six times longer than optimal. Sabine is generally credited with founding the field of architectural acoustics; the unit of absorption is the Sabin. (Figure from Rebka thesis, 1961)

[8] R. V. Pound and G. A. Rebka, Jr., “Resonant absorption of the 14.4-keV γ from $0.10\text{-}\mu\text{s}$ Fe^{57} , *Phys. Rev. Lett.*, 3, 12, 554-56 (1959).

10^{-12} – a hundred times better than that of Mössbauer’s discovery paper, and the narrowest resonance by far, at the time – but the predicted redshift up or down the 22m Jefferson tower was just 2 parts in 10^{15} . Measuring a shift that’s 500 times smaller than the line width (and doing it to, say, 10%) is asking for trouble. And this experiment delivered trouble, on both shores of the Atlantic.

The best way to measure a small shift is by “slope detection” (Figure 4) – deliberately offsetting the resonance (via an imposed velocity’s Doppler shift) to compare the absorption near the inflection points. Pound and Rebka experimented with both magnetic and piezoelectric transducers, choosing the latter, which oscillated the radioactive source at 50Hz with a peak velocity of $\sim 1\mu\text{m/s}$. The frequency was chosen to stay below mechanical resonances, but high enough to stay clear of “ $1/f$ ” noise and system drifts. The detected gammas were gated to a set of pulse counters, according to the phase of the oscillatory motion, performing “synchronous detection” of the resonance line offset.

But we’re only beginning – this was just the inner layer of what could be described as a nested set of three synchronous detectors. Next was a hydraulic piston that imposed a precise back-and-forth calibration velocity ($\pm 0.634\mu\text{m/s}$ – just a wavelength of light per second, enough to produce a Doppler shift approximately equal to the predicted redshift), with a 10-minute-long periodicity.

What could possibly go wrong? Plenty: there was no assurance that the source and absorber did not suffer from a congenital resonance offset. It would take an offset of only 0.2% of the line width to completely wipe out the predicted redshift signal. To address this possibility, the entire experiment was periodically inverted: the source (with its own

“monitor” channel) and detector, along with their accoutrements, were carried up and down the winding staircases. Figure 5 shows the experimental hookup as published in Rebka’s thesis.

Tuning It Up

It’s a long slog from conception to fully working experiment, filled with sleepless nights. There’s space enough here only to hint at the many tasks that had to be mastered – for example finding and preparing sources of isotopically enriched iron (Fe^{57} comprises only $\sim 2\%$ of natural iron) and of the Co^{57} parent isotope with substantial activity; arranging a hexagonal array of thin-crystal scintillation detectors and matching their sensitivities; boring a 2-foot hole through floors and ceilings and filling the resulting 22m path with a helium bag (because in air the gammas would be absorbed in just a few feet); building the (vacuum-tube!) electronics to do the modulation, switching, phasing, and signal routing; rigging up and calibrating the hydraulic motion system; and so on. Figure 6 is a photograph of Pound at the helm, illustrating a portion of the experiment’s complexity.

The Troubles

With the bugs shaken out by mid-January, and encouraging initial results with round-trip (i.e., accounting for system inversions) redshifts in the ballpark, Pound and Rebka expected to have preliminary experimental confirmation of Einstein’s prediction ready to report a week later at the New York meeting. But by the 24th (when this narrative began) the expected improvement from the statistics of additional runs was not in sight; quite the opposite – some runs produced wildly varying results. Something was wrong.

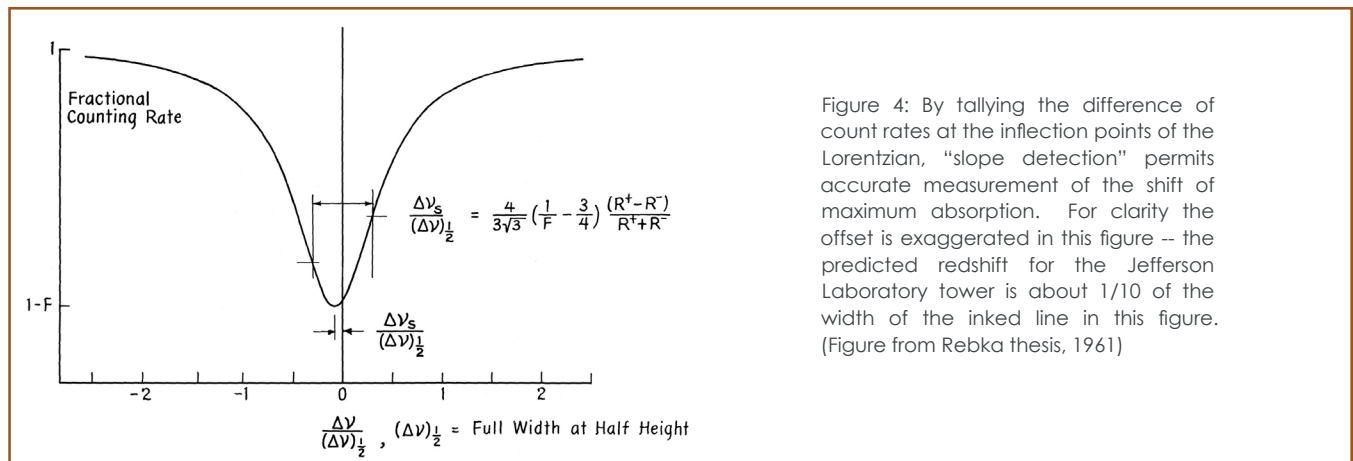
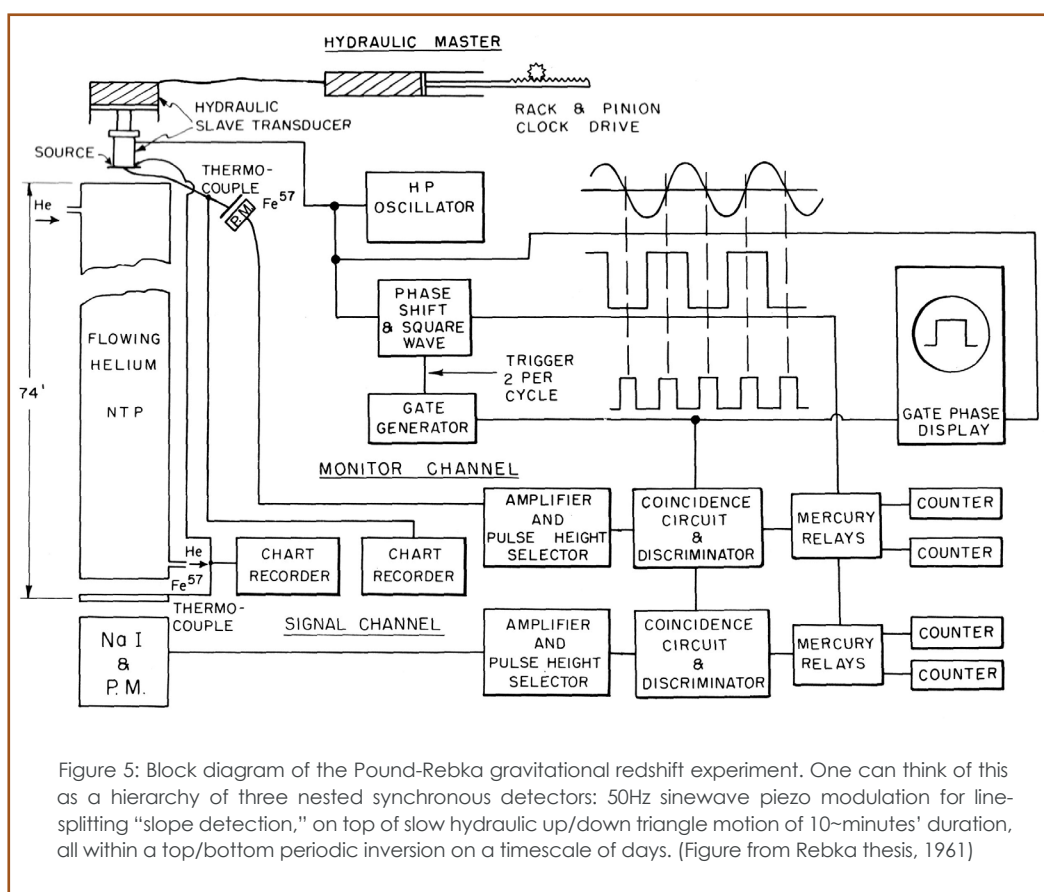


Figure 4: By tallying the difference of count rates at the inflection points of the Lorentzian, “slope detection” permits accurate measurement of the shift of maximum absorption. For clarity the offset is exaggerated in this figure -- the predicted redshift for the Jefferson Laboratory tower is about 1/10 of the width of the inked line in this figure. (Figure from Rebka thesis, 1961)



Being an extraordinarily careful experimenter, Pound, when he gave his APS talk a week later (demonstrating successful use of Fe^{57} and its narrow linewidth in the experiment), declined to report any conclusion about the redshift. The Harwell group from the U.K. also spoke, saying that more data was needed, but making the claim (from their preliminary data) that the chance of there being no redshift was less than one in sixty. For reasons that will become evident, their claim was without any foundation.

As sometimes happens, it’s the opportunity of explaining something to a student that clears one’s mental fog. Here’s Pound’s account of a chance encounter that unlocked the mystery:

One day, as frequently happened, an undergraduate student wandered into the room where the data was coming in and which I was evaluating, and he asked about how the experiment worked. I proceeded to tell him about it and explained how, in the Mössbauer effect, in spite of the presence

of large thermally-excited vibrations, there is no Doppler broadening because, over the time of emission, the net displacement, and so the average thermal velocity along a given direction of emission or absorption, vanishes. I added, “of course the mean-squared velocity doesn’t vanish.” I then added, “my word, what about the second-order (special-relativistic) Doppler effect?” I quickly jotted some numbers down for a quantity estimating v^2/c^2 , at room temperature, which would be of the order of kT/Mc^2 , where k is Boltzmann’s constant, T the absolute temperature, and M the atomic mass... No wonder we had instability, when this thermal effect of a one-degree temperature change should shift the frequency as much as the whole effect we sought.

In a remarkable convergence, a certain Brian Josephson at the University of Cambridge, hearing about the redshift experiments at Harwell and at Harvard, independently discovered this temperature effect (and by a quite different calculation), which he sent for publication in *Physical Review Letters*.^[9]

[9] B. D. Josephson, “Temperature-dependent Shift of γ rays Emitted by a Solid,” *Phys. Rev. Lett.* 4, 7, 341-42 (1960). Pound put in a transatlantic telephone call to Josephson (a big deal, in those days), but was told by the Porter at Trinity College that undergraduates were not allowed to receive telephone calls.

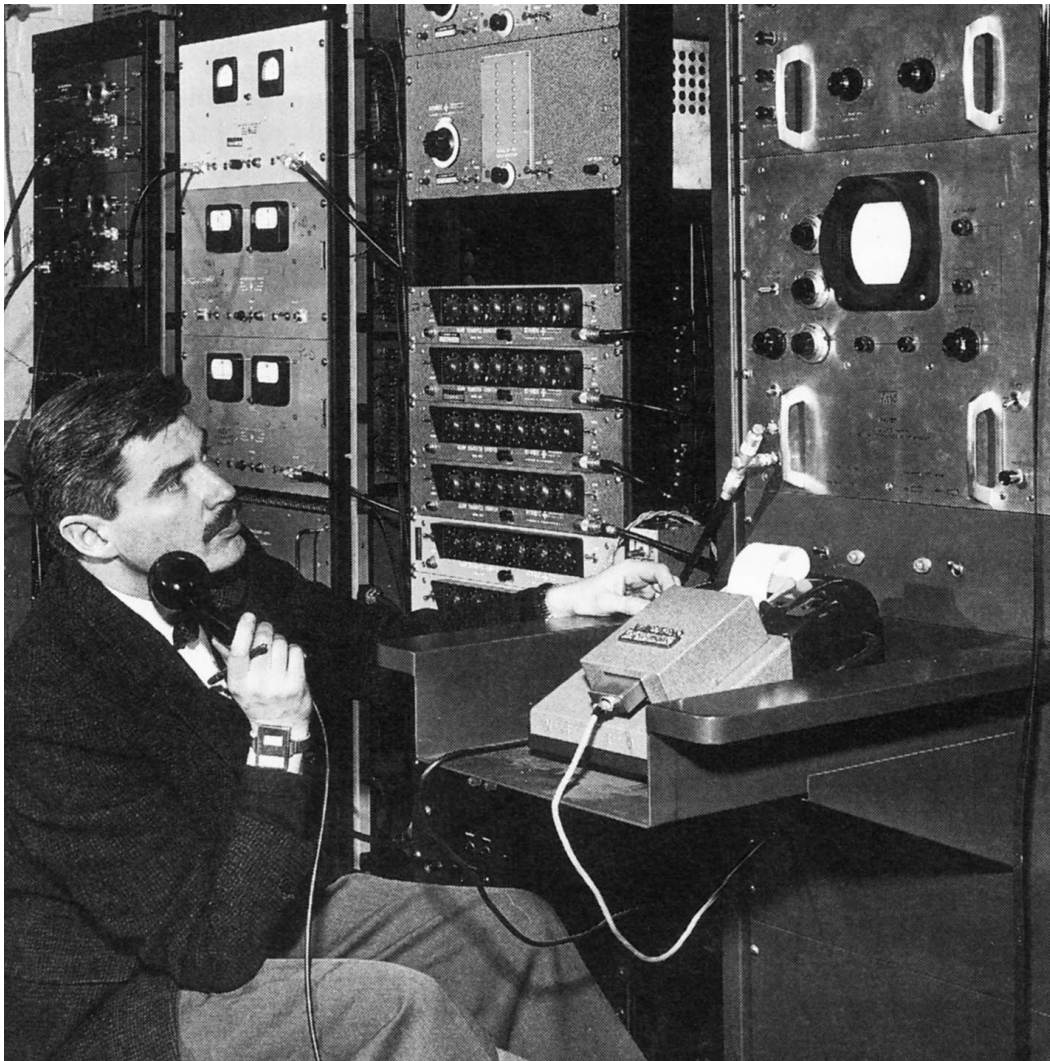


Figure 6: Pound at the 2nd-floor control area. Equipment in 1960 was large and slow: the two rack-mounted units above the printer comprise a 100-channel vacuum-tube pulse-height analyzer; the rack to its left houses a set of 6-decade “glow-transfer counters” that can run as fast as... 20kHz!; they are preceded by the two decades counters above, which can handle 1MHz. Farther to the left are power supplies and single-channel discriminators. (Photo: Harvard News Office)

Clear Sailing

As Pound relates in his “Weighing Photons” memoir, “This discovery was clearly the answer to our problem with the gravitational experiment, and looking at the data we had accumulated earlier, we now could see why there seemed to be almost a periodicity of two days or so in the shifts. Our penthouse temperature... was very closely coupled to the variable New England weather... It also seemed to us that the ignorance of the importance of this factor by the Harwell group rendered any conclusion based on the one-way measurement questionable.”

With the installation of thermocouples at both ends, the temperature effect was removed from further measurements, and, after a month of data accumulation, the duo was able to report^[10] that:

The shift observed agrees with -4.92×10^{-15} , the predicted gravitational shift for this ‘two-way’ height difference.

Expressed in this unit, the result is

$$(\Delta\nu)_{\text{obs}} / (\Delta\nu)_{\text{theor}} = +1.05 \pm 0.10$$

where the plus sign indicated that the frequency increases in falling, as expected.

[10] R. V. Pound and G. A. Rebka, Jr., “Apparent Weight of Photons,” *Phys. Rev. Lett.*, 4, 7, 337-41 (1960).

A contemporaneous page from Pound's notebook is reproduced in Figure 8, where the excitement of the normally placid professor is evident in the red-lined box.

Epilogue

In the years following, Joe Snider joined the experiment, modified in important ways to reduce systematic uncertainties and thus enhance the accuracy. In a pair of publications^[11] they reported “the result of the experiments on the full two-way baseline $2h$ of 44.96m is 0.9994 ± 0.0084 times the value of $2gh/c^2$.”

And with that, Einstein's gravitational redshift was confirmed to an accuracy of 1%.

In subsequent years the redshift was measured in other ways. In 1981 a group in Helsinki used the Mössbauer effect in Zn^{67} (half-life of 78 hours, fractional line width of 10^{15} , 600 times

narrower than that of Fe^{57}) in a 1m-path cryogenic experiment, demonstrating the shift versus angle with 5% accuracy. And in 1976 a hydrogen maser (invented by Ramsey, Goldenberg, and Kleppner at Harvard^[12]) was flown in a rocket to an altitude of 10,000km, in an experiment led by Robert Vessot at the Harvard-Smithsonian Astrophysical Observatory (and to which Pound made an essential contribution that eliminated errors from differential ionospheric delays of the transponder signals). Continuous tracking of the transmitted signal, combined with precise trajectory data, confirmed the redshift to an accuracy of 0.007%.^[13]

Recent experiments exploiting the stability of strontium optical-lattice clocks have confirmed the Einstein redshift to comparable precision (10^{-4}) over a *terrestrial* path^[14] of 450m (the Tokyo Skytree), and, in a stunning demonstration of the precision of such lattice clocks, the redshift over a mere one *millimeter* has been measured^[15] to some 20%. It seems incontrovertible that Einstein got it right.^[16]

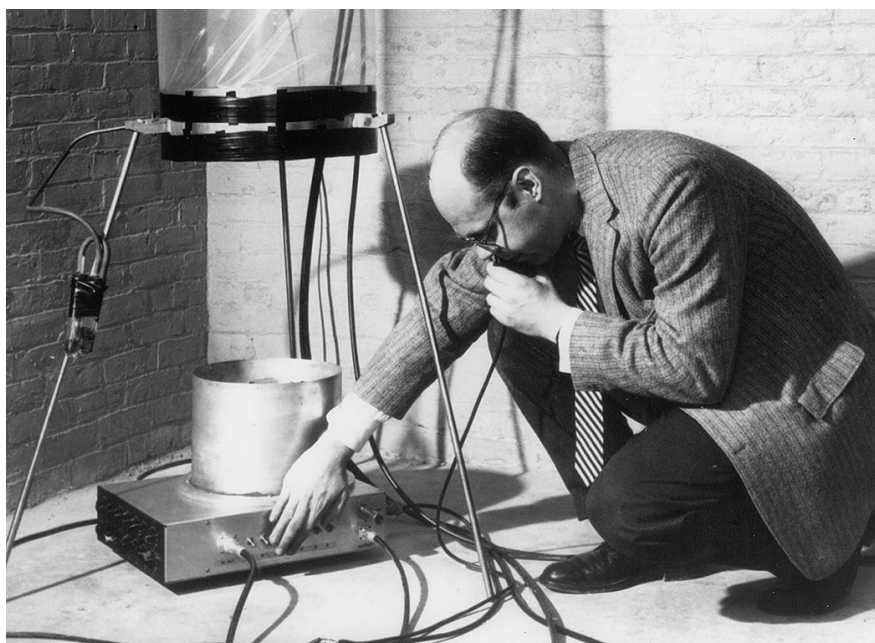


Figure 7: Pound's student Glen Rebka adjusting the scintillator array in the Sabine sub-basement of Jefferson Lab

[11] R. V. Pound and J. L. Snider, “Effect of Gravity on Nuclear Resonance,” *Phys. Rev. Lett.*, 13, 539-40 (1964); R. V. Pound and J. L. Snider, “Effect of Gravity on Gamma Radiation,” *Phys. Rev.*, 140, B788-B803 (1965).

[12] “H. M. Goldenberg, D. Kleppner, and N.F. Ramsey, “Atomic Hydrogen Maser,” *Phys. Rev. Lett.*, 5, 361-62 (1960).

[13] R.C. Vessot et al., “Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser,” *Phys. Rev. Lett.*, 45, 2081-84 (1980).

[14] Takamoto et al., *Nat. Photonics* 14, 411 (2020).

[15] Bothwell et al., arXiv:2109.12238 (2021).

[16] And to whom is indebted the global positioning system (GPS), whose operation requires appropriate corrections.

SOURCES AND REFERENCES

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

- G.A. Rebka, "Gravitational Shift of Frequency," Ph.D. thesis, Harvard University (1961);
- E.H. Hall, "Do Falling Bodies Move South?" *Phys. Rev.*, 17, 3, 179-90 (1903);
- Oral Histories at the American Institute of Physics (Niels Bohr Library and Archive);
- R.V. Pound's laboratory notebook 1959-60;
- helpful comments by Pound advisee Bill Vetterling, whose Ph.D. thesis was "Techniques for Improved Gravitational Red-Shift Measurements";
- and many delightful conversations with Robert Pound, my Ph.D. advisor.

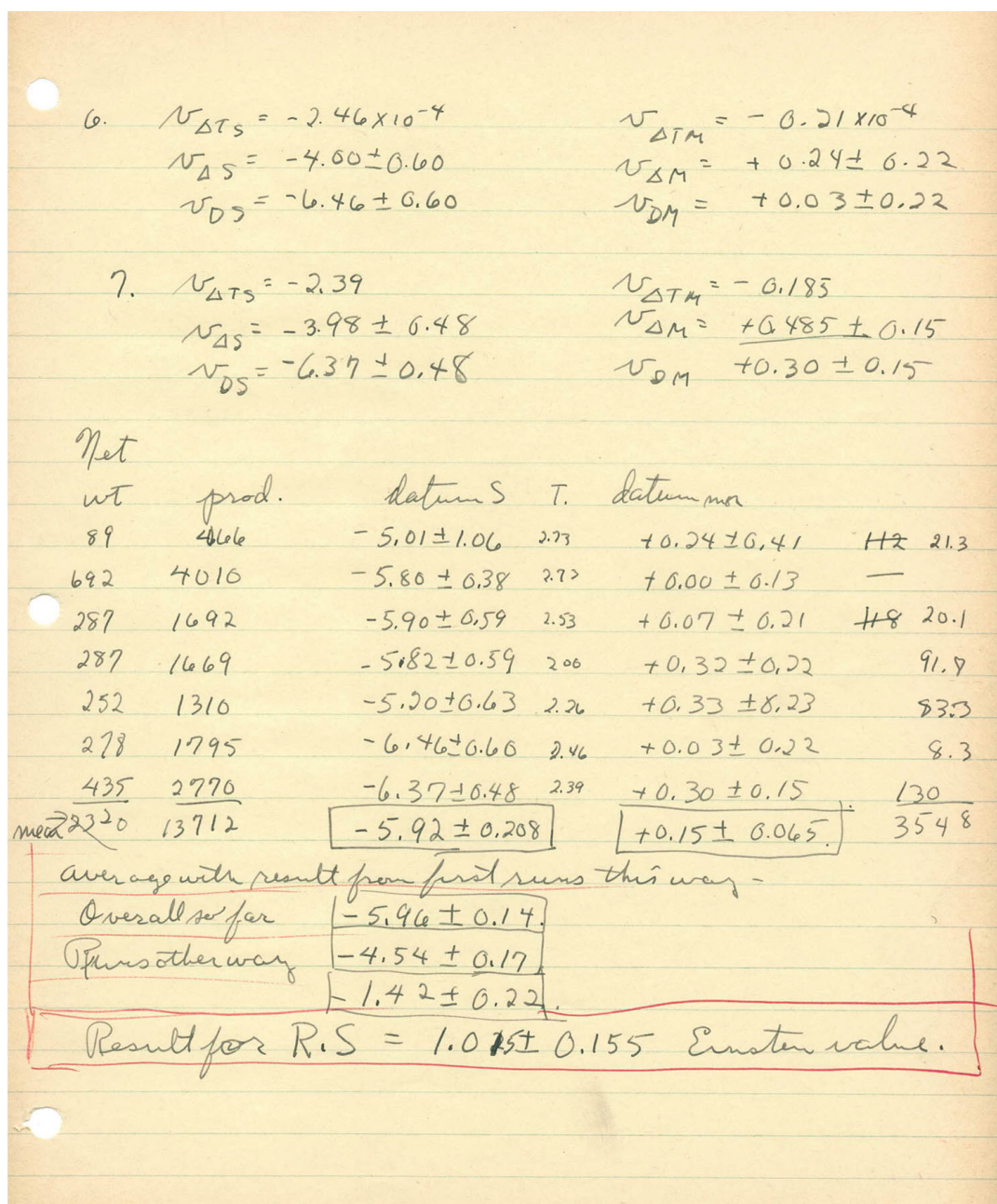
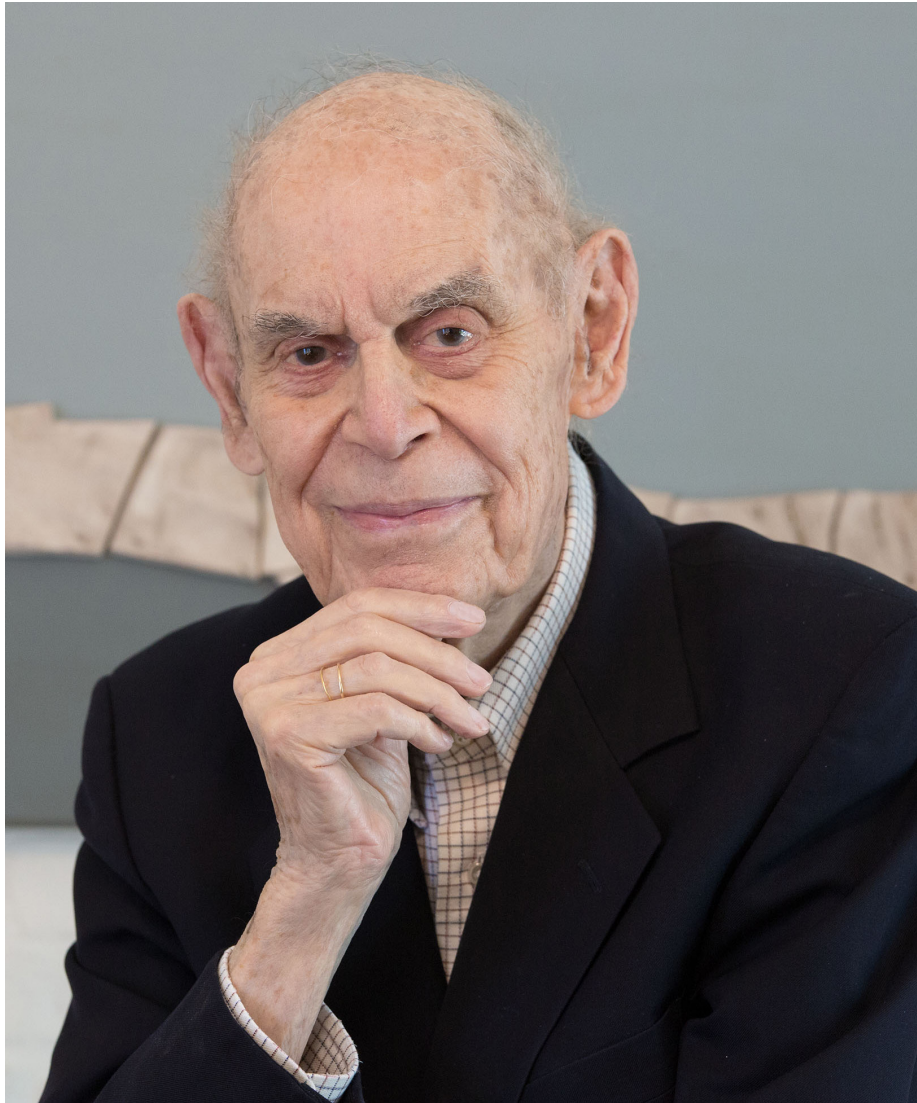


Figure 8: A page from Pound's notebook, with the first results of the temperature-controlled experiment. The bottom line summarizes (with barely concealed excitement): "Result for Red Shift = 1.015 ± 0.155 [of the] Einstein value."



An Afternoon with Gerald Holton

by Paul Horowitz

Photograph of Prof. Holton
by Paul Horowitz

On a lovely Saturday last May I had the pleasure of joining Gerry, at the large dining table in their elegantly decorated contemporary home near the Divinity School, for a wide-ranging conversation about Harvard's Physics Department – and the remarkable people who have contributed to it over time.

Just a week earlier Gerry had participated in a fine celebration of his upcoming 99th birthday, an occasion on which many of us learned of the varied intellectual threads in the tapestry of the man.

Gerry greeted me (still in COVID-style face-mask, but quickly unmasked) as we celebrated with appreciation the triumph of the novel RNA-based vaccines that had liberated both of us from a year of medical house arrest. Our conversation was old-school and technology-free: no recorder, just pen and pad. And an understanding that, in Gerry's diffident words, "we may try something while aware of its quite possibly not getting to anything useful."

Gerry launched right in, saying that the department "does not really know how good it is," and does not fully appreciate its heritage. It has a "magnificent balance" – of ages, interests, and of experimental and theoretical activities – to Gerry it is an exemplar of a great department. But it was not always that way: When Gerry came as a graduate student in 1945, it was called the "Spectroscopy Department"; five years later, in his words, "it was shooting for the moon."

How did this come about? In 1945 President James Conant returned from his wartime science role, where he had come to know amazing scientists (and non-scientists: a lunch with Churchill, and an audience with King George VI); his view of the Physics Department was that "more is needed." Within three years the department acquired Purcell, Ramsey, and Schwinger (thus the moonshot: NMR, atomic beam spectroscopy with separated oscillatory fields, and quantum electrodynamics). To Gerry this was one of the "jumps" in the department's history – somewhat analogous to the idea of punctuated equilibrium in biological evolution.

Another such jump had happened earlier in the century. Cambridge native Percy Bridgman (Holton's Ph.D. advisor, whose graduate school expenses had been secretly paid for by Physics Professor Wallace Sabine), a giant in high-pressure physics, became a full professor in 1919, with a vision to put the department on a higher level. In Bridgman's words, "the local and national mandate" was "to put Harvard pretty near the top in the country," and help "put this country on the map in theoretical physics." In 1919 (the same year that Arnold Sommerfeld published *Atombau und Spektrallinien*) Bridgman recruited Edwin Kemble to grow the department in the new theoretical areas of atomic structure, photoelectric phenomena, and radiation theory. To expand the Department also into frontier work on quantum physics, it tried to bring back the sensational young Robert Oppenheimer. Invitations went to

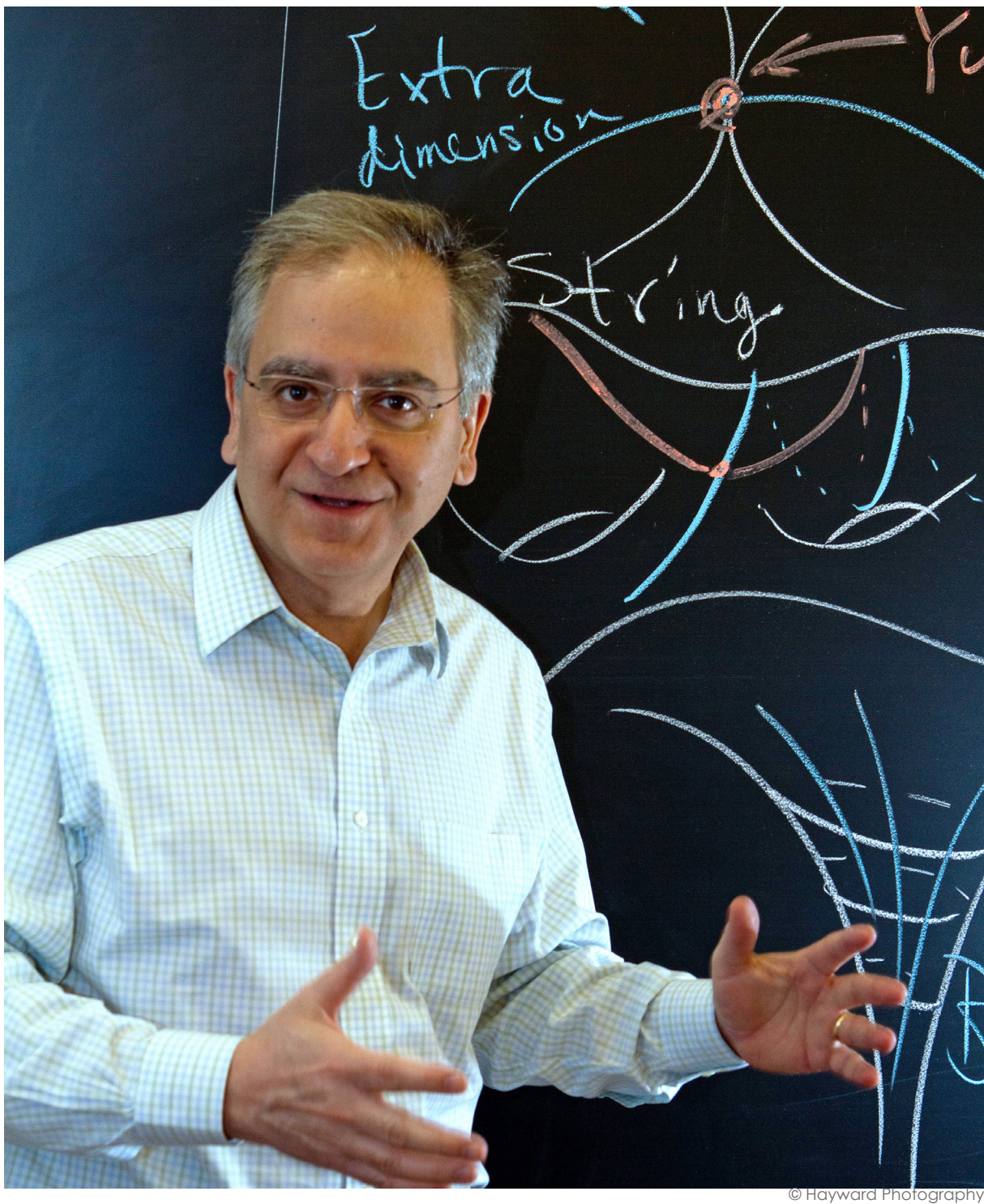
him from Bridgman, Kemble, Slater, even Theodore Lyman. But the offer did not include a promise of advancement, and what Oppenheimer received from sunny California did. Perhaps this taught the lesson that for a big target you need a big net.

Kemble had heard R. A. Millikan at a 1912 AAAS meeting, becoming excited about the "new European physics." Gerry related Kemble confessing "having fallen in love with anything that had h in it," and it was Kemble who brought quantum physics into the department. He taught quantum physics to Purcell, and his first graduate student was J. H. Van Vleck. Gerry knew Kemble well, and admired him greatly – both for his warm attitude toward others (his parents were missionaries, and he had been expected to follow), and for his energetic work on behalf of physics and the continuing growth of the department. In a poignant remembrance, Gerry related being at Kemble's bedside at his last breaths, at age 95. Lying there, with a strong voice still, Kemble repeated just one word: "yes, yes, yes..." To Gerry, this enigmatic statement meant "I was not privileged to be a preacher, but I did my part." Indeed, in his first three decades Kemble and his student had trained about one-third of this country's theoretical physicists.

What started Gerry's career at Harvard? He came to Cambridge in 1943, joining wartime work at Harvard's Electro-Acoustic Laboratory on noise suppression in aircraft communications (in spite of his designation as a German "enemy alien"); he also taught operation and repair of radar to Navy personnel.

With his background in acoustics, he looked into related graduate work, but found himself drawn to Bridgman. As Gerry put it (having discovered Bridgman's *Logic of Modern Physics* in the library) "I could not move, I had to read it through, standing up." Here was a physicist and a philosopher! This appealed powerfully to Gerry, whose broad secondary education at the Humanistische Gymnasium in Vienna had prepared him flexibly to enter a variety of professional fields. In his words, "it prepared me for more than physics – more like 'physics plus.'" And Bridgman's attitude toward his students – "let them do what they can do" – was congenial to the multitalented Holton.

What advice, from our colleague who has experienced 78 years of our department's history? Perhaps just the feeling, from the successes of previous "jumps" (there was another, in the 30's, with Oldenberg, Street, and Bainbridge), that one should not hesitate to inject an occasional big jolt of new talents. The integral of such a delta function creates a salutary step in an already-excellent department.



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CUMRUN VAFA: A Career Built on Strings

by Steve Nadis

As a student, Cumrun Vafa had a hard time choosing between physics and mathematics. It seemed to him that each of those disciplines, when taken alone, had their own peculiar drawbacks. It was not until he entered graduate school in the early 1980s that he discovered string theory, a subject where physics and mathematics came together in a natural way—one that he found pleasing, both intellectually and aesthetically. His earlier qualms and hesitance quickly vanished, and he has pursued string theory ever since, making major contributions to the field at many pivotal junctures. While some skeptics have attacked string theory, claiming that it is unfalsifiable and unable to produce any testable predictions, Vafa believes the field is strong, vibrant, and consequential. And if that view is correct, it is due in no small part to his steadfast efforts.

Although Vafa showed an aptitude for both mathematics and physics early in his childhood while growing up in Iran, it was not preordained that he would end up in either of those fields. Nevertheless, he displayed an inquisitiveness in his youth that may be common among those destined to become scientists. When he was in second grade, he remembers looking at the moon and wondering why it didn't fall down. He could see that streetlights were fastened to poles, but what was holding up the moon?

He was introduced to geometry in third grade and was taught that objects had height, width, and depth. "Why just those three things?" he wondered. "Why not more? Or less?"

When he was 12 years old, he was astounded to see an older cousin figuring out the trajectory of a projectile. "How could math possibly be powerful enough to enable a calculation like that?" he mused to himself.

In high school, he learned that atoms in the water molecule are connected with bonds that make an angle of 104 degrees. That number struck him as arbitrary, and he wanted to understand why it was not 90 or 180 degrees instead. "I tried to use my knowledge of geometry to answer that question," Vafa says, "but of course I got nowhere. Still, I got excited just by thinking about using my knowledge of geometry to answer questions in physics and chemistry."

His father pursued graduate studies in the United States—at Indiana University, in his case—and Vafa assumed that when the time came for him to go to college, he would study abroad as well. He was accepted at Harvard, even with a 320 on his verbal SAT scores, though he scored considerably higher in math. He considered it a great honor to get into Harvard, but he heard that the university was strong in the humanities. That could require a lot of reading in English, he surmised, which

was not his forte. Luckily, he got into MIT, which was his top choice, and he arrived there in the fall of 1977—a 17-year-old bent, for practical reasons, on majoring in engineering and economics.

Coming from Iran, he faced two problems early on. First, his command of the English language was definitely lacking, which meant he had a hard time following discussions—inside and outside of the classroom. His second challenge was adjusting to American culture. MIT was a coed school, whereas he'd attended a male-only high school. "The mingling of the sexes was unfamiliar to me," he recalls. "Also, in Iran, you don't randomly say hi to someone you don't know. For me, getting a casual hello from a classmate on one day, and then being ignored the next day, was very strange." He couldn't tell whether the person greeting him was a friend or not. In addition, it took him a while to adjust to MIT's culture, which he later realized was more eccentric than American culture in general.

Meanwhile, he was not thrilled with his courses in engineering and economics. In electrical engineering, for example, his professor presented rules for circuit design in the same way one might hand out a cookbook recipe. "I asked him why it works that way, and he told me you don't need to understand that to solve these problems," Vafa says. "I found that response very unsatisfactory."

In his economics course, he was frustrated by the "triviality of the math," as well as by the "lack of a moral compass." His professor asked the class to come up with strategies for dismantling OPEC—the Organization of the Petroleum Exporting Countries. That assignment bothered Vafa, who had come from a place where oil production was a source of national pride. "Why do you want to dismantle OPEC?" he asked. His professor told him to not worry about questions like that and just do the assignment. But Vafa didn't do the assignment and instead changed his mind about studying economics.

At the same time, Vafa was really enjoying the required introductory courses in math and physics—taking classical mechanics during the first semester and electricity and magnetism in the second. While at home in Iran during the summer of 1978, he told his parents of his confusion: "I seem to be liking math and physics courses a lot but dislike the things I thought I'd major in—economics and engineering."

His parents arranged for him to speak with a friend (Dr. Niazmand) who was considered a great patriot as well as the father of modern Iranian industry. Vafa explained his dilemma—the fact that he was interested in physics and math,

At that time, according to Vafa, “there was still some shyness in the physics community about using mathematical ideas. For many physicists, it seemed almost distasteful to use too much math.”

despite his sense that he couldn't do much with that training in Iran other than becoming a high school teacher. “You don't have to come back to Iran,” the friend told him. “You can do what you like.” Based on that advice, given by an esteemed Iranian patriot, Vafa decided to pursue a joint major in physics and math.

While his path had become considerably clearer, the matter of choosing between physics and math was still unsettled. Vafa found the connection between the two subjects interesting, though some of the issues in math struck him as less urgent. “If you wanted to prove certain theorems, you often needed to set some exotic conditions,” he notes. For him, the precision of those conditions introduced an element of artificiality, which made the subject less attractive to him.

In physics, he started studying quantum field theory, but he found that somewhat unappealing because the structure seemed too vague. “On the one hand, math was too precise—too specific and therefore too narrow,” he says. “On the other hand, physics was not precise enough.” Those factors, which tugged him in opposite directions, made the decision even more difficult, but in the end he chose physics, explaining that “the reward of understanding how nature works was a bigger draw for me.”

Vafa received valuable counsel on these matters from Fields Medalist Daniel Quillen, his undergraduate math advisor at MIT, who encouraged him to study areas of math—such as topology—that would be important in physics.

He applied to graduate school in physics, with Princeton as his top choice because of the presence of Edward Witten, a rising star who focused on the connections between physics and math. Vafa came to Princeton in the fall of 1981, and Witten soon directed him toward string theory. At first, Vafa thought string theory was “too far off the beaten path,” but it eventually became his path—as well as the leading candidate for a theory of quantum gravity.

A swift change in his attitude, and that of many others, came in September 1984 with the publication of a paper by the physicists Michael Green and John Schwarz. Prior to that time, many of the string theories under development suffered from inconsistencies or anomalies that made them incompatible with quantum theory and seemingly at odds with the laws of nature. However, Green and Schwarz found a way of

reformulating string theory so that troublesome anomalies, which had plagued earlier versions, canceled themselves out. After this breakthrough, part of what came to be called the first superstring revolution, Vafa says, “everybody started working on string theory.” He was among them but, unlike many others, he's never stopped.

At that time, according to Vafa, “there was still some shyness in the physics community about using mathematical ideas. For many physicists, it seemed almost distasteful to use too much math.” But in string theory, math took a central place, which was ideal for him, as he had long wrestled with the dichotomy between physics and math. After some digging, he discovered that dichotomy was mostly on the surface, and that underneath one could find harmony. Finally, he says, “I came to feel more at home with both subjects and their relation to each other.”

In 1985, Vafa began a three-year stint as a Harvard Junior Fellow. He had turned down Harvard twice before—when applying both for undergraduate and graduate studies—but this time he was at Harvard to stay. And he was no longer searching for a research topic, or trying to balance his sometimes competing interests between physics and math, because his focus was almost exclusively on string theory.

None of the senior faculty in Harvard's physics department were working on string theory in 1985, and none of them were big proponents of the theory either. But Vafa did not feel isolated since he found other junior fellows and junior faculty to work with. And it happened to be an extraordinarily fertile time in string theory, with an outpouring of ideas from researchers all over the world. He has continued to explore the subject since joining Harvard's physics faculty in 1988, where he presently serves as the Hollis Professor of Mathematics and Natural Philosophy.

One area of great excitement concerned the notion of dualities: two theories or models that look very different on the surface yet nevertheless describe identical physics. In a 1989 paper, Vafa and two collaborators, Wolfgang Lerche and Nicholas Warner, proposed what has become a very important duality known as mirror symmetry. Their conjecture relates to so-called Calabi-Yau manifolds, which constitute the tiny, curled-up spaces in which six of string theory's ten dimensions lie hidden. Lerche, Warner, and Vafa suggested that six-dimensional Calabi-Yau manifolds come in pairs and that two

such manifolds—which are topologically distinct and display no obvious kinship—still give rise to the same physics.

“We boldly proposed that the mirror conjecture was true, without mathematical justification, based purely on physical reasoning,” Vafa says. “Mirror symmetry is an idea that came from string theory that can be verified mathematically regardless of whether string theory describes our universe.”

In 1989, after the paper with Lerche and Warner came out, Vafa’s graduate student Ronen Plesser, working with then-Harvard postdoc Brian Greene, constructed the first example of Calabi-Yau manifolds that constituted a “mirror pair.” Greene and Plesser did not prove the mirror conjecture outright, but they provided strong supporting evidence. And even today, more than three decades later, mirror symmetry remains an important topic in both mathematics and physics, with international conferences devoted to it on a regular basis.

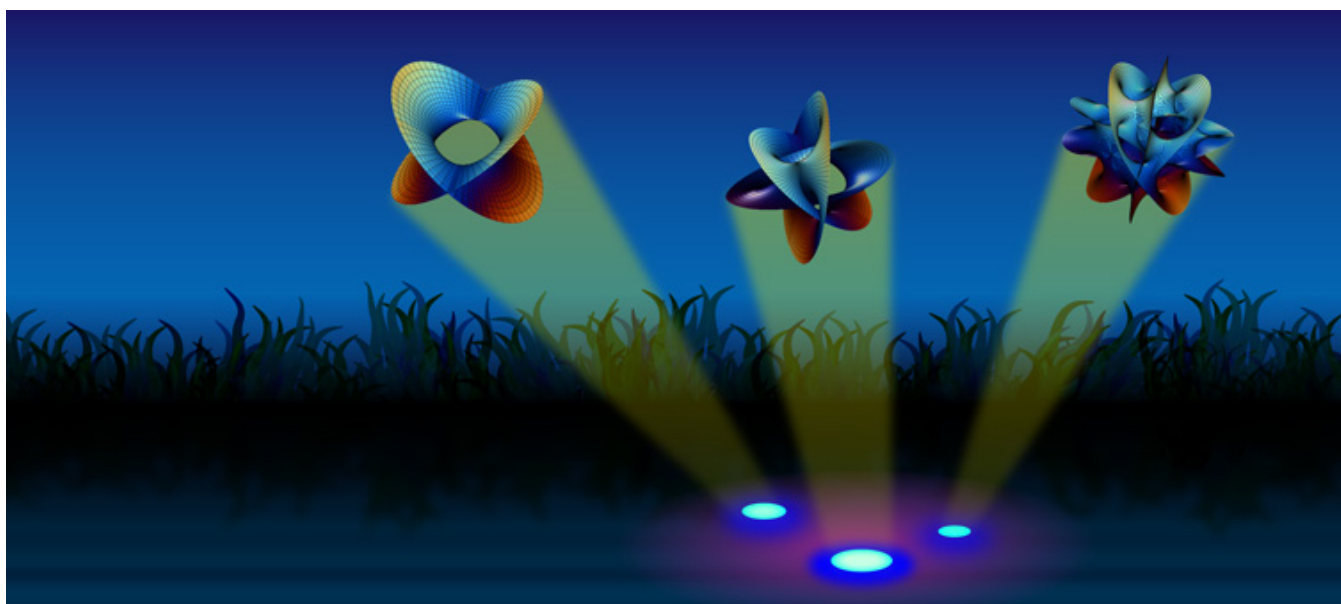
In 1996, Vafa teamed up with his Harvard physics colleague, Andrew Strominger, using string theory to provide a detailed picture of a black hole’s inner structure. In the early 1970s, Jacob Bekenstein and Stephen Hawking devised a remarkable formula: A black hole’s entropy, they concluded, is proportional to the area of the event horizon surrounding the black hole. The entropy itself relates to the makeup of a black hole’s interior and all the possible ways that the particles and other stuff inside a black hole can be arranged on a microscopic level without changing the black hole’s macroscopic properties—such as its mass, spin, and electric charge. Each of these possible arrangements corresponds to a unique “microstate.”

Based on the Bekenstein-Hawking formula, it was apparent that black holes had unexpectedly high entropy, which meant their inner structure was more complicated than physicists had previously suspected. But neither Bekenstein nor Hawking nor anyone else could say exactly what that internal complexity stemmed from—that is until Strominger and Vafa offered their insights on the subject.

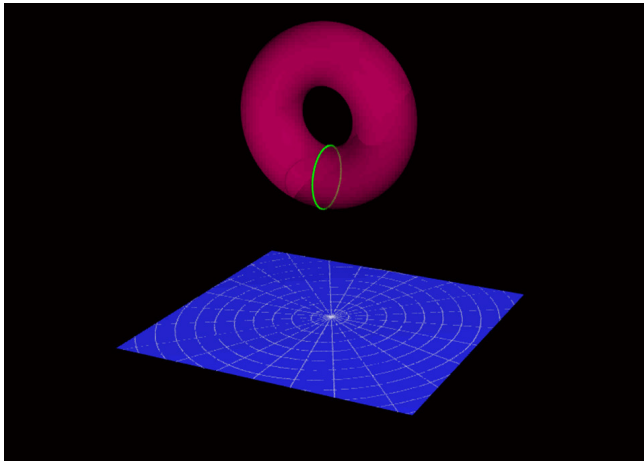
In the 1980s, string theorists posited that all the particles in nature could be viewed as tiny, one-dimensional strands, or strings, vibrating in ten-dimensional space. By the mid-1990s, the theory came to include not only one-dimensional strings but their higher-dimensional counterparts called membranes or “branes.” And there was a special category of branes called D-branes to which open strings (those not closed up in loops) attach. The number of microstates associated with a given black hole, Strominger and Vafa determined, equals the number of D-branes (wrapped up into the shape of a sphere) that can fit inside a Calabi-Yau manifold. And that number is indeed proportional to the area of the black hole’s horizon.

“Hawking wasn’t an expert on string theory at the time,” Vafa says. “In the beginning, he was a bit skeptical, but he gradually changed his view.”

The Strominger-Vafa paper was a significant advance for string theory because the black hole area-entropy correlation was a well-known problem that theorists of all stripes were trying to explain, Vafa says. “People would say: If string theory is a consistent theory of quantum gravity, then show us the microstates, and that’s what we did. Not only did we get the



In string theory, high-energy solutions in higher dimensions (shown above) are compacted into four-dimensional quantum field theories that belong to the “landscape” (shown as blue dots). Outside of the landscape is the “swampland,” where reside four-dimensional quantum field theories that are not consistent with gravity. (Photo: APS/Alan Stonebraker)



Black hole as wrapped branes in the internal dimensions

Hawking answer, we calculated the exact number of states, whereas the Hawking formula was only approximate.”

This work, moreover, was one of the earliest examples of the holographic principle—the notion that information about a black hole’s interior could be encoded within its lower dimensional surface—which has been a vital area of theoretical physics over the past 25 years.

Vafa authored another influential paper in 1996 that introduced a new form of string theory called F-theory. Unlike the 10-dimensional superstring theory of the 1980s and the 11-dimensional M-theory of the 1990s, F-theory has 12 dimensions in all—1 time dimension, 3 large (and visible) space dimensions, and an 8-dimensional Calabi-Yau manifold, which, in turn, consists of a 6-dimensional Calabi-Yau manifold plus a 2-dimensional torus that’s shaped like a donut.

What’s the benefit of having yet another version of string theory with a different number of hidden (unseen) dimensions? You can’t say that one form of string theory is better than another, or that one number of dimensions is better than another, Vafa maintains. “It all depends on the question you are trying to answer. Different questions have different best vantage points.” And the different forms of the theory—superstring, M, and F—“all belong to the same soup,” he adds. “I call the whole thing string theory, with 10 dimensions comprising one corner, 11 dimensions another corner, and 12 dimensions yet another still.”

F-theory may prove to be particularly helpful in the realm of phenomenology, which Vafa defines as “the attempt to explain the particles we have found in our universe, as well as the particles we have not yet found, from a consistent quantum gravity framework.” The challenge in this case is reducing a

12-dimensional spacetime to the 4 dimensions (3 of space and 1 of time) of our everyday world. There are more possible ways of going from 12 to 4 than there are of going from 10 to 4, Vafa explains. “With these added possibilities you can get more possible solutions”—with each solution describing a universe with a unique set of particles, forces, and other distinct features.

In the past, string theorists had largely been limited to studying situations in which strings were weakly coupled and hence interacted weakly with each other. For geometric reasons, F-theory has made it easier for physicists to take on cases involving strongly interacting strings—an advantage that has made F-theory a convenient setting for connecting string theory to particle physics.

But string theory has long faced a perennial problem, which Vafa refers to as “an embarrassment of riches. We have too many options to get to the real world—too many choices.” The challenge of string theory is finding a way of narrowing the options, and discarding the bad choices, so we can get to the universe we inhabit amidst a very large landscape of possible solutions—estimated at roughly 10500, an almost absurdly high number.

Although this landscape is indeed vast, Vafa has proposed that the bulk of it consists of a “swampland” that can be weeded out on the grounds that the hypothetical universes it contains are logically inconsistent and therefore cannot exist. He believes, in other words, that the swampland is much larger than the landscape.

In 2006, Vafa and three colleagues—Nima Arkani-Hamed, Lubos Motl, and Alberto Nicolis—proposed a theory holding that any universe in which gravity is not the weakest of all the forces of nature must be classified as part of the swampland, and hence relegated to the bin of failed, unrealizable universes. This proposition, dubbed the weak gravity conjecture, holds that particles with an electric charge experience greater electrical repulsion or attraction than gravitational pull. “That is true in our universe,” Vafa explains. “And the swampland tells us that gravity is the weakest force not just in the universe we inhabit but in any universe.”

In 2009, Vafa and his former graduate student Jonathan Heckman made two assumptions that led to a further “narrowing” of the landscape. First, they posited that gravity is not involved in the unification of the strong, weak, and electromagnetic forces. Second, they suggested that supersymmetry might be observable at the relatively low energies accessible to the Large Hadron Collider (LHC). If

"There's no doubt that string theory is the only game in town when it comes to quantum gravity."

our universe is indeed supersymmetric, which is a built-in property of many string theories, every particle in the so-called Standard Model has a partner particle of a different type and spin. And if the above assumptions held—Vafa and Heckman predicted, employing a string theory-based argument—a new particle called the “stau” might be detected at the LHC.

That has not yet happened, nor has the LHC found any signs of supersymmetry. But there’s nothing problematic about this negative finding, Vafa says, “because the idea of supersymmetry surviving at low energies is not an actual prediction of string theory; we were just hoping that might be the case.” The existence of the stau, moreover, has not been ruled out; it might still be found at higher energies than have yet been probed experimentally.

The swampland program initiated by Vafa now comprises one of the main research directions in string theory, and one intriguing prediction has come from it—namely that the inflaton field, which is believed by some physicists to have driven cosmic inflation in the early universe, cannot be exerted over too large a distance. This idea is formally known as the Swampland Distance Conjecture.

In March 2014, researchers at the BICEP2 telescope at the South Pole announced that they had apparently detected signs of gravitational waves generated during the universe’s brief but explosive inflationary period. At the time, Vafa and other string theorists realized that, if confirmed, the BICEP2 findings would have contradicted the distance conjecture. “Many people in the string community, myself included, noticed this discrepancy,” he says.

Some months later, it was determined that the signal detected by BICEP2 had been misinterpreted; it was due to dust and was unrelated to primordial gravitational waves. “This and other examples have shown that the swampland criteria can yield relevant predictions, even for observations that people are making of the universe.”

In 2018, Vafa and his colleagues made another bold pronouncement that came out of the swampland program:

Dark energy, which is driving the accelerated expansion of our universe, cannot be stable. Rather than being a “cosmological constant,” dark energy is doomed to decay away, eventually to nothing. The consequences of that decay are profound, Vafa maintains. “Not just the energy will change but all the properties of matter will change too.” The lifetime of our universe is the same as the lifetime of dark energy in our universe, he adds. “We don’t yet know whether the decay of dark energy will be gradual or something faster, but we don’t expect our universe to be long-lived.”

The age of the universe is presently thought to be nearly 14 billion years old, and perhaps 1/10th or 1/100th of its projected lifetime has elapsed so far. Within 140 billion to 1.4 trillion years, Vafa estimates, the entire universe could disappear.

Fortunately, that still leaves time for string theorists to review these calculations and continue their studies on other fronts. Vafa insists that this research is important, even though some critics have, over the past decade or so, been trying to write string theory’s obituary. He admits that the question of when we’ll see experimental evidence for the theory is valid. “We don’t know when we’ll get there,” he says, “or whether it will be through particle physics or through early- or late-universe cosmology.”

His enthusiasm for the field has increased over time rather than diminished. “We need to keep our eye on the ball,” he stresses. “Some colleagues are enamored with the elegance of the subject, but to me the connection between string theory and reality is the most exciting thing going on.” He further believes that the swampland program is giving physicists hope that string theory can be predictive, and he and his colleagues are currently developing new tools to make it even more predictive.

“We may or may not be in the middle of the ‘third string revolution,’ as some physicists are calling it,” Vafa says. “But there’s no doubt that string theory is the only game in town when it comes to quantum gravity.”



THE NON-STOP SHOPS:

Even a Pandemic Couldn't Close the EIDL and Physics Machine Shops

by Clea Simon

Above: Stan Cotreau and chemistry & physics concentrator Brayant Garcia working on the milling machine.
(Photo by Paul Horowitz)

The basement room would be cavernous, were it not chock-full of machinery. Shelves of material – lengths of copper and stainless-steel piping – are stacked in one corner. A safety curtain, dulled with age, isolates a laser. Near the center, a huge lathe, dating from 1957, dominates the room, the molded steel grip on its hand wheel a stark contrast to the plastic handle on the newer machine nearby, while numerous other waist-high machines for cutting and shaping materials fill the rest of the space. On the floor, arrows laid out in red tape demarcate the flow of foot traffic, while a sign on the door notes maximum occupancy of eight (seven students and one instructor).

Because even in the depths of the COVID lockdown, this space – the Physics/SEAS Instructional Machine Shop – largely stayed open, as did the Scientific Instrument Shop, the Fabrication Machine Shop (also known as the Particle Physics Machine Shop), and the Electronic Instrument Design Lab (EIDL), all of them playing a vital role in allowing researchers and graduate students in physics and SEAS to continue their work.

“It’s a very valuable resource,” said Can Knaut, a Ph.D. student in experimental physics. Masked and with safety goggles protecting his eyes, he’s working in the Instructional Machine Shop in the basement of the Lyman Building at 15 Oxford Street, milling a length of Invar, a nickel-iron alloy, for use as a housing for an optical cavity. The material, he explains, is “notable for its uniquely low coefficient of thermal expansion.” In other words, necessary for his experiment of building up a Quantum network node and not something that he could order from a conventional supplier. “The ability to quickly machine custom-designed components for our complex experiments has been invaluable, especially since we could access the machine shop throughout the entire pandemic.”

That access has been the result of a university-wide safety protocols and rigorous testing of ventilation and air quality, along with the dogged persistence of the shop managers. The professionally staffed Scientific Instrument Shop was able to resume functioning after the university-wide three-week closure, and the Fabrication Shop re-opened in less than three months, albeit with new awareness of social distancing and masking at both. For the Instructional Machine Shop and the tiny EIDL, staying operational required the kind of inventiveness that is usually reserved for the tools they create.

“Like everybody else, we had to submit a reopening plan that had to get approved by the leadership of FAS and SEAS,” explained Stan Cotreau. Manager of the Physics/SEAS Instructional Machine Shop since 1993, the teacher and machinist customarily divides his time between the Instructional Machine Shop and the Scientific Instrument Shop, which is located beneath the Northwest Building. However, on March 13, when all that came to a screeching halt, Cotreau locked his office and went home – for three days. Even as the rest of the university was still figuring out how to adjust to remote work, and while plans were still being formulated for how essential parts of the university could safely re-open, Cotreau came back part-time to the deserted shop to help manufacture an essential component of the personal protective equipment then in short supply. Working

with SEAS’s Hansjorg Wynn Professor of Biologically Inspired Engineering Jennifer Lewis, Cotreau began manufacturing face shields out of an acrylic-like plastic for first-responders and healthcare workers.

Once the various workshops were given a plan for reopening, teaching at the Instructional Machine Shop resumed – with some changes. Because the space, which previously could easily host 15 people working simultaneously, was now limited to much fewer simultaneous users, new sign-up sheets came into play. And with his office upstairs limited to one-person capacity, Cotreau began spending more of his time in the workshop, where he would be accessible for questions. However, even with the walkways laid out to keep people separated as well as masking protocol and social distancing in place, not every class could be restarted. Welding, for example, was temporarily off Cotreau’s schedule. “It’s hard to teach from six feet away,” he explained.

Still, the workshops were soon humming, as new projects as well as the backlog of projects that had been summarily abandoned, quickly filled the schedule. If anything, Cotreau explained, the pandemic closure added to the workload. The post-docs and professors “can do their calculations at home, but they can’t build their experiments at home. They can’t put together the components at home,” he said. “So we were actually fairly busy.”

Having these workshops re-open, even while most of Harvard worked remotely, was vital to the researchers who occupy the labs above and around them. “Sometimes you need something very special for your experimental setup,” explained Isaac Silvera, the Thomas Dudley Cabot Professor of the Natural Sciences. Silvera, whose research group is based in Lyman, often works in the Instructional Shop beside his students. Among the projects Cotreau has helped them fabricate are diamond anvil cells that can generate extremely high pressure, and Silvera credits Cotreau’s guidance with enabling his research. “It might just be a tapped hole in a piece of apparatus or it could be a small little device that might take 10 or 20 minutes for a machinist to make,” he said. “But you need it right away, because you can’t advance without it.”

While the Instructional Shop has welcomed back a mix of students, post-docs, and professors, the Scientific Instrument Shop has a professional staff that has only recently grown from three back to four, as a position left vacant by a retirement has finally been filled. Working with only this small staff, said Cotreau, has made functioning under COVID protocols a little easier. “We just don’t work side-by-side



James MacArthur with a TipTone instrument
(photo by Paul Horowitz)

machines,” he said. “We make sure that there’s an empty machine between us.”

That kind of accommodation wasn’t possible for the Electronic Instrument Design Lab. Carved out of a DEAS undergraduate instructional lab space in the Cruft Lab, the EIDL – as chief engineer Jim MacArthur’s domain is better known – is, at best, cozy. (The word “Cruft,” MacArthur likes to point out, has become a science slang synonym for “junk.”) During a regular semester, he explained, he acts as an electronics “short-order cook,” designing and building custom instruments that can be fabricated in a few hours. There’s also bench space in the crowded second-floor room “for people to mess around,” as well as to allow researchers to casually drop in and discuss their projects.

Those conversations, MacArthur explained, have often proved as essential to a project as any bit of circuitry. For example, he recalls working with a researcher who was hoping for help with building a drone that could measure volatile organic compounds. “That sounds pretty simple,” MacArthur noted. But with 21 years of experience as the shop manager, he waited – suspecting further conversation would produce a twist. “Oh, yeah, and it has to be able to do this in the Amazon jungle.” He laughed as he recalled the complications:

Yes, the drone would only need to perform a simple task. But it would have to be built to withstand jungle conditions, and, most likely, dunking in a river.

When COVID hit, all that came to a halt. “I had grabbed a few boxes of tools and parts when I left Cruft and set up a workbench in a spare bedroom,” recalled MacArthur. “But those few boxes didn’t include any metalworking tools, nor my more exotic components, so I found that I basically couldn’t make anything.” Inspiration struck when he recalled a design concept that he had used while collaborating on a project with the Music Department, a technique for what he called “making cheap, rugged, ugly, electronic music gear.”

“This technique, which we dubbed ‘Tiptone,’ had a very useful feature,” he explained. “It could be built with common components and hand tools. In other words, it was the perfect pandemic build technique.” With its use of only a soldering iron and the few tools he had taken home from the lab, this technique allowed him to create custom electronic instruments at home. “I started casting the incoming build requests into Tiptone designs and discovered that most of them fit well in the new format.”

When Cruft re-opened in June, MacArthur was once again able to access his “wonderful parts and tools.” With COVID restrictions limiting occupancy of the small space to two, however, students were forced to work at night, after MacArthur has left, and discussions have been largely moved outside. And faced with a significant backlog and pandemic protocol that restricted his time in the shop, MacArthur has turned again to the new technique. “The limit of four hours a day on campus meant that I needed to spend that time building as quickly as possible,” he said. Working from designs he created at home, he made the most of his time back in Cruft. “I discovered that, even in a fully equipped lab, I could build Tiptone instruments almost twice as fast as conventional ones, which was hugely helpful, given the time constraints,” he said.

A year later, he’s still at it. “I’ve delivered 42 Tiptone instruments so far,” he said, referring to the Lego-looking creations. “Some researchers are a bit put off by the ‘neo-brutalist’ look, but they like how fast I can build things for them.”

Attractive or not, being forced to improvise with the Tiptone technique may have a long-term advantage, noted MacArthur. “I will think about efficient design where it really wasn’t necessary before.”

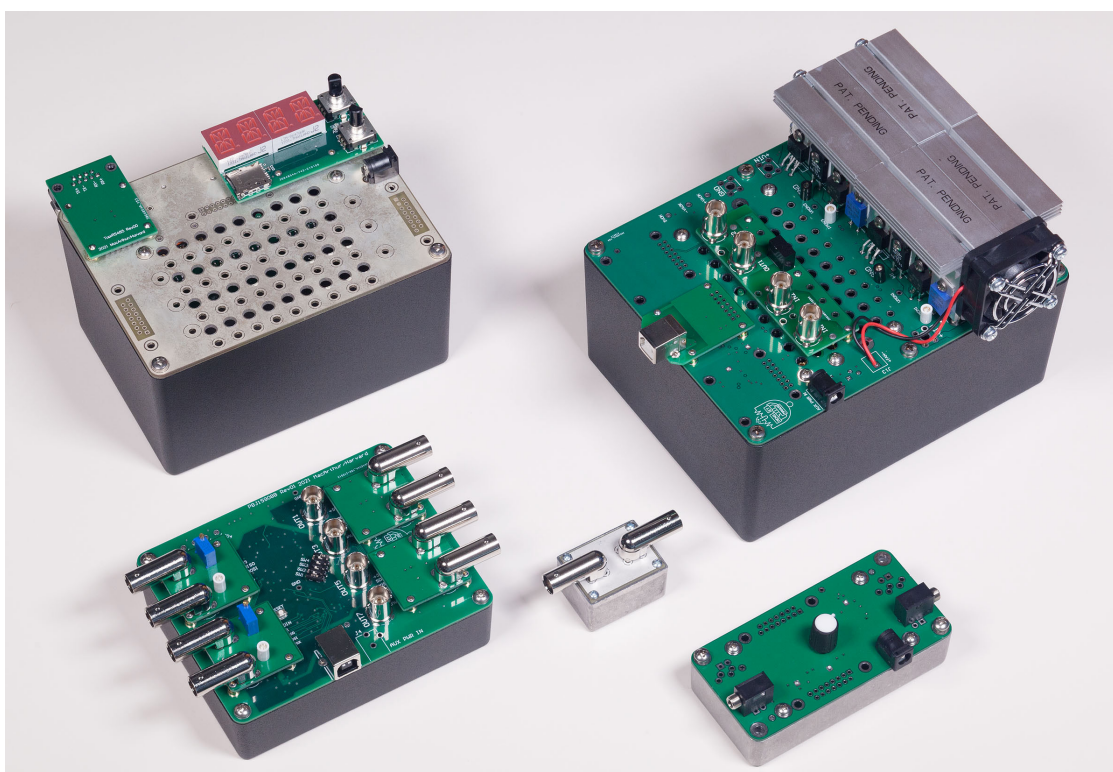
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For Paul Horowitz, Professor of Physics and of Electrical Engineering, Emeritus, who calls the EIDL his “laboratory home,” the work MacArthur does is essential. “To do research, you need instruments, you need measurements, and oftentimes it's custom stuff, equipment you can't just buy off the shelf,” he added. The sensitive electronic instruments MacArthur fabricates and trains students to create “enable research at the cutting edge, because you can design custom instruments.”

Space and social distancing were never an issue for the Fabrication Machine Shop. Steve Sansone, director of the 38 Oxford Street workshop, works alone in the cavernous space, which produces everything from widgets for displays at the Peabody Museum to large-scale equipment (such as a receiver

for the Kovac cosmology research group that is both sensitive enough to pick up microwaves from deep space and sturdy enough to be used at the South Pole). The underground space, which from 1956 to 1974 used to house the Cambridge Electron Accelerator (CEA), stayed closed for nearly three months at the start of the pandemic, returning in May. But once COVID protocols were in place, Sansone returned to the often Brobdingnagian machines that line the back of the warehouse-like room, walking down the ramp that allows access to a fork-lift and 40-ton crane.

“We can cut almost any material on there, any shape, any thickness,” explained Sansone during a recent walkthrough. That has included equipment for Melissa Franklin’s research



Closup of several TipTone instruments produced by EIDL (photo by Paul Horowitz)

"I go down with [the students] and I instruct them and I'll do it myself to show them how you do it. And they learn how to do it. And then they take over and hopefully they're going to do it better than I do," said Silvera. "They may have new ideas. They may say, 'well, why don't we do it this way?' And so you say, 'let's try it out and see if it works.' This is how research advances."

group, which is part of the ATLAS experiment at the Large Hadron Collider, as well as a mass spectrometer for Professor of Organismic and Evolutionary Biology Peter Girguis' study of deep-sea microorganisms. For such specialized tools as the Girguis group spectrometer, the space – and that access ramp – are vital. "We have a truck come down and I pick them up with a crane, put them on that, and then they get shipped to the West Coast and they get put on a boat," said Sansone.

As with the other workshops, this necessary work couldn't be done remotely. "We need the machines," said Sansone. "They're not going to ship them to my house and set them up in my garage. So when they let us back in, we got really busy."

These shops provide the underpinning for much of the research and teaching in the department – and they evolved with the labs and vice versa. The Fabrication Machine Shop, for example, moved into the former CEA space once the redevelopment of the area, which includes the Northwest Science Building, was completed in 2008, and has since drawn several research groups, such as Professor of Astronomy and Physics John M. Kovac's cosmology team, into the capacious space.

The Scientific Instrument Shop is now part of the Northwest Building, but its origins – as well as those of the Instructional Machine Shop – certainly pre-date the 21st century facility. Cotreau, who has been with the university since 1984, believes the Instructional Machine shop had been around "40 or 50 years," before he took over and created a teaching curriculum. "We're a hundred percent instructional now," he noted. "We've gone to computerized equipment, which they didn't have when I took it over. We've introduced laser cutting, which is a new technology. We do a lot of computer programming where it used to all be manual."

Looking at the history of the EIDL, Horowitz cites tool building that helped advance research into nuclear magnetic resonance, the basis for magnetic resonance imaging (MRI), as resulting from a World War II radar project "down the river at MIT." Similarly, work on the radio waves from galactic hydrogen in 1951 relied on tools created in workshops at Harvard. "Done by cobbling together wartime equipment and some custom stuff," said Horowitz.

Each of these shops was born out of a specific need. The Cruft Laboratory dates back to 1915, when it was built as a gift from the donor Harriet Otis Cruft, and housed the Physics Department's radar lab during World War II. For researchers who sought any kind of specialized equipment, "it was sort of an ad hoc situation where people would come and ask somebody if they knew how to build the things they needed," said Horowitz. In 1998, he wrote a proposal for the EIDL, outlining the need for a facility "to assist in circuit and instrument design" as well as "to provide facilities where the design can be built and tested." While other functions, such as contract work of the type undertaken by the Scientific Instrument and Fabrication lab are mentioned, design assistance is listed as "mission #1a."

"That's the infrastructure for science," said Horowitz, who in 1974 originated the Laboratory Electronics course at Harvard and whose authoritative and enormously successful textbook, *The Art of Electronics* (co-authored with Winfield Hill), is now in third edition. He then recruited MacArthur, who had been working in industry, most recently as a design engineer at Lexicon. As MacArthur pondered the switch to academia, a friend said "You have a choice. You can work in the factory or work in the cathedral." He chose the cathedral.

Various university archives illuminate how long the shops have been part of the physics department. *A Harvard Crimson*

article from the winter of 1932, for example, notes that three machine shops were built into the then-new Physics Research Laboratory, which incorporated the gift of a lathe “and other tools” once the property of the late Dr. W. W. Gannett, Harvard '74 – 1874, that is. The shops pre-date even this gift, as the article goes on to explain: “The new building joins the Jefferson Physical Laboratory, built in 1884, to the Cruft High Tension Electrical Laboratory, completed in 1914. By locating the new construction at this point the Department has been able to revise and consolidate the electrical installations in the older buildings,” noting that this connection gives “a new value to its machine shops through centralizing them.”

The Crimson archives offer up tantalizing tidbits from earlier as well. For example, the Harvard summer school curriculum for 1905 included: “blacksmithing, pattern making and foundry practice, [and] machine-shop practice,” noting “These courses must be taken together, and will count for the degree of S.B. only.”

The teaching function of these workshops remains central to their mission. “I’ve used the EIDL mainly for circuit board

design and consultation about all manner of electronic and electrical issues,” said Jonah Weissman, a post-doc in the Kim Group, working on thermal transport measurement in low-dimensional materials. “Jim has helped me think through many of our tricky situations, even if it wasn’t directly his expertise, he was always a willing and able sounding board – with plenty of amazing stories sprinkled in from his glorious past.”

“I go down with [the students] and I instruct them and I’ll do it myself to show them how you do it. And they learn how to do it. And then they take over and hopefully they’re going to do it better than I do,” said Silvera. “They may have new ideas. They may say, ‘well, why don’t we do it this way?’ And so you say, ‘let’s try it out and see if it works.’ This is how research advances.”

This element of teaching – of passing along know-how – is also the shops’ legacy. “Through the years, students from my machine shops have become professors around the country,” recalled Cotreau. “So when they have questions about how to build things, sometimes they call. It’s actually very rewarding.”



The Fabrication Shop



A Tribute to Anne Trubia

by Mary McCarthy

Please join me in calling for congratulations and warm wishes for our Director of Administration, Anne Alence Trubia, on her well-deserved retirement at the end of June 2021.

Anne's career at Harvard spanned 30 years, with over 11 years devoted to Physics. Anne's first introduction to Harvard began as a summer temp working in the student loan office. In 1991 she began working full time as a Staff Assistant in the General Accounting office, formerly located in Holyoke Center (now The Richard A. and Susan F. Smith Campus Center). From there she moved across the River to the Department of Microbiology at Harvard Medical School. At that time, the departments of Microbiology and Pathology were managed by one administrative director. When the departments moved to each having their own administrative and finance team, Anne went to work in Pathology in 1993.

Under the leadership of the department chair, Dr. Peter Howley, Anne enjoyed a halcyon 17 year career in pathology, working her way up from Financial Associate to the Director of Finance and Staff Administration. In 2010 she assumed the role of the Director of Administration in the Department of Physics.

The timeline of Anne's directorship reads like a veritable roadmap of firsts: the first Alumni Reunion, the first Harvard Physics Newsletter, the first Physics Phenom—Staff Reward & Recognition Program, the first Administrative Fellow, the first Equity & Inclusion Committee (EIC), then in spring on 2020, leading the entire administration in transition to remote work during a global pandemic, and later co-leading the Physics Occupancy Oversight Committee charged with campus re-entry. "As a member of her team, I've always admired Anne's ability to make the tough decisions that drive our mission forward," said Dionne Clarke, Administrator to Mitrano, Mundy, and Samuel Labs, and Chair of the Physics Social Committee.

In addition to many firsts, Anne pushed for numerous excellent hires and enhancements to the teaching labs, the finance, and administration teams. She spearheaded construction of six faculty labs and numerous renovations around the building. Like all strong leaders, Anne was able to cultivate the best out of her staff and shepherd multiple technological and process advancements, such as introducing Corporate Cards to the faculty, transitioning staff off the Physics server, embracing OpenScholar as our new web platform, and overhauling Department's website, in addition to tremendous improvements in the areas of graduate admissions.

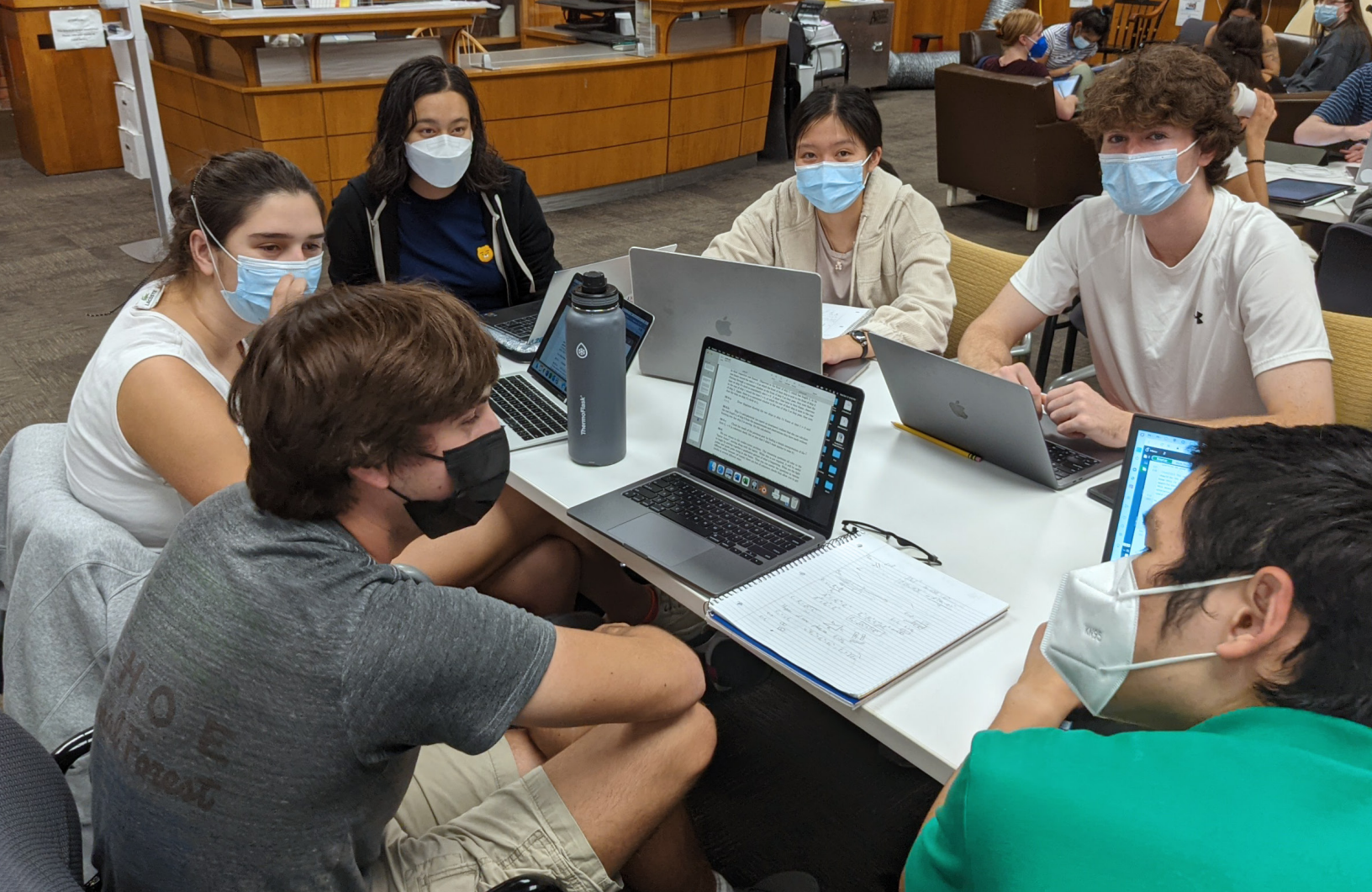
Anne has been a tireless advocate for the Department, seeking to build connections and bolster morale. She launched the

"Let's Talk Physics" program in which faculty member present their research to the administrative staff in a series of talks, hosted monthly lunches with the graduate students to build connections between students and the department's administration, and reallocated resources to provide better support for research scholar and graduate students. In partnership with the EIC, Anne instituted weekly office hours with the Chair and established an anonymous web portal repository, in which members of the physics department can raise concerns related to equity and inclusion issues. During Anne's directorship, the pool of applicants to our graduate program ballooned from about 400 to well over 1,000, and the graduate student body increased from 200 to 250 Ph. D. candidates. The undergraduate program has grown as well.

Prof. Masahiro Morii, who has worked with Anne in his role as Chair of the Physics Department and, later, as Chair of the Physics Occupancy Oversight Committee, said "Anne was a wonderful partner in running the Department together. Her vision was firmly anchored to the reality of the day-to-day experiences of the members of the Department. She was passionate about making the Jefferson Lab a beautiful and friendly space to work. Best of all, Anne could keep her cool when the going got rough — as it did in Spring 2020 — and kept smiling as she managed crises over Zoom calls. Thank you, Anne, for shepherding the Department through an eventful decade."

Anne's leadership style was marked by her candid, no-nonsense approach and good humor. Anne embraced the softer side of physics as well, calling for the creation of the tremendously popular Social Committee which has been charged with developing programming and events that engage staff in teambuilding and social activities. Some memorable events include a Boston Duck Boat excursion, an Escape-room event, a scavenger hunt hosted at the Museum of Fine Arts, and countless virtual gatherings which were deemed by all as wildly successful, side-splittingly fun, and rejuvenating.

As a skilled and talented administrator with a strong command of general administration and sponsored and operational finance, coupled with her collaborative style, strategic perspective, resourcefulness, and dedication to supporting the department's research and education mission, Anne will be greatly missed.



ACADEMIC PROGRAMS

Undergraduate Program

The Fall '21 semester has brought a welcome return to in-person 3D instruction, complete with live classroom demonstrations, professors covered in chalk dust, and students raising actual hands. The halls of Jefferson and Lyman are now filled with people to wave “hi” to, and the only telling sign that the campus hasn’t fully returned to normal is the ubiquitous face masks in indoor spaces.

The past year-plus of remote 2D Zoom instruction proceeded about as smoothly as it could have, with all parties stepping up to the challenge. However, no amount of faculty preparation or student dedication could replace the crucial aspects of education that were missing: the community and the fun. But with everyone on campus once again, we’re pleased to report that the fun is back!

“Physics Night” on Wednesdays once again involves ~75 students working together on their assignments. Formerly located in a house dining hall, it is now held in the Physics Reading Room (splendidly outfitted with a dozen air filters and some hearty window fans). The multitude of picnic tables and tents near Jefferson Lab are filled with mask-free smiling faces during outdoor office hours, group meetings, and lunches. The Society of Physics Students is geared up for all sorts of new events and initiatives this fall, including the Polaris mentoring program, informal chalk talks, and other fun social gatherings.

We couldn’t be happier that the familiar hustle and bustle of Harvard life, albeit tempered by health precautions, has returned to campus.

Above: Students working on problem sets during “Physics Night” in the library. (Photo by Howard Georgi)

Student Profiles



SAMANTHA O'SULLIVAN

Samantha O'Sullivan, who will be graduating in 2022 with a joint degree in Physics and African-American studies, has done research in Jenny Hoffman's experimental condensed matter group from 2019 to 2021. Samantha worked on imaging and characterizing the high temperature superconductor monolayer FeSe/SrTiO₃, with the goal of understanding the structure of the material's

interface and the ways it may contribute to its high temperature superconductivity. Her work resulted in a submitted manuscript (arxiv.org/abs/2104.01904v), currently in journal review. She most enjoyed the hands-on nature of her project, as well as the ability to grow, measure, analyze, and interpret the sample all in one lab.

Samantha also conducted transport measurements of topological insulator SmB₆ with Prof. Johnpierre Paglione at the Maryland Quantum Materials Center (University of Maryland). These projects have inspired her to continue with her investigation of high temperature superconductivity, and she intends to pursue experimental condensed matter physics research in graduate school.

For her African-American studies, Samantha has been exploring the intersection of African-American linguistics and science communication. Her senior thesis examines the possibility of communicating science in the language of Gullah, spoken in the South Carolina region of the United States. She hopes to continue to advocate for inclusive and diverse science communication throughout her career. She also co-founded and served as president of the Generational African-American Students Association which advocated for social justice and increased African-American student community on campus.

Samantha is from Washington, D.C., where she loves to go on runs by the monuments, spend time with friends, and play with her mini goldendoodle puppy Nala. She enjoys visiting museums, and works as an Explainer at her favorite, the Smithsonian National Air and Space Museum.



ZACHARY GELLES

Zack Gelles '22 spent the past year doing research in black hole imaging with the Event Horizon Telescope (EHT). Using an array of radio dishes around the world, the EHT captures images of supermassive black holes located millions of light-years away, a task as difficult as seeing an atom held at arm's length. Zack has been involved in the theoretical side of EHT research, working to improve

both the numerical and analytic tools needed to properly understand the appearance of strongly lensed light. When light is bent around a black hole, it produces a sharp "photon ring" of self-similar, demagnified copies of itself. Zack worked with Dr. Michael Johnson to speed up a geodesic ray-tracing code by a factor of 10 and simulate this phenomenon at unprecedented resolutions. He then applied a similar analysis to polarized light

while working with graduate student Mina Himwich. Together, they developed an analytic model that approximates how the frame-dragging of spacetime rotates photon polarization vectors. Most recently, Zack worked with Prof. Ramesh Narayan to investigate the appearance of turbulent black hole accretion flows, ultimately finding that the time variability of a black hole image can illuminate clear signatures of strong lensing. With a deeper understanding of black hole images, novel ways of exploring general relativity in the future can be developed.

Zack has genuinely enjoyed his time with the EHT and is thankful for the opportunity to work with such talented and devoted researchers. Prior to joining the EHT, Zack conducted research with Prof. Melissa Franklin and the ATLAS experiment at CERN, where he had an equally educational experience optimizing trigger efficiencies for detection of long-lived particles. Zack wants to obtain a Ph.D. in physics and continue studying theoretical astrophysics, particle theory, and the overlap between the two. Outside of physics, Zack is a member of the Harvard Parliamentary Debate Team, and he has directed the Chinatown ESL community service program of PBHA. He loves riding roller coasters, learning languages, and exploring the Boston food scene.



ACADEMIC PROGRAMS

Graduate Program

This year an unprecedented number of applicants—over 1000—applied to the Harvard Physics Ph.D. program. Thirty-one students who have been accepted into the program came from far and wide, including China, Vietnam, Pakistan, Cambodia, Ethiopia, Kazakhstan, Taiwan, Japan, Singapore, India, Egypt, Canada, and the US. We are happy to report that we were

able to give an ‘almost normal’ orientation to the new G1s, as well as the first formal welcome to our G2s, who missed out on all the fun last year. After 16 months of eerie stillness, the hallways and common areas are finally buzzing with bright young voices as the grads settle (or settle back) into their Harvard lives.

Above: Graduate students in the G1 area. (Photo by Paul Horowitz)

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.

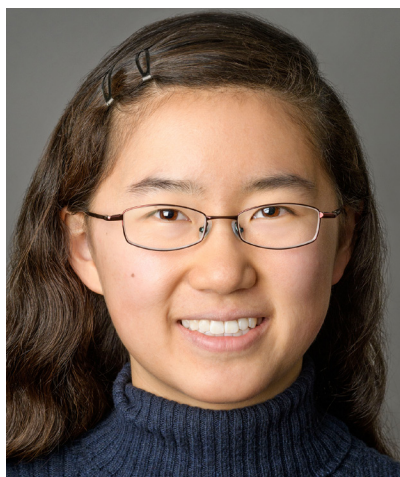


Alek Bedroya

2021 GOLDHABER PRIZE WINNER

Alek Bedroya's road to physics started with math. He represented Iran in international mathematics Olympiads and won two gold medals. His interest in math prompted him to pursue it academically in college, where he discovered his passion for physics. Eventually, he graduated with two Bachelor's degrees in physics and mathematics from the Sharif University of Technology. During his undergraduate studies, he worked on black hole physics with Prof. Hessamedin Arfaei. In particular, he studied the effect of quantum corrections on charged black holes.

To pursue his growing interest in theoretical physics, Alek came to Harvard to do his Ph.D. under Prof. Cumrun Vafa, one of the most prominent string theorists. In the past few years, he has worked on various aspects of the Swampland program, which aims to understand better the landscape of different theoretical possibilities in string theory. His work with Prof. Vafa has led to a conjecture with exciting experimental implications in cosmology. Alek also works on the classification of supersymmetric field theories consistent with quantum gravity.



Iris Cong

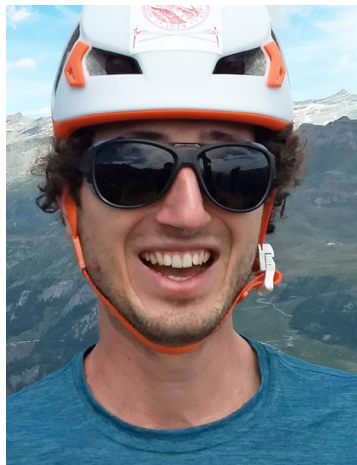
2021 GOLDHABER PRIZE WINNER

As an undergraduate, Iris Cong studied computer science at the University of California, Los Angeles, and performed research at Tsinghua University's Institute for Interdisciplinary Information Sciences as well as at Microsoft Station Q at UCSB. She graduated as UCLA Engineering School's sole Outstanding Bachelor of Science in the Class of 2017 and is now pursuing a Ph.D. in physics as a theorist in Prof. Mikhail Lukin's group.

As a joint Hertz and P.D. Soros Fellow, Iris is excited to be contributing to the frontiers of quantum information research by unlocking the potential of near-term quantum information processors. During her first two years at Harvard, she exploited her background in computer science to develop the quantum convolutional neural network (QCNN) -- a novel quantum machine learning method for state-of-the-art and intermediate-scale quantum computers. QCNN is now one of the flagship examples in Google's new quantum machine learning package (TensorFlow Quantum).

Recently, Iris has been collaborating with multiple theorists and experimentalists to achieve a practical implementation of QCNN on the Rydberg atom-based quantum computer developed in Prof. Lukin's group. She is also working to develop hardware-efficient quantum error correction schemes for these Rydberg atom platforms, with the goal of enabling more complex near-term quantum applications.

Goldhaber Prize *(continued)*



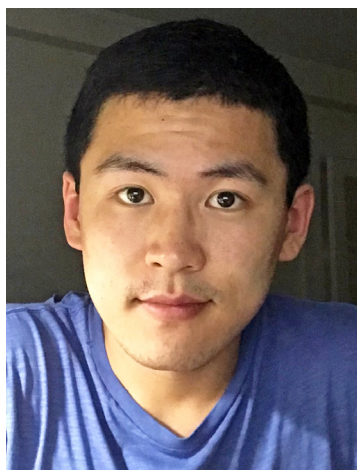
Nicolò Foppiani

2021 GOLDHABER PRIZE WINNER

Nicolò Foppiani obtained his Bachelor's in Physics in 2015. He became interested in experimental particle physics after participating in the Summer Student Program at CERN in 2016. His 2017 Master's thesis on the measurement of the mass of the W boson with the Compact Muon Solenoid (CMS) experiment (from the University of Pisa and Scuola Normale Superiore) was awarded the Tito Maiani's prize.

At Harvard since 2017, Nicolò is working on his Ph.D., where his research combines experiment and theory and addresses the anomalies observed in short baseline neutrino experiments that could unveil the existence of new particles and interactions. In the group of Prof. Roxanne Guenette, he has done experimental analyses of neutrino interactions with the Micro Booster Neutrino Experiment (MicroBooNE) at the Fermi National Laboratory, where he contributed to the development of particle reconstruction and identification techniques as well as to the measurement of electron neutrinos. On the phenomenological side, Nicolò tests new physics models by combining and reinterpreting data from different experiments and sources in the group of Prof. Carlos Argüelles-Delgado.

Originally from Genova, in the northwest of Italy, Nicolò returns there often to enjoy swimming and sailing in the Mediterranean Sea, and climbing and skiing in the Alps.



Zeyu Hao

2021 GOLDHABER PRIZE WINNER

Zeyu Hao obtained his bachelor's degree in physics from Xi'an Jiaotong University in China and spent one year at UC Berkley working with Prof. James Analytis on quantum phase transitions. He's currently a G5 in Prof. Philip Kim's group at Harvard, where he has been researching different ways of manipulating two-dimensional materials for engineering highly tunable structures to explore complex physics, including new quantum phenomena. An example of such a structure is two layers of graphene (a single atomic sheet of carbon atoms) with a thin insulating layer in between. The induced interlayer interactions between electrons lead to the observation of novel fractional quantum Hall states, which host exotic quasiparticles and hold promise for realizing topological quantum computation.

Another system Zeyu has been investigating is twisted multilayer graphene, where two or more sheets of graphene are stacked together at a relative twist angle. Inspired by the discovery of superconductivity in twisted bilayer graphene and observations of its myriad of other enigmatic phenomena, Zeyu and his colleagues pushed the field forward by showing that a second twisted system, twisted trilayer graphene, has even more robust superconductivity. This key discovery might shed light on the long-sought mystery of high temperature superconductors.



Jacob McNamara

2021 GOLDHABER PRIZE WINNER

Jacob McNamara received an A.B. in mathematics and an A.M. in physics from Harvard and is now continuing his studies in the Harvard Physics Ph.D. program. Since his senior year of college, Jake has worked with Prof. Cumrun Vafa, studying the geometric and topological properties of quantum systems, mainly under the umbrella of the Swampland Program, an international research effort to identify the basic physical principles behind string theory and quantum gravity.

Together with Prof. Vafa, Jake proposed the Swampland Cobordism Conjecture, stating that all theories of quantum gravity are fundamentally connected, which has proven to be a powerful and novel tool for the broader Swampland community. They further reformulated this conjecture in terms of the uniqueness of the state of baby universes, revealing a connection with recent puzzles in the holography community and the ER = EPR conjecture. More recently, Jake's research has focused on the relationship between the absence of global symmetries and the completeness of the charge spectrum. He and his collaborators have sharpened the relationship between these two conjectures and uncovered a link with non-invertible symmetries, a new and exciting notion of symmetry that has arisen in the study of condensed matter physics and low-dimensional quantum field theories.



Taylor Patti

2021 GOLDHABER PRIZE WINNER

Taylor graduated from Chapman University with a B.S. in physics and computational science, B.S. in mathematics, a B.A. in Spanish, and a minor in Chemistry. She holds a masters of physics from Harvard University, where she is currently completing a Ph.D. in theoretical physics in the group of Susanne Yelin. Taylor is a National Science Foundation fellow and has completed internships with both NVIDIA Research and IBM Quantum.

Taylor works in quantum information, computation, and control. Her research interests include quantum stabilization, engineering solid state and atomic media for quantum information/computation platforms, quantum variational algorithms, quantum applications for classical machine learning, and large-scale tensor network quantum simulation.

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.



Haoyu Guo

2021 MERIT SCHOLARSHIP WINNER

Haoyu Guo is a G4 student in Prof. Subir Sachdev's group. Prior to entering MIT as an undergraduate, he competed in the International Physics Olympiad and won a gold medal. During his time at MIT, he worked with Prof. Leonid Levitov on hydrodynamic transport in graphene. This work resulted in a surprising finding that that Coulomb interaction between electrons, instead of impeding the current, serves as a lubricant for the collective flow of electrons.

At Harvard, Haoyu's research focuses on theories related to high temperature cuprate superconductors. He tries to describe properties of the cuprates using Sachdev-Ye-Kitaev models: A highly simplified model of quantum many-body system which is believed to capture the underlying quantum entanglement within the material. Another aspect of his research concerns the thermal Hall effect that is recently being observed in the material. He is interested in constructing a theory of this remarkable phenomenon, which has a potential to become a step toward ultimate understanding of the cuprates.



Elizabeth (Mina) Himwich

2021 MERIT SCHOLARSHIP WINNER

Mina Himwich, a former Yale undergraduate, is in her sixth year of graduate school. She has been working with Andy Strominger since her second year. Most of her research has focused on the symmetries of gauge theory and gravity in asymptotically flat four-dimensional spacetimes. In such spacetimes, four-dimensional scattering amplitudes can be recast on the two-dimensional "celestial sphere" where particles enter and exit the spacetime. The Lorentz symmetry of scattering in four dimensions is isomorphic to the global conformal symmetry of a theory in two dimensions. A two-dimensional theory with conformal symmetry is a natural candidate for a holographic dual of quantum gravity in asymptotically flat spacetime, and Mina's work investigates this proposal.

In the past two years, Mina has also studied the signatures of gravitational effects in the observations of electromagnetic radiation around black holes. Over the course of that work, she became a member of the Event Horizon Telescope Collaboration.

More Graduate Student Awards and Fellowships^[1]

Certificate of Distinction in Teaching (Fall 2020):

Benjamin Augenbraun
Adam Ball
Arindam Bhattacharya
Dan Borgnia
Anthony Badea
Maine Christos
Erin Crawley
Tamara Dordevic
Ruihua Fan
Eliot Fenton
Haoyu Guo
Seung Hwan Lee
David Levonian

Qianshu Lu
Benjamin Mazel
Walker Melton
Grace Pan
Nisarga Paul
Lewis Picard
Ana Diaz Rivero
Giovanni Scuri
Alyson Spitzig
Justina Yang
Kexin Yi
Jeremy Yodh
Hengyun Zhou

DOE Krell Fellowship:

Rahul Sahay
Hertz Foundation
Fellowship:
Katherine Ann Van Kirk

Rabia Husain
EliseAnne Koskelo
Noah McNeal
Walker Melton
Paige Robichaud
Adam Tropper

NDSEG Fellowship:

Simon Evered
Betty Hu
Katherine Van Kirk

Robbins Prize:

Taylor Contreras
Katie Fraser
Madelyn Leembruggen
Grace Pan
Grace Zhang

NSF Graduate Research Fellowship Program:

Sambuddha Chattopadhyay
Alexander Douglas

Recent Graduates

Solomon Barkley

Thesis: "Applying Bayesian Inference to Measurements of Colloidal Dynamics"
Advisor: Vinothan Manoharan

Ana Diaz Rivero

Thesis: "Statistically Exploring Cracks in the Lambda Cold Dark Matter Model."
Advisor: Cora Dvorkin

Anne Hébert

Thesis: "A Dipolar Erbium Quantum Gas Microscope"
Advisor: Markus Greiner

Mihir Bhaskar

Thesis: "Diamond Nanophotonic Quantum Networks"
Advisor: Mikhail Lukin

Bo Dwyer

Thesis: "NV Centers as Local Probes of Two-Dimensional Materials"
Advisor: Mikhail Lukin

Geoffrey Ji

Thesis: "Microscopic Control and Dynamics of a Fermi-Hubbard System"
Advisor: Markus Greiner

Bogdan Bintu

Thesis: "Genome-Scale Imaging: From the Subcellular Structure of Chromatin to the 3D Organization of the Peripheral Olfactory System"
Advisors: Catherine Dulac, Xiaowei Zhuang, David Nelson

Delilah Gates

Thesis: "Observational Electromagnetic Signatures of Spinning Black Holes"
Advisor: Andrew Strominger

Andrew Joe

Thesis: "Interlayer Excitons in Atomically Thin van der Waals Semiconductor Heterostructures"
Advisor: Philip Kim

Mingyue Chen

Thesis: "On Knotted Surfaces in R^4 "
Advisors: Clifford Taubes, Cumrun Vafa

Hofie Hannesdottir

Thesis: "Analytic Structure and Finiteness of Scattering Amplitudes"
Advisor: Matthew Schwartz

Alexander Keesling

Thesis: "Quantum Simulation and Quantum Information Processing with Programmable Rydberg Atom Arrays"
Advisor: Mikhail Lukin

Minjae Cho

Thesis: "Aspects of String Field Theory"
Advisor: Xi Yin

Connor Hart

Thesis: "Experimental Realization of Improved Magnetic Sensing and Imaging in Ensembles of Nitrogen Vacancy Centers in Diamond"
Advisors: Ronald Walsworth, Hongkun Park

Aaron Krahn

Thesis: "Erbium Gas Quantum Microscope"
Advisor: Markus Greiner

continues on the next page...

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

Recent Graduates *(continued)*

Nicholas Langellier

Thesis: “Analytical and Statistical Models for Laboratory and Astrophysical Precision Measurements”

Advisor: Ronald Walsworth,
Cora Dvorkin

Harry Levine

Thesis: “Quantum Information Processing and Quantum Simulation with Programmable Rydberg Atom Arrays”

Advisor: Mikhail Lukin

David Levonian

Thesis: “A Quantum Network Node Based on the Silicon Vacancy Defect in Diamond”

Advisor: Mikhail Lukin

Albert Lin

Thesis: “Characterizing Chemosensory Responses of *C. elegans* with Multi-Neuronal Imaging”

Advisor: Aravinthan Samuel

Shang Liu

Thesis: “Symmetry, Topology and Entanglement in Quantum Many-Body Systems”

Advisor: Ashvin Vishwanath

Yu Liu

Thesis: “Bimolecular Chemistry at Sub-Microkelvin Temperatures”

Advisor: Kang-Kuen Ni

Bart Machielse

Thesis: “Electronic and Nanophotonic Integration of a Quantum Network Node in Diamond”

Advisor: Mikhail Lukin

Matthew Melissa

Thesis: “Divergence and Diversity in Rapidly Evolving Populations”

Advisor: Michael Desai

James Mitchell

Thesis: “Investigations into Resinicolous Fungi”

Advisors: Donald Pfister,
Aravinthan Samuel

Nicholas Mondrik

Thesis: “Calibration Hardware and Methodology for Large Photometric Surveys”

Advisor: Christopher Stubbs

Anjalika Nande

Thesis: “Mathematical Modeling of Drug Resistance and the Transmission of SARS-CoV-2”

Advisors: Alison Hill, Michael Desai

Abigail Plummer

Thesis: “Reactions and Instabilities in Fluid Layers and Elastic Sheets”

Advisor: David Nelson

Victor Rodriguez

Thesis: “Perturbative and Non-Perturbative Aspects of Two-Dimensional String Theory”

Advisor: Xi Yin

Emma Rosenfeld

Thesis: “Novel Techniques for Control and Transduction of Solid-State Spin Qubits”

Advisor: Mikhail Lukin

Polnop Samutpraphoot

Thesis: “A Quantum Network Node Based on a Nanophotonic Interface for Atoms in Optical Tweezers”

Advisor: Mikhail Lukin

Elliot Schneider

Thesis: “Stringy ER = EPR”

Advisor: Daniel Jafferis

Tyler St. Germaine

Thesis: “Beam Systematics and Primordial Gravitational Wave Constraints from the BICEP/Keck Array CMB Experiments”

Advisor: John Kovac

Steven Torrisi

Thesis: “Materials Informatics for Catalyst Stability & Functionality”

Advisors: Efthimios Kaxiras,
Boris Kozinsky

Matthew Turner

Thesis: “Quantum Diamond Microscopes for Biological Systems and Integrated Circuits”

Advisors: Ronald Walsworth,
Adam Cohen

Siddharth Venkat

Thesis: “Modeling Excitons in Transition Metal Dichalcogenide Monolayers”

Advisor: Eric Heller

Aditya Venkatramani

Thesis: “Quantum Nonlinear Optics: Controlling Few-Photon Interactions”

Advisors: Mikhail Lukin,
Vladan Vuletić

Ann Wang

Thesis: “A Search for Long-Lived Particles With Large Ionization Energy Loss in the ATLAS Silicon Pixel Detector Using 139 fb⁻¹ of $\sqrt{s} = 13$ TeV pp Collisions”

Advisor: Melissa Franklin

Grey Wilburn

Thesis: “An Inverse Statistical Physics Method for Biological Sequence Analysis”

Advisors: Sean Eddy,
David Nelson

Linda Xu

Thesis: “Searching for Dark Matter in the Early and Late Universe”

Advisor: Lisa Randall

Kexin Yi

Thesis: “Neural Symbolic Machine Reasoning in the Physical World”

Advisors: L. Mahadevan
Douglas Finkbeiner

Yichao Yu

Thesis: “Coherent Creation of Single Molecules from Single Atoms”

Advisor: Kang-Kuen Ni

Leo Zhou

Thesis: “Complexity, Algorithms, and Applications of Programmable Quantum Many-Body Systems”

Advisor: Mikhail Lukin



ACADEMIC PROGRAMS

Research Scholars

by Bonnie Currier

On September 17, 2020, we had our eighth annual Research Scholar Retreat, which had to be virtual, via Zoom. Sheldon Glashow, Harvard Higgins Professor of Physics, Emeritus, was our plenary speaker.

We hope to be able to have our ninth annual Retreat in person, on May 11, 2022. If we cannot meet live, we will again schedule virtually. We are currently planning our agenda.

Every year we try to have a panel for our graduate students on how to get a post-doctoral position. The panel, which is composed of some of our current scholars, is moderated by two of our current graduate students, and this year's panel was via Zoom on January 22, 2021.

On March 26, 2021, we had a panel on getting positions in US research labs, via Zoom. This panel, moderated by two of

our current research scholars, was composed of representatives from the following labs: Army Research Lab, Air Force Research Lab, Sandia National Labs, Brookhaven National Lab, National Institute of Standards and Technology, Fermi National Accelerator Lab, and Lawrence Livermore National Lab.

On June 11, 2021, we also had a panel on transitioning from academia to data science, again led by two of our current research scholars. The panel was composed of representatives from the following organizations: Amazon Web Services, Facebook, Google, Google Zurich, and PrognomiQ, Inc.

We are happy to report that all persons on all these panels were most receptive to our participants' questions about career opportunities and encouraged scholars and students to contact them any time.

Above: Research scholars enjoying lunch outdoors, October 2021.
(Photo by Bonnie Currier)

Alumni/ae Notes

1953

Stanley Deser (Ph.D.): I was just elected Foreign Member of the Royal Society, of whom there are only ~180 in all sciences worldwide, only 3 in Theor Phys.

1962

Barbara Wayne Abraham Shrauner (Ph. D.): My most notable accomplishment this academic year at 87 (6-21-2021) is being here despite two falls with an injured lymphedema left arm and fractured left rib. The new Wikipedia page was a pleasant surprise. The last journal publication was in 2019 but I have delayed projects on discontinuities in solar wind plasmas and hidden symmetries of nonlinear differential equations. Son, Jay Shrauner, Ph.D. in physics from Princeton, retired from Google and daughter Elizabeth Caspari teaches French and heads the language group at Clayton High. I have four grandchildren and two great grandchildren. Sadly, physicist husband Ely Shrauner died in 2015.

1963

Christopher McKee (A.B.): I retired from the Physics and Astronomy Departments at UC Berkeley in 2012, although I was recalled for administrative service twice after that. During the pandemic, I moved my office to my home and continued to do research in astrophysics, albeit at a slower pace than before my retirement.

1965

Diana Hartridge McSherry (A.B.): Until 2020 I loved my job and the company I founded, Digisonics. But remote work destroyed much of the joy I found from discussions on software for Medical IT. As my next door neighbor said, “2020 was the year from hell and then it froze over.” So last December I sold my company and for the first time since 1970 I do not go to work every day. I make lists for small items of interest, but soon, I hope to settle on a new project, perhaps in the astonishing overlap of physics and biology. A new type of battery based on Archaea organisms? Implications of crystal seed regeneration as step toward RNA? The rate of scientific discovery is astonishing, and I hope to find a place in this.

1967

Neal K. Baker (A.B.): After forty years of working on meteorological satellite programs, I have finally retired. I was in charge of development and production of meteorological sensors and the ground systems that processed the data to operational use. The sensors covered the electromagnetic spectrum from 19 GHz to X-rays for earth observations; magnetometers and particle detectors were used to measure the ionosphere. All the latest sensors are still operational on board the Suomi spacecraft

launched in 2011 and JPSS-1 spacecraft launched in 2017. The physics department taught me the importance of accurate calibration. In the space environment, calibration has been very challenging dealing with the various thermal and sun angle variations over the orbit.

Kevin Cahill (Ph.D.): During the pandemic, I've attended two conferences via Zoom and plan to attend a third and possibly a fourth later this year. If I had to pay to travel to these conferences, I would have gone to at most one of them. I've also attended many Zoomed seminars and colloquia. We also benefited from Zoomed colloquia, including excellent ones by Cumrun Vafa and Alan Guth. I hope that the physics community continue to allow people to attend conferences, seminars, and colloquia virtually. That would advance physics and be a huge advantage to most physicists.

Andrew A. Zucker (A.B.): A July report from the NAS/NRC, *Building Opportunity for the Future*, recommends improving equity in K-16 science education. It also recommends teaching students how to evaluate sources of “scientific” information (will a raw onion in your sock really draw toxins from your body?) and teaching students how to use science when making decisions in everyday life (products to buy, ballot initiatives, etc.). Are there implications for science education at Harvard, including the physics department? I believe there are. Professor Gerald Holton was co-author of a high school physics textbook in the 1960s. There is important history in this department.

1968

Joseph Seale (A.B.): As I enter my 76th year on Planet Earth, I approach my 40th wedding anniversary and am pleased to see three adult kids and two grandkids all managing to do well through the Pandemic and beyond. I retain the title of Principal Physicist for a contract engineering company, though the work has transitioned from full time to consulting when I'm needed. I was indeed needed throughout the Pandemic and co-headed the development of a surgical device. That has felt very fulfilling, and I continue to enjoy the work of employment and my own inventing.

1969

James K. Baird (Ph.D.): My wife, Peggy, passed away in 2017. We met in Oak Ridge, TN in 1965, while I was on GSAS “traveling guidance” status working on Norman Ramsey's neutron electric dipole moment experiment at the Oak Ridge National Laboratory. Because in youth, I didn't develop any hobbies, other than physics and chemistry, I am continuing my academic career as Professor of Chemistry and Adjunct Professor of Physics at the University of Alabama in Huntsville, Huntsville, AL.

1971

Richard J. Cohen (A.B.): After completing my undergraduate degree, I obtained a Ph.D. in Physics at MIT with George Benedek and an M.D. at Harvard Medical School. After several years of clinical training, I joined the faculty at MIT where I have conducted research using quantitative tools to study the cardiovascular system and to develop new diagnostic and therapeutic technologies. I have taught a wide range of courses in biomedicine, biomedical physics and engineering, and - more recently - biomedical enterprise. The time I spent in the Harvard Physics department inspired all that I have done professionally since then. Perhaps at Harvard I was inspired most by Edward Purcell with whom I maintained contact for many years after I finished my undergraduate degree.

1975

Jacquelyn A. Weiss (Ph.D.): After Harvard I was post-doctoral fellow in neurobiology at Stanford. Attended the Ph.D. -> M.D. program at University of Miami (two year program for science Ph.D. holders; M.D. received in 1979). Became a neurologist with additional training in clinical neurophysiology. Now live in the SF Bay Area working part-time (consultations) but may be moving back to the Boston area next year.

1980

Stephen Parke (Ph.D.): Currently Distinguished Scientist in Theoretical Physics Dept. Fermilab. [Article](#) and [podcast](#) in *Quanta Magazine* on byproduct of research on Neutrinos.

Marshall Thomsen (A. B.): I have been part of the faculty at Eastern Michigan University since 1987, thoroughly enjoying teaching students with wide-ranging backgrounds. I just finished a two-year stint on the APS Ethics Committee. I have served on the editorial board of the Online Ethics Center (onlineethics.org) for many years, a site that recently migrated from the National Academy of Engineering to the University of Virginia. Most recently, I have found myself immersed in helping update physics standards in Michigan for secondary ed science programs.

1984

Andrew Cooksy (A. B.): Perhaps believing that I could not make things any worse during the pandemic, my colleagues elected me chair of the Department of Chemistry and Biochemistry at San Diego State University in 2020. I hope to hire a chemical physicist, probably with a search to be carried out in Fall 2022, and hope that we may see applications from other alumni or your students.

Ethan Taub (A.B.): I came to Zurich as an HMS Moseley Traveling Fellow 25 years ago after completing neurosurgical training and have lived here ever since. I have been Head of functional neurosurgery (including deep brain stimulation) at the University Hospital in Basel since 2007. A sound knowledge of mathematical and physical principles is essential for competence

in my sub-specialty, and I am very glad to have studied these things in depth as an undergraduate. My wife, Elizaveta Shnayder Taub, from St. Petersburg, is a violinist in the Zurich Tonhalle Orchestra; our children, Alexandra, Ephraim, and Jeremy, are 13, 11, and 3.

1986

Jonathan Feldschuh (A.B.): My professional career doing scientific things unrelated to physics continues. My current role is as the Chief Scientific Officer for Daxor, a medical technology company, where I oversee research and development. My artistic career as a painter who takes physics as an inspiration also continues. I am looking forward to a solo show at 1GAP gallery in Brooklyn in the fall of 2021, featuring my works based on Feynman diagrams and the Large Hadron Collider.

Larry Guterman (A.B.): Loved physics but ended up going to USC Film School. Directed sequences in *Antz* for DreamWorks, then directed the movie *Cats & Dogs* for Warner Bros and other films and tv. I've incorporated my love for science/physics with my experience directing movies by co-founding a tech startup called SonicCloud in 2015, which personalizes the sound on smart-phones and computers for people with hearing loss. Mass. Eye & Ear/Harvard Medical School recommends it enthusiastically, and Apple featured us for Global Accessibility Awareness Day 2020. The need to level the playing field for people with hearing loss has increased during the pandemic because of the prevalence of remote work via conferencing platforms like Zoom, etc.

Eric B. Sirota (Ph.D.): I'm still doing soft condensed matter physics at ExxonMobil's basic research lab in Clinton, NJ, where I've been for 35 years. I'm also a composer/writer of musical theatre. My musical, *Frankenstein*, based on Mary Shelley's novel, played Off-Broadway in NYC for three years, just prior to the pandemic; I'm currently developing my new musical *A Good Day – Music, memory, an old flame and Alzheimer's*. www.EricSirota.com.

Michael Sokolov (A.B.): Contemporaries may remember my (legendary) Physics 123 project, a z80 microprocessor audio sampler that blasted "my name is Mike" repeatedly, or they may not. In any case our singular last year left my work life, still tormenting computers, largely unchanged, but the other dimensions mostly collapsed. To fill the void, I constructed a Greenland kayak in my garage out of wood and canvas and can occasionally be seen paddling it up and down the Charles.

Michael Weiss (A.B. '78; Ph.D. in biophysics): Adventures in biophysics continue as a Distinguished Professor at Indiana University and chair of the Department of Biochemistry & Molecular Biology at the IU School of Medicine. Studies of the folding and function of insulin, begun 35 years ago with the encouragement of the late Prof. Edward M. Purcell (undergraduate advisor) and emeritus Prof. M. Karplus (graduate advisor; Chemistry), recently culminated in two articles, one

demonstrating the evolution of insulin at the "edge of foldability" (<https://www.pnas.org/content/117/47/29618>) and the other its redesign with a self-regulating molecular switch (<https://www.pnas.org/content/118/30/e2103518118>). Medical implications of these findings (i.e., a "smart" form of the hormone) are leading to creation of a new company, GRI Therapeutics, Inc., that seeks to transform insulin replacement therapy for diabetes. Daughter Leah (Physics A.B. '13) received a Ph.D. in Physics at Cambridge UK (Trinity College '19) and is now a post-doc in condensed-matter physics at the University of Chicago.

1988

Daniel M. Kammen (Ph.D.): Dan's RAEL laboratory developed partnerships on off-grid energy and community-centered social justice to build and link networks of mini-grids in Rwanda, the DR Congo, and separately in Malaysia and Laos. RAEL's NGO spin-off, Energy Peace Partners, was recognized with for creating the "Peace Renewable Energy Credit" funding vehicle that has now been used to build the largest off-grid energy projects in Africa. In California, Dan co-directs projects on innovation in long-duration energy storage (with UC Merced), and on 100% clean energy community solutions in partnership with the California Energy Commission. With colleagues, Dan developed a pathway to an 80% decarbonized California by 2030. This year, Dan co-taught a new course, Envres 160 "Climate Justice," with Isa Ferrall. Dan chairs a new campus-wide Roundtable on Climate and Environmental Justice and has joined the board of directors of Native Renewables (Flagstaff, Arizona).

1989

Robin Blumberg Selinger (Ph.D.) is a Professor of Physics at Kent State University, working in computational soft matter theory. She was elected as General Councilor to the American Physical Society (APS) Council of Representatives for 2019-2022, and presently serves as Speaker-Elect of the Council and as a member of the APS Board of Directors. Robin is hoping for a return to in-person conferences so she can reprise her role as a volunteer performer at the March Meeting Rock-n-Roll Physics Sing-Along, organized by fellow alum Walter Smith (Ph.D. '89) of Haverford College.

1991

Giacomo Vacca (A.B./A.M.): In February 2020 we celebrated the 10th anniversary of the founding of my company, Kinetic River Corp.—a product development business focused on laser-based life science instrumentation. We have averaged 50% year-over-year growth over the past six years, and have been fortunate to receive four research grants from the NIH to help us demonstrate and develop our novel blood cell analyzers. The pandemic forced some adaptation, but last summer we were able to complete and deliver our first CE-marked instrument to a national laboratory in Naples, Italy. Recently I was issued my 60th patent, with lots more on the way.

1992

Bill Ashmanskas (A.B.): Physics 123, in fall 1991, taught by Melissa Franklin and Tom Hayes, was by far my favorite course—opening my eyes to a whole new way to see the world. A fun update is that lately I've had the good fortune to teach a similar electronics course, passing on the Physics 123 inspiration to the next generation. Shout-out to Melissa and Tom!

Christopher Ball (A.B.): I'm a Research Scientist at The Ohio State University and worked from home most of the past year. Months into the pandemic, an electrical fire in our kitchen displaced my family to a rental house for four months. Through this, I learned I'm very bad at working from home. I am too easily distracted by household chores and kids, and I really need separation from home to work most effectively. Ironically, I also learned that I missed the commute that I previously thought I hated. Turns out I really need that time between work and home to switch gears mentally.

1993

Joseph Barranco (A.B.): I was promoted to the rank of Full Professor in 2019 and was elected in 2021 to serve a second term as Chair of the Department of Physics & Astronomy at San Francisco State University, where I have been a professor since Fall 2007. My area of research is computational astrophysical & geophysical fluid dynamics with applications to star & planet formation and vortex dynamics on gas giant planets. Most recently, I am trying to transition my research into the physics of climate change, physical oceanography, and cloud physics.

Jean Cottam Allen (A.B.): I started a new job as the Deputy Director of the Division of Physics at the National Science Foundation just before the COVID shutdown began. It's been a difficult but rewarding 18 months. I've witnessed the challenges as well as the resilience of the Physics community, and I've had the opportunity to lead efforts to mitigate COVID impacts, particularly for students, postdocs and junior faculty in Physics.

2000

David Kaiser (Ph.D.) is Professor of Physics and Germeshausen Professor of the History of Science at MIT, where he also serves as Associate Dean for Social and Ethical Responsibilities of Computing. He co-directs a research group on early-universe cosmology with Alan Guth. A NOVA documentary film, *Einstein's Quantum Riddle*, which featured his group's efforts to conduct a novel "Cosmic Bell" experimental test of Bell's inequality, premiered in 2019. His most recent book, *Quantum Legacies: Dispatches from an Uncertain World*, was included among the "Best of Physics in Books, TV, and Film in 2020" by *Physics World* magazine.

Martino Poggio (A.B.): Since the fall of 2019 I've been serving a 2-year term as Chair of the Physics Department of the University of Basel, where I have been a professor since 2009. Recently an [interview](#) of mine appeared in the newsletter of the Condensed Matter Division (CMD) of the European Physical Society (EPS).

2001

Ben Dreyfus (A.B.): was awarded the 2020 Teaching Excellence Award at George Mason University, where he teaches physics and coordinates the undergraduate Learning Assistant program for the College of Science. He lives in Washington DC with his spouse and two children.

Alejandro Jenkins (A.B.): I'm currently finishing a one-year Ulam Fellowship at the International Centre for Theory of Quantum Technologies, in Gdansk, Poland, with a project on "energy conversion by open quantum systems." The pandemic limited my interactions during my stay, but I was glad to get out of online teaching! I'll stay in Gdansk for another couple of years as a mid-life postdoc. The most exciting work to emerge from this so far is a "Quantum theory of triboelectricity," *PRL* 125, 186101 (2020), co-authored with Robert Alicki, which opens new perspectives for understanding irreversible, active transport processes.

Chess Stetson (A.B.): In late 2019, Chess Stetson, Ph.D., raised a seed round for dRISK.ai, which sits roughly at the intersection of knowledge graphs and artificial intelligence. Whereas internet search engines make a knowledge graph of the internet, dRISK is making a knowledge graph of the real world, to retrain autonomous vehicles to be more performant than humans. Also involved in the effort was Kris Chaisanguanthum, Ph.D. (B.A., Physics, '01, Ph.D., Physics, '08), advisor to the company. dRISK received a major grant from the UK's Centre for Connected and Autonomous Vehicles to improve the way autonomous vehicles are tested and trained. After dRISK solves the autonomous vehicle problem, our ambition is to make the internet interesting again by using graphs as a common substrate for humans and computers to solve problems together.

2005

Thomas Pologruto (Ph.D. Biophysics): I was made the Chief Data Architect and Chief Technology Officer for Data Science and Liquid Markets at Blackstone last year. I very much enjoy helping the whole Blackstone family answer questions with data.

2006

Marc Parris (A.B.): Since graduating in 2006, I worked as a high school physics and chemistry teacher in Cambridge for four years, before attending medical school at UC San Francisco and residency in pediatrics and anesthesia at UC Irvine. After completing a fellowship in pediatric anesthesia in 2021 at the

Children's Hospital of Philadelphia, I will be joining the faculty as a Pediatric Anesthesiologist and an Assistant Professor of Anesthesiology and Critical Care Medicine at the UPenn School of Medicine. I currently live in Philadelphia with my wife, Arielle, and my two dogs, Thor and Ms. Cleo.

Eran Mukamel (A.B.): Responding to your call for updates, I'm happy to report that I was promoted to Associate Professor of Cognitive Science at UCSD. I am planning to spend a sabbatical during the 2021-22 academic year in Cambridge, MA and look forward to connecting with Harvard friends/colleagues.

2007

Alex Wissner-Gross (Ph.D.): Dr. Alex Wissner-Gross was delighted to announce a new strategic alliance between his AI software company, Gemedi, and Two Six Labs for continued development of innovative cybersecurity technologies. Also, his vision of the future of computing was featured in a book named Amazon's #1 New Release in Science Essays & Commentary: John Brockman, *The Last Unknowns: Deep, Elegant, Profound Unanswered Questions About the Universe, the Mind, the Future of Civilization, and the Meaning of Life*. To learn more, visit <https://www.alexwg.org>.

2008

Kevin Grosvenor (A.B.): I completed the 2020-2021 academic year as a Hallwachs-Roentgen postdoctoral fellow at the Max-Planck Institute for the Physics of Complex systems in Dresden. Earlier this year, I was awarded a Marie Curie Fellowship, which I will take to the Leiden Institute of Physics to work in the Quantum Matter Theory Group headed by Koenraad Schalm and Jan Zaanen.

2009

Michinao Hashimoto (Ph.D. Chemical Physics): I moved to Singapore after my Ph.D. and postdoc in Cambridge, and I am now running a research group studying microfluidics, soft matter, and 3D printing. Stop by if you are in the area! (Twitter: @SoftFluidics).

2011

Corry L. Lee (Ph.D.) had two novels come out from Solaris Books during the pandemic. In *Weave the Lightning* (2020), a young female resistance fighter hides a treasonous secret from the fascist state. The Russian-inspired fantasy epic continues in *The Storm's Betrayal* (2021). *NYTimes* Bestselling Author Seanan McGuire calls *Weave the Lightning* "focused and honed as a lightning strike, beautifully balanced and directed... a cutting story of revolution, rebellion, romance, and the sort of strange sorcery that we don't see very often."

2012

Benjamin Li (A.B.): I am currently in residency training in radiation oncology. It is one of the few fields in medicine that incorporates physics in its daily work, and it has been a pleasure to stay connected to philanthropic physicists in my medical physics department. I graduated with an MD/MBA from Vanderbilt in 2018 and am currently at UCSF Radiation Oncology in San Francisco. In 2018, I founded a non-profit organization to support medical physicists and other radiation oncology professionals in low-to-middle income countries where there is a thirst for knowledge and self-improvement! It has been a delight to lead this organization, which you can see at www.rayoscontracancer.org.

2013

Joanna Behrman (A.B.): earned her Ph.D. in the History of Science and Technology at Johns Hopkins University in July 2020, after which she began a new position at the American Institute of Physics as an Assistant Public Historian. In July 2021 she married Abel Corver (A.B. Linguistics 2016).

Juliana Cherston (A.B.): Wrapping up the final year of my Ph.D. at the MIT Media Lab. My work focuses on bringing unconventional technology into fundamental physics. Currently, I am evaluating electronic textiles in the context of astrophysics. My north star is to turn the fabric thermal blanket common on persistent spacecraft into an interstellar dust sensor, and next year electrically active swatches will launch to the Space Station's exterior walls. During my master's, I built a sonification platform that made it possible to listen to a tiny subset of musically interpreted proton collision data from ATLAS in real-time. I'm looking for postdocs either in interesting physics instrumentation or space-based condensed matter experiments.

Tony Pan (Ph.D.): Co-founder, Modern Electron. MIT Technology Review recognized our work on sustainable energy at Modern Electron in their annual [Innovators Under 35 list](#).

2014

Nick Hutzler (Ph.D.): My wife Mary Wahl and I had a son, Isaac, in January of 2019, and have another kiddo on the way for the fall. We are staying warm at Caltech in Pasadena and invite everybody

to come out and visit when that sort of thing becomes not a huge hassle.

2016

Alexander Isakov (Ph.D.): In late 2020, I was fortunate to have an opportunity to move abroad despite the pandemic – all the way to Seoul, South Korea – to take a leadership role at Coupang. While my role is far from physics research, I find myself using core principles of my Harvard training every day: mentoring junior colleagues, team-building, asking “why” and thinking critically about complex data for major business decisions. And (sometimes) I do discuss AI and large-scale optimization challenges with peers. I believe this is an often overlooked part of the beauty of the department: it provides a stable foundation no matter where you are or what you do.

2017

George D. Torres (A.B. Physics & Math): I got married in early 2020 and am entering my last year of a Math Ph.D. at UT Austin focusing on moduli spaces of curves and tropical geometry. During my spare time, I also started working in the defense industry as a machine learning engineer and data scientist. As part of that role, I have deployed overseas twice in support of US government data science operations overseas.

2018

Denis Turcu (A.B. Physics & Math): After graduation, I transitioned to studying Theoretical Neuroscience for my Ph.D. at Columbia University. I am glad to have landed on a cool project which involves quite a bit of electromagnetism knowledge and had me dust off the Jackson book. I am modeling a weakly electric fish and its behavior - the fish can figure out resistive and capacitive properties of nearby objects by generating electric currents from its tail. I hope to learn how this fish has such a good understanding of electromagnetism and who taught it. For this project, I was awarded the Boehringer Ingelheim Fonds Ph.D. Fellowship.

2020

William Weiter (A.B. Physics & Math): Ph.D. candidate applied math SEAS Harvard. Never leaving Cambridge.

IN MEMORIAM: ARIANNA WRIGHT ROSENBLUTH

Innovative Physicist Built Foundation for Modern Computer Science



by Madeline Whitacre

Archivist-historian at the
National Security Research
Center, Los Alamos
National Laboratory*

Arianna Wright Rosenbluth — former Los Alamos physicist and last surviving contributor to the seminal 1953 paper “Equation of State Calculations by Fast Computing Machines” on the first uses of what is now known as the Metropolis algorithm — passed away in December 2020 at age 93 from COVID-19 related causes.

The Metropolis algorithm is a Markov chain Monte Carlo method that continues to be foundational in the modern world of computer science. Its applications today range from weather forecasting to climate change modeling, computer graphics, AI, economic analysis, and more.

“The Metropolis algorithm enabled the application of the Monte Carlo method to a broad class of problems to which the original Monte Carlo techniques of Ulam and von Neumann were inapplicable. Its simplicity facilitated the eventual spread of its use throughout the quantitative sciences and engineering and even in the social sciences and humanities. It helped establish the Monte Carlo method as a ‘go-to’ method for understanding large, complex problems,” said Jim Gubernatis of the Laboratory’s T-4 group.

Early years

Growing up in Texas, Rosenbluth showed an affinity for science at an early age. She graduated with a bachelor’s in physics from Rice University at age of 18 and a master’s in physics from Radcliffe College a year later. In 1947, she began working on her doctorate at Harvard University, where she studied under John Van Vleck, who won the Nobel Prize in Physics in 1977.

Rosenbluth completed her thesis under Van Vleck in February 1949 on the subject of paramagnetic relaxation. Following graduation, she took a postdoc position working for the Atomic Energy Commission under physicist Felix Bloch, who won the Nobel Prize in Physics in 1952.

MANIAC and other important work

[...]Arianna was offered a position at what was then known as the Los Alamos Scientific Laboratory (LASL) in 1950, and married fellow physicist Marshall Rosenbluth in 1951. Soon after, the two collaborated on calculations for Ivy Mike — the codename given to the first full-scale test of a thermonuclear device, which occurred at Enewetak Atoll — using the Standards Eastern Automatic Computer (or Standards Electronic Automatic Computer) at the National Bureau of Standards in Washington, D.C.

At LASL, Arianna and Marshall continued working together on problems involving early computers, including MANIAC — one of the first computers built under the direction of famed Manhattan Project physicist Nicholas Metropolis.

With MANIAC, the Rosenbluths, along with Edward and Augusta Teller and Metropolis developed an advanced statistical problem-solving method they called the Metropolis algorithm.

Arianna played a large role in the work, programming the computer implementation of the algorithm. In 1953, Metropolis, the Rosenbluths, and the Tellers penned and published the aforementioned “Equation of State Calculations by Fast Computing Machines.”

Although her contributions were instrumental to the success of the project, until recently, Arianna’s contributions have often been overlooked. In fact, Arianna was able to successfully program and run the algorithm almost single-handedly.

In June of 1956, Arianna quit working at LASL. The Rosenbluth family moved to California, where Marshall worked at General Atomic. Despite her previous success, Arianna did not return to work, instead choosing to stay at home to raise her children.

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(Arianna Wright Rosenbluth photo credit: Rosenbluth family)

A Tribute to Staff Members Who Have Recently Retired

by Steve Nadis



BARBARA DRAUSCHKE

More than 45 Years of Dedicated Service

In 1972, Barbara Drauschke graduated from Wheelock College with a degree in early childhood education. Her plan, all along, had been to become a teacher, but at that time she was unable to find a good

position in the Boston area, so she instead took a temporary job at the Cambridge Electron Accelerator (CEA), a joint Harvard-MIT facility where she had worked during the three previous summers. After a year at the CEA, Drauschke crossed Oxford Street to become a faculty assistant in the Physics Department; she remained there over a span of 48 years until her retirement on April 30, 2021.

While it may have been a loss for the world of early childhood education, “the fact that Barbara ended up at Harvard Physics all this time has been transformational for us,” said Arthur Jaffe, the Landon T. Clay Professor of Mathematics and Theoretical Science. “I’ve never come across an assistant who was as talented and had such good instincts as Barbara.” Jaffe first recognized her abilities, he said, “by seeing the alacrity with which she could prepare technical manuscripts using an old-fashioned IBM typewriter with two keyboards and replaceable symbol keys.”

Drauschke worked for about a dozen professors during her tenure at Harvard, which started in 1973, but she worked for Jaffe the entire time—a staff-faculty partnership that may well have been a record in terms of longevity within the Physics Department and perhaps any department in the university.

In 1979, Jaffe became chief editor of *Communications in Mathematical Physics*. When he was first offered the position,

which he ended up retaining for 21 years, Jaffe insisted that he “wouldn’t take the job unless Barbara served as my assistant, and that started a very long collaboration.”

“Working on that journal was definitely a highlight of my career,” said Drauschke, who stayed on as the *Communications* copy editor for 33 years.

During those three-plus decades, Jaffe noted, “Barbara was the only person in the entire world who read every article accepted for publication in the journal.” And even though she never studied mathematics or physics, he added, she found an enormous number of errors in these papers—not just errors in grammar, but sometimes mathematical errors or critical gaps in logic. One journal author wrote a letter to “Dr. Drauschke,” thanking her for spotting a mathematical mistake in his paper, which she discovered through his incorrect use of English. Later, another aspiring author thanked “Professor Drauschke” for uncovering a mathematical error that had eluded a highly qualified referee but was so serious that the paper had to be withdrawn. “And that was how Barbara was promoted first to a Ph.D. in mathematics and then to full professor,” Jaffe quipped.

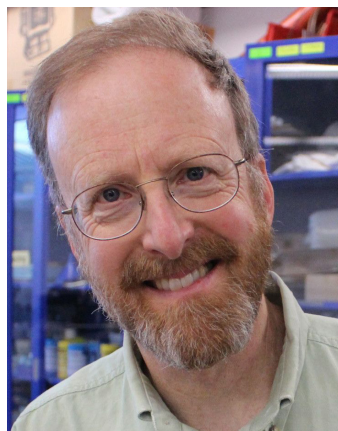
Before leaving the department in April, Drauschke had turned down two previous offers to retire because she “loved working at Harvard and was happy to go to work every day. And on most days, I encountered something different, which enabled me to learn something new.”

Just as Drauschke enjoyed going to work, her colleagues enjoyed her presence, and contributions, too. “Barbara was such an asset to the department and her colleagues,” said Hannah Belcher, a physics student coordinator and former faculty assistant. “I’ve never met someone with such a capacity for helping everyone with absolutely everything.”

Samantha Dakoulas, another faculty assistant, felt “extremely lucky to have overlapped with just a short portion of Barbara’s tenure in the department. She is one of the kindest people I’ve ever worked with, always willing to lend a helping hand or troubleshoot a problem,” Dakoulas commented. “In times of

stress, I know many of us have appreciated her calm demeanor.”

Although her “life plan” of becoming a teacher never happened, Drauschke said, “I’m very happy with the way things worked out.”



ROB HART

Finding the Right Balance in Harvard Physics

For much of his professional life, Rob Hart was pulled in two different directions: He really liked working in physics labs—devising experiments, designing apparatus, and taking precision

measurements. But he also

found teaching extremely rewarding. The problem was that in the jobs he took on, he was forced to pick just one of those pursuits—that is, until 2007, when he landed a position in the Harvard Physics Department that provided the balance he’d long yearned for.

Born and raised in rural Indiana, Hart attended Hanover College (also in Indiana) where he majored in physics and music. Upon graduating in 1978, he spent three years researching laser spectroscopy at Bell Labs. He then attended graduate school at Cornell, earning a Ph.D. in 1991 for his research on semiconductor physics. After that, he taught for two years at Union College and Barnard in New York. He then worked for a decade at Abiomed, a Massachusetts-based medical technology company, where he utilized his skills in building scientific instruments. He worked, for example, on developing an artificial heart, which was tested in clinical trials. He also holds a patent on a rotary blood pump designed to reduce the strain on the heart.

In 2002, Hart shifted gears, taking a teaching position at the Waring School near Boston. For three years, he taught physics, chemistry, math, and music to students in grades 6 through 12. The experience was intellectually satisfying and exhilarating but also exhausting, he said. “I needed to get back into the lab and solve some technical problems to balance out the time spent teaching.”

In 2006, he taught physics at the Harvard Extension School, where he met Wolf Rueckner, who also worked in the Physics Department’s teaching labs. At Rueckner’s prompting, Hart joined the teaching labs staff in the summer of 2007, staying until he retired in January 2021. Within Harvard’s physics department, Hart finally found the mix of technical work and teaching that he had sought for years.

“Rob has the skill set that complements everyone else in our group,” commented Joe Peidle of the teaching labs. “He’s very good at rapid prototyping and brainstorming. If a professor wanted a lab experiment on oscillators for, say, ‘The Physics of Music and Sound’ course, Rob could come up with lots of good ideas and even prototypes within five minutes.”

“Rob’s designs are very elegant,” added physic professor Mara Prentiss, who worked closely with Hart. “Rob showed particular creativity in helping students with experiments involving music and sound.”

In 2014, Hart created a section for Harvard students in the MIT course, “How to Make Almost Anything.” He took an empty room in the Harvard Science Center and turned it into a “maker space” that is now used by physics students in that and other courses, and also by students from the Design School, Education School, and other parts of the university. “Rob had an enormous impact that extended well beyond the Physics Department,” Prentiss commented.

Hart, for his part, is gratified to see that “genuine learning” is going on in the space he helped create. “The students are motivated by their own curiosity and by what they want to make,” he said, “rather than following a recipe that someone else came up with.” The great challenge in instructional labs, he added, “is to leave enough questions open so that students have room to learn on their own.”



TOM HAYES

By All Accounts, an Unconventional Career in Physics

The author's bio to the book, *Learning the Art of Electronics*, reads as follows: "Tom Hayes reached electronics via a circuitous route." That would seem to be an understatement, and the same word, "circuitous,"

also applies to Hayes' path to the Harvard Physics Department, where he worked from 1977 until December 2020 when he chose to retire.

As a Harvard undergraduate in the 1960s, Hayes might have majored in English, but he was dissuaded by his roommate Wally Shawn (the playwright and actor) who told him that would likely ruin his enjoyment of literature. So Hayes majored in history instead. He eventually went to Harvard Law School, which is what his family had expected him to do, earning his J.D. in 1969. He then joined a Wall Street firm for three years, where he learned, among other things, that he was totally unsuited to being a lawyer. "I didn't care about what we were working on," Hayes said. "And I didn't care whether our clients won or lost."

He quit his job and took a three-month hiatus in order to decide whether to become a lawyer for good or resume his education and become a law school teacher instead. After three months, he decided he didn't want to do either, at which point, Hayes said, "things were absolutely wide open."

He moved back to Cambridge, because he had friends there and felt that New York City just didn't have enough trees. He devoted his mornings to writing and the afternoons to electronics, tinkering with the various inventions he had dreamed up. At nights, he worked in the Original Steve's Ice Cream Shop, which was located a mile or so from Harvard Square.

Hayes had some success in writing and even published a "Talk of the Town" piece in the *New Yorker*. But he realized that pursuing electronics on his own was inefficient, especially considering that he'd never taken an electronics or physics course. He started sitting in on classes at MIT, where he met a student who told him to try Harvard's Laboratory Electronics

course taught by the (now-retired) physicist Paul Horowitz. "That was my dream course in electronics—one that seemed to have been designed just for me," Hayes said. "I was so enthusiastic that they asked me to become a teaching assistant." Hayes joined the department in 1977, working alongside Horowitz as an assistant first and then a lecturer.

"Paul taught me practically everything I know about electronics," Hayes noted. "He presents the subject in an intuitive way, using lots of examples. His general approach is to avoid rushing into the math, as he felt that could obscure—rather than illuminate—the picture."

Horowitz insisted that he enjoyed and benefitted from the collaboration too. "We learned from each other," he said. "It was so much fun working with Tom and learning the craft of teaching from him."

They split the course into two sections and complemented each other's strengths. "Given my peculiar background, it was easier for me to understand what was baffling to the students," Hayes said.

Horowitz agreed: "Students found Tom the easier one to approach. 'Horowitz knows everything,' they would say, 'but Tom holds our hands.' As Tom put it, he was Tom State and I was Paul University."

But Horowitz gives his former co-teacher a lot more credit than that. "Sometimes Tom would come up with an innocent question like: 'How come variable speed drills work well but variable speed train sets don't?'" Well, that question was not so naïve after all, Horowitz said, as it led to a new section in the advanced, 2020 edition of *The Art of Electronics* (which he wrote with Winfield Hill).

Horowitz appreciated the humor that Hayes brought into their joint writing effort, *Learning the Art of Electronics*, of which Hayes was the lead author. To explain negative feedback, for example, Hayes drew a cartoon depicting a scene from "On the Waterfront" and another involving a horse and a cowboy. "The book is full of that kind of stuff," Horowitz commented.

"As things turned out," he added, "Tom State and Paul University made a pretty good combo."



Departmental Events

For details about our upcoming events, please consult the Harvard Physics Calendar webpage: <https://www.physics.harvard.edu/events/genca1>.

Loeb and Lee lectures are coming back, including in-person and remote options!

For access to Zoom sessions, please email:
physics_colloquium@fas.harvard.edu.

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

and YouTube channel: <https://youtube.com/harvardphysics>.

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Above: Joint Lukin and Park groups meeting in one of the tents in front of Jefferson Lab. These tents are being used for course sessions, group study, and various other meetings. (Photo by Paul Horowitz)