EQuad News
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PRINCETON

School of Engineering
and Applied Science

THE POWER OF THE SMALLEST REALM

DEAN'S NOTE

Investing in the revolution of quantum engineering

Princeton's vision for making audacious, long-term investment in transformative research has driven tremendous growth in Princeton Engineering. The impacts we are having right now in solving problems and bringing innovations to society are the products of sustained work in bioengineering, robotics, machine intelligence, the future of cities, energy and the environment, and other fields. To maximize our impact for the decades ahead, we must invest boldly and strategically to spawn research and innovation that will serve humanity through the next century.

Quantum engineering is a great example of an audacious bet on research we are making now. In the middle of the last century, physicists discovered the strange behaviors of atomic particles – like an electron that can be in two places at once or particles that can be "entangled" over long distances despite no discernable connector. Today, our engineers are at the cusp of harnessing these otherworldly behaviors to create new technologies with the potential to drastically enhance computing, security, and energy efficiency for the good of humanity and the planet.

Please read this issue of EQuad News to learn about just a few of the exceptional Princeton Engineers in this area and where they are moving this important field. And, as always, I look forward to hearing from you about how you are bringing technology and innovation together to benefit humanity, in small ways and large.

Andrea Goldsmith
Dean
Arthur LeGrand Doty
Professor of Electrical
and Computer Engineering

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Note on alumni class years
Following Princeton University convention, undergraduate alumni are indicated by an apostrophe and class year; graduate alumni, whether master's or doctoral, are indicated with a star and class year.

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A FLUID INTERACTION INSPIRED A BREAKTHROUGH IN FLUID DYNAMICS

It's a little-known fact that tiny particles like blood cells drift sideways when moving past a rough surface, but this quirk has drawn much attention from researchers solving industrial problems.

If engineers can unlock the rules behind this tiny movement, industries can use them to isolate biological samples, detect and diagnose disease, or sort synthetic particles.

Danielle Chase, a graduate student at Princeton Engineering, and Christina Kurzthaler are co-first authors of a paper in the Proceedings of the National Academy of Sciences that offers the first general model describing the interaction of patterned surfaces and sedimenting particles.

Chase, advised by Professor Howard Stone, worked closely with Kurzthaler, a former postdoctoral fellow in Stone's lab and now a research group leader at the Max Planck Institute for the Physics of Complex Systems. Together they pinned down the system's "rules" so researchers can predict how their designs will work instead of using trial-and-error.

"It was satisfying to finally understand the mechanism causing the helical trajectories and overall drift and to have a hydrodynamic model that described our experimental observations so that we could predict what would happen if, say, someone tried to separate two objects of different sizes," Chase said.

Beyond the achievement itself, Chase said she enjoyed the sense of open-ended discovery and collaboration. Chase designed and built the physical experiments while Kurzthaler developed the theoretical model describing the behavior.

While previous researchers used experimental setups to observe particles flowing through thin channels, Chase and Kurzthaler got rid of the walls except for one patterned surface. This allowed them to limit the variables and focus just on the particle and the surface.

"I think what we learned in the end really benefited from us both having different approaches to the problem," Chase said. "Having a theory helps to design good experiments and having measurements helps to confirm the theory."

Now close to completing her doctoral work, Chase is excited to continue research in fluid dynamics. "The more you learn, the more questions you find." **– by Steven Schultz**

Danielle Chase is a graduate student in the lab of Professor Howard Stone. Photo by David Kelly Crow

EQUATIONS EXPLAIN ENIGMA OF EXPANDING ORIGAMI

Most materials — from rubber bands to steel beams — thin out as they are stretched, but engineers can use origami's interlocking ridges and precise folds to reverse this tendency and build devices that grow wider as they are pulled apart.

Researchers increasingly use this kind of technique, drawn from the ancient art of origami, to design spacecraft components, medical robots, and antenna arrays. However, much of the work has progressed via instinct and trial and error. Now, researchers from Princeton Engineering and Georgia Tech have developed a general formula that analyzes how structures can be configured to thin, remain unaffected, or thicken as they are stretched, pushed, or bent.

Some origami figures expand when stretched, a configuration useful to scientists and engineers. Photo by Robert Felt/Georgia Tech

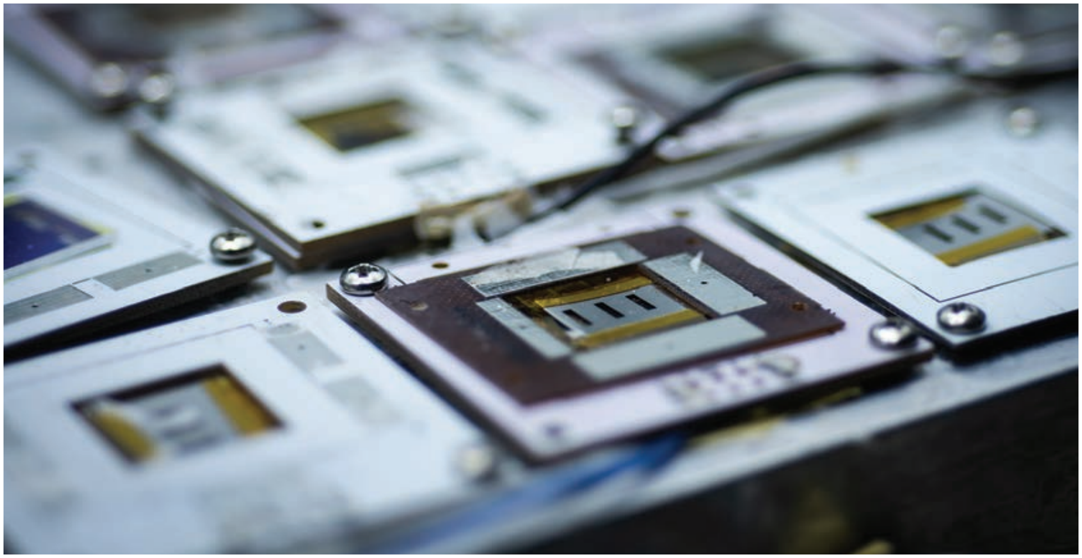
In work published in the Proceedings of the National Academy of Sciences, the researchers laid out their general rule for the way a broad class of origami responds to stress. The rule applies to origami formed from parallelograms (such as a square, rhombus, or rectangle) made of thin material. In their article, the researchers used origami to explore how structures respond to certain kinds of mechanical stress — for example, how a rectangular sponge swells in a bowtie shape when squeezed in the middle of its long sides. Of particular interest was how materials behave when stretched, like a stick of chewing gum that thins as it is pulled at both ends. The ratio of compression along one axis with stretching along the other is called the Poisson ratio.

"Most materials have a positive Poisson ratio. If, for example, you pick up a rubber band and stretch it, it will become thinner and thinner before it breaks," said study coauthor Glaucio Paulino, the Margareta Engman Augustine Professor of Engineering at Princeton. "Cork has a zero Poisson ratio, and that is the only reason you can put the cork back in a wine bottle. Otherwise, you would break the bottle."

The researchers were able to write a set of equations to predict how origami-inspired structures will behave under this kind of stress. They then used the equations to create origami structures with a negative Poisson ratio — origami structures that grew wider instead of narrower when their ends were pulled, or structures that snapped into dome shapes when bent instead of sagging into a saddle shape.

"With origami you can do this," said Paulino, a professor of civil and environmental engineering and the Princeton materials institute. "It's an amazing effect of geometry."

– by John Sullivan



An emerging class of solar energy technology, made with perovskite semiconductors, has passed the long-sought milestone of a 30-year lifetime. The Princeton Engineering researchers who designed the new device also revealed a new method for testing long-term performance, a key hurdle on the road to commercialization. Photo by Bumper DeJesus

ONCE SEEN AS FLEETING, A NEW SOLAR TECH PROVES ITS LASTING POWER

Princeton Engineering researchers have developed the first perovskite solar cell with a commercially viable lifetime, marking a major milestone for an emerging class of renewable energy technology. The team projects their device can perform above industry standards for around 30 years, far more than the 20 years used as a threshold for viability for solar cells.

The device is not only highly durable, it also meets common efficiency standards. It is the first of its kind to rival the performance of silicon-based cells, which have dominated the market since their introduction in 1954.

Perovskites are semiconductors with a special crystal structure that makes them well suited for solar cell technology. They can be manufactured at room temperature, using much less energy than silicon, making them cheaper and more sustainable to produce. And whereas silicon is stiff and opaque, perovskites can be made flexible and transparent, extending solar power well beyond the iconic panels that populate hillsides and rooftops across America.

But unlike silicon, perovskites are notoriously fragile. Early perovskite solar cells (PSCs) lasted only minutes. The projected lifetime of the new device represents a five-fold increase over the previous record, set by a lower-efficiency PSC in 2017.

The Princeton team, led by Lynn Loo, the Theodora D. ’78 and William H. Walton III ’74 Professor in Engineering, revealed their new device and their new method for testing such devices in a paper published in Science.

Loo said the record-setting design has highlighted the durable potential of PSCs, especially as a way to push solar cell technology beyond the limits of silicon. But she also pointed past the headline result to her team’s new accelerated aging technique as the work’s deeper significance.

“We might have the record today,” she said, “but someone else is going to come along with a better record tomorrow. The really exciting thing is that we now have a way to test these devices and know how they will perform in the long term.” **– by Scott Lyon**

THE BEST PLACE TO STORE ENERGY FOR THE ELECTRIC GRID? YOU MIGHT BE STANDING ON IT.

For parts of the United States, the best place to store massive amounts energy for the electric grid could be right beneath our feet.

Geothermal energy, which relies on hot rock far below the earth's surface, has long been used as a source of heating and electricity generation. But recent advances in drilling technology have opened new opportunities to widely deploy geothermal power, and spurred Princeton researchers to demonstrate that geothermal also can serve as an ideal technology for energy storage. What's more, geothermal can complement wind and solar energy, providing power when the sun is not shining or the wind dies down, the researchers reported in the journal Applied Energy.

"Across the western United States where there's a lot of geothermal potential, this could be the missing piece of the puzzle to get all the way to a carbon-free electricity system in conjunction with lots of wind and solar and shorter-duration batteries and demand flexibility," said Jesse Jenkins, the project's lead researcher and an assistant professor of mechanical and aerospace engineering and the Andlinger Center for Energy and the Environment.

Blue Mountain Geothermal Plant, Nevada Geothermal Power, Humboldt County, Nevada. Photo by Dennis Schroeder/NREL

Geothermal is an ancient technology and has been used for heating for centuries. In modern times, geothermal has expanded to power industry, drive heat pumps, and supply electric power to the grid. The renewable energy technology's advantages include its constant generation, relatively low maintenance, and zero carbon production.

But for grid-scale electricity, geothermal remains a niche player. That's because the technology requires specific locations. Mainly, engineers need hot geological regions fairly close to the surface, fissured rock formations that serve as radiators, and access to fluid to move the heat to the surface. That is changing rapidly as engineers are developing new technologies with an eye to vastly expanding geothermal electricity generation.

The key innovation harnesses technologies from the oil and gas sector, including directional drilling and hydraulic stimulation, to create artificial fracture systems wherever one can find hot, impermeable rock. If successful, companies commercializing these new techniques could unlock a clean, renewable resource capable of eventually supplying hundreds of gigawatts of power in the United States alone.

"That ability to move away from these very specific locations where you have all the right things in the right place, to just anywhere where you have hot enough rocks accessible without drilling too deep, means that enhanced geothermal can open up a much broader resource base," Jenkins said.

– by Sharon Waters

STUDY POINTS TO STRATEGIES FOR CLOSING THE PARTICIPATION GENDER GAP IN ENGINEERING COURSES

Students' identities can play a key role in how comfortable they feel and how often they speak up in the classroom, especially in STEM fields. For instance, women generally speak far less than men in undergraduate engineering classes, but this is not always the case, according to Princeton researchers. When classes are taught by women instructors, the gender gap practically disappears.

Another major factor in women's class participation is participation by other women — the researchers found that women are much more likely to speak after another woman has spoken in class.

"That was one of the findings that I was most excited about, because it felt like something that could really be leveraged to change teaching practices," said study coauthor Nikita Dutta, who completed a Ph.D. in mechanical and aerospace engineering at Princeton in 2021 and is now a Director's Postdoctoral Fellow at the National Renewable Energy Laboratory.

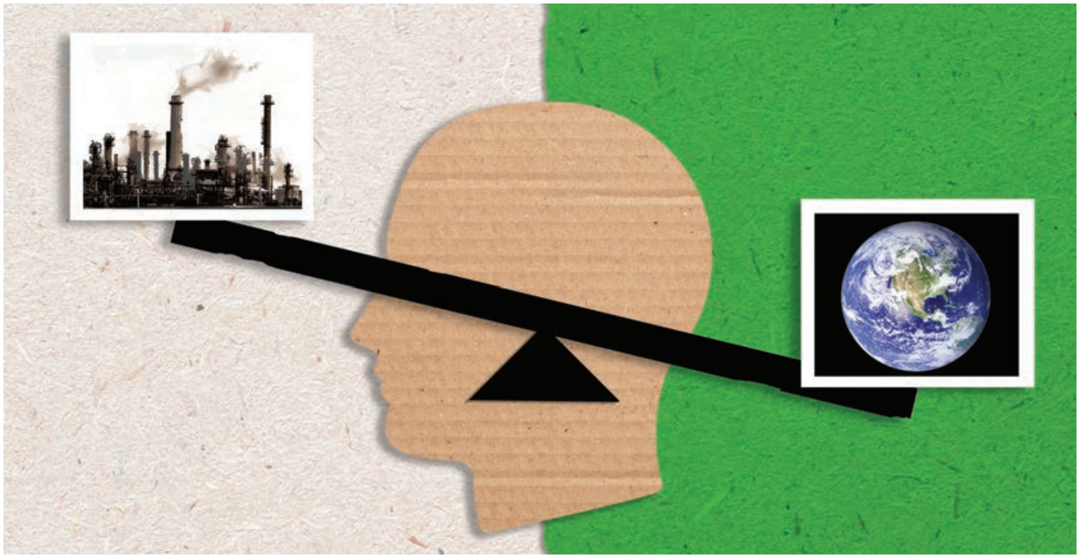
The study, published in IEEE Transactions on Education, included observations of 1,387 student comments in 10 different courses in Princeton's engineering school. While the students observed in the courses were 45.5% women and 54.5% men, only 20.3% of the classroom comments came from women. This gender gap widened slightly when the researchers considered only courses taught by men, but almost disappeared with a woman instructor.

Investigating the timing of students' comments, the researchers found that after one woman participated in class, during the next minute the proportion of comments by women rose to 32.4% — an effect that decayed over time but lasted for nine minutes after the initial comment.

Women generally speak far less than men in undergraduate engineering classes, but this is not always the case, according to Princeton researchers. When classes are taught by women instructors, the gender gap practically disappears. Image by iStock

The classroom observers labeled students' comments as "concept questions," "clarifiers," "answers" or "general comments" not directly related to course content. Women participated more frequently after another woman's comment, regardless of comment type, which points to icebreaker questions as a strategy that instructors can employ to promote participation and refresh students' attention.

Involving more women as co-instructors, guest lecturers and teaching assistants could also help close the participation gender gap by tapping into the effect seen in courses taught by women, said Dutta, who coauthored the research with Craig Arnold, the Susan Dod Brown Professor of Mechanical and Aerospace Engineering and Princeton's vice dean for innovation. **– by Molly Sharlach**



Most Americans support action to address climate change but public perception doesn't reflect this. Illustration by Bumper DeJesus

FIGHTING CLIMATE CHANGE IS WILDLY POPULAR BUT MOST AMERICANS DON'T KNOW THAT

Just after the U.S. Congress passed the nation's most substantial legislation aimed at battling climate change, a new study showed that the average American badly underestimates how much their fellow citizens support substantive climate policy. While 66-80% of Americans support climate action, the average American believes that number is 37-43%, the study found.

"It's stunning how universal and shared that idea is, among every demographic," said Gregg Sparkman, a postdoctoral research associate at Princeton and the paper's first author.

The research, led by Elke Weber, the Gerhard R. Andlinger Professor in Energy and the Environment and professor of psychology and the School of Public and International Affairs, was published in Nature Communications.

The study found that conservatives underestimated national support for climate policies to the greatest degree, but liberals also believed that a minority of Americans support climate action. The misperception was the norm in every state, across policies, and among every demographic tested, including political affiliation, race, media consumption habits, and rural vs. suburban. The actions that the researchers surveyed were major climate policies that could play a role in the United States mitigating climate change, including a carbon tax, siting renewable energy projects on public lands, sourcing electricity from 100% renewable resources by 2035, and the Green New Deal. The trend of Americans largely underestimating such support held true for every single policy.

Sparkman said that this underestimation of support is problematic because people tend to conform to what they think others believe, which would weaken actual support for such policies.

"They fall into a trap of: I support this but I think other people don't, so in a democratic society, that means there's nothing else to be done, beyond maybe convincing your peers," said Sparkman.

Sparkman added that this research could provide a morale boost for climate advocates or even for Americans who are experiencing soaring levels of anxiety related to climate change. It could also help focus the agenda for climate activists who think they are facing an uphill battle with fellow Americans.

– by Molly A. Seltzer

ENGINEERING FACULTY NAMED TO LEADERSHIP ROLES

In 2022, four Princeton Engineering faculty members took on new leadership roles at the University.


Rodney Priestley. Photo by Frank Wojciechowski

Rodney Priestley, the Pomeroy and Betty Perry Smith Professor of Chemical and Biological Engineering, was named dean of the Graduate School.

Nearly 3,000 students are enrolled in the Graduate School pursuing master's and doctoral degrees in 42 departments and programs. The dean of the Graduate School reports to the provost.

Priestley will continue as co-director of the NSF Innovation Corps (I-Corps) Northeast Hub, a Princeton University-led consortium of regional universities that will form a new innovation network with a $15 million grant from the National Science Foundation, fostering innovation at Princeton and throughout the region.


Craig Arnold. Photo by David Kelly Crow

Craig Arnold, the Susan Dod Brown Professor of Mechanical and Aerospace Engineering, succeeded Priestley as the University's vice dean for innovation, a role established in 2020 to provide academic leadership for innovation and entrepreneurship activities across campus.

The role of the vice dean includes strengthening the University's capacity to engage with technology investors, industry, entrepreneurs, alumni, and other potential partners. The position leads the Princeton Innovation initiative and oversees the University's efforts to grow Princeton's culture of innovation across disciplines.

Richard Register '86, the Eugene Higgins Professor of Chemical and Biological Engineering, was named director of the Princeton Institute for the Science and Technology of Materials. Register succeeded Arnold, who served as the institute's director for seven years.

Register takes over the institute after several years of expansion. With core facilities in imaging and microanalysis, and in micro- and nanofabrication, the institute has developed into a leading facility for analysis and design both nationally and internationally. Research volume has increased by 50% in the past three years, and course enrollment has grown by 35%. The institute has doubled the area of its facilities, adding three new centers and spearheading new industrial programs with the state of New Jersey.


Richard Register. Photo by David Kelly Crow

Arvind Narayanan was appointed director of the Center for Information Technology Policy (CITP), effective July 2023. Narayanan is a computer scientist whose pioneering approach to teaching and research has shaped the study of fairness in algorithms, cryptocurrencies and blockchains, and advanced privacy technologies.


Arvind Narayanan. Photo by David Kelly Crow

Narayanan is on sabbatical during the 2022-23 academic year. In the interim, CITP is being led by Prateek Mittal, a ssociate professor of electrical and computer engineering.

CITP is a joint initiative of the School of Engineering and Applied Science and the Princeton School of Public and International Affairs.

– by the Office of Engineering Communications

While this magazine was on press, Princeton University appointed **Jennifer Rexford** '91 as provost, effective March 13. Rexford is the Gordon Y.S. Wu Professor in Engineering and chair of the Department of Computer Science.

HURRICANE PROJECTIONS POINT TO RISING RISKS — AND SMART SOLUTIONS FOR RESILIENCE

Ning Lin*10 takes a holistic approach to studying the risks and impacts of hurricanes, including the combined hazards of extreme winds, storm surge, and heavy rainfall. An associate professor of civil and environmental engineering, Lin uses computational modeling to predict the effects of climate change on extreme storms, and inform strategies to mitigate impacts on power systems and communities.

Ning Lin. Photo by David Kelly Crow

One of her group's recent studies, published in Nature Climate Change, is among the first to assess how climate change could impact the frequency of extreme rainfall-surge events. Using physics-based climate and hurricane hazard models and statistical analyses, the study projected a dramatic rise in how often joint 100-year events — that is, events with a 1% chance to happen in any given year for both rainfall and storm surge in the historical period — will occur by the year 2100.

Climate change could make heat waves a dangerous hazard of future hurricanes. Photo by iStock

Along the Gulf of Mexico, extreme rainfall-surge events have historically occurred on average every 200-500 years. But by the end of the 21st century, according to the study's findings, these extreme events may occur on average every 10-30 years. The outlook is even direr in New England, where extreme joint events are rare in the historical climate, happening on average less than once in a thousand years. However, by the end of the century, these calamitous events may occur on average once every five years.

"We've been learning that as joint hazards, surge and rainfall really should be studied together, and right now that's where my work is going," said Lin. "The current and future joint hazard posed by hurricanes has not been well quantified, but with this study, we're now getting a clearer, and unfortunately, sobering picture."

A second study, published in Nature Communications, investigated the risk of a compound hazard involving a hurricane followed by a blackout and a heat wave, using Harris County, Texas, as an example. Lin's team estimated that the risk of this compound event lasting more than five days in a 20-year span would increase 23 times by the end of the century. But there is some good news: Strategically burying just 5% of power lines — specifically those near main distribution points — would almost halve the number of affected residents.

"Climate can drive multiple hazards with compound effects that we don't understand, and that may be new to us in the future," Lin said. "Considering this kind of compounding of multiple climate hazards and infrastructure vulnerability is an important direction both for the research community and for decision-making."

– by the Office of Engineering Communications

THE POWER OF THE SMALLEST REALM

BUILDING A TECHNOLOGICAL STACK

by Andrew Houck '00, Professor of Electrical and Computer Engineering and associated faculty in the Department of Physics

It's a quirk of inheritance that we see the world the way Isaac Newton described it 350 years ago. Our senses evolved to perceive human-sized threats — we had more to fear from a tiger than from an electron — so we developed an intuition and language to describe human-sized physics. That's what Newton codified into his laws of motion and gravity.

In fact, the entire world is governed by quantum physics, its effects ever-present though usually lurking under the surface. Objects can be in more than one state at the same time. The act of measuring an object fundamentally changes it. Objects can be entangled no matter how far apart they are. These observations at first seem strange, but in truth, they are no weirder than Newton's.

We used to say that quantum mechanics was the physics of atoms and molecules, because that is the realm where it was first discovered and where its effects are most pronounced, but all of that is changing now. We are building larger and larger systems — actual technologies — that harness the apparent strangeness of quantum mechanics to achieve unprecedented capabilities in computing, communications, and sensing. None of this is easy. It will take decades of work to establish these technologies, to uncover the still-hidden secrets of what we can do with quantum mechanics and what still-deeper truths the universe holds.

The challenges are considerable, and great technical challenges require more than just great minds. They require the right environment that facilitates those great minds joining in a common vision and concerted effort. The speed of communication and push toward globalization have been a great boon for ▶

science. But therein lies a trap, as well. Breakthroughs propagate at lightning speed, pushing everyone to the cutting edge, but often to the same cutting edge. This monoculture can at times stifle creative thinking. And in science, often the best ideas are the ones that seem to come from nowhere. Of course, more often than not, that nowhere is simply down the hall, where you bump into a colleague while getting coffee.

This is where Princeton excels. Quantum technology requires bringing together engineers, physicists, chemists, and computer scientists; on top of that, scientists are working with an abundance of physical systems, from atoms to semiconductors to superconductors to as-yet-undiscovered quantum materials. While it may seem tempting to double down on a single system with a single area of focus, Princeton has done the opposite.

We have excellence in nearly all physical systems and all levels of the technological stack. By prizing a willingness to talk across disciplinary boundaries, and by hiring outstanding faculty in diverse subfields of quantum science and engineering, we have cultivated a truly special environment for intellectual cross-pollination. Certainly, my best work has been inspired by working with colleagues who think much differently than I do. Much of this interaction happens through our vibrant culture in which students engage one another across domains — formally through weekly talks and research collaborations and informally through the spontaneous conversations that grow out of them. At an institutional level, this will pave the way for decades of scientific and technological progress in this emerging field.

Andrew Houck teaching the first-year calculus course “The Mathematics of Shape and Motion.”
Photo by Tori Repp/Fotobuddy

DEFECTS IN DIAMOND COULD SENSE STRUCTURES OF SINGLE MOLECULES

by Molly Sharlach

A perfect diamond may be a jeweler's dream, but for quantum scientists, beauty lies in a stone's tiny defects.

These flaws hold the power to trap and control single electrons, opening possibilities for both quantum computing and mapping molecular structures.

Controlled defects in the dense lattice of a diamond's carbon matrix create one of the few systems available for exploring quantum phenomena at room temperature, instead of the supercooled environment typically required. The problem is creating precise defects in diamond's adamantine structure.

Nathalie de Leon, an associate professor of electrical and computer engineering, has pioneered the production of diamonds with calibrated defects. Diamond is made up of tightly packed carbon atoms, and de Leon's team specializes in replacing two carbon atoms with one of nitrogen and a carefully placed empty space, or vacancy, in the atomic lattice.

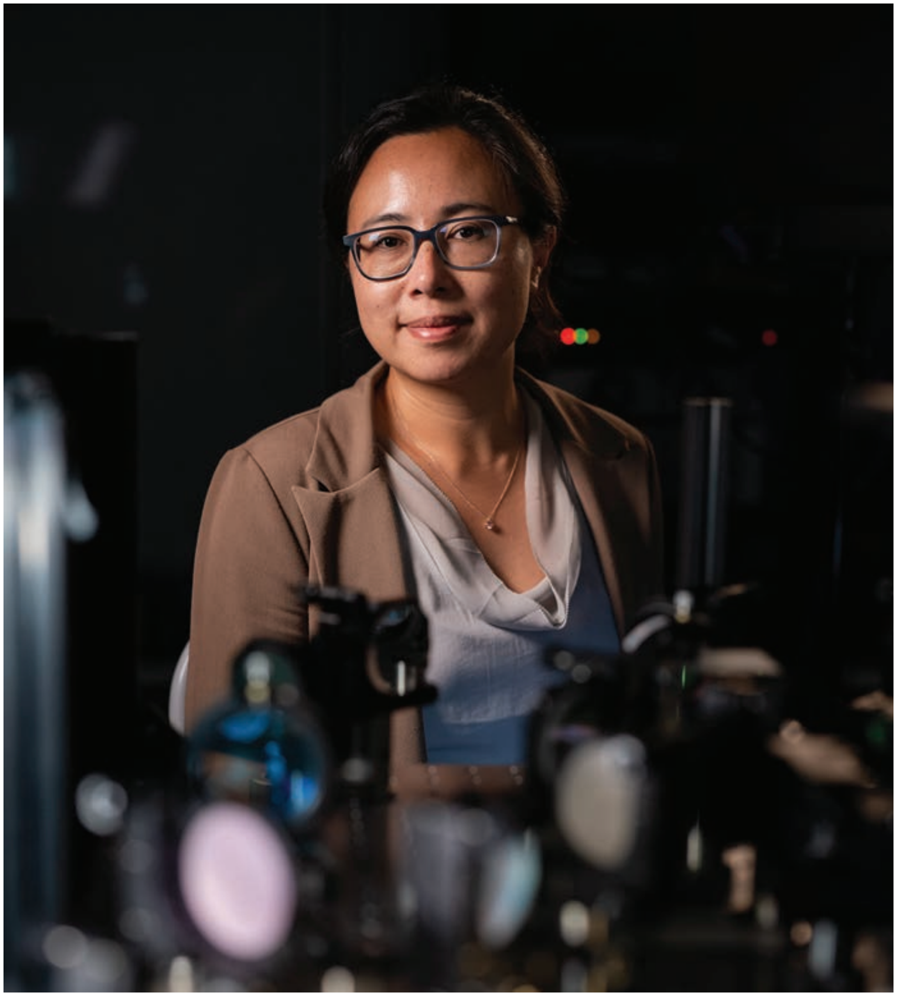
These introduced defects, called nitrogen-vacancy (NV) centers, have useful quantum properties. The vacancy can trap electrons that spin in a controlled manner. The way the electrons spin — a promising feature for encoding quantum information — is exquisitely sensitive to pulses of laser light, microwave radiation, or magnetic fields.

The NV centers' sensitivity also opens a path toward imaging the structures of single molecules. By measuring the tiny magnetic fields arising from electrons and nuclei, scientists could use the NV centers to study the structures of molecules like proteins, which are critical to cellular functions.

To get a picture of the molecule, it needs to hold still, and binding molecules to diamond is incredibly difficult. In fact, it had eluded efforts for decades until de Leon, Princeton chemistry professor Robert Knowles, and their collaborators uncovered a chemical technique for attaching target molecules. Now, Lila Rodgers, a Ph.D. student who was part of the research team, is working to improve the method.

Besides uncovering new chemistry to bond different kinds of molecules, Rodgers is working to eliminate microscopic nicks or rough spots caused by the process that could interfere with a sensor.

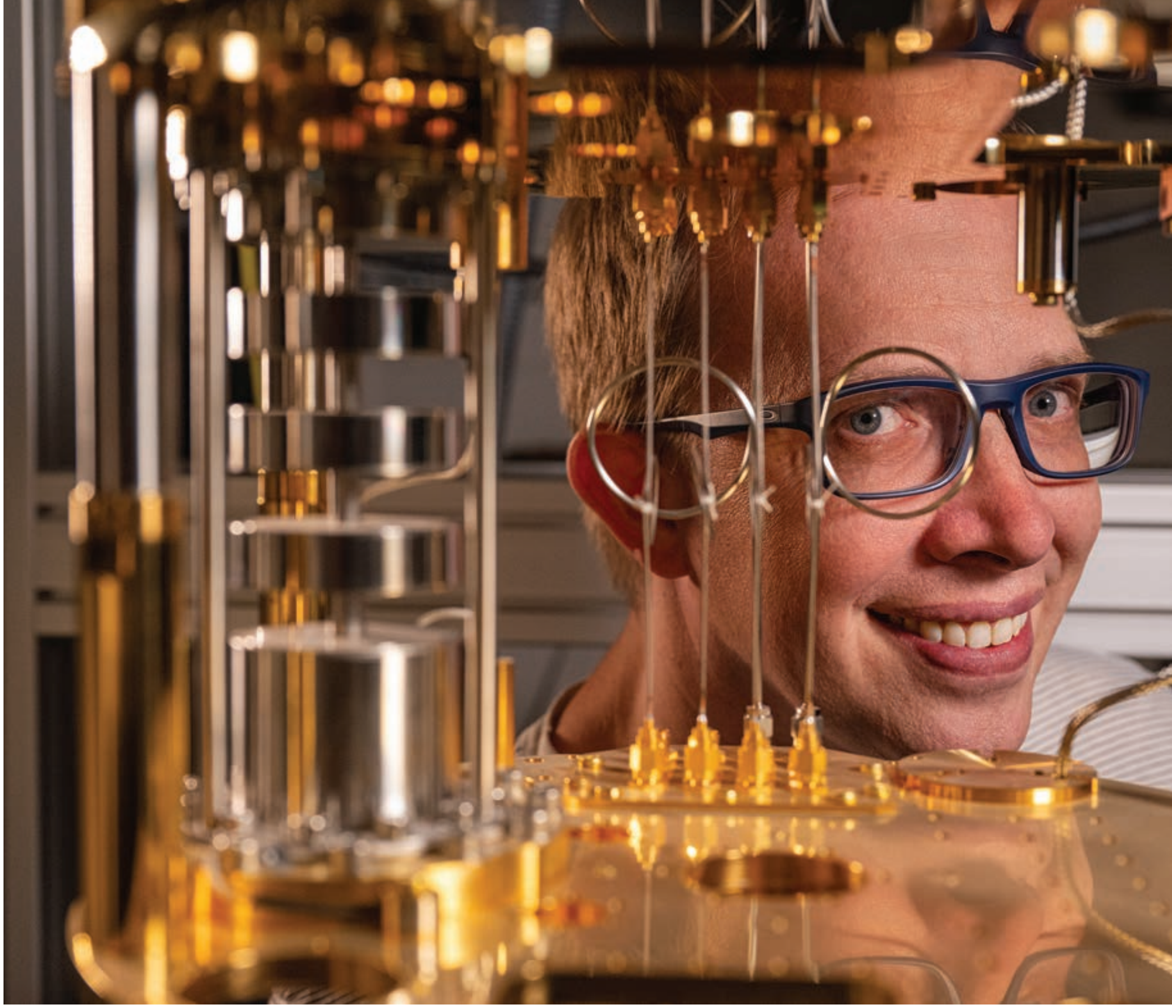
This type of single-molecule sensing could improve the ability to study the dynamic structures of proteins as they change in response to their environment — a potential boon to biology and pharmaceutical research, said Rodgers.



Nathalie de Leon. Photo by Sameer A. Khan/Fotobuddy

ANDREW HOUCK SEEKS A QUIETER QUANTUM WORLD

by Scott Lyon



Andrew Houck. Photo by Sameer A. Khan/ Fotobuddy

In a gray cylinder on the EQuad's fourth floor, at temperatures colder than interstellar space, a coiling wirework of exotic metals bring pairs of electrons into delicate embrace.

Their union holds the power of a new information age. But orchestrating this fastidious machinery means contending with a barrage of cosmic rays, caroming particles, and stray magnetic fields. At every moment, chaos threatens to tear the union apart.

"A single atom out of place could spell disaster," said Andrew Houck, a professor of electrical and computer engineering and a leading expert on quantum information technology.

"We are trying to preserve these incredibly weak signals and isolate them from the world," he said. "At the same time, if we have a computer that's completely isolated from the world, we can't actually program it. We can't use it."

Scientists have a simple term for all those unwanted effects. Noise. Houck said when he talks about noise, he isn't talking about sound but about the sum of destructive forces threatening to knock his systems out of balance.

In 2021, Houck was named director of the U.S. Department of Energy's Co-design Center for Quantum Advantage, where he leads a team of 88 principal investigators from 25 institutions. Their mission? To quell the noise and put quantum computers on the path to practical use.

"We're actually looking for the sources of noise," he said, "and we're trying to get rid of them." What he can't eliminate, he tries to dampen, he said, "like wearing earplugs." Another approach, which he likened to wearing noise-cancelling headphones, actively corrects for the error-causing noise that leaks into a system despite all other efforts. Combined, these three approaches have brought quantum computing to the edge of viability.

Houck has focused much of his work on the earplugs approach, designing systems that are insensitive to specific kinds of noise. In 2007, while a postdoc at Yale, he was part of a team that invented a component called the transmon. It's now the foundation for the world's most advanced quantum computers, including those built by Google and IBM.

The transmon is a circuit that acts like an atom with discrete energy levels. Pairs of electrons jump between two metal islands in the circuit, creating states that can be processed as quantum bits of data called qubits. Qubits contain richer information than classical bits. But at the slightest provocation, that information collapses, and the qubit's information is lost. The transmon's key breakthrough was its insensitivity to noise from electric charge, eliminating one source of qubit-killing error.

A recent redesign spearheaded by Houck's graduate students, in collaboration with the groups of Nathalie de Leon and Robert Cava, swapped metals in a key part of this circuit, making the device indifferent to another source of noise. That change brought the biggest improvement to transmon performance since 2012, representing a three-fold increase in the qubits' lifetimes. Longer lifetimes yield more reliable machines that can solve the kinds of intractable problems that make quantum computing so promising.

"That framework is going to allow us to move forward and think, more broadly, what are other metals we might use? What are the other things we could try?" Houck said.

He said the next phase of quantum computing will involve developing better and more specialized components that are integrated into a complex architecture.

"Different pieces of a chip have different roles to play," he said. "So maybe there's a qubit that can act as memory and store data for a long time. Maybe there's a qubit that you use for active processing. Maybe there's a qubit that doesn't ever actually store any information, but it mediates the coupling between other qubits and enables better gates."

Today's best quantum computers use a few dozen general-purpose qubits, compared to classical computers that contain billions of specialized parts. Houck said scaling quantum computers is a job for industry, and that academics are best suited for inventing pieces that change how scaling works.

"We're knocking on the door of the threshold," he said.

Scientists don't quite know what lies beyond that threshold, but they know it will bring a fundamental shift.

"All the computers that we have built have only ever been operating in this subset of what the universe allows," Houck said. "There is some deeper and more fundamental element of computing, and maybe quantum computers are it. If we could build those, then we could really access everything that is solvable." **E**

NEW COURSE BUILDS STUDENTS' INTUITION FOR QUANTUM EXPERIMENTS

by Molly Sharlach

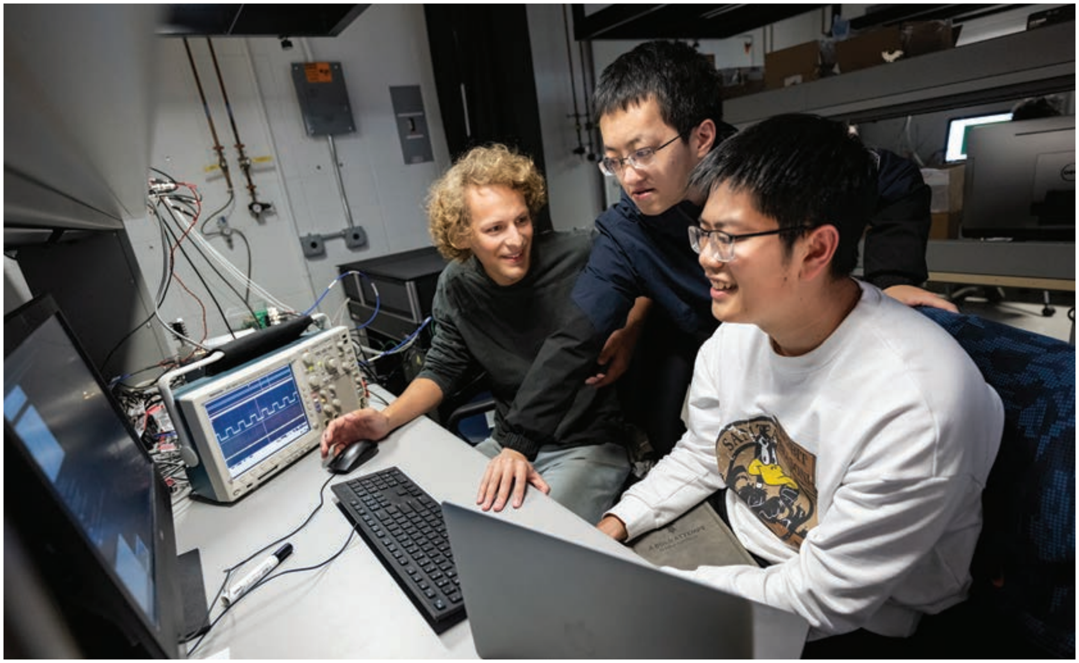


Photo by Sameer A. Khan/ Fotobuddy

Students watch as oscillating line graphs pop up on a computer screen, measuring the photons emitted by defects in a thin slice of diamond.

They confer before tweaking the code that dictates the pulsing of a laser, manipulating the qubits stored in the defects.

This hands-on lesson in writing computer code to control scientific instruments is a key part of the course "Experimental Methods in Quantum Computing," offered for the second time in fall 2022. Electrical and computer engineering professors Jeff Thompson and Nathalie de Leon developed the course to help undergraduates and first-year graduate students gain experimental skills as a foundation for future work in quantum science and engineering.

They intentionally designed open-ended lab exercises, said Thompson. "We gave them the parts that they would need to do an experiment, but then encouraged them to tinker and figure out how to do it."

The course introduces students to three types of qubits: nuclear spin qubits, electron spin qubits based on defects in diamond, and superconducting qubits. Students experiment with the first two using scaled-down versions of research lab setups. And by writing code to remotely control an IBM machine, they send microwave pulses to control a superconducting qubit and measure its properties.

In her lab, de Leon's team uses optical setups the size of a dining table, which offer flexibility for different experiments. For the course, she worked with graduate student Zhiyang Yuan to "strip down a lot of the components and try to make it really small and robust," said de Leon.

After learning the basics of the different qubit platforms, the students work in small groups on projects of their choosing. In the inaugural spring 2022 course, one group explored a two-qubit system on an IBM machine — building on the experiments they had done with a single qubit and beginning to probe the types of circuits that can process quantum information.

Working through qubits' fundamental properties "gives you really good intuition for everything else" in quantum research, de Leon said. **E**

HARNESSING THE **POWER** OF **SINGLE ATOMS** FOR **QUANTUM COMPUTING**

by Steven Schultz

In Jeff Thompson's lab, much power lies in a single atom.

Thompson, associate professor of electrical and computer engineering, engineers the quantum behaviors of individual atoms for use in emerging computing, communications, and sensing technologies. In September, the Breakthrough Foundation awarded Thompson and colleagues the New Horizons in Physics Prize for work controlling individual atoms for quantum computing and other uses.

In recent years, Thompson's group has pioneered a new approach to storing and processing quantum information, which is based on isolating and manipulating individual ytterbium atoms. Ytterbium is slightly more complex than more commonly used atoms such as rubidium or cesium, but has a number of unique features that are advantageous for building large-scale quantum computers. In recent experimental papers, they demonstrated lifetimes for quantum states exceeding several seconds, as well as techniques for manipulating them that are robust against imperfections such as misalignment of laser beams.

Thompson likened the choice of atom to the choice of a multitool, "and this ytterbium is the bigger, fatter Swiss army knife."

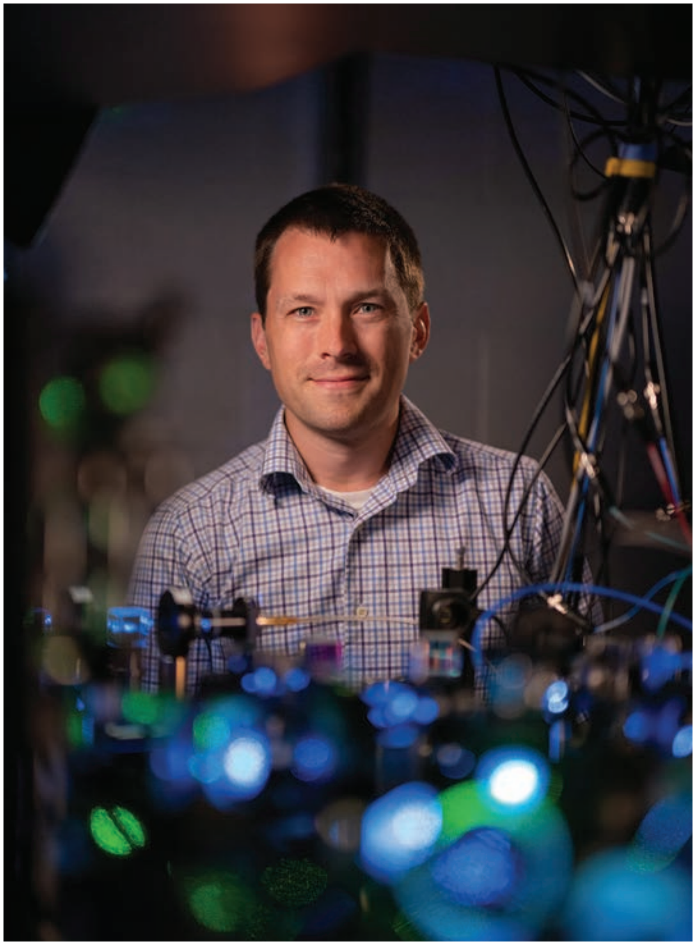
In one recent advance, published in Nature Communications, Thompson and collaborators showed how a new ytterbium qubit could dramatically improve a quantum computer's tolerance for faults, a problem well understood in conventional computers but exceedingly difficult in quantum systems.

In their proposed solution, the team found that they could store data in ytterbium atoms while ensuring that most errors can be easily seen without disturbing the qubits, converting them into so-called "erasure errors." The technique increases the acceptable error rate four-fold, from 1% to 4%, a practical level for quantum computers currently in development.

Thompson said the idea of engineering qubits such as ytterbium to have more favorable types of errors could be useful beyond his ytterbium atoms. Researchers working on entirely different approaches to quantum computing are also now exploring the idea.

At Princeton, Thompson said, cross-pollination of ideas is common and leads to new advances. His motivation to think about new approaches to error correction came from a Princeton colleague talking about similar challenges for different types of quantum computers. The emphasis at Princeton, Thompson said, is not so much on competition as a collective interest in what is possible.

"I think what is important and fairly unique about our community is that we all do different things but still talk with each other in depth about our work," he said. "That is an investment that has paid dividends for all of us." **E**



Jeff Thompson. Photo by Sameer A. Khan/Fotobuddy

COMPUTER SCIENTISTS HAVE A KEY ROLE IN SHAPING QUANTUM SYSTEMS

by John Sullivan

Margaret Martonosi. Photo by Sameer A. Khan/Fotobuddy

A chance meeting more than a decade ago drew Margaret Martonosi into the inherently uncertain world of quantum computing.

Waiting for coffee to brew in Princeton's Engineering Quadrangle, Martonosi spoke to her colleague Stephen Lyon, who was developing a quantum bit (or qubit) technology with unique physical and computation characteristics. While the coffee brewed, Lyon and Martonosi, an expert in architecting the hardware organization of computing systems, discussed how best to design a system to take advantage of Lyon's technology.

"Years later, and many pots of coffee later, I am still doing this," Martonosi, the Hugh Trumbull Adams '35 Professor of Computer Science, said in a lecture on the state of quantum computing. "And we are still collaborating."

When it comes to quantum, Martonosi is a computer scientist working on a type of computer that is still advancing toward at-scale practical usage. It's a challenging spot, but one where computer scientists can make a big difference in how a powerful new tool takes shape, she said. Martonosi, an expert in computer architecture and power efficiency, recently led Princeton's contribution to a multi-institutional effort to advance quantum computing across a wide range of areas.

Currently, Martonosi says, quantum computing is similar to classical computing in the 1950s. Computer scientists and mathematicians have designed powerful algorithms to take advantage of quantum's unique capabilities. Engineers and physicists have created the basic elements of machines and qubit technologies, and the means for them to compute and interact. But there is currently a large "algorithm-to-machine" gap between the resources promising practical algorithms need, and the capabilities of systems that are currently buildable. Martonosi, along with other computer scientists, seeks to bridge that gap in order to accelerate the path to practical, at-scale quantum computing.

The payoff will be different from the computer revolution we have witnessed over the last 50 years. Unlike classical computing, which encompasses nearly every aspect of modern society, quantum computing systems are likely to remain devoted to very specialized tasks, Martonosi said, but those tasks will be important.

"You will not have a quantum laptop," she said. "Think about it being something like an accelerator in the cloud for particular applications, whether they're optimization applications, financial analysis, understanding molecular dynamics or chemistry, agriculture, pharmaceuticals. In those kinds of things, it is potentially game-changing."

In quantum, a major challenge is designing systems that work quickly, accurately, and efficiently enough to take advantage of qubits' unique features. Superposition, the ability of very small objects to exist in more than one state at the same time, is one feature; entanglement, the phenomenon of linking quantum objects into a network with no visible means of connection, is another. But superposition and entanglement are extremely fragile. Fluctuations in magnetism or electrical charge, or operations of the computer itself, can cause them to dissipate or decohere.

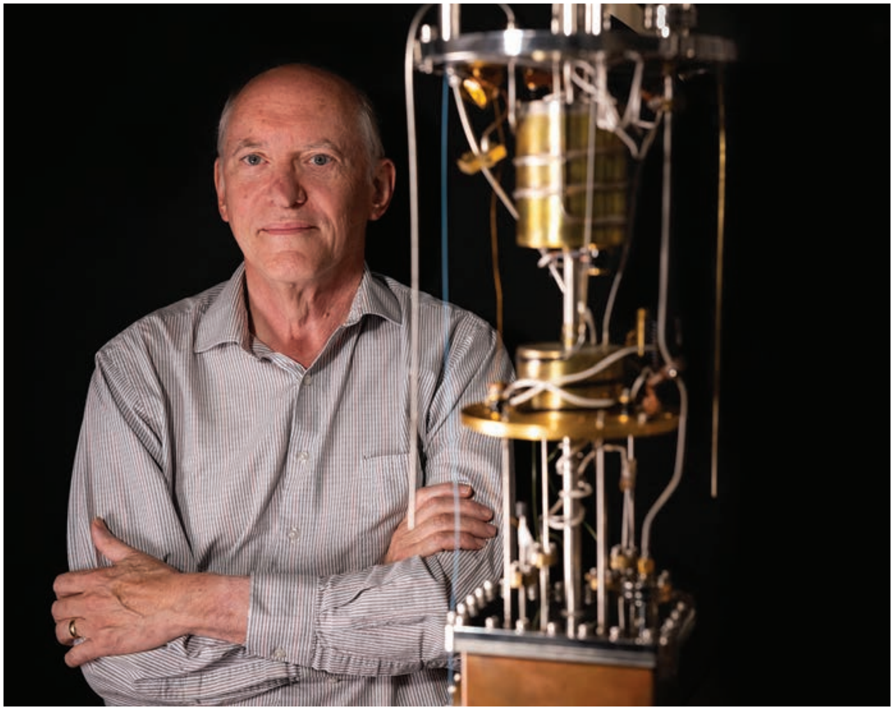
"The very things that make qubits interesting and rich in terms of compute capabilities also make them challenging," Martonosi said. "Manipulating the state of a qubit is a 'noisy' operation and also tends to disrupt other nearby ones."

Martonosi said computer scientists and engineers must learn how to work with these challenges to develop systems, either by creating methods to better manipulate qubits or building hardware that can account for introduced errors. The encouraging news, she said, is that engineers have been rapidly increasing the length of time that they can maintain coherence in quantum systems. They have also been getting better at implementing the hardware for new machines.

"One thing that skeptics tend to ask is, if these quantum computers barely exist, why don't we just leave it to the physicists for a little while longer?" Martonosi said. It is a valid question, but it does not take into consideration the critical decisions that computer scientists can influence as the first working systems take shape. Every design involves tradeoffs, such as how many resources are best applied to one task over another. As new quantum systems are built, computer scientists will have to answer fundamental questions about how they will work.

"We will need to decide how we're going to program quantum computers. What are the operations?" she said. "We need to decide how to optimize them so we can crunch a computation into the very limited resources that we have." E

Margaret Martonosi is currently on leave from Princeton, leading the National Science Foundation's Directorate for Computer and Information Science and Engineering.



HELIUM'S UNEXPECTED BEHAVIOR OFFERS PROMISING PLATFORM FOR QUBITS

by Molly Sharlach

Stephen Lyon. Photo by Sameer A. Khan/ Fotobuddy

Helium is best known for making balloons buoyant.

This second lightest and second most abundant element in the universe (after hydrogen) also has a high-tech side: It's integral to manufacturing fiber-optic cables and semi-conductors, and could be key to creating a new kind of quantum computer.

When cooled to a temperature close to absolute zero (–273.15 degrees Celsius, or –459.67 Fahrenheit), helium behaves as a superfluid. "It's an amazingly interesting material," said Stephen Lyon, a professor of electrical and computer engineering. "A superfluid can flow without viscosity. Stir it, and it'll just keep going forever."

In this state, first discovered in the laboratory in the 1930s, helium atoms are "entirely governed by quantum mechanics, so you get a bunch of rather unexpected behavior," said Lyon.

In the basement of Princeton's Engineering Quadrangle, Lyon's research group pumps superfluid helium into a vacuum-tight box, where it coats the surface of a silicon chip lined with precisely etched channels, but free of the wire pathways that direct electrons on a typical computer chip.

"An electron inside of a silicon semiconductor will get trapped — it'll just get stuck," said Lyon. "The superfluid helium gives us a surface where we can hold the electrons, but they can move across it very freely."

This translates to long decoherence times, meaning that the spin of an electron — the property that allows it to function as a qubit in a computer — could preserve quantum information long enough to perform computations. Lyon estimates that electrons on superfluid helium could preserve their spin coherence for as long as 10 seconds — about a million times longer than mobile electrons in a silicon chip. His research team is now searching for the best conditions to measure and maximize a qubit's coherence time in the superfluid helium system.

Building a system with sufficient qubits for complex quantum computations is a critical challenge, and Lyon believes that "piggy–backing" on known silicon technology is a promising path to a large-scale quantum computer.

In 2021, he became the chief technology officer of EeroQ, a Chicago-based startup working to commercialize current electron-on-helium technologies for quantum computing. While his industry role offers a valuable perspective on research, Lyon said, his laboratory at Princeton is focused on "inventing the future of this technology." **E**

INTERNSHIP IMMERSES UNDERGRADUATES IN QUANTUM RESEARCH AT PRINCETON AND IBM

by Molly Sharlach

Laura Futamura spent her summer internship analyzing ghostly particles and crafting microscopic diamonds, but one of the most memorable moments came in a parking lot.

Waiting out a fire drill outside IBM's research center in Yorktown Heights, New York, Futamura spotted Talia Gershon, the host of a popular YouTube video explaining quantum computing.

"That video is what got me into quantum computing," Futamura, a rising junior at Stanford University, told Gershon before posing for a selfie with the IBM scientist. "Meeting her during the program was really cool."

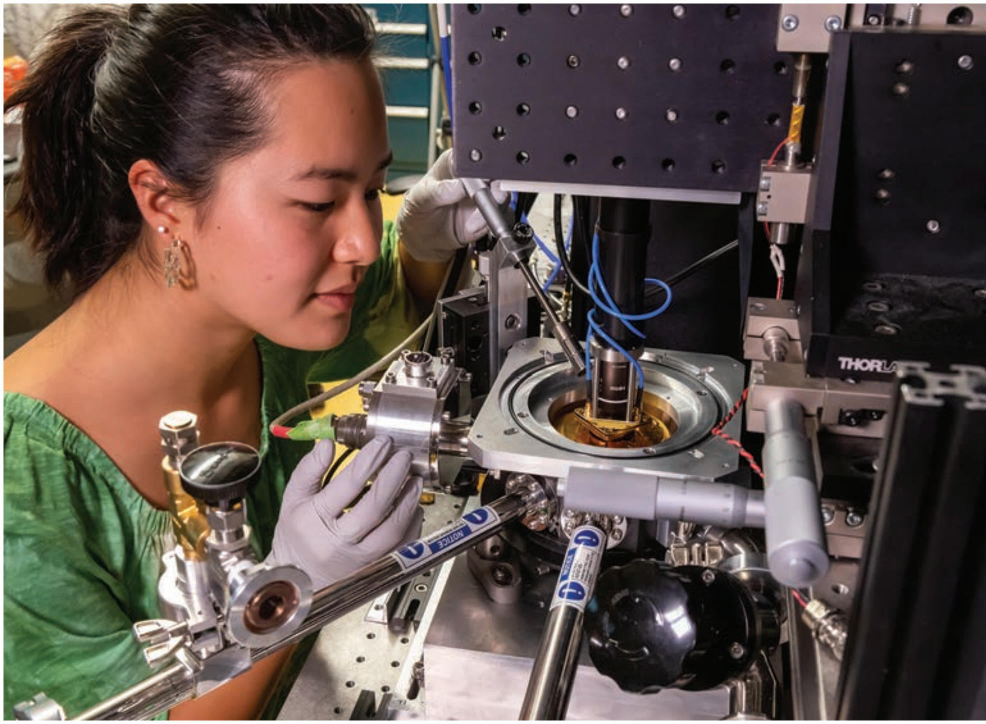
Fostering such connections is an important part of a joint internship program with IBM called Quantum Undergraduate Research at IBM and Princeton (QURIP). Interns from colleges and universities throughout the United States spend six weeks at Princeton followed by six weeks at IBM's Thomas J. Watson Research Center. The program is competitive — in 2022, 10 students were selected from a pool of more than 300 applicants.

It's a rigorous research experience, said Nathalie de Leon, an associate professor of electrical and computer engineering at Princeton. "We have had students win awards at major research conferences based on their work at QURIP, and several have been authors on academic papers — both rare achievements for summer research, and all the more remarkable given the fast pace," she said. De Leon cofounded the program in 2019 with Pat Gumann, manager of quantum processor and system integration at IBM Research.

IBM Research is expanding its education and outreach in response to a critical need for skilled workers to advance quantum technology, Gumann said. Building on the success of QURIP, IBM recently launched a similar program with the University of Illinois Urbana-Champaign.

At Princeton, students conduct research with faculty mentors from the departments of electrical and computer engineering, computer science, physics, and chemistry, often working closely with graduate students or postdoctoral researchers. While the students are on campus, the Princeton Quantum Initiative, with support from the University's materials institute, hosts a weekly quantum seminar for Princeton faculty members to share their latest research, and a Distinguished Quantum Seminar featuring a guest speaker. The Princeton portion of the program culminates in a poster session where QURIP students and Princeton researchers present their work.

The QURIP program is funded by IBM, with additional support from the Princeton Materials Institute and the Princeton Quantum Initiative. E



Laura Futamura's internship research at Princeton involved using a network of lasers to measure minute movements of electrons. Photo by David Kelly Crow

EVADING NATURE'S NOISE TO REACH PRISTINE QUANTUM SIGNALS

by Molly Sharlach

Moment by moment, our brains sift through a massive amount of sensory information to focus on what's most pertinent.

This ability to operate efficiently in noise-filled environments could inform the workings of quantum computers, according to Hakan Türeci, an associate professor of electrical and computer engineering.

Trained as a theoretical physicist, Türeci is interested in the fundamental limits of computing with physical systems. He aims to help create a new generation of quantum computers that process information using minimal amounts of energy — and with negligible interference from the vagaries of ambient fields and other disturbances.

Türeci's team is helping to build experimental quantum systems that use machine learning algorithms modeled after the brain's neural processes, which are "designed for messy systems," he said. These algorithms' outputs may be less precise than the standards of digital computation, but this is often a more faithful reflection of the data they take in, he said.

At the same time, Türeci's group is exploring methods to read qubits' states more directly than current systems, which rely on several stages of amplifiers. With these techniques, the signals "are corrupted by a huge amount of noise, and we've been fighting this fact of life with the most basic tools," said Türeci. "We can do a lot more to make these signals robust." **E**

Hakan Türeci

THEORIST ILLUMINATES ADVANTAGES OF QUANTUM COMPUTERS

by Molly Sharlach

What problems can quantum computers approach that lie beyond the reach of classical computation? Ran Raz, a professor of computer science, is using mathematics to find out.

Evaluating the limits of computation can be extremely difficult. Computer scientists group problems into levels of complexity determined by their demand for resources, usually computation time or computer memory. One fundamental grouping begins with problems approachable by today's classical computers and extends to powerful theoretical systems with enormous capabilities. Scientists refer to this ranking as the polynomial hierarchy.

In 2018, Raz and a former graduate

FORENSIC APPROACH SHOWS GAPS IN THE ACCOUNTING FOR QUANTUM DATA

by Scott Lyon

Today's computers keep track of massive amounts of data with relative ease. But for quantum computing, keeping track of data is still a central technological challenge.

Sarang Gopalakrishnan studies the rules governing data in quantum systems, where the deep uncertainty of every exchange makes bookkeeping next to impossible. To get around that uncertainty, he's developing new mathematical techniques to piece together events moment by moment.

"I'm trying to exploit these connections between quantum information and what we know about how quantum systems evolve in time," said Gopalakrishnan, assistant professor of electrical and computer engineering, who joined the Princeton faculty in September 2022. He said quantum systems are rich in answers to some of the deepest questions we can think to ask — you just have to know where to look.

His work touches on a fascinating mix of topics from information theory, computer science, machine learning, and signal processing. It also builds on the foundation laid by a Princeton icon: physicist and Nobel laureate Philip Anderson. Anderson pioneered modern solid-state physics and revolutionized the way scientists understand phases of matter. This more subtle view of matter turns out to be useful in accounting for quantum data. "In some sense, Anderson is the central figure in my entire field," Gopalakrishnan said. "His work is central to all of my thinking." **E**

Sarang Gopalakrishnan

Ran Raz

student, Avishay Tal, demonstrated that quantum computers can grapple with problems that are outside the polynomial hierarchy. These problems cannot be solved, or have their answers checked, by classical computers, no matter how advanced.

Raz and Tal (now an assistant professor at the University of California-Berkeley) constructed their proof relative to an oracle — an imaginary answer key — and investigated how many times a quantum and a classical computer would need to consult the oracle to reach a solution. The quantum computer only needed one hint, while a classical computer could only solve the problem with an exponential number of hints.

"Our current understanding is that nature is governed by quantum physics, so as a theorist it's interesting to consider the computational power of quantum physics — regardless of what types of quantum computers are built in the future," said Raz. **E**

Photos by David Kelly Crow


Anu Ramaswami


Celeste Nelson


Clifford Brangwynne

RECENT FACULTY AWARDS, PROMOTIONS, AND HONORS

CIVIL AND ENVIRONMENTAL ENGINEERING

Glaucio Paulino
Melville Medal, American Society of Mechanical Engineers

Anu Ramaswami
Science Award, American Academy of Environmental Engineers and Scientists
Steven K. Dentel AEESP Award for Global Outreach, Association of Environmental Engineering and Science Professors

CHEMICAL AND BIOLOGICAL ENGINEERING

José Avalos
Young Investigator Award, Division of Biochemical Technology of the American Chemical Society

Clifford Brangwynne
Breakthrough Prize for Life Sciences

Pierre-Thomas Brun
Early Career Award for Soft Matter Research, American Physical Society

Sujit Datta
Camille Dreyfus Teacher-Scholar Award
InterPore Award for Porous Media Research

Emily Davidson
Early Career Research Program Award, Department of Energy

Pablo Debenedetti
Aneesur Rahman Prize for Computational Physics, American Physical Society

Celeste Nelson
Director's Pioneer Award, National Institutes of Health

Rodney Priestley
America's Greatest Disruptors, Newsweek
Carl S. Marvel Award for Creative Polymer Chemistry Award, American Chemical Society

Robert Prud'homme
Nanoscale Science and Engineering Forum Award, American Institute of Chemical Engineers

Sankaran Sundaresan
Elsevier Particle Technology Forum Award for Lifetime Achievements, American Institute of Chemical Engineers

Michael Webb
Howard B. Wentz, Jr. Junior Faculty Award

COMPUTER SCIENCE

Mark Braverman
Fellow, Association for Computing Machinery
IMU Abacus Medal, International Mathematical Union

Danqi Chen
E. Lawrence Keyes, Jr./ Emerson Electric Co. Faculty Advancement Award
Sloan Research Fellowship, Alfred P. Sloan Foundation

Adam Finkelstein
Phillip Y. Goldman '86 Professor in Computer Science

Elad Hazan *06
Fellow, Association for Computing Machinery

Felix Heide
Packard Fellowship, David and Lucile Packard Foundation

Brian Kernighan *69
William O. Baker '39 Professor in Computer Science

Karthik Narasimhan
Howard B. Wentz, Jr. Junior Faculty Award

Yuri Pritykin *14
New Innovator Award, National Institute of Allergy and Infectious Diseases

Szymon Rusinkiewicz
Fellow, Association for Computing Machinery

Olga Russakovsky
CAREER Award, National Science Foundation
Pattern Analysis and Machine Intelligence Young Researcher Award, The Computer Vision Foundation

Mona Singh
Wang Family Professor in Computer Science

ELECTRICAL AND COMPUTER ENGINEERING

Minjie Chen
E. Lawrence Keyes, Jr./ Emerson Electric Co. Faculty Advancement Award

Nathalie de Leon
Rolf Landauer and Charles H. Bennett Award in Quantum Computing, American Physical Society

Yasaman Ghasempour
CAREER Award, National Science Foundation
Rising Stars in Computer Networking and Communications, N2Women

Andrea Goldsmith
ACM SIGMOBILE Outstanding Contributions Award, Association for Computing Machinery

International Fellow, Royal Academy of Engineering

President's Council of Advisors on Science and Technology

H. Vincent Poor *77
Foreign Fellow, Royal Society of Canada

Jeffrey Thompson
New Horizons Prize in Physics, Breakthrough Prize Foundation

MECHANICAL AND AEROSPACE ENGINEERING

Emily Carter
Gerhard R. Andlinger Professor in Energy and the Environment

Materials Theory Award, Materials Research Society

Board of Directors, The Kavli Foundation

Daniel Cohen '08
Alfred Rheinstein Faculty Award

Kelsey Hatzell
Early Career Faculty Award, NASA

Chung Law
Lifetime Achievement Award, International Association for Green Energy

Michael Mueller
Hiroshi Tsuji Early Career Researcher Award, The Combustion Institute

Radhika Nagpal (joint with Computer Science)
*Norman R. Augustine '57 *59 Professor in Engineering*

America's Greatest Disruptors, Newsweek

Howard Stone
Foreign Member, Royal Society

Fellow, American Philosophical Society

OPERATIONS RESEARCH AND FINANCIAL ENGINEERING

Matias Cattaneo
Fellow, Institute of Mathematical Statistics

Boris Hanin
CAREER Award, National Science Foundation

Alfred Rheinstein Faculty Award

Emma Hubert
Paul Caseau Prize, French Academy of Technology and Électricité de France

Ludovic Tangpi
CAREER Award, National Science Foundation

MGB-SIAM Early Career Fellowship, Society for Industrial and Applied Mathematics


Mark Braverman


Sankaran Sundaresan


Chung Law


Emily Carter

Clifford Brangwynne photo by Steven Freeman; Chung Law photo by Frank Wojciechowski; all other photos by David Kelly Crow

ENGINEERING FACULTY RECOGNIZED FOR EXCELLENCE IN TEACHING AND MENTORING

Four Princeton Engineering faculty members were honored this year for outstanding teaching and mentoring.

Peter Ramadge, the Gordon Y.S. Wu Professor of Engineering and professor of electrical and computer engineering, was one of four recipients of the Princeton University President's Award for Distinguished Teaching.


Peter Ramadge. Photo by David Kelly Crow

The detailed lecture notes that Ramadge distributes every week are legendary. They have proved to be indispensable to the many students who have taken his courses over the years since Ramadge, whose scholarship focuses on signal processing and machine learning, joined the faculty in 1984.

"The level of preparation and care he puts into his lectures is unparalleled," one graduate student said. He makes the material "accessible for all students, yet interesting and engaging at the deepest levels." Another agreed: "Professor Ramadge has an extraordinary ability to break down technical material in a way that is easy to understand."

Matt Weinberg, assistant professor of computer science, also received a 2022 President's Award for Distinguished Teaching.


Matt Weinberg. Photo by David Kelly Crow

Weinberg's dedication to undergraduate students is evident in the number he has advised on thesis work or one-semester projects: more than 60 in just the five years since he joined the computer science department in 2017, well outside the norm. Weinberg, whose scholarship focuses on algorithmic mechanism design, is just as committed to mentoring his graduate students, who rave about how generous he is with his time and his dedication to assisting them develop as researchers.


Yiguang Ju. Photo by Frank Wojciechowski

Yiguang Ju, the Robert Porter Patterson Professor of Mechanical and Aerospace Engineering and director of the Program in Sustainable Energy, received the engineering school's annual Distinguished Teaching Award. A faculty member since 2001, Ju leads research in the exploration and development of new combustion technologies and functional nanomaterials to enable renewable fuels, advanced propulsion, efficient energy conversion, and bio-imaging.

Students have long been impressed by Ju's clear presentation, passion, and dedication to teaching. He "makes every class a delight," said one student. "His enthusiasm for his subject and delight for the transfer of knowledge are an inspiration."


Mark Brynildsen. Photo by David Kelly Crow

Mark Brynildsen, an associate professor of chemical and biological engineering, was one of four recipients of the 2022 Graduate Mentoring Awards from the McGraw Center for Teaching and Learning. A faculty member since 2010, Brynildsen studies biomolecular engineering as well as cellular and tissue engineering.

One of his students observed that graduate school "is filled with highs and lows, and many points when you feel like you are spinning your wheels." After each meeting with Professor Brynildsen, "I've always left with a new sense of invigoration and a path forward."

ON CLASS DAY, GRADUATES WERE TOLD THEIR DEDICATION WOULD BE THE FOUNDATION OF FUTURE SUCCESS

Welcoming graduates, friends and families to the annual Class Day ceremony on May 23, Dean Andrea Goldsmith expressed "joy and pride" at presiding over the first in-person ceremony for Princeton Engineering graduates in three years.

She praised the Class of 2022's outstanding work and determination through the unprecedented challenges of the COVID-19 pandemic. "My faculty colleagues and I are deeply impressed, not only with what you have accomplished, but with the many ways that you've been shaped by this pandemic," Goldsmith, the Arthur LeGrand Doty Professor of Electrical and Computer Engineering, told students at the gathering in the Friend Center courtyard. "We've been inspired by your hard work, dedication, and perseverance. These are the attributes that brought you to Princeton in the first place and that led you to succeed here, and they will be the foundations of your future successes." With 343 graduates receiving engineering degrees and 44 receiving bachelor of arts degrees in computer science, the class included 387 students, representing 31% of the University's Class of 2022.

The major award winners at the 2022 Princeton Engineering Class Day, as presented by Associate Dean for Undergraduate Affairs Peter Bogucki, were:

J. Rich Steers Award
Zachary Hammack
Computer Science
Logan O'Donnell
Mechanical and Aerospace Engineering

Jeffrey O. Kephart '80 Prize In Engineering Physics
Xuan Hoang Le
Electrical and Computer Engineering

Tau Beta Pi Prize
Hayden Burt
Mechanical and Aerospace Engineering

Joseph Clifton Elgin Prize
Sydney Hughes
Chemical and Biological Engineering
Nick Thielsen
Civil and Environmental Engineering

George J. Mueller Award
Isabelle Grosgogeat
Operations Research and Financial Engineering
Cole Becker
Electrical and Computer Engineering

Calvin Dodd MacCracken Senior Thesis/Project Award
Joshua Eastman
Civil and Environmental Engineering
Nicole Meister
Electrical and Computer Engineering
Harry Shapiro
Mechanical and Aerospace Engineering

Lore von Jaskowsky Memorial Prize
Selena Chiu
Chemical and Biological Engineering
Xuan Hoang Le
Electrical and Computer Engineering

James Hayes-Edgar Palmer Prize In Engineering
Anthony Hein
Computer Science
Claire Wayner
Civil and Environmental Engineering

Class of 2022 award winners with Dean Andrea Goldsmith and Distinguished Teaching Award recipient Yiguang Ju. Photo by Frank Wojciechowski

SENIOR THESIS REVEALED NEW WAYS TO CUT CAMPUS CARBON EMISSIONS

Harry Shapiro was six when he first toured the plastics factory his father managed near their home in Chicago. He walked out with a spark of attraction for industrial plants that he carried with him to Princeton.

In his first semester on campus in 2018, Shapiro toured the University's energy plant, where he marveled at the "genius and brilliance" of how the plant's different components fit together to supply much of the campus's heating, cooling, and electricity.

For his senior thesis project, Shapiro synthesized more than two million data points on campus energy use, developing a mathematical model to help reduce costs and carbon emissions. The model aims to optimize the University's hour-by-hour dispatch of its various energy sources — an increasingly complex challenge as Princeton moves toward its goal of net-zero carbon emissions by 2046.

"Designing for efficiency is my favorite part of engineering. Princeton could put an A/C unit in every window of every building, or a jet airliner could have six engines on it, but that's not exciting or challenging," said Shapiro, who earned a B.S.E. in mechanical and aerospace engineering (MAE), as well as certificates in the history and practice of diplomacy, engineering and management systems, and robotics and intelligent systems.

The plant tour was part of a thermodynamics course, taught by MAE lecturer Lamyaa El-Gabry, which showed him "how to be creative and make the most out of every ounce of energy that you're producing — how to not be wasteful," he said.

When it came time for a senior project, he "immediately thought back to that plant tour." He asked El-Gabry to serve as his adviser, and they met with campus energy plant director Ted Borer and other Facilities staff members to explore research ideas that could impact the campus's day-to-day energy operations.

"This gave Harry a chance to work with real-world data that has an immediate engineering need," said El-Gabry.

To create the optimization model, Shapiro used a large data set including: records of recent campus energy use; information on the economic and carbon costs of generating electricity in a natural gas-powered turbine; data on heating and cooling with steam from the turbine's exhaust; and records of electricity purchased from utilities. He primarily used data from before the COVID-19 pandemic, which drastically altered energy demand on campus in 2020 and 2021. He also factored in projections of the output and efficiency of the geo-exchange-linked TIGER Plant, set to be completed in 2023..

Borer, the energy plant director, said the research was complex because the University designed its energy system to include a variety of systems with overlapping roles. He said the different systems — the turbine, the solar field, the exhaust power — were like "instruments in an orchestra."

"Sometimes we need all of them," Borer said. "But when it's not the hottest day or the coldest day of the year, we don't need all the instruments."

The plant operators have to balance economics, reliability, and emissions against power demands that fluctuate constantly depending on needs across the campus. With major industrial equipment heating up and cooling down, "it becomes a very complex economic problem," Borer said.

Shapiro developed new software to wrestle with those details. At the same time, he emphasized that the software is modular, with the ability to add capacity for geo-exchange or other new energy sources, and to test different pricing scenarios for natural gas, grid energy, and carbon emissions.

For Shapiro, along with building the model itself, the process of communicating his ideas to different audiences and refining his work based on their feedback was a valuable aspect of the thesis experience. He presented his research to Facilities staff, the Princeton Sustainability Committee, and engineers from Icetec Energy Services, the firm that developed Princeton's current dispatch system.

"I've had four years [at Princeton] learning a lot of engineering and communication skills, and now I want to take that to the real world to learn how to run a business, how to invest, and how to collaborate with people in that world," said Shapiro. **– by Molly Sharlach**

Harry Shapiro '22 (second from left) developed a mathematical model to help reduce costs and carbon emissions from campus energy use. He worked with (from left) Ijeoma Nwagwu, assistant director of academic engagement and Campus as Lab initiatives at the Office of Sustainability; Ted Borer, director of the campus energy plant; and thesis adviser Lamyaa El-Gabry, a lecturer in mechanical and aerospace engineering. Photo by Tori Repp/Fotobuddy

GRADUATE STUDENTS FORGE NEW SOLUTIONS FROM NATURAL COMPLEXITIES

See more profiles of #PrincetonEngineers on Instagram @eprinceton.

Trevor Jones inflates a bubble-cast gripper robot in the laboratory. Photo by Sameer A. Khan/Fotobuddy

Trevor Jones
Ph.D. Candidate
Chemical and Biological Engineering
Adviser: Pierre-Thomas Brun, Assistant Professor of Chemical and Biological Engineering

"Bubble casting is a method we created that's a lazy design of soft robotics. This lazy design uses fluid mechanics to do all the heavy lifting for the fabrication of bending actuators. While bending actuators are not new, using fluid mechanics instead of direct manufacturing methods allows us to create new soft robotic systems.

For example, the bubble casting method allows fabrication of very long and tortuous actuators. We can make a robot that's as tall as me but as thin as a pencil. We can create spirals that morph into spheres. We can create little grippers that will gently grasp soft objects.

Other benefits of bubble casting are actuators that are programmable, precise, and defect-free. Thus, we can confidently build a series of digits that with a single pressure source will bend sequentially, kind of like fingers playing a piano."

Jones was the lead author of a paper on the bubble casting technique for soft robots that was featured on the cover of Nature in November 2021.

Jiarong Wu
Ph.D. Candidate
Mechanical and Aerospace Engineering
Adviser: Luc Deike, Assistant Professor of Mechanical and Aerospace Engineering and the High Meadows Environmental Institute


Jiarong Wu. Photo by Michael Franken

"When I started studying engineering, I realized that I was more interested in the common, basic principles behind things, more specifically the fluid dynamics that govern everything that flows. From one set of equations an endless complexity emerges," said Wu.

Her work focuses on understanding how the wind amplifies the waves that cover more than 70% of the Earth's surface. While the sea is vast, Wu's work takes place on a much smaller scale, examining waves of centimeters to meters in scale.

This research has important applications for both weather prediction and climate change. For example, when there is a tropical cyclone, ocean wave models can predict how tall the waves will become and what coastal regions will be affected. Her research is also used for climate modeling. When waves break, they greatly enhance the gas exchange between the atmosphere and the ocean, which has a big impact on the greenhouse gas intake by the ocean.

Wu said it can be difficult to relax near the ocean because she is always observing the waves. "Every time I see the breeze make even the smallest ripples on a puddle I think about my research," she joked. "There is so much pure beauty and intrigue in exploring fluid dynamics all around us."

Gökçe Dayanıklı
Ph.D. 2022
Operations Research and Financial Engineering
Adviser: René Carmona, Paul M. Wythes '55 Professor of Engineering and Finance


Gökçe Dayanıklı. Photo by Bachir El Khadir

"My research uses game theory and machine learning tools to find optimal policies for a large number of agents that decide individually to optimize their own goals. These agents can be people, companies, robots, etc. In my research I focus on real-life problems, such as finding optimal carbon tax levels for electricity producers or finding optimal social distancing measures to mitigate an epidemic. Since people cannot be directly controlled and behave individually, I use game theoretical approaches in problem modeling, and to solve complex models that capture reality better, I use machine learning tools.

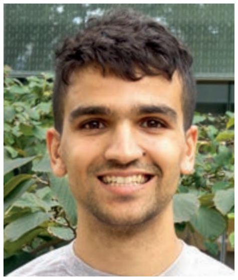
While at Princeton, I participated in the ReMatch program of the Office of Undergraduate Research. First, I wanted to gain some experience mentoring students, because I was planning to continue my academic career. Second, as an undergraduate, I wanted to get involved with research, but didn't have these types of opportunities. I thought this would be very beneficial for undergraduates, and I wanted to be a part of it. I learned how to communicate complex ideas in a simplified way to attract the attention of students. I also tried to mentor them to help in their academic lives and career paths. Now, I am planning to start a tenure-track job at the University of Illinois Urbana-Champaign after a one-year position at Columbia University. The ReMatch program helped me to be more confident in communicating with and mentoring students."

GRADUATE STUDENTS RECOGNIZED FOR EXCELLENCE IN TEACHING

In May 2022, the Graduate School presented 29 graduate students with its annual Teaching Awards in recognition of their outstanding abilities as teachers.

The selection committee recognized a graduate student assistant in instruction (AI) from each of the four divisions with a special commendation.

Other honorees in engineering included:
Danielle Chase
Mechanical and Aerospace Engineering
Bernardo Gouveia
Chemical and Biological Engineering
Julie Kim
Civil and Environmental Engineering
James Roggeveen
Mechanical and Aerospace Engineering
Joanna Schneider
Chemical and Biological Engineering


Rajiv Sambharya. Photo courtesy of Princeton ORFE

Rajiv Sambharya, the awardee from the engineering division, is a Ph.D. student in operations research and financial engineering. He served as an AI for "Optimization: Decision-Making in the Age of Computers." Sambharya went "above and beyond" in his teaching duties, said Assistant Professor of Operations Research and Financial Engineering Bartolomeo Stellato: "Rajiv has been extremely supportive and understanding with his students while being generous with his time," offering extra review sessions, extended office hours, and one-on-one meetings with students.

Students were thankful for Sambharya's meticulous preparation. "The students appreciated the depth of his notes and how his notes complemented what was taught in lecture, boosting our confidence in unfamiliar topics and solidifying other topics that we may have learned in the past," one student said.

Katelyn Randazzo was honored with the Quin Morton Graduate Teaching Award for instructors in the Princeton Writing Program. A Ph.D. student in chemical engineering and materials science, she served as the Quin Morton '36 Teaching Fellow in the Princeton Writing Program, teaching a writing seminar titled "Eureka! Moments" that examines the intersection between discovery narratives and the work of innovation.

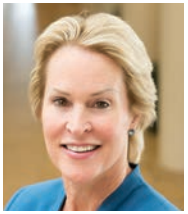
Amanda Irwin Wilkins, director of the Princeton Writing Program, said Randazzo teaches"by first building a bond, and then draws on that bond to lead her students to new depths of understanding and complexity. Katelyn has demonstrated remarkable skill at leading her students to cultivate their critical curiosity and to deepen their sense of why scholars research and write the way they do."


Katelyn Randazzo. Photo by Frank Wojciechowski

Students commented that their writing had improved dramatically because of her in-depth comments on their papers and the extra time she spent with them. Her feedback "helped crystallize how to write a nuanced, arguable but also original thesis and how to put scholarly sources into conversation with each other without just parroting the ideas of the sources," one student said.

–by Jennifer Altmann

ALUMNI HONORED FOR RESEARCH AND INNOVATION


Frances Arnold

Frances Arnold '79 and **John Dabiri** '01 were appointed members of the President's Council of Advisors on Science and Technology. This diverse and distinguished body of external advisors is made up of individuals from industry, academia, and nonprofit organizations who possess a range of perspectives and expertise. Arnold, the Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry at Caltech, received the Nobel Prize in Chemistry in 2018 for her pioneering work in directed evolution to create improved enzymes. John Dabiri, the Centennial Chair Professor at Caltech, is focused on biological fluid dynamics in the ocean and next-generation wind energy. Arnold and Dabiri each received a B.S.E. in mechanical and aerospace engineering from Princeton.


John Dabiri

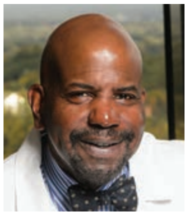
Stuart Cooper *67, a distinguished professor of chemical engineering at The Ohio State University College of Engineering, was elected to the National Academy of Inventors. He was recognized for his focus on polymer science and engineering and on the structural integrity of polyurethanes, leading to the study of polyurethane thermoplastic elastomers and their biomedical applications. Cooper, who graduated from Princeton with a Ph.D. in chemical engineering in 1967, joined Ohio State in 2004 as chair of the Department of Chemical and Biomolecular Engineering.


Stuart Cooper

Marian Rogers Croak '77 was one of the first two Black women inducted into the National Inventors Hall of Fame. She was recognized for advancing Voice over Internet Protocol (VoIP) technologies, a key development in audio and video conferencing. She joined Google in 2014, where she is currently a vice president of engineering. Previously, she spent over 30 years at AT&T Bell Laboratories in various positions, the most recent as senior vice president of research and development. Croak, Class of 1977, received a Ph.D. from the University of Southern California.


Photo by mo
Marian Croak

Cato Laurencin '80 was awarded the 106th annual Spingarn Medal, the highest honor of the National Association for the Advancement of Colored People (NAACP), for his accomplishments in tissue regeneration, biomaterial science, nanotechnology, and regenerative engineering, a field that he founded. In addition, he received the 2022 Gold Medal of Honour for Independence from the government of Saint Lucia for his many contributions to bioengineering and medicine. Laurencin is CEO of the Connecticut Convergence Institute for Translation in Regenerative Engineering; the director of the Raymond and Beverly Sackler Center for Biomedical, Biological, Physical and Engineering Sciences; and an Albert and Wilda Van Dusen Distinguished Professor of Orthopedic Surgery at the University of Connecticut.


Cato Laurencin

Photos courtesy of the subjects

ALUMNI HONORED FOR RESEARCH AND INNOVATION (CONTINUED)


Photo by Institute of Navigation
Mark Psiaki

Mark Psiaki '79 *87 is the Kevin T. Crofton Faculty Chair of Aerospace and Ocean Engineering at Virginia Tech. For his accomplishments and advancements in the field of dynamics and control, he was recently awarded the Johannes Kepler Award from the Institute of Navigation, the American Institute of Aeronautics and Astronautics' Mechanics and Control of Flight Award, and the Institute of Navigation's 2021 Samuel M. Burka Award. Psiaki earned an A.B. in physics in 1979 and a Ph.D. in mechanical and aerospace engineering in 1987, both from Princeton.

Charles Wyman *71 was elected to the National Academy of Engineering for his advances in transforming lignocellulosic feedstocks to low-carbon-footprint fuels and chemicals. He is currently the Ford Motor Company Chair in Environmental Engineering at the Center for Environmental Research and Technology at the University of California-Riverside. Before joining UC Riverside in 2005, he was a distinguished professor at Dartmouth College and director of the Biotechnology Center for Fuels and Chemicals at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. Other positions he held while at NREL include director of the NREL Alternative Fuels Division and manager of the Biotechnology Research Branch. Several years ago, he founded Vertimass to develop and expand the use of sustainable transportation fuels. Wyman received a Ph.D. in chemical engineering from Princeton in 1971, a B.S. from the University of Massachusetts, and an M.B.A. from the University of Denver.

ALUMNI NAMED TO LEADERSHIP ROLES


Suzanne Akers

Suzanne Akers '83 has been appointed chief risk officer at Alberta Investment Management Corporation, a Canadian institutional investment manager. She will also serve as the company's chief compliance officer. Akers moves from Franklin Templeton's Investment Risk Management Group. Previously, she served in risk, operation, and technology roles at Morgan Stanley in their New York and London offices. Her B.S.E in chemical engineering, earned in 1983, is from Princeton and her M.B.A. is from Stanford University in 1987.


Lydia Contreras

Lydia Contreras '03 was named vice provost for faculty diversity, equity and inclusivity at the University of Texas-Austin. She holds the Jim and Barbara Miller Endowed Faculty Fellowship in Chemical Engineering, and was previously managing director of diversity in the Office of the Executive Vice President and Provost.

Contreras received her B.S.E. in chemical engineering from Princeton in 2003, followed by a Ph.D. in chemical and biomolecular engineering from Cornell. Her research focuses on the interface of RNA biochemistry and protein engineering.

H. Gaye Erkan *06 has been appointed chief executive officer at Greystone, a company headquartered in New York City that offers commercial real estate financing options. Before joining Greystone, she held executive positions for almost eight years at First Republic Bank. Erkan earned a Ph.D. from Princeton in operations research and financial engineering (ORFE) in 2006 and a B.S. from Turkey's Boğaziçi University in industry engineering in 2001. She also completed business programs at Harvard and Stanford. Erkan maintains ties with Princeton as a member of ORFE's advisory council.

ALUMNI NAMED TO LEADERSHIP ROLES (CONTINUED)

Jennifer Kim Lin '92 is the senior vice president and new chief platform officer at Trimble, an industrial technology company. She is responsible for the platform strategy to develop and deliver industry work-flows for the company's markets. Lin joins Trimble after serving as vice president of product and user experience at Google. She received a B.S.E. in civil engineering and operations research from Princeton 1992.


Jennifer Kim Lim

Troy McKenzie '97, a former student and then professor at the New York University (NYU) School of Law, recently became its dean. McKenzie earned a B.S.E. in chemical engineering from Princeton in 1997 followed by a J.D. from NYU in 2000. He clerked for Judge Pierre N. Leval of the U.S. Court of Appeals for the Second Circuit and for U.S. Supreme Court Justice John Paul Stevens, then was an associate at Debevoise & Plimpton before joining the faculty at NYU. McKenzie took a public service leave from 2015 to 2017 to serve in the U.S. Department of Justice as a deputy assistant attorney general for the Office of Legal Counsel. He is the Cecilia Goetz Professor of Law and a scholar of bankruptcy, civil procedure, and complex litigation.

Kevin W.H. Tan *01 was appointed chief financial officer of Selecta Biosciences, Inc., a clinical-stage biotechnology company advancing biologic therapeutics and gene therapy. Prior to Selecta, he was treasurer at Sarepta Therapeutics and before that served as senior portfolio manager at CPP Investments. Tan holds an undergraduate degree in commerce from Queen's University in Ontario, Canada; an M.B.A. from the University of Chicago Booth School of Business; and a master's degree in operations research and financial engineering from Princeton.


Kevin W.H. Tan

Jay S. Yook '97 was named chief operating officer of Aquarian Holdings, a diversified holding company. He will work with portfolio businesses to help manage their respective strategic growth plans. For 12 years before joining Aquarian, Yook was head of transformation of the hedge fund Bridgewater. In prior years he was employed at McKinsey and Deloitte. Yook's M.B.A. is from Harvard and his B.S.E. from Princeton in 1997 is in electrical engineering.


Jay S. Yook

Photos courtesy of the subjects unless otherwise indicated

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