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PRINCETON

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ROBOTICS

DEAN'S NOTE

Creating robots that serve humanity

In this issue of EQuad News we highlight just a few examples of pathbreaking research in robotics. An explosion of innovation in computing, hardware, and materials make this an exciting time for robotics, with a richness of interdisciplinary interactions and great potential to benefit society. As we make major investments in new faculty and new spaces, and build existing strengths across science and engineering, Princeton is emerging as a leading hub of innovation in robotics.

As the stories in this magazine illustrate, robotics research at Princeton spans the foundational mathematics behind machine learning and artificial intelligence to innovations in materials, hardware, and devices. Researchers are drawing on the collective behaviors of animals and even the performing arts to envision novel ways for teams of robots to work together, while thinking deeply about safety, security, privacy, fairness, and public policy related to robotics.

Robotics is just one area of growth at Princeton Engineering. A major focus during my first year as dean was to work with colleagues and leaders across the school and university to develop a compelling strategic plan for engineering. The plan calls for significant growth over the next decade in order to maximize Princeton's impact in solving the most pressing societal challenges. In addition to departmental growth, we plan to expand in interdisciplinary areas such as robotics, bioengineering, data science, quantum computing, materials, along with energy and sustainability. These areas all build on each other, and also align with our vision to build industry partnerships and a culture of entrepreneurship to catalyze a regional tech hub with Princeton at its center.

Please visit our website and follow us on social media to learn more and to engage!

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

A note about the cover:
The illustration of the robotic arm is inspired by the work of Professor Glaucio Paulino (page 19), whose recent paper in the Proceedings of the National Academy of Sciences demonstrated how to use sophisticated control of magnetic fields to actuate origami-like units in multiple dimensions.

Photo of Andrea Goldsmith by David Kelly Crow

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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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Students gathered in the Friend Center courtyard to mark the return to campus this fall. Photo by David Kelly Crow

FACULTY WELCOME STUDENTS BACK TO CAMPUS

Dean of Engineering Andrea Goldsmith welcomed first-year students to campus on Sept. 2, celebrating the joy of reopening after more than a year of remote education.

"I can't tell you how thrilled I am to be seeing you all in person," Goldsmith, the Arthur LeGrand Doty Professor of Electrical and Computer Engineering, told students gathered in the Friend Center courtyard. "It's just so joyful to me and everybody here at Princeton. We're so delighted that you are here."

With 343 students, engineering students represent about 21% of the entering Class of 2025. In her welcoming address, Goldsmith urged the students to take advantage of Princeton not only as a top engineering school but also as a world-class liberal arts university.

"I can tell you based on my own experiences that having a unique and broad perspective through a liberal arts education allows you to see the future of technology" in ways that a purely technical education cannot, she said. "It also allows you to apply technology to solve the greatest problems facing humanity."

Goldsmith noted that the engineering school will grow during the class's time at Princeton. She said the school is undertaking an expansion of the faculty by 30 to 40 positions and is focusing its efforts on areas of study including bioengineering, robotics, quantum computing, artificial intelligence and machine learning, and the future of cities.

Peter Bogucki, the associate dean for undergraduate affairs, introduced faculty representatives of the school's engineering departments, who provided brief introductions to the departments and the opportunities they offer. The faculty members were followed by representatives of engineering student organizations. Goldsmith closed her address by urging students to follow their interests and passion for learning.

"Explore your interests even if it is not clear that this is going to have anything at all to do with your degree or your ultimate career," she said. "If it is something inspiring and interesting and captures your attention, you may use it five, 10, or 20 years down the road." **– by the Office of Engineering Communications**

MAJOR GIFT SUPPORTS PURSUIT OF 'GRAND CHALLENGES' IN BIOENGINEERING

A major gift from alumni will provide the Princeton Bioengineering Initiative funding to pursue some of the biggest questions and opportunities emerging at the intersection of biology and engineering.

The Gilbert S. Omenn, M.D., '61 and Martha A. Darling *70 Fund for Grand Challenges in Bioengineering will allow the recently created initiative to move rapidly on several fronts, including hiring postdoctoral investigators, seeding research, and starting a series of lectures on technical and societal frontiers of bioengineering.

"Research and innovation in bioengineering are going to yield incredible, transformative impacts over the next decades," said Clifford Brangwynne, the June K. Wu '92 Professor of Chemical and Biological Engineering. "This gift from Martha and Gil comes at a key moment for Princeton Bioengineering, and will give us resources and flexibility to expand the scope of our growing program, to create new understanding and improve health for people and the environment, and to understand the broader societal implications."

Gilbert S. Omenn '61 and Martha Darling *70

Among the big questions that researchers will pursue are the genetic and cellular origins of disease, and how to harness and manipulate cells to improve health. Scientists and engineers will also investigate how to use bioengineering to mitigate the world's environmental challenges. Brangwynne said that across these areas, further challenges are to maximize university-industry collaborations to speed innovation and to examine policy and ethical implications that arise from the work.

"Our message in creating this gift is to give Cliff, as director of the initiative, maximal flexibility," said Omenn, who graduated from Princeton in 1961 and has had a distinguished career as a physician, biomedical researcher, and leader at the University of Washington and the University of Michigan. Darling earned a master's of public affairs from Princeton in 1970, worked in leadership roles at The Boeing Company, and served in numerous national and state policy roles, including as a White House Fellow and member of the White House Commission on Presidential Scholars.

"We think this is an opportunity where Princeton has remarkable strengths and terrific young leaders," said Omenn, who is the Harold T. Shapiro Distinguished University Professor at the University of Michigan.

Princeton established the Princeton Bioengineering Initiative in 2020, naming Brangwynne as the inaugural director. Brangwynne has been widely recognized for discovering previously unknown structures within cells that affect a wide range of basic functions in living organisms. **– by the Office of Engineering Communications**

'HARD TECH' ACCELERATOR AND NSF PROGRAM HELP CATALYZE REGIONAL INNOVATION HUB

Two separate initiatives recently announced by federal and state leaders are helping catalyze a regional hub for innovation and entrepreneurship with Princeton University as a central player.

On Aug. 25, the National Science Foundation announced a $15 million grant for Princeton to lead one of five national I-Corps hubs, a system for accelerating the economic impact of federally funded research through entrepreneurship. On Sept. 15, New Jersey Gov. Phil Murphy announced that venture capital firm SOSV selected Newark, N.J., to establish the U.S. headquarters for HAX, its program for launching early-stage "hard tech" companies focused on solving difficult and complex technological problems.

The federal grant provides five years of funding to create the NSF Innovation Corps (I-Corps) Northeast Hub to provide entrepreneurial training, mentoring, and resources to enable researchers to form startup companies that translate laboratory discoveries into breakthrough products and services.

"Princeton is excited to lead this initiative to develop the talent and dynamism of our region's researchers," said Princeton University President Christopher L. Eisgruber. "I am especially pleased that the hub will assist those who historically have faced barriers to opportunity and expand the societal impact of new discoveries and innovations."

Rodney Priestley, Princeton University's vice dean for innovation and the Pomeroy and Betty Perry Smith Professor of Chemical and Biological Engineering, will be the hub's co-director.

In the HAX initiative, Princeton partnered with the New Jersey Economic Development Authority (NJEDA) to attract the accelerator. SOSV selected Newark over six other locations in a national search and aims to invest $25 million in 100 new technology companies over the next five years with a focus on "re-industrialization and decarbonization of the U.S."

Princeton will play a key role in new initiatives to foster regional entrepreneurship. Image by iStock

NJEDA chief executive officer Tim Sullivan said Princeton Dean of Engineering Andrea Goldsmith played a key role in SOSV's decision. Goldsmith is a founder of two companies based on innovations in her research area of wireless technologies.

"This partnership with HAX will be instrumental in our plans for Princeton Engineering to catalyze a diverse and inclusive high-tech hub throughout the tri-state area," Goldsmith said. "HAX's outstanding track record of supporting entrepreneurs in traversing the challenging path from ideas to companies will be transformative in creating an innovation ecosystem across the region, with Princeton at its center," Goldsmith said. **– by Engineering and Corporate Engagement Communications**

RESEARCHERS INVENT WORLD'S SMALLEST BIOMECHANICAL LINKAGE

Researchers at Princeton have built the world's smallest mechanically interlocked biological structure, a deceptively simple two-ring chain made from tiny strands of amino acids called peptides.

In a paper published in Nature Chemistry, the team detailed a library of such structures made in their lab — two interlocked rings, a ring on a dumbbell, a daisy chain, and an interlocked double lasso — each around one billionth of a meter in size. The study also demonstrates that some of these structures can toggle between at least two shapes, laying the groundwork for a biomolecular switch.

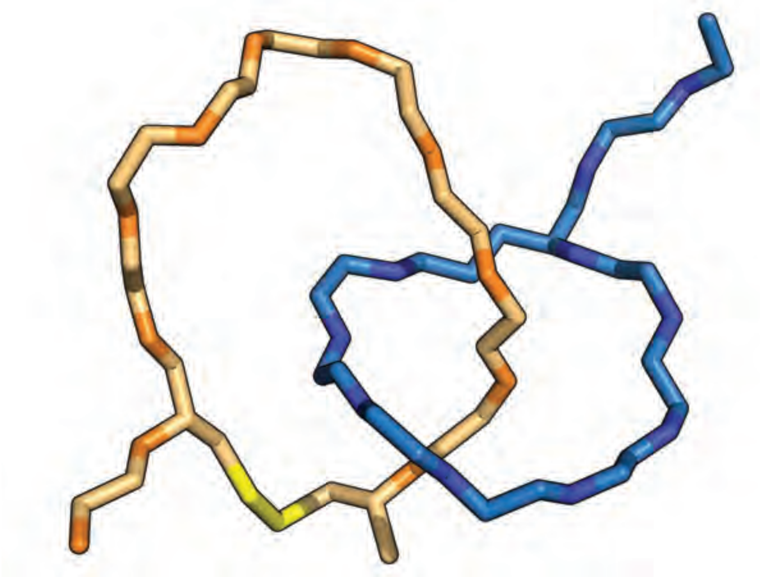
"We've been able to build a bunch of structures that no one's been able to build before," said A. James Link '00, professor of chemical and biological engineering, the study's principal investigator. "These are the smallest threaded or interlocking structures you can make out of peptides."

To craft these gadgets, dubbed mechanically interlocked peptides, or MIPs, the researchers used genetic engineering to manipulate individual amino acids in a naturally occurring lasso peptide, microcin J25, and direct the peptide to self-assemble into new shapes. They also bypassed the need for the harsh solvents and metal ions used in building similar synthetic molecular architectures, work that was the focus of the 2016 Nobel Prize in chemistry. This work, using a single-pot protocol in water, leverages minimal control over the peptides' own form-finding program to create an entirely new class of technology.

"Entangled structures are being found more and more frequently in proteins, peptides, and other natural products," wrote Hendrik V. Schröder, a postdoctoral researcher in Link's lab and the study's first author, in an accompanying blog post. "We are only beginning to understand how these natural structures are made in water by complex enzyme machineries and what role mechanical bonding plays in biomolecules."

While there's no clean distinction between peptides and proteins, peptides are generally smaller than proteins, which tend to be very long and often intricately folded. Entangled peptides, such as the class known as lasso peptides, are extremely robust molecules with many potential uses in biomedicine, including the treatment of bacterial infections. Combining those threaded peptides and the rings they form into more complex structures, as in this work, establishes a new foundation for higher-order biomolecules that could revolutionize materials design and human health.

"It's really building a bridge between the biological world," Link said, "and what until now has been the playground of synthetic chemistry." **– by Scott Lyon**



Researchers from A. James Link's lab have invented a class of biotechnology they call mechanically interlocked peptides, a library of tiny, deceptively simple structures that establish a new foundation for higher-order bio-mechanical systems. Image by the researchers

RESEARCHERS MEASURE THE BREAKUP OF A SINGLE CHEMICAL BOND

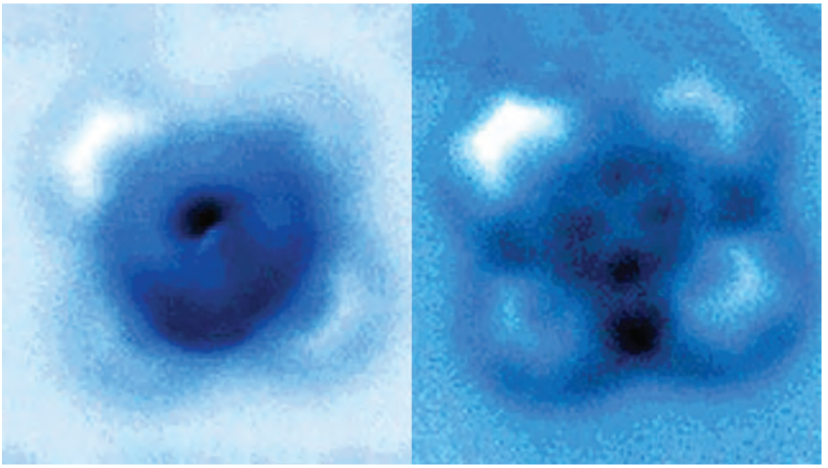
Using advanced microscopy techniques at Princeton University, researchers recorded the breaking of a single chemical bond between a carbon atom and an iron atom on different molecules.

The team used a high-resolution atomic force microscope (AFM) operating in a controlled environment at Princeton's Imaging and Analysis Center. The AFM probe, whose tip ends in a single copper atom, was moved gradually closer to the iron-carbon bond until it was ruptured. The researchers measured the mechanical forces applied at the moment of breakage, which was visible in an image captured by the microscope. A team that also included researchers from the University of Texas-Austin and ExxonMobil reported the results in a paper published Sept. 24 in Nature Communications.

"It's an incredible image — being able to actually see a single small molecule on a surface with another one bonded to it is amazing," said coauthor Craig Arnold, the Susan Dod Brown Professor of Mechanical and Aerospace Engineering and director of the Princeton Institute of Materials.

"The fact that we could characterize that particular bond, both by pulling on it and pushing on it, allows us to understand a lot more about the nature of these kinds of bonds — their strength, how they interact — and this has all sorts of implications, particularly for catalysis, where you have a molecule on a surface and then something interacts with it and causes it to break apart," said Arnold.

Nan Yao, a principal investigator of the study and the director of the Imaging and Analysis Center, said the experiments also revealed how bond breaking affects a catalyst's interactions with the surface on which it's adsorbed. Improving chemical catalysts is useful for biochemistry, materials science, and energy technologies, added Yao, who is also a professor of the practice and senior research scholar at the Institute of Materials.



Researchers measured the mechanical forces applied to break a bond between carbon monoxide and iron phthalocyanine, which appears as a symmetrical cross in scanning probe microscope images taken before and after the bond rupture. Image by Pengcheng Chen et al.

In the experiments, the carbon atom was part of a carbon monoxide molecule and the iron atom was from iron phthalocyanine, a common pigment and chemical catalyst. Iron phthalocyanine is structured like a symmetrical cross, with a single iron atom at the center of a complex of nitrogen- and carbon-based connected rings.

Yao and colleagues used the AFM instrument to break the iron-carbon bond by precisely controlling the distance between the tip and the bonded molecules, down to increments of 5 picometers (5 billionths of a millimeter). The breakage occurred when the tip was 30 picometers above the molecules — a distance that corresponds to about one-sixth the width of a carbon atom.

– by Molly Sharlach

WHITE HOUSE APPOINTS DEAN ANDREA GOLDSMITH TO PANEL OF SCIENCE ADVISORS

Andrea Goldsmith.
Photo by David Kelly Crow

The Biden administration has appointed Andrea Goldsmith, dean of Princeton's School of Engineering and Applied Science, to the President's Council of Advisors on Science and Technology.

The council advises the president on policy related to science, technology, and innovation. It is led by geneticist and Princeton alumnus Eric Lander '78 and co-chaired by Nobel Laureate and Princeton Engineering alumna Frances Arnold '79 and astronomer Maria Zuber.

The council also will include Stephen Pacala, Princeton's Frederick D. Petrie Professor in Ecology and Evolutionary Biology and associated faculty in the High Meadows Environmental Institute, and alumni John Dabiri, who earned his undergraduate degree in engineering in 2001, and Terence Tao, who earned his Ph.D. in mathematics in 1996.

"As a nation and a global community, we have an opportunity like never before to harness science, technology, and innovation to benefit humanity, including improved health and welfare as well as making our planet more resilient and sustainable," said Goldsmith, the Arthur LeGrand Doty Professor of Electrical and Computer Engineering. "I am honored to serve on this panel with amazing colleagues all focused on realizing that potential."

Biden said the members of the council, which is part of the cabinet-level Office of Science and Technology Policy, "represent enormous possibilities."

"They are the ones asking the most American question, 'What next?'" Biden said. "They are not asking questions for the sake of questions; they are asking these questions as a call to action, to inspire, to help us imagine a future and figure out how to make it real to improve the lives of the American people and people around the world."

Biden charged the committee with addressing questions concerning public health, climate change, equitability, and technological leadership.

Goldsmith, who joined Princeton as dean of engineering in 2020 from Stanford University, is an expert in wireless technologies. She is an elected member of the National Academy of Engineering and the American Academy of Arts of Sciences and was the first woman to win the Marconi Prize, the highest honor in telecommunications research. She is a founder of two companies focused on wireless technologies.

Goldsmith said that her role on the presidential council aligns with Princeton University's mission of service and particularly with the engineering school's focus on harnessing technology, innovation, and design for broad societal good. "Science and engineering are woven into our day-to-day lives and the future of the planet," she said. "As engineers, our job is not just to discover and innovate but to think broadly and inclusively about the impacts of our work. That is the kind of human-centered approach I hope to bring to the council and its work for society." **– by the Office of Engineering Communications**

STUDY SHOWS HOW CITIES CAN CONSIDER RACE AND INCOME IN HOUSEHOLD ENERGY EFFICIENCY PROGRAMS

Climate change and social inequality are pressing issues that often overlap. A new study led by Princeton researchers offers a roadmap for cities to address inequalities in energy use by providing fine-grained methods for measuring disparities in energy use intensity according to both income and race. The work could guide the equitable distribution of rebates and other measures that decrease energy costs and increase efficiency.

According to results reported in the Proceedings of the National Academy of Sciences, cities must take a more nuanced approach to truly understand and fully address energy use inequality, unpacking energy race-related disparities from income. As the authors report, examining the issue solely through the lens of income risks missing significant race-related inequalities that exist beyond income effects.

"Often, in discussions about social justice, people sometimes ask, 'Oh, how do you know it's a race effect and not 'just' an income effect?'" said Anu Ramaswami, a professor of civil and environmental engineering and the High Meadows Environmental Institute at Princeton University and the study's lead principal investigator and corresponding author. "This paper actually shows you the data, that there's a structurally linked income-race effect, and an additional race effect even within the same income group."

Ramaswami, who also is Princeton's Sanjay Swani '87 Professor of India Studies and director of the Chadha Center for Global India, and her colleagues arrived at their findings by studying two cities, Tallahassee, Florida, and St. Paul, Minnesota. The findings showed that when evaluating annual energy use, homes in the lowest-income neighborhoods on average used 25-60% higher energy use per square foot compared to the highest-income neighborhoods. Within the income groups, predominantly non-white neighborhoods had higher energy use intensity compared to predominantly white neighborhoods.

The researchers' methods can be applied to a wide range of cities and utilities such as energy, water, and transportation. Image by iStock

The researchers hope to follow up to determine what is driving disparities in energy use intensity, so cities can use that information to address inequality.

"The new understanding gained from this study is already quite a lot," said Kangkang Tong, the study's first author and a postdoctoral researcher at Princeton University. "But it will take another several studies to really understand the reasons behind our findings, to help communities improve their energy use efficiency." **– by Rachel Nuwer**

RESEARCHERS TAKE STEP TO USING CELLULAR MOVEMENT TO HELP WOUND HEALING

Princeton researchers have taken an important step in directing skin cells to migrate en masse to close wounds – "literally making skin crawl," said principal investigator Daniel Cohen '08, an assistant professor of mechanical and aerospace engineering.

In a study published in the Proceedings of the National Academy of Sciences, the researchers overcame skin tissue's inertia by breaking the molecular connections between cells, directing their migration with an electrical field and then rebuilding the connections. This approach improves the controllability of tissues and may one day help optimize wound healing.

The German physician Emil du Bois-Reymond first described an electric current flowing from a cut on his finger in 1848.

Later research showed that cells can sense and follow an electric field, a process called electrotaxis. Electric fields generated in the body promote healing by directing cells to move toward the wound and are also vital for growth.

"There are a lot of reasons why people think electrical stimulation might help wound healing," said Gawoon Shim, the study's lead author and a graduate student in Cohen's lab. But despite evidence from decades of clinical use, scientists have yet to understand how cells respond to electric fields or how electrical stimulation can best be applied therapeutically.

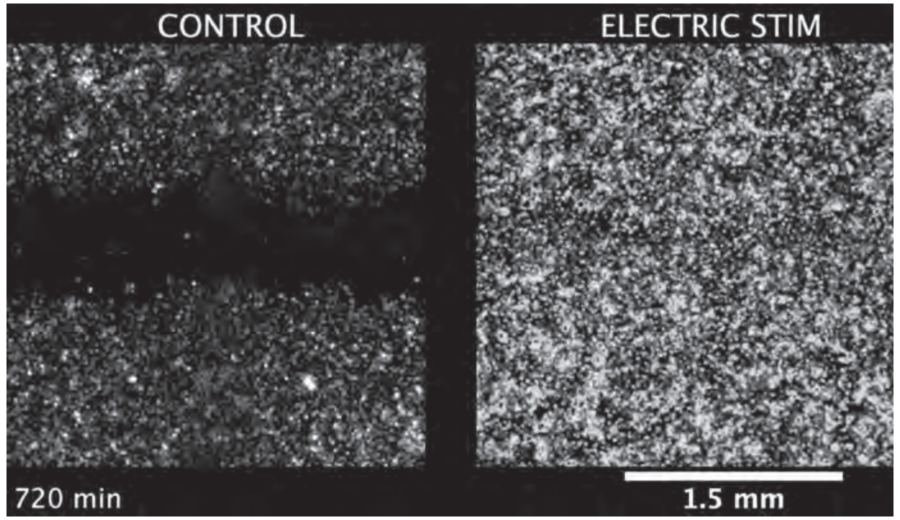
"We discovered this basic phenomenon 175 years ago and we don't yet have commercial electric Band-Aids," said Cohen, senior author of the study. "No one really knows the rules for how to design these things."

In past studies, Cohen's group has used electric fields to program thousands of individual cells to move in circles and around corners. Their new study used a model of more mature skin, which is harder to control. Instead of quickly responding to an electric current, the mature skin cells inched along.

Cohen and Shim suspected that this inertia related to proteins called cadherins that anchor cells together. Cadherins need calcium ions to complete their connections, so Shim grew the cells with different amounts of calcium and measured their response to electrical stimulation.

After working out the ground rules of cell adhesiveness, the researchers developed a solution. Shim grew a layer of skin cells in a high calcium solution so they made normal connections. Then she treated the cells with a chemical that grabs calcium ions to break the cellular handshakes. When Shim lowered the calcium level and applied the electric field, the cells moved on command. Finally, she restored the high-calcium level to reinstate the connections, resulting in a healthy and cohesive layer of skin cells.

– by Patricia Waldron



Princeton researchers used an electrical field to direct the migration of cells. The researchers' new technique improved the controllability of tissues and could someday help heal wounds. Image courtesy of the researchers

Safe, resilient, scalable robotics in the service of humanity

Robots and robotic systems, once specialized equipment for factories or other controlled environments, operate increasingly in our everyday lives. Self-driving cars, drones, and "smart" household devices integrate human inputs, artificial intelligence, and wireless connectivity to assist in highly complex tasks. At Princeton, researchers are working across many disciplines to take a holistic view of robotics. Their goal is to develop systems that truly serve society, with both large-scale impact and long-term safety.

With a quickly growing faculty and new, highly adaptable lab space for multidisciplinary projects, robotics at Princeton Engineering is on the rise, spurring innovation, corporate partnerships, and entrepreneurship. The stories and people featured here represent just a portion of this exciting work. Please follow us at **engineering.princeton.edu** or **@eprinceton** on Twitter or Instagram for all the latest.

Jaime Fernández Fisac works to improve the safety of robots' interactions with humans. Photo by Sameer A. Khan/Fotobuddy

TO GUARANTEE SAFETY, THESE ROBOTS DANCE THE BOLERO

by Scott Lyon

They aren't old-style droids welding parts on a factory line. These are the robots that will sense, think, and act in society's liveliest spaces.

Guided by advanced models, the systems Jaime Fernández Fisac designs will navigate simulated street traffic, maneuver gusts in synchronized flight, and lead human dance partners in a back spot turn. But the models are not the real world. In the gap between theory and broad use that widely benefits society, lurk the dangers of overconfidence. And Fisac insists these robots be safe.

"No matter how carefully you design your model, and no matter how much data you feed your machine learning algorithm to train a very accurate model, at the end of the day this gap will exist," said Fisac, an assistant professor of electrical and computer engineering who joined the faculty in fall 2020. "And it's going to show up at the least convenient time."

If he can train the systems to reason about those gaps, Fisac believes robotics will be in a far safer position. He combines game theory (a field rich in Princeton history) and cognitive science with reinforcement learning, an AI technique that trains the models to reason through millions of variations of a task.

Dance provides a neat case study as robots' sophisticated algorithms learn how to read human behavior in ever finer detail. And they will eventually be able to predict all likely outcomes for a given scenario, moment by moment. That could be arm in arm, dancing the bolero, or zipping along the interstate in heavy traffic.

But Fisac zeroes in on the qualifier — likely. It helps him flag the chasm between the plausible and the real. That sparse, intractable outer limit of the probabilistic long tail. That's where we find real surprise. And Fisac says to guarantee safety, robots need to respond dynamically to their own failing predictions, anticipating and avoiding no-win situations.

"There's this mutual dependence between your decisions and the decisions of others that makes or breaks your safety," he said. "It really is a dance. And it's probably the most important form of uncertainty that we're going to need to grapple with in modern robotics." **E**

MODELS EQUIP ROBOT TEAMS TO MOVE SMOOTHLY AROUND PEOPLE

by Molly Sharlach

Approaching someone in a hallway, do you both bear right to avoid a collision? Veer left?

It turns out that this awkward moment of deadlock is not just a human experience. Robots can encounter the same issue when working in teams or moving around humans in a warehouse or at a disaster recovery scene.

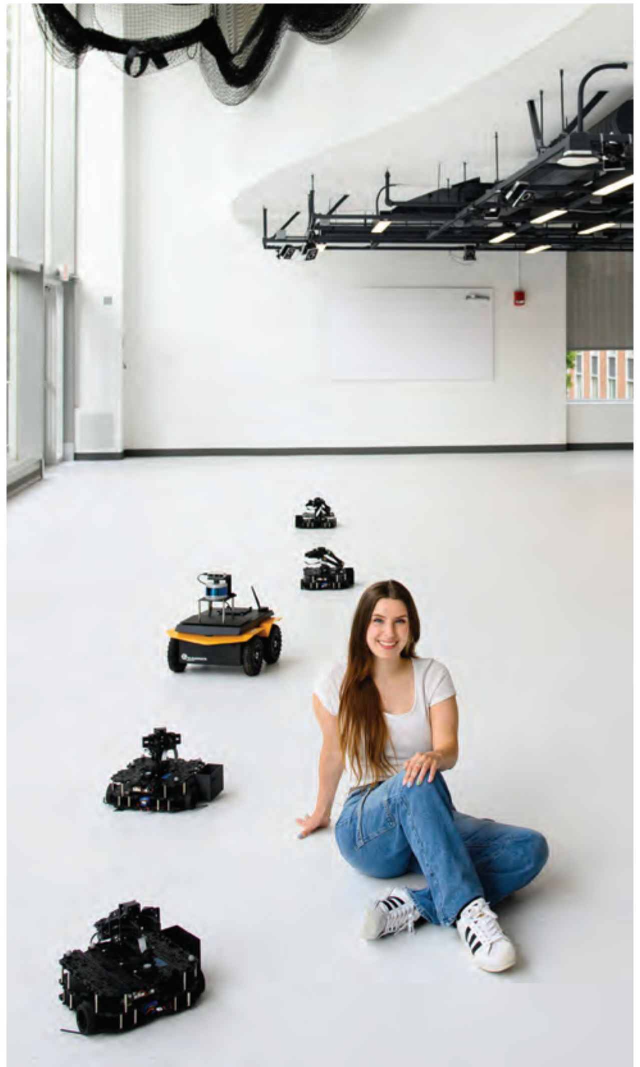
Research in the lab of Naomi Ehrich Leonard '85 aims to help robots move safely and gracefully around humans while achieving desired goals. Using mathematical models — some rooted in evolutionary biology or social sciences — her team explores how groups of robots can autonomously coordinate their activities.

"A big challenge in my group is developing mathematical models that reveal underlying mechanisms of collective sensing, learning, and decision making, and providing principled and systematic means to design the actions that robots in a group should take when they're working together or working with people in complex settings," said Leonard, the Edwin S. Wilsey Professor of Mechanical and Aerospace Engineering.

Her group has collaborated with scholars from many disciplines to study flocks of starlings, schools of fish, colonies of ants, and troupes of dancers. With new insights into group dynamics and decisions, they've created systems that have guided robot teams to explore the ocean depths and to search out anomalies in nuclear facilities.

Charlotte Cathcart, a Ph.D. student in Leonard's group, is working with other current and former group members on a project to apply their new models of opinion dynamics to robot navigation — to spare robots and the humans around them from collisions, as well as irritating and unproductive deadlocks. Opinion dynamics models are commonly used in the social sciences to examine the spread of views on politics or public health, but are also useful for programming robots to choose safe, predictable pathways as they navigate around people, obstacles, and other robots in dynamic environments.

"How do I tell a robot to be more assertive or more cooperative, or to pay attention to how a human is walking toward it and play a submissive role? Or to take time to make sure that the person is very comfortable as the robot passes, as opposed to moving full speed ahead toward a goal?" asked Cathcart. "These are all things that opinion dynamics can help us figure out." **E**



Charlotte Cathcart. Photo by Sameer A. Khan/Fotobuddy

ROBOTICS LAB OPENS FOR EXPERIMENTATION AND COLLABORATION

In January, the engineering school opened a new collaborative research space for robotics to support the increase in faculty, students, and researchers in the field. Spanning two stories at the northern end of the EQuad building, the robotics lab includes an aerial drone-flying space, a mobile robot area, a "living lab" furnished like a home, and a prototyping area, as well as faculty offices, grad student desks, and space for a robotics lab manager and technical specialists. The goal is to allow a range of experimental techniques and easy cooperation among teams from varied disciplines.

Photo by Sameer A. Khan/Fotobuddy

SMALL, EFFICIENT SENSORS HELP DRONES FLY IN HIGH WINDS

by Molly Sharlach

Drones are well suited for finding fractures in bridges, people stranded in disasters, and new sites for renewable energy plants — among other tasks that are dangerous or difficult for humans.

But the expanded use of these unmanned aerial vehicles (UAVs) has been hampered in part by an inability to handle high winds or complex airflows around buildings.

Now, two Princeton engineers have teamed up to help drones fly better in gusts and gales. Anirudha Majumdar, an assistant professor of mechanical and aerospace engineering, focuses on safety and performance guarantees for robotic control systems, while Marcus Hultmark *09, associate professor in the same department, specializes in fluid mechanics.

Hultmark's group has developed a new type of flow sensor — a micro-electromechanical system that uses a nanoscale conductive wire to measure humidity, temperature, or velocity with high speed and sensitivity.

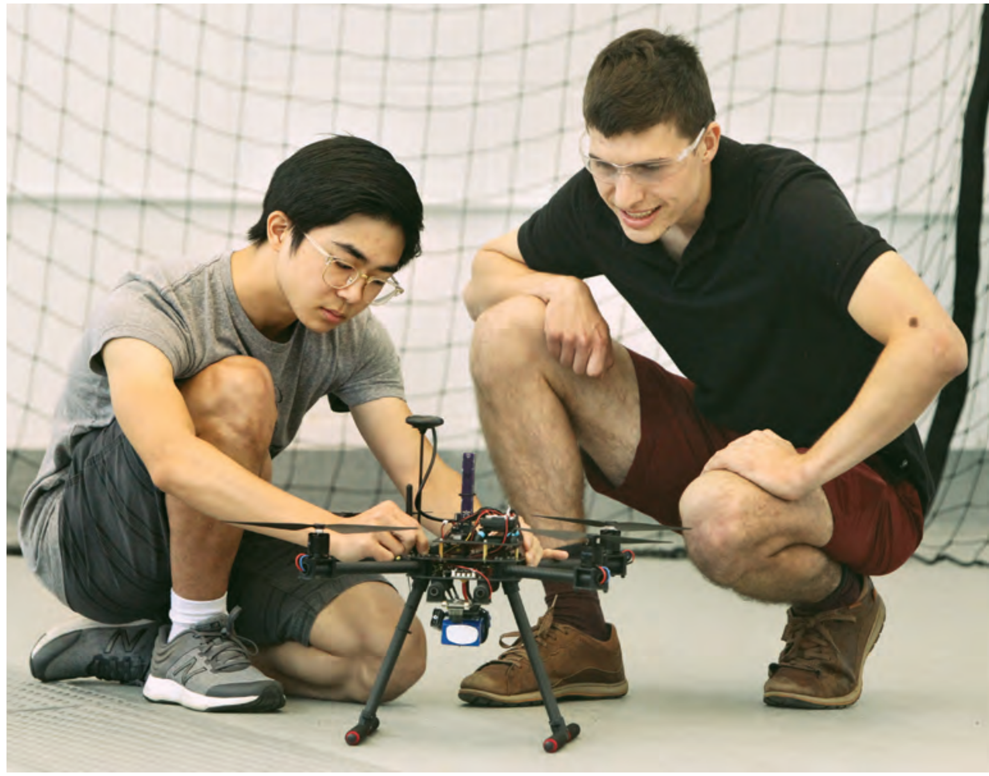
Drones currently gauge airflow using downward-facing cameras or pitot tubes, which use a fluid pressure measurement. State-of-the-art drones can fly well at wind speeds of up to 20 miles per hour (like a typical windy day at the beach), but falter in stronger winds or shifting conditions, said Majumdar.

With an innovation grant from the engineering school's Project X Fund, Majumdar and Hultmark are integrating their microsensors with a commercially available quadrotor drone. They aim to achieve safe, autonomous flight amid obstacles, with wind gusts of 40 to 50 miles per hour.

"For pilots, wind is a huge factor — it's an invisible, often unpredictable force. This is especially true for flight near obstacles, like drone infrastructure inspections. To give drones the ability to sense and react to changes in the airflow would be game-changing," said Nathaniel Simon, who is leading the work as a Ph.D. student coadvised by Majumdar and Hultmark. Simon has piloted small planes since age 13.

Also contributing to the project is Kyle Ikuma, a junior in the mechanical and aerospace engineering department, who has been a drone hobbyist since eighth grade. "For me, it was always more fun building the drones than flying them," said Ikuma. "That's how I learned about 3D printing and how to use [computer-aided design software]" — valuable skills in his collaboration with Simon as part of the department's Summer Practical Research Experience program.

Along with testing the microsensor-equipped drone in a wind tunnel, the researchers are developing new airflow models and simulations to optimize placement of the sensors and integrate airflow data with autonomous control algorithms. **E**



Undergraduate Kyle Ikuma (left) and Ph.D. student Nathaniel Simon (right) work on a project to develop systems that allow drones to fly in high winds. Photo by Frank Wojciechowski

BUILDING BOTS COULD BRAVE HARSH ENVIRONMENTS, CREATE NEW TYPES OF STRUCTURES

by the Office of Engineering Communications

Construction doesn't often leap to mind in discussions of cutting-edge robotics, but automation promises to revolutionize many parts of the building industry in both methods and environments.

"There are many things that are extremely difficult for a human to build," said Sigrid Adriaenssens, an associate professor of civil and environmental engineering. "There are also environments that are difficult or hazardous for humans."

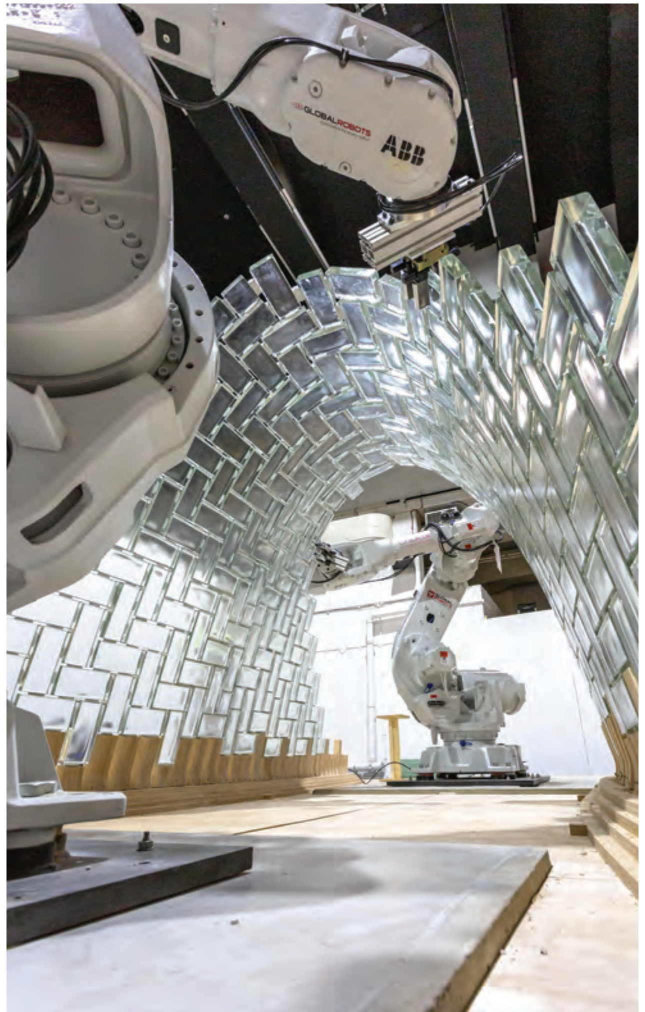
Adriaenssens leads the University's Form Finding Lab and specializes in structures and designs that involve minimal, self-adapting, and flexible materials. Recently, she has been collaborating with colleagues across an array of disciplines to identify how robots could improve building techniques and, in some cases, allow for construction that is impossible with current methods. In 2020, she co-led an effort with Stefana Parascho, an assistant professor of architecture, to demonstrate ways that robots could help reimagine the way that architects and engineers think about building. Joining with the international engineering and design firm Skidmore, Owings, and Merrill, the team used two repurposed automotive assembly robots to build a vault of 338 transparent glass bricks for the "Anatomy of Structure" exhibition in London.

The twin robots were able to build the 7-foot-tall vault without the need for scaffolding, which reduced the amount of material required. Because the machines could place the bricks with far more precision and regularity than any human, they were able to work more efficiently.

"My work is not trying to replace human labor by automating it, but to increase the possibilities for architecture by using robots for tasks that humans are rather bad at," Parascho said at the time.

Adriaenssens said realizing the full potential of robotics in construction will require engineers and architects to work closely with colleagues who specialize in software and robotics.

"The goal is to make the robot so smart that when we give it certain criteria, the robot has enough information and knowledge about the mechanics of structures that it can design and create structures without specific instructions," she said. "The ultimate dream is you put a robot on Mars or in Antarctica, and it would start building by itself." **E**



Researchers used automotive assembly robots to build a glass arch during an exhibition in London.

Ryan Adams is working to improve manufacturing robots. Photo by David Kelly Crow

MACHINE LEARNING: IN THIS LAB, MACHINES LEARN TO MAKE MACHINES

by John Sullivan

Manufacturing robots are a modern wonder, building everything from packaged food to microchips.

Ryan Adams, a professor of computer science, agrees that these machines are the foundation of the modern economy, but he thinks there is a lot of room for improvement.

"Right now, manufacturing machines run blindly and execute code," Adams said. "The question is, how can these things be smarter? How can they be aware of themselves and make things better, faster, and cheaper?" The programming that guides the spinning and weaving machines that make up a modern assembly line is already sophisticated, Adams said. But he said the machines are following rigid guidelines set by their programmers instead of adapting and reacting to their tasks.

"The tools are sophisticated, but they are not adaptive," he said.

Artificial intelligence offers possible paths to creating manufacturing robots that are more adaptable and easier to manage and deploy. One possible improvement could come in the area of precision. Currently, manufacturers achieve precision by making heavy robots to provide a stable platform for cutting or shaping tools. With proper software, controls, and design, it should be possible to create machines that can use feedback rather than weight to achieve stability.

"What if the software understood the dynamics and adapted to them on the fly?" Adams said. "Instead of a machine that might weigh 10,000 pounds, what if we could create a machine with the same level of precision that might only weigh 100 pounds?"

Adams cautioned that this is not a problem likely to be solved immediately, but it is part of his lab's goal of using artificial intelligence to make robots more efficient and versatile builders. Ultimately, the researchers would like to use artificial intelligence to design the robots themselves. Integrating intelligence into the systems from the start could allow sophisticated capabilities to emerge more naturally, in the same way the knowledge of grasping seems inherent to the human hand.

"I want to design algorithms that are sophisticated in designing the robot itself," he said. "If I pick up a glass, my hand has passive properties that make it easy to do this without thinking about it. This intrinsic 'mechanical' intelligence is something we don't often build into our systems, and yet every biological system has that." **E**

COMPUTATION AND OPTICS UNITE TO SHARPEN ROBOTIC VISION

by Molly Sharlach

Since arriving at Princeton last year, Felix Heide has unveiled a flock of new cameras that push the edge of the visual world.

Some allow cars to peer through dense fog and heavy snow, while others glance around corners for hidden objects or pedestrians.

Heide has accomplished these feats by closely integrating hardware and software, aiming to optimize cameras for specific purposes. His group's research in computational imaging could advance real-time sensing and object detection capabilities for personal devices, medical imaging, robots, and autonomous vehicles.

"We are interested in thinking about codesign of the optics and the algorithms together," said Heide, an assistant professor of computer science. "We want to build domain-specific camera systems: the best camera for object detection, or low-light imaging, or scene understanding, or medical imaging."

One of the imaging systems that Heide focuses on is vision technology for self-driving cars. His group has developed an automated system that uses radar to allow cars to peer around corners and spot oncoming traffic and pedestrians. And with a new grant from Princeton's Metropolis Project, they are working on systems for navigation in adverse weather.

Existing systems for driverless cars rely heavily on lidar, which uses laser beams to detect objects in the environment. Lidar and other current imaging systems perform poorly in snow, fog, and rain, and at distances beyond about 1,000 feet (300 meters), which is essential for the safety of trucking. This is a major hurdle to their wide adoption, especially for transportation into cities from outlying areas, which will have less support infrastructure for driverless vehicles.

Using a test vehicle from Mercedes-Benz, a partner on the project, Heide's team is collecting data from sensors during varied weather conditions in Princeton and New York City, and creating physical simulations based on this data. Using machine learning and optimization methods, they will develop systems enabling suites of sensors to dynamically adapt their activities based on changing conditions. **E**

Felix Heide (above), an assistant professor of computer science, is working to improve the imaging and computer vision capabilities of sensors for autonomous vehicles. Panels show a street scene in heavy snow using a standard vehicle imaging system (left), and the output of ZeroScatter (right), a technique developed by Heide's team that improves image quality and reveals objects at long distances, such as the house at the end of the road. Research images by Zheng Shi et al., photo of Heide by Sameer A. Khan/FotoBuddy

BOOSTING SIGNALS TO BOOST ROBOTS' PERFORMANCE

by Molly Sharlach

In the coming decade, wireless networks will operate at higher radio frequencies than their predecessors, bringing unprecedented data transmission rates and opportunities for sensing with submillimeter accuracy.

These changes will be a boon for many types of communication, including coordination among teams of autonomous robots, but will come with major tradeoffs, as higher-frequency signals do not travel as far as longer radio waves.

Yasaman Ghasempour, who joined the faculty in January 2021 as an assistant professor of electrical and computer engineering, is pioneering next-generation wireless tools that couple communications and sensing. Antennas typically broadcast at a range of frequencies in all directions, but Ghasempour is exploring devices that transmit signals with a laser-like focus, emitting a specific frequency in a specific direction.

The technique, which involves a specialized set of antennas, novel architectures, and control protocols, could someday boost the speed and localization accuracy of robot teams on time-sensitive missions, said Ghasempour.

"Each [robot] may have different sensing modalities, but they require sharing their sensing information in a collaborative mission," she said. "The type of technology we are building can enable ultra-low-latency communications for time-critical missions, and also adds to the sensing modality of robots because now they can use wireless signals to sense the environment and localize other robots." **E**

Yasaman Ghasempour. Photo by David Kelly Crow

SPEEDING DECISIONS TO EASE AUTOMATION

by Molly Sharlach

Driving demands that the driver constantly react to changes on the road, deciding whether and how much to turn, brake, or accelerate.

For driverless cars and robots, creating algorithms to automate these types of decisions in milliseconds is a critical challenge.

Computational methods for complex, real-time decisions were first advanced decades ago, but took hours to produce results, said Bartolomeo Stellato, an assistant professor of operations research and financial engineering. They were useful, for example, in chemical plants to control the temperature of mixtures in large tanks that took hours to fill.

"In terms of algorithms and software, we've taken a giant step forward in being able to solve some of these problems," said Stellato, who joined Princeton in July 2020. "However, some problems are still very hard to solve, or even with all the advances we cannot solve them in milliseconds or less."

Stellato is applying machine learning and data-driven techniques to optimize tasks such as obstacle avoidance by vehicles or drones, or high-frequency trading in financial markets. He hopes to test these methods on real systems in collaboration with robotics researchers at Princeton.

"My goal is to devise algorithms that become smarter over time, in terms of how fast they can provide solutions, how reliable they are, and how confident we are about the decisions they allow us to make," he said. **E**

Bartolomeo Stellato. Photo by Andrea Fanelli

ROBOTICS FACULTY SPAN MANY DEPARTMENTS

For more details, visit robo.princeton.edu

Sigrid Adriaenssens
Civil and Environmental Engineering
Robotics in Construction

Amir Ali Ahmadi
Operations Research and Financial Engineering
Optimization and Learning Dynamical Systems

Jia Deng
Computer Science
3D Vision

Jaime F. Fisac
Electrical and Computer Engineering
Safety-Critical Learning and Control, Human Interaction

Elad Hazan
Computer Science
Control and Reinforcement Learning, Optimization

Naomi Leonard
Mechanical and Aerospace Engineering
Nonlinear Control and Dynamics, Multi-agent Systems

Anirudha Majumdar
Mechanical and Aerospace Engineering
Safety and Generalization Guarantees

Stefana Parascho
School of Architecture
Robotic Fabrication in Architecture

Szymon Rusinkiewicz
Computer Science
3-D Representation, Localization, and Planning

Olga Russakovsky
Computer Science
Vision, Human Interaction

Bartolomeo Stellato
Operations Research and Financial Engineering
Data-driven Optimization and Control

Naveen Verma
Electrical and Computer Engineering
Intelligent Sensing

NEW FACULTY BRING WIDE-RANGING EXPERTISE IN ROBOTICS

As part of a broad initiative to grow Princeton Engineering, the School of Engineering and Applied Science has hired several faculty members who are pioneering new capabilities at the frontiers of robotics.

Radhika Nagpal will join the faculty from Harvard University in January 2022 as a professor jointly appointed in mechanical and aerospace engineering and computer science. Her research is at the intersection of robotics, artificial intelligence, and biology, with a focus on collective intelligence.

"I'm interested in bio-inspired robot designs for swarm robotics, especially future underwater robots, robots for environment or infrastructure monitoring, and robots for construction," she said. This builds on her overall work in the theory of self-organizing systems, including algorithm design for distributed systems and understanding natural collectives like ant colonies and fish schools.

"I am also very interested in collective culture, and how to make science culture more equitable and inclusive for the future," she said.

Reza Moini joined the Department of Civil and Environmental Engineering in 2021 from Purdue University, where he earned his Ph.D. in civil engineering. His work focuses on advanced robotic manufacturing technologies, such as autonomous concrete additive manufacturing, as a means to enable new designs of engineering materials and structures that were previously unimagined.

"Developing advanced robotic manufacturing tools, we commonly draw inspiration from the internal themes and forms found in natural materials and engineer them into functional and resilient civil engineering materials," Moini said. "Our work aims to contribute to the development of resilient and sustainable civil infrastructure and renewable energy infrastructure, in response to the world's growing population, climate change, and the need for a rapid switch to renewable resourcing and storing of energy."

Aimy Wissa joins the Department of Mechanical and Aerospace Engineering as an assistant professor in January 2022 from the University of Illinois-Urbana Champaign. Her Bio-inspired Adaptive Morphology Lab works in the area of bio-inspired locomotion, especially in environments where there are interactions between fluids and structures.

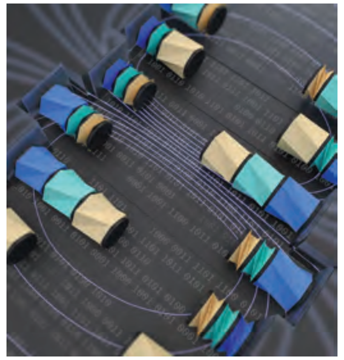
Current projects in Wissa's lab include: dynamics of insect-inspired ultra-fast movement; flow control for small unmanned aerial vehicles through feather-inspired deployable structures; and the design of robots capable of multiple modes of locomotion, such as swimming and gliding or gliding and jumping.

Glaucio Paulino came to Princeton in September from Georgia Tech and is appointed the Margareta Engman Augustine Professor of Engineering and the Princeton Institute for the Science and Technology of Materials.

Paulino builds on his expertise in computational mechanics and topology optimization to design robotic systems that fold like origami and behave like natural organisms, such as worms or octopus tentacles.

"My dream is to have robots that are soft and small and can do many different functions," Paulino said.

In work published in the Proceedings of the National Academy of Sciences, Paulino and collaborators demonstrated a robotic arm with many segments, each of which can be moved independently by applying magnetic fields, creating complex shapes and behaviors. Such technology could one day be used in medical devices and, at a very small scale, in drug delivery. E



A "Kresling pattern" is a way of folding a cylinder so that it collapses into a disc when twisted. New faculty member Glaucio Paulino recently published a series of results showing how this origami pattern could be controlled by magnetic fields to make a highly flexible robotic arm. Image courtesy of the researchers

EMPOWERING YOUNG AI RESEARCHERS, AND ADVANCING ROBOTS' POWERS OF PERCEPTION

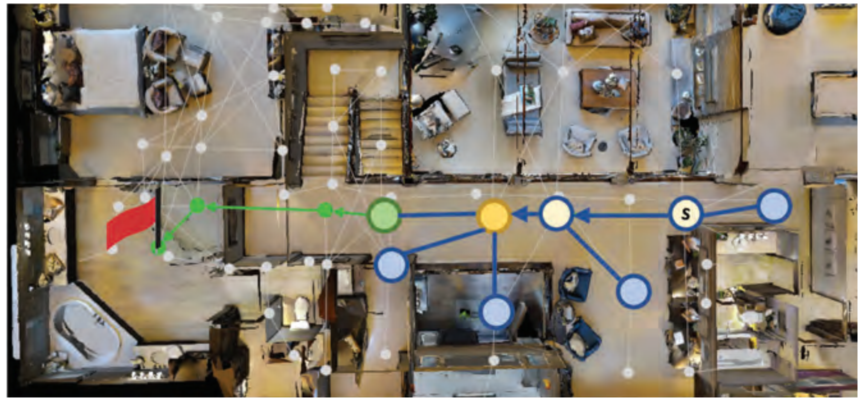
by Molly Sharlach

Olga Russakovsky's Princeton Visual AI Lab develops artificial intelligence (AI) systems with new capabilities in computer vision, including automated object detection and image captioning.

Her team also creates tools to identify and mitigate biases in AI systems, and promote fairness and transparency.

Russakovsky, an assistant professor of computer science, is a cofounder of AI4ALL, a national nonprofit that aims to bring young people from underrepresented groups into AI research. Since 2018, she has codirected an AI4ALL camp for rising 11th graders at Princeton. In the 2021 virtual program, 24 students from around the country spent three weeks learning programming and AI basics, and applying their skills in group projects with guidance from Princeton graduate student instructors.

One group of participants explored the use of computer vision to process data from motion-activated cameras that scientists use to monitor wildlife. Another team developed algorithms to detect misinformation related to COVID-19, while a third group focused on systems that enable robots to predict human motion. Participants examined issues of privacy, security, and ethics, including how the choice of data used to train AI algorithms can introduce unintended biases.



Researchers used a computer simulation to develop AI systems for robots to navigate an unfamiliar space by following a human's instructions. Image courtesy of the researchers

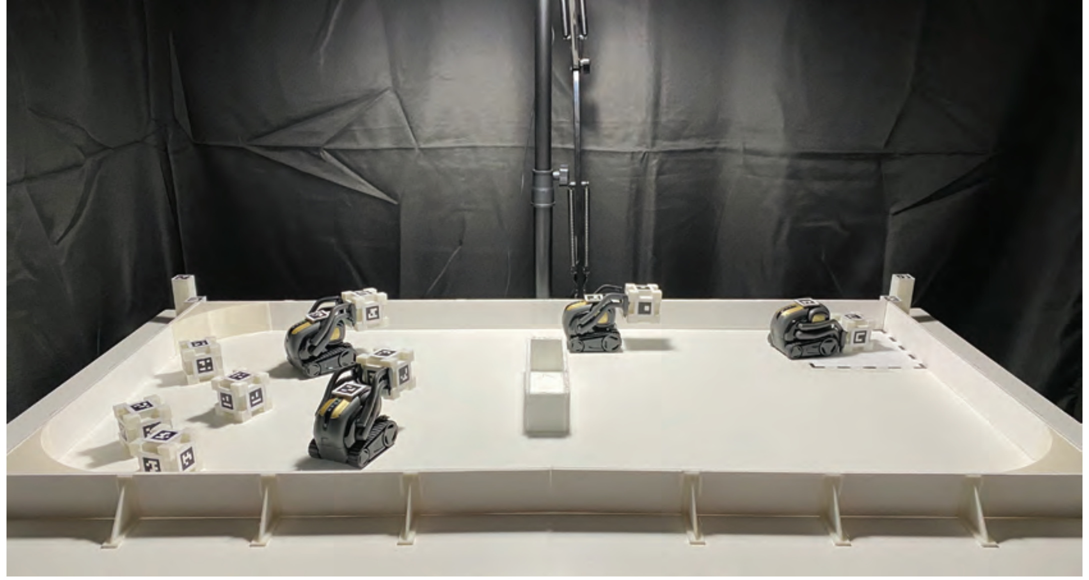
Beyond its summer programs, hosted by 15 universities throughout North America, AI4ALL provides resources and mentorship for its alumni to continue their learning, launch independent projects, and pursue careers in AI.

A current project in Russakovsky's lab addresses how a robot can navigate an unfamiliar space by following a human's instructions. This complex task requires robust systems for processing natural human language, as well as abilities to map the environment, plan movements, and course-correct when needed.

The lab recently made progress toward a single, adaptable computational model that combines all these features. At each step of navigation, the model's algorithms direct the robot to efficiently explore many possible actions, and the robot continues to update the map of its environment and its past actions, which improves error correction.

The researchers tested their method on a benchmark simulation for natural language navigation that includes 22,000 sets of instructions directing a robot to move from one room of a building to another. The model allowed the robot to successfully follow instructions more than 50% of the time, outperforming previous methods.

"Even humans sometimes fail to find a location in a new building or campus," said Zhiwei Deng, a postdoctoral research associate who coauthored the work with Russakovsky and Karthik Narasimhan, an assistant professor of computer science. "Errors can come from the new appearance of the room that the robot has never seen during training, and ambiguity on the language side when performing grounding to visual inputs. This problem requires the model to gradually accumulate information along with the navigation, perform error corrections when realizing a deviation from the instructions, and redo the planning based on current information." **E**



FROM PICKING UP TRASH, ROBOTS PICK UP NEW APPROACHES TO WORK

by John Sullivan

In Jimmy Wu's apartment, a scrum of mini robots bump, swerve, and zip chaotically across a tabletop. It looks like an aggressive bumper car rally, but within a few minutes, order emerges.

The swarm coalesces as the robots race in formation to scoop up bits of trash and deposit them in a goal marker.

The amazing thing: The robots are teaching themselves.

"We're trying to tell the robots 'Look, you're going to get a reward every time you successfully put a piece of trash into the wastebasket,' and that's all they know," said Szymon Rusinkiewicz, the David M. Siegel '83 Professor of Computer Science. "We have algorithms where if they do this thousands and thousands of times in simulation, eventually they learn what it is that causes them to get rewards."

Wu is a graduate student on Rusinkiewicz's research team, which is working to apply a technique called reinforcement learning to robotics. The method, familiar to dog trainers everywhere, offers rewards for good performance. In the case of robots, the rewards are mathematical, like points in a video game. The basic algorithms guiding the robots' behavior are adaptable and change with the rewards, so the robots can develop their own methods for solving problems based on millions of computer simulations.

Rusinkiewicz said the long-term goal will involve cooperation from many different Princeton labs working on projects such as sensor arrays, safety protocols, and group dynamics.

"The work dovetails very nicely with research that's going on by other people in robotics," he said.

In a recent project, the researchers assigned action figure-sized robots the task of picking up small plastic blocks labeled trash and moving them into a goal. At the start, all the robots were equipped with tiny bulldozers, but as the experiment progressed, the bots used different techniques. Rusinkiewicz said the robots learned to work together in surprising ways.

"The throwing agent throws stuff in the general direction of the goal, and another agent hangs out near the goal, picks it up and drops it in," he said. "The exciting thing is, we are giving these agents the same setup, the same reward, but they learn to exploit their own strengths and they learn to cooperate. We are very interested in how far we can develop this idea. Can we get agents that learn to collaborate, to have even more specialized ideas without telling them what to do?" **E**

Photo by Jimmy Wu

RECENT FACULTY AWARDS, PROMOTIONS, AND HONORS

CIVIL AND ENVIRONMENTAL ENGINEERING

Sigrid Adriaenssens
Fellow, American Society of Civil Engineers Structural Engineering Institute

Ning Lin *10
Walter L. Huber Civil Engineering Research Prize, American Society of Civil Engineers

Catherine Peters
George J. Magee Professor of Geological Engineering

Zhiyong "Jason" Ren
Paul L. Busch Award, Water Research Foundation

CHEMICAL AND BIOLOGICAL ENGINEERING

Clifford Brangwynne
June K. Wu '92 Professor of Chemical and Biological Engineering

Pierre-Thomas Brun
CAREER Award, National Science Foundation

Sujit Datta
Pew Scholars Program in the Biomedical Sciences

Celeste Nelson
Wilke Family Professor in Bioengineering

Rodney Priestley
Pomeroy and Betty Perry Smith Professor of Chemical and Biological Engineering

Michele Sarazen
Howard B. Wentz, Jr. Junior Faculty Award

COMPUTER SCIENCE

Barbara Engelhardt
Overton Prize, International Society for Computational Biology

Michael Freedman
Robert E. Kahn Professor of Computer Science

Felix Heide
CAREER Award, National Science Foundation

Margaret Martonosi
Member, National Academy of Engineering

Eckert-Mauchly Award, ACM/IEEE Computer Society

Jonathan Mayer
Alfred Rheinstein Faculty Award

Ravi Netravali
Sloan Research Fellow, Alfred P. Sloan Foundation

CAREER Award, National Science Foundation

Ben Raphael
Innovator Award, International Society for Computational Biology

Olga Russakovsky
Excellence in undergraduate teaching award, Phi Beta Kappa

Howard B. Wentz, Jr. Junior Faculty Award

Olga Troyanskaya
Fellow, Association for Computing Machinery

Mark Zhandry
Sloan Research Fellow, Alfred P. Sloan Foundation

ELECTRICAL AND COMPUTER ENGINEERING

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

Andrew Houck '00
Fellow of the American Physical Society

Kaushik Sengupta
Outstanding Young Engineer, Microwave Theory and Techniques Society

Jeffrey Thompson
CAREER Award, National Science Foundation

MECHANICAL AND AEROSPACE ENGINEERING

Daniel Cohen
CAREER Award, National Science Foundation

Luc Deike
Alfred Rheinstein Faculty Award

Kelsey Hatzell
CAREER Award, National Science Foundation

Yiguang Ju
Propellants and Combustion Award, American Institute of Aeronautics and Astronautics

Anirudha Majumdar
CAREER Award, National Science Foundation
Young Faculty Researcher Award, Toyota Research Institute

Luc Deike
Alfred Rheinstein Faculty Award

Michael Mueller
Associate Fellow, American Institute of Aeronautics and Astronautics

Early-career combustion investigator award, Combustion Institute

Clarence Rowley '95
Sin-I Cheng Professor in Engineering Science

Alexander Smits
Batchelor Prize in Fluid Mechanics

OPERATIONS AND FINANCIAL ENGINEERING

Jianqing Fan
Faculty Research Award, Two Sigma

Ronnie Sircar
Eugene Higgins Professor of Operations Research and Financial Engineering

Ludovic Tangpi
E. Lawrence Keyes, Jr./Emerson Electric Co. Faculty Advancement Award

TEACHING AWARDS HONOR "OFF-THE-SCALE" DEDICATION

Three members of the engineering school faculty were recognized this year for excellence in teaching and mentoring students.

Andrew Houck '00, a professor of electrical and computer engineering, received the School of Engineering and Applied Science Excellence in Teaching Award. Houck, whose research applies quantum mechanics to engineering, is known as an enthusiastic and engaging teacher and sought-after adviser. He has been a leader in successful efforts to restructure the first-year engineering curriculum to increase interest and retention among students. A recipient of the University's President's Award for Distinguished Teaching, Houck has been included in the Dean's Commendation List for Outstanding Teaching 15 times. Sharad Malik, chair of electrical and computer engineering, called Houck an "off-the-scale" teacher.

Students called Houck a "phenomenal instructor" who demonstrated "pure pedagogical mastery." Dean Andrea Goldsmith said Houck "embodies the fact that you can be an outstanding teacher and an outstanding researcher, and that they are intertwined."

Olga Russakovsky, an assistant professor of computer science, was awarded the undergraduate teaching award by the Princeton chapter of Phi Beta Kappa. Russakovsky's work encompasses the intersection of computer vision, machine learning, and human-computer interaction. Recognized as a leader in efforts to increase diversity in computer science and artificial intelligence research, Russakovsky was a cofounder of the national AI4ALL Foundation, which seeks to increase inclusion in computer science through mentorship and education, and now serves as director of the organization's Princeton chapter.

Students praised Russakovsky's enthusiasm, consideration, and ability to present challenging subjects clearly. In the classroom, she makes subjects such as the concept of computer vision accessible by breaking down "even the most complex topics into digestible parts," said senior Dora Zhao, a computer science concentrator.

Howard Stone, the Donald R. Dixon '69 and Elizabeth W. Dixon Professor of Mechanical and Aerospace Engineering, received Princeton University's Graduate Mentoring Award, which recognizes excellence in supporting graduate students' development as researchers, scholars, and professionals. Stone, chair of mechanical and aerospace engineering, studies fluid dynamics, especially as they arise in research and applications at the interface of engineering, chemistry, physics, and biology.

Students commended Stone for his eagerness to help them work through difficult problems. "Whether it be in his classes or with students in his lab, he always makes time for us and comes to any conversation completely engaged," one of his advisees said.


Andrew Houck. Photo by Tori Repp/Fotobuddy


Olga Russakovsky. Photo by Sameer A. Khan/Fotobuddy


Howard Stone. Photo by David Kelly Crow

VALEDICTORIAN PLANS TO PURSUE INTEREST IN GLOBAL HEALTH

Taishi Nakase, the Class of 2021 valedictorian and an operations research and financial engineering concentrator from Melbourne, Australia, delivers his remarks. He is wearing two stoles — gold for the Asian American Pacific Islander (AAPI) affinity group and green for the first-generation/lower-income (FLi) affinity group. Photo by Denise Applewhite

Taishi Nakase, an operations research and financial engineering concentrator from Melbourne, Australia, was selected as valedictorian of Princeton's Class of 2021.

Nakase plans to become a doctor and is interested in using mathematical modeling to confront global health challenges. After Princeton, he will pursue a master of science in modeling for global health at Oxford University before attending medical school.

"I was drawn to the program at Oxford because of its focus on mathematical modeling as a way of confronting challenges in global health," Nakase said. "My research focus will be on the modeling of infectious diseases, particularly measles, in developing countries." Nakase is the first in his family to attend college. He credited the mentorship of Princeton faculty and research experiences through the Global Health Program with supporting his studies and inspiring his career path.

"Professor Bryan Grenfell introduced me to the world of infectious diseases and encouraged me as a first-generation college student to pursue my interests in the field," Nakase said. Grenfell is the Kathryn Briger and Sarah Fenton Professor of Ecology and Evolutionary Biology and Public Affairs. "He has also tirelessly supported me in my independent work in infectious diseases by providing valuable insights and finding the time to help me think through the problems."

Nakase said Bill Massey, the Edwin S. Wilsey Professor of Operations Research and Financial Engineering, was also a valuable mentor and teacher. "Professor Massey was incredibly approachable and always delighted to spend time discussing his material with me," he said.

While at Princeton, Nakase received the Class of 1939 Princeton Scholar Award and was twice awarded the Shapiro Prize for Academic Excellence. He is a member of the Phi Beta Kappa society and the Tau Beta Pi Engineering Honor Society.

Nakase's senior thesis examines the modern challenges of measles control in Vietnam, modeling vaccination campaigns under limited health care resources in the country. Through Princeton's Global Health Program, he interned with Dr. Marc Choisy at the Oxford University Research Clinic in Hanoi. Nakase continues to work with Choisy remotely on research modeling measles dynamics in Vietnam.

"My global health internship was a transformative experience," he said. "It inspired a passion for the modeling of infectious diseases and encouraged me to pursue questions in global health." **– by Emily Aronson**

CLASS DAY CELEBRATES GRADUATES' COURAGE, CREATIVITY, AND OPTIMISM

Dean Andrea Goldsmith commended the "accomplishments and resilience of the great Class of 2021" during the virtual Class Day ceremony May 24. "The Class of 2021 is the centennial class, marking the 100-year anniversary of the [engineering] school," said Goldsmith, the Arthur LeGrand Doty Professor of Electrical and Computer Engineering. "You join a very long list of distinguished scholars and engineers that have contributed to the technology that allows us to operate in the modern world." With 282 graduates receiving engineering degrees and 45 receiving bachelor of arts degrees in computer science, the class included 327 students, representing 28% of the Princeton class.

The major award winners at the 2021 Princeton Engineering Class Day, as presented by Associate Dean for Undergraduate Affairs Peter Bogucki, were:

J. Rich Steers Award
Paige Bentley
Operations Research and Financial Engineering
Jacob Walrath
Mechanical and Aerospace Engineering

Jeffrey O. Kephart '80 Prize In Engineering Physics
Charles Zhao
Computer Science

Joseph Clifton Elgin Prize
Elaine Wright
Electrical Engineering
Dora Zhao
Computer Science

George J. Mueller Award
Joseph Sartini
Operations Research and Financial Engineering
MaryKate Neff
Chemical and Biological Engineering

Award recipients were recognized during an online Class Day ceremony.

Calvin Dodd MacCracken Senior Thesis/Project Award
Henry Birge-Lee
Computer Science
Trisha Madhavan
Electrical Engineering
Rei Zhang
Civil and Environmental Engineering

The Tau Beta Pi Prize
Shalaka Madge
Mechanical and Aerospace Engineering
Meghan Slattery
Operations Research and Financial Engineering

The Lore Von Jaskowsky Memorial Prize
Bianca Gabrielle Acot
Civil and Environmental Engineering
Wenyuan Hou
Mechanical and Aerospace Engineering

James Hayes-Edgar Palmer Prize In Engineering
Taishi Nakase
Operations Research and Financial Engineering

Left: Princeton Senior Gabbie Acot (left) discusses her senior thesis exploring the reconstruction of traumatic head injuries with advisers Annegret Dettwiler-Danspeckgruber, principal investigator at the Neuroscience of Traumatic Brain Injury Research Laboratory at Princeton Neuroscience Institute (center), and Branko Glišić, associate professor of civil and environmental engineering (right). Acot combined her interests in medicine, engineering, and neuroscience, offering a promising approach to understanding how the brain is injured during a concussive hit. Photo by Denise Applewhite

THESIS MIXES ENGINEERING AND NEUROSCIENCE TO BETTER UNDERSTAND HEAD INJURIES

Gabbie Acot started off on a premed track at Princeton before broadening her studies to include structural engineering and then neuroscience. Her senior thesis project brought together all these interests, combining video analysis, neuroimaging, and numerical modeling to perform a forensic reconstruction of college football head impacts.

Acot's adviser called her project "very Princetonian" because of its mix of engineering and the natural sciences. "I always consider Princeton as almost a neo-Renaissance place, where you have scholars who are both engineers and artists in a sense, and I think her work is fitting this very well," said Branko Glišić, associate professor of civil and environmental engineering.

Acot's research scientifically reconstructed head impacts to explore the mechanics of football concussions as a pathway to

understanding, identifying, and preventing the injuries.

Acot analyzed case studies of two Princeton University football players. She studied videos to reconstruct the mechanics of head impact events and calculated biomechanical metrics using a numerical engineering technique called the finite element method.

Comparing the biomechanical data with data and calculations from neuroimaging, Acot found that they correlated well, and suggested areas of improvement within the accident reconstruction and finite element simulation processes. She believes that researchers can improve the processes by which head impact accidents are simulated to eventually use this tool for diagnostic and prevention purposes, even on football field sidelines.

Acot's idea for her thesis took shape while studying at University College Dublin during her junior year. She worked with Michael Gilchrist, a professor of mechanical engineering, who was researching rugby player and equestrian rider head impacts using finite element modeling, and became one of Acot's advisers. "All throughout Princeton, I never really knew how to combine my interest in civil engineering and medicine," said Acot. "This was the first time that I saw an intersection of both."

When she returned to Princeton, Acot discussed her thesis idea with Glišić. Then she did a Google search for "Princeton concussion" and found articles by Annegret Dettwiler-Danspeckgruber, principal investigator at the Neuroscience of Traumatic Brain Injury Research Laboratory at Princeton Neuroscience Institute. Acot sent her an email, seeking advice. "She ended up being my adviser," said Acot. "I wasn't even expecting an answer because I was just a random senior emailing her."

Acot said one of her biggest challenges was coordinating three advisers from different disciplines in different countries. "The way we came together was kind of magic," said Acot. Noting it is rare for an undergraduate to have three advisers, Glišić praised the multidisciplinary approach of Acot's thesis, comparing it to what the National Science Foundation calls convergence research.

Gilchrist, a third adviser, agreed. "This project would have been challenging for even a good Ph.D. student, but Gabbie relished the challenge of learning and mastering these advanced topics," said Gilchrist, adding Acot's project has laid the groundwork for future collaboration among the three advisers.

Another challenge was obtaining Institutional Review Board (IRB) approval for the project so Acot could access video footage from Princeton football games. The IRB, which oversees research involving human subjects, granted approval in November 2020. To find football players for her project, Acot received support from Dettwiler-Danspeckgruber, who has conducted research involving Princeton's football team.

Dettwiler-Danspeckgruber said Acot's thesis is a promising approach to increase understanding of how the brain is injured during a concussive hit, and could eventually serve as a diagnostic tool.

"Gabbie is a unique and admirable individual, and I have been very impressed by her perseverance to gain access to the necessary data allowing her to carry out the accident reconstruction and, in addition, to assimilate the basic knowledge of how to view DTI images, a skill that was novel for her," said Dettwiler-Danspeckgruber, who was also the second reader of the thesis. "Gabbie's thesis required her to expand her primary field of study in engineering to the one of neuroscience, more specifically neuroimaging, and she handled this aspect of her thesis with serious scientific purpose and great ease."

– by Sharon Waters

ENGINEERING GRADUATE STUDENTS PURSUE CREATIVE, HIGH-IMPACT RESEARCH

Each student's story is different, but a common motivation is the desire to harness science and technology to achieve a wide and positive impact. The students featured below reflect a small fraction of the diverse expertise and backgrounds that form the Princeton Engineering community.

"I'm a Princeton engineer because I want to decrease human impact on the water cycle."

Einara Zahn
Ph.D. candidate
Civil and Environmental Engineering

Zahn researches hydrology, specifically how urbanization disrupts the water cycle and water quality. Her research looks at two areas, water temperature and evaporation. Regarding water temperature, she looks at how an increase in impervious surfaces such as roads and parking lots, can lead to spikes in temperature of small streams from rain water runoff. In evaporation, she studies wetlands and different soils to determine how evapotranspiration is affected by the ratio of transpiration (how much water plants transpire compared to the amount of green matter they produce).

"I'm a Princeton Engineer because I want something better than X-ray vision."

Hooman Saeidi
Ph.D. candidate
Electrical and Computer Engineering

Saeidi studies high-frequency circuits, including millimeter-wave and terahertz signals. This range of frequencies has many uses, from optical to radio devices. Because high-frequency signals transit the human body without harm or major loss of information, these devices are ideal for medical and security uses.

Despite being small, scalable, and inexpensive, high-frequency circuits often are inefficient in power use. Signals require high energy to create and decay fairly rapidly. One of Saeidi's aims is to increase the efficiency of terahertz signals by using harmonics and other methods.

"I am a Princeton engineer because I joyfully follow curiosity wherever she leads and make sure to follow up with execution."

Laura Leal
Ph.D. candidate
Operations Research and
Financial Engineering

Leal researches high-frequency trading to understand agents' behavior in financial markets. In one project, she applied a machine learning model to market statistics to optimize and estimate best practices for traders. In another, she developed a system to assist regulators who set market guidelines in verifying models' dependability.

Photo by Sameer A. Khan/Fotobuddy

GRADUATE STUDENTS RECOGNIZED FOR OUTSTANDING TEACHING

In May 2021, the Graduate School presented 34 graduate students with its annual Teaching Awards in recognition of their outstanding abilities as teachers.

Given the significant contributions made by many graduate student assistants in instruction (AIs) as the University transitioned to remote education, additional prizes were awarded.

The selection committee recognized a student from each of the four divisions with a special commendation.

Nick Caggiano, the awardee from the engineering division, is a Ph.D. student in chemical and biological engineering. He has been an AI twice for "Design, Synthesis, and Optimization of Chemical Processes."

Caggiano "was single-handedly responsible for the success of the course in achieving its educational objectives," said Athanassios Panagiotopoulos, the Susan Dod Brown Professor of Chemical and Biological Engineering and department chair. Panagiotopoulos cited Caggiano's "enthusiasm, love of learning, and willingness to listen carefully and address all issues at the appropriate level of detail."

Nick Caggiano. Photo by Frank Wojciechowski

Students praised Caggiano for being available at odd hours to answer questions. "Nick provided amazing support to his students beyond what is expected of a typical AI," said one student, who found Caggiano was "always patient and approachable."

Other graduate students in engineering and computer science who were honored included:

Ameet Deshpande
Department of Computer Science
Moriah Hughes
Department of Civil and Environmental Engineering
Sadhika Surya Malladi
Department of Computer Science
Matthew Myers
Department of Computer Science
Andrew Shapiro
Department of Electrical and Computer Engineering
Christopher Ushay
Department of Chemical and Biological Engineering
Zhi Jiang (Tony) Ye
Department of Operations Research and Financial Engineering
Hongtao Zhong
Department of Mechanical and Aerospace Engineering
Chengjie Zhu
Department of Electrical and Computer Engineering.

–by Jennifer Altmann

ALUMNI NAMED TO LEADERSHIP ROLES

Mark Baumgartner

Mark Baumgartner *97 joined Carnegie Corp. of New York as its chief investment officer. Previously he was chief investment officer at the Institute for Advanced Study, and before that he was at the Ford Foundation. Baumgartner's undergraduate degree is in aerospace engineering from the University of Florida. He received a Ph.D. in mechanical and aerospace engineering from Princeton in 1997.

Christine Feng '04, who earned a B.S.E. in electrical engineering from Princeton in 2004 and an M.B.A. from Harvard in 2010, is the new senior managing director at Blackstone, a global investment business. She was formerly a senior executive at Amazon, focusing on mergers and acquisitions. Before that, she was a senior member of the corporate development team at Microsoft. At Blackstone, she will direct her attention to technology investing and work with its credit investing platform.

Christine Feng

Robert Hampshire *07 was designated the Department of Transportation's chief science officer by Transportation Secretary Pete Buttigieg. Hampshire will advise the secretary on science and technology issues with a focus on climate change. It has been 40 years since the position was last filled. Hampshire, who earned a Ph.D. from Princeton in operations research and financial engineering in 2007 and a B.S. from the University of Cincinnati, moves from the position of associate professor at the University of Michigan's Gerald R. Ford School of Public Policy.

Robert Hampshire

Rebecca R. Jones, S.E., P.E., LEED BD+C *06 joined the Hatfield Group, a New York-based engineering firm, as principal. She is experienced in designing complex and high-performance structural systems: 10 Hudson Yards in New York City is one notable example. Previously she was the senior project manager at Simpson, Gumpertz & Heger Inc. and senior associate at Thornton Tomasetti. A dedicated mentor, Jones cofounded The Knitting Club to foster the advancement of women engineers and created the National Women Advancement Committee of Women@ Thornton Tomasetti. Her B.S. from Iowa State University was followed by an M.S.E. in civil and environmental engineering from Princeton in 2006.

Rebecca R. Jones

Eron Kelly '94 was named corporate president of Inovalon, a provider of cloud-based platforms that empower data-driven healthcare. Prior to his new position, Kelly was the general manager of worldwide product marketing for Amazon Web Services and before that was general manager and worldwide sales leader at Microsoft. Kelly served as an officer in the United States Air Force as a program manager, materials directorate, at the Air Force Research Laboratory in Dayton, Ohio. He received his B.S.E. from Princeton in 1994 and a master's in business administration from Harvard Business School.

Montgomery McNair '06 was hired as the chief of basketball operations for the Sacramento Kings. He was formerly the assistant general manager for the Houston Rockets. Before that he was employed at STATS Inc., a provider of sports information and statistics. In 2006 McNair received an A.B. in computer science from Princeton, where he was also a letter winner for football. ▶

Photos courtesy of the subjects

ALUMNI NAMED TO LEADERSHIP ROLES (CONTINUED)

Marc Napp M.D. '81, was appointed senior vice president and chief medical officer by the Memorial Healthcare System in South Florida. He was previously employed as the deputy chief medical officer at Mount Sinai Health System in New York, and led its system-wide emergency management program, including the response to COVID-19. Earlier in his career Napp oversaw medical staff operations at New York's Northwell Health and Lenox Hill Hospital. His medical degree is from Albert Einstein College of Medicine, and he holds an M.S. in administrative medicine from the University of Wisconsin-Madison. His B.S.E. is in chemical engineering from Princeton in 1981.

Eric Schmidt '76, former chair and CEO of Google, and Wendy Schmidt together as Schmidt Futures have partnered with the Rhodes Trust to launch Rise, a global talent program for 15- to 17-year-olds. Teens who have a desire to better their communities, bring about social change, and dedicate themselves to public service can apply for support that can last a lifetime. Eric Schmidt received his B.S.E. in electrical engineering from Princeton in 1976 and went on to receive an M.S. in electrical engineering and a Ph.D. in computer science, both from the University of California-Berkeley.

Sridhar Vembu *94, founder and CEO of Zoho Corporation, is a 2021 recipient of the Padma Shri Award, one of India's highest civilian honors. The annual award, instituted in 1954, is given for distinguished service. Vembu's contributions, from software development to workforce training in rural regions of India, fall into the award's trade and industry category. Vembu received a Ph.D. in electrical engineering from Princeton in 1994 and a B.S. from the Indian Institute of Technology.

ALUMNI HONORED FOR RESEARCH AND TEACHING

Alfred Aho *67 and **Jeffrey Ullman** *66 were presented with the 2020 Turing Award by the Association for Computing Machinery for their impact on the field of computer science. Both worked to refine the compiler, a critical component of a computer that allows programming languages to be translated into the ones and zeros that computers understand, and together coauthored nine influential textbooks plus numerous papers and programming techniques. Aho, who has an undergraduate degree from the University of Toronto, and Ullman, who earned a B.S.E. from Columbia University, met while grad students in the Department of Electrical Engineering at Princeton. Afterward they joined Bell Labs. Aho went on to hold corporate positions before becoming a faculty member at Columbia. Ullman was a faculty member at Princeton, then moved to Stanford in 1979.

Photo by David Kelly Crow

Yueh-Lin (Lynn) Loo

Yueh-Lin (Lynn) Loo *01 has stepped down from her position as director of the Andlinger Center for Energy and the Environment at Princeton to join the newly founded Global Centre for Maritime Decarbonisation based in Singapore. As its first chief executive officer, Loo will develop a strategic plan for the organization, with a focus on testing and implementing energy technologies to reduce emissions in the shipping sector. Loo holds a Ph.D. in chemical engineering from Princeton and two B.S.E. degrees from the University of Pennsylvania, one in chemical engineering and the other in materials science and engineering.

In addition, Loo and two former chemical engineering graduate students, **Nicholas Davy** *14 and **Melda Sezen-Edmonds** *18, received a 2020 Edison Patent Award from the Research & Development Council of New Jersey for their patent on technology that protects ultraviolet solar cells and any high-efficiency organic solar cells. Davy is the cofounder and CEO of Andluca Technologies, the company licensed to commercialize the transparent solar cell, and Sezen-Edmonds is a principal scientist at Bristol Meyers Squibb.

Steven McLaughlin *86 who earned a B.S.E.E. from Northwestern, an M.S.E. in electrical engineering from Princeton in 1986, and a Ph.D. in engineering from the University of Michigan, was named provost and executive vice president for academic affairs at Georgia Tech. He will also co-chair the steering committee for the school's new strategic plan. For nearly 25 years McLaughlin has held various leadership roles at Georgia Tech, including serving as dean of the College of Engineering from 2017 to 2020.

Nicolas Pegard

Nicolas Pegard *14 is an assistant professor of applied physical sciences with a joint appointment in biomedical engineering at the University of North Carolina-Chapel Hill. He was presented with a Beckman Young Investigator Award to develop new optical technology and computational methods that can lead to future applications in neurology and rehabilitation medicine for brain function. Pegard received his Ph.D. in electrical engineering in 2014 from Princeton and his B.S. is from the École Polytechnique in Paris.

Stephen Silliman '79 was named dean of the new Trevecca Nazarene University School of Science, Technology, Engineering & Mathematics. From 2012 to 2018, he was the dean of Gonzaga University's School of Engineering and Applied Science. In the following year he served at the U.S. Agency for International Development's Global Development Lab, then returned to Gonzaga. He has also participated in service projects to bring water and health initiatives to low- and middle-income countries. Silliman received a B.S.E. in civil engineering from Princeton in 1979 and a Ph.D. in hydrology and water resources from the University of Arizona.

Avi Wigderson *83 from the Institute for Advanced Study (IAS) in Princeton and László Lovász, a former visiting IAS professor from the Eötvös Loránd University in Budapest, shared the 2021 Abel Prize, often referred to as the Nobel Prize for mathematics. They were recognized for advances in understanding the foundations of what can and cannot be solved with computers. Wigderson received his Ph.D. in electrical engineering and computer science from Princeton and his undergraduate degree from the Israel Institute of Technology.

Avi Wigderson

Photos courtesy of the subjects unless otherwise indicated