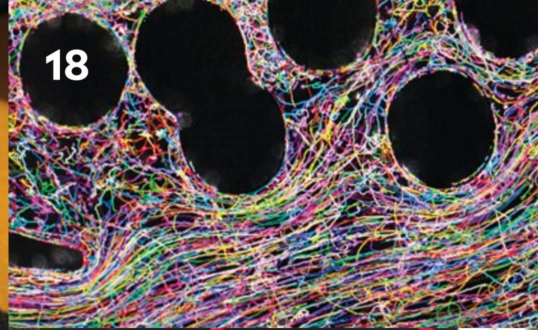
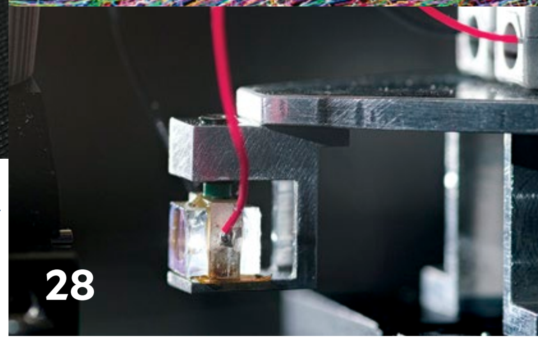
Fluid thinking / When machines join the team / Scaling intelligence

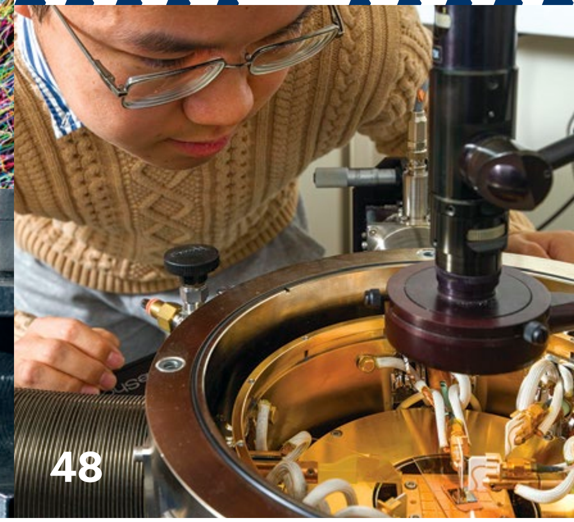
2026

# Y/ Yale Engineering

## Back to the quantum future


# In this issue

## Yale Engineering 2026



***Front cover:*** *What began as a 19th-century innovation is finding new life in Peter Rakich's lab, transformed to amplify and stabilize tomorrow's quantum machines.*
***Photo by:*** *Tanner Pendleton*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# What's Next

***Jeffrey F. Brock***
*Dean / Yale Engineering*
*William S. Massey Professor of Mathematics*

We're excited to share groundbreaking advances on multiple fronts at Yale Engineering. Our cover story explores a crucial advance in the quantum race: Researchers in **Peter Rakich's** lab demonstrated the first ultra-stable "self-injection" locked laser. The laser, created by fine-tuning a Fabry-Perot resonator to the frequency of a on-chip laser, enables the longer coherence times essential for the creation of a practical quantum computer. Rakich's team also created a non-magnetic optic isolator — a breakthrough for the use of photonic integrated circuits (PIC) to create better and cheaper sensors, smartphones, and other devices.

Next, we look at a partnership with the Korea Center for Industrial Technology-Yale (KCITY) pioneered by **Jaehong Kim**, a promising international collaborative center with a focus on robotics, artificial intelligence, semiconductors and manufacturing processes, and other strategic areas of research.

We then explore why a deep-Earth research tool called the Kawai multi-anvil press is proving crucial in the quest for practical superconducting materials. The machine, designed to simulate the conditions deep in Earth's mantle, enables **Lisa Pfefferle** to explore the potential of sulfur trihydride ($H_3S$) — which acts as a superconductor under extreme pressure — to maintain superconducting properties under normal conditions.

In a story that showcases how innovation co-evolves with community, we explore the partnership between the Center for Engineering Innovation & Design and New York's Solomon R. Guggenheim Museum, as students in the **Making Spaces** seminar assess the accessibility challenges presented by the Guggenheim's iconic exhibition space.

Human-robot teamwork is the focus of work in **Marynel Vázquez's** lab, where a partnership with Tata Consulting Services looks at how robots interpret explicit and implicit cues in mixed human-robot working environments.

Elsewhere in robotics, we look at advances in the ways that robots navigate unstructured environments. Robot wrists present a longstanding engineering challenge, one that **Aaron Dollar** and **Vatsal Patel** are working to solve. Researchers in **Danny Rakita's** lab are using calculus to program faster and more graceful robots. **Tara Boroushaki** is exploring how Radio Frequency Identification (RFID) tags plus algorithms can help robots root out items that aren't in plain view. And **Ian Abraham** is using hybrid control theory to help robots get better at switching between tasks.

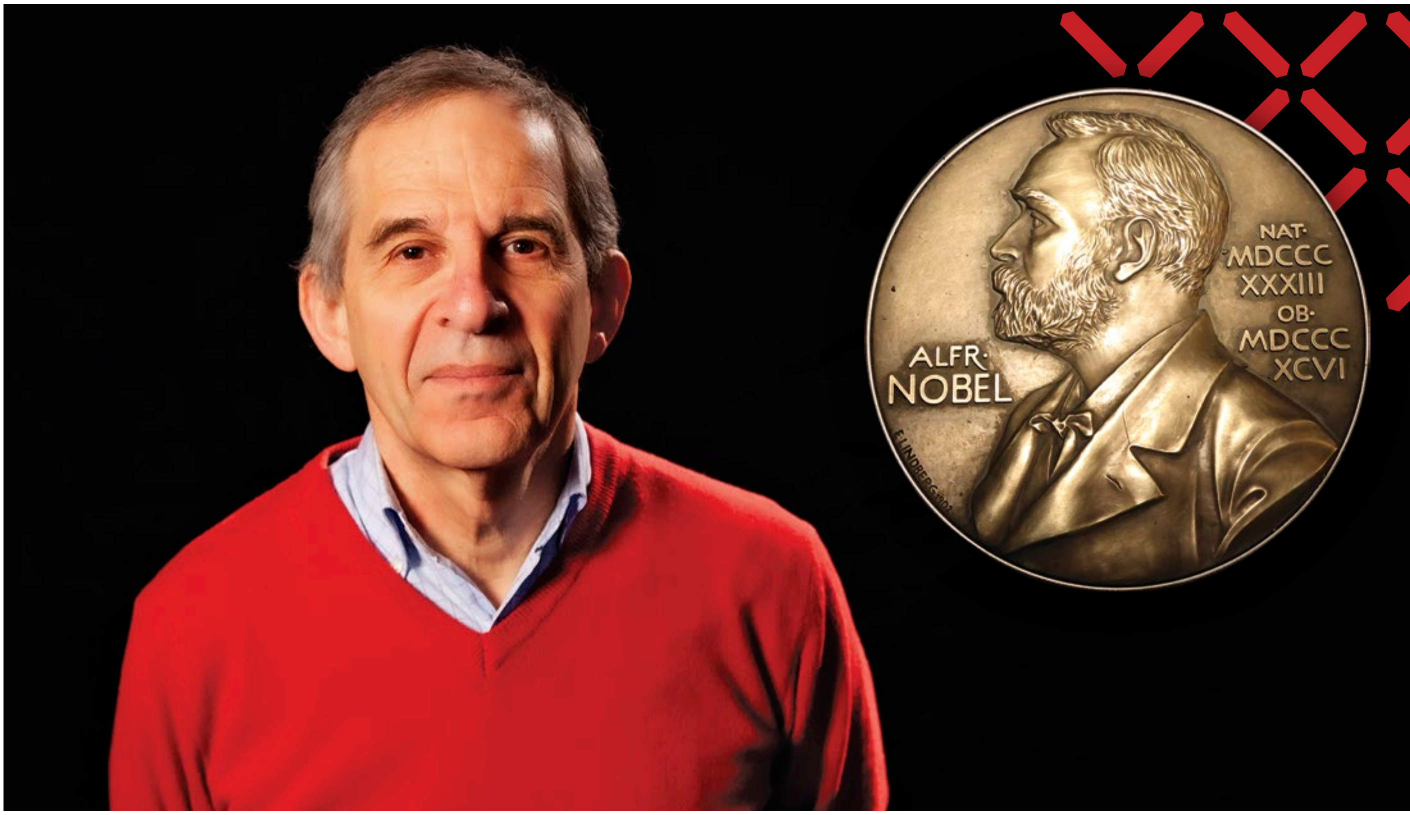
We check in on the quest to design chips that work the way the human brain does, and how **Rajit Manohar** is tackling the challenges inherent in making these neuromorphic chips scalable.

Microbes don't have a great reputation, but sometimes they can be good for you. Researchers **Jordan Peccia** and **Drew Gentner** have teamed up with colleagues from Yale's School of Public Health and School of Medicine to create a Healthy Building Microbiome Index. This multidisciplinary effort aims to create a more holistic model of the way interior air impacts public health.

Finally, we look at how **Amir Pahlavan** and **Bauyrzhan Primkulov** are using numerical simulations and modeling to improve predictions in fluid mechanics, with implications for drug delivery, mining, filtration, wastewater treatment, contaminant remediation, and more.

Ignited by the spirit of collaboration, creativity, and tireless inquiry that drives our work here at Yale Engineering, these projects demonstrate true innovation toward a better future. We hope you find them as inspiring as we do.

# Insights & impacts




## Devoret wins 2025 Nobel Prize for quantum computing breakthroughs

/ Michel Devoret, the Frederick W. Beinecke Professor Emeritus of Applied Physics, was awarded the 2025 Nobel Prize in Physics for pioneering work that fundamentally changed our understanding of quantum mechanics. Devoret shares the prize with John Clarke of UC Berkeley and John M. Martinis of UC Santa Barbara for groundbreaking research conducted in the 1980s that proved quantum physics could operate at a macroscopic, visible level in electrical circuits — work the Nobel committee said, "revealed quantum physics in action."

After conducting seminal design work on artificial atoms and qubits, Devoret joined the Yale Engineering faculty in 2002. Here, collaborating with colleagues Robert Schoelkopf and Steven Girvin, he pioneered circuit quantum electrodynamics (circuit QED) — an approach to quantum computing using microwave photons in superconducting resonators. In 2002, Devoret and his Yale colleagues designed the transmon qubit, a breakthrough that reduced sensitivity to charge noise and became widely adopted by quantum researchers worldwide.

At Yale, Devoret and his team achieved a remarkable series of breakthroughs: creating the first solid-state quantum processor, discovering new types of quantum "friction" for improved quantum memory storage, developing the first quantum system to achieve "break even" in qubit preservation, and devising systems to predict quantum data jumps and correct quantum computation errors.

"This is about an entire field of research being honored," Devoret said. "It's about 40 years of work by students, post-docs, and fellow researchers." He retired from Yale's fulltime faculty in mid-2024 and now serves as chief scientist for Google Quantum AI, although he remains a professor emeritus and research professor in Yale Engineering's Department of Applied Physics.

# Converting plastic waste to fuel

/ As tons of plastic waste continue to build up in landfills every day, researchers have developed a way to efficiently and cheaply turn waste into something useful. Led by Yale Engineering professors Liangbing Hu and Shu Hu, they're using a method known as pyrolysis, a process of using heat in the absence of oxygen to molecularly break materials down. In this case, it's used to break plastics down to the components that produce fuels and other products.

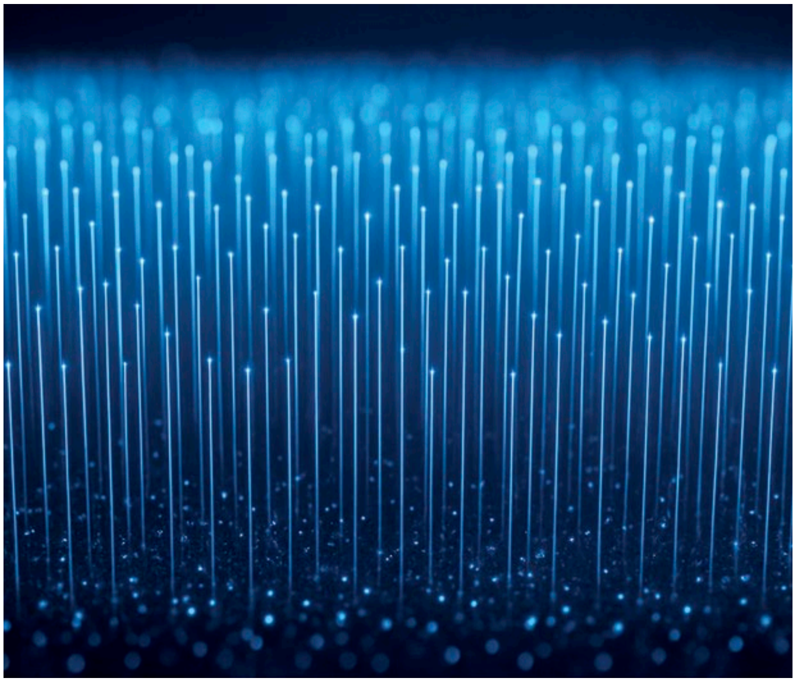
Conventional methods of pyrolysis often use a catalyst, but this is expensive and requires a lot of maintenance. Without a catalyst, though, the conversion rate is very low. The researchers cleared these obstacles by developing a 3D-printed electrically heated carbon column reactor that allowed them to precisely control the process. The result was an impressively high rate of converting wasteful plastics into useful chemicals.

# Yale Engineering student's reinvented cello takes national stage

/ For three centuries, the cello has remained largely unchanged — and largely expensive and fragile. Traditional wooden instruments cost $5,000 or more, making them inaccessible to many aspiring musicians. Elijah Lee, a Yale Biomedical Engineering senior — together with co-founder Alfred Goodrich — set out to reimagine the instrument entirely. Their company, Forte3D, uses carbon fiber panels and 3D-printed components — including the ribs, neck, and scroll — while preserving traditional elements like the sound post and fingerboard to maintain tonal authenticity. The result is a durable, affordable cello that can withstand travel and temperature fluctuations while producing rich, resonant sound.

The innovative design has caught the attention of world-renowned musicians, including Yo-Yo Ma and The Piano Guys. In November, Forte3D appeared on Shark Tank and secured a $250,000 investment from entrepreneur Lori Greiner. With momentum building, the team is now expanding to violins and other string instruments, with an ambitious goal: bringing high-quality instruments to students and musicians worldwide who lack access to traditional instruments.

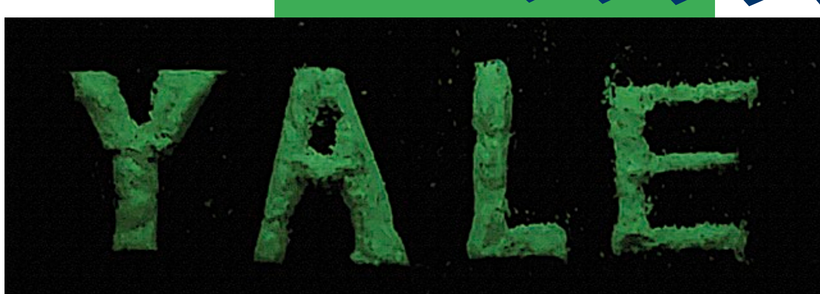
## A better way to make nanowires



/ One-dimensional topological nanomaterials — that is, extremely thin nanowires — hold great promise for quantum and electronic devices. Making them on a large scale, though, is tricky and time-consuming. A team of researchers led by Jan Schroers, the Robert Higgin Professor of Mechanical Engineering and Materials Science, developed a new method for creating these materials that's quick and easy to scale up. Their approach allows atoms to essentially self-organize, automatically moving from a high-pressure environment to a low-pressure one to form single-crystal nanowires — each one up to 40,000 times thinner than the human hair. The process is easier and approximately 100 times faster than conventional methods. The breakthrough could lead to a practical way to manufacture nanowires at a large scale for industries and research fields specializing in quantum computing, optoelectronics, and beyond.

## Turning to trees for sustainable photoluminescence

/ Photoluminescent materials, which absorb and re-emit light for displays, solar cells, and sensors, are essential to modern technology. However, they typically rely on toxic heavy metals and halogenated frameworks, creating risks for consumers, workers, and the environment. Yale Engineering researchers developed photoluminescent solid-state emitters using lignin, a waste product from paper manufacturing, combined with histidine, a natural amino acid. The result: safe, renewable, metal-free materials.




Lignin is the most abundant natural material containing aromatic groups typically sourced from petroleum. While the materials are not yet optimized, researchers believe varying composition and exploring different lignin types will improve properties. "This study can hopefully lay the groundwork to develop other renewably sourced and non-toxic photoluminescent materials," said co-author Hanno Erythropel.

# AI model targets livestock methane emissions

/ Purushottam Dixit, assistant professor of biomedical engineering, won $2 million from the Bezos Earth Fund's AI Grand Challenge for Climate and Nature — selected from over 1,000 global entrants competing to address climate change through AI solutions.

Dixit's project, developed with the Alliance of Biodiversity International and the International Center for Tropical Agriculture, creates the "Rumen Digital Twin" — an AI-driven model to reduce enteric methane, a significant contributor to climate change. The digital twin allows researchers to create virtual livestock cohorts with precise detail, identifying which feed additives most effectively reduce methane in specific conditions.

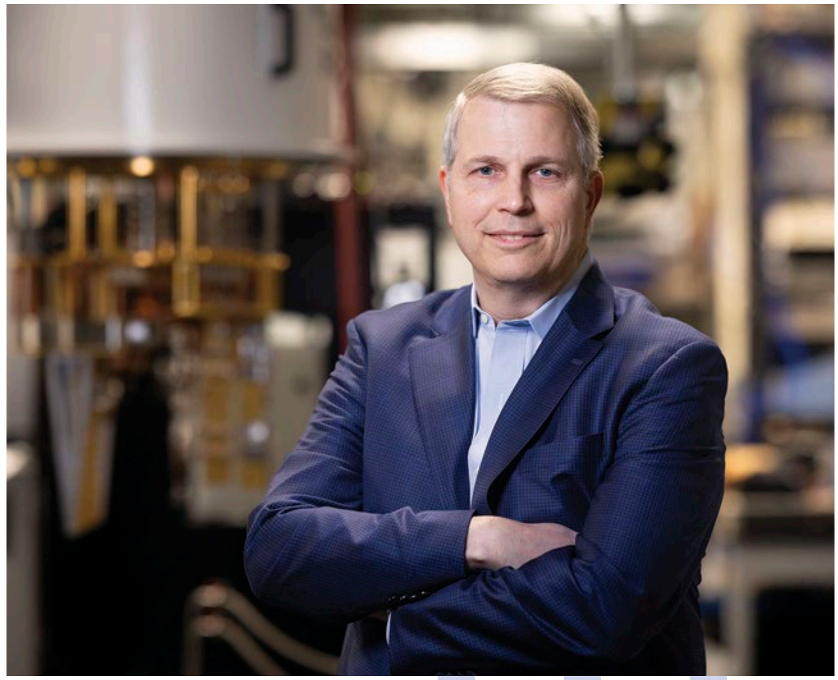
"The microbiome of livestock is incredibly complicated," Dixit said. "What works in small-scale experiments often doesn't generalize to different farms on different continents." The model will enable farmers and researchers to test sustainable livestock strategies quickly and cost-effectively before real-world implementation.

# A protein folding mystery solved

/ In living organisms, every protein carries out specific functions, such as catalysis, molecule transport, or DNA repair. It's critical to life, but there remain many open questions about this complex process. To gain more insight, mechanical engineering professor Corey O'Hern and his research team developed computational models for numerous proteins and measured their cores to determine how densely packed these proteins were when they folded. For every protein, they discovered 55% of the core space was occupied by atoms. The individual amino acids couldn't compress any further when the protein folded. This information fills many gaps in our understanding about proteins and their functions. It could also lead to new ways to design proteins for drug therapeutics, novel biomaterials, and other applications.

# Insights & impact

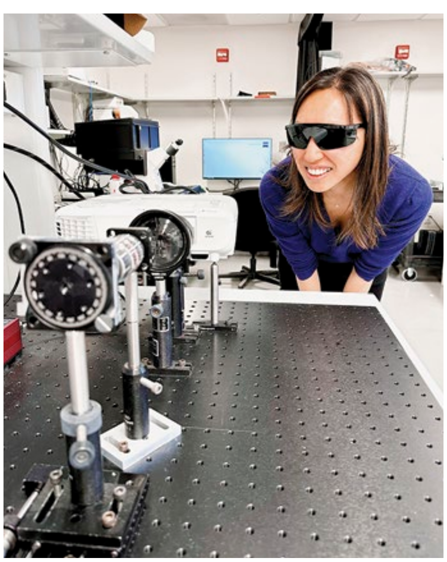
## From Yale Engineering lab to $550M sale



/ Quantum Circuits Inc., a Yale startup built on two decades of pioneering quantum computing research, was acquired by D-Wave for $550 million — validating Yale Engineering's commitment to translating groundbreaking research into real-world impact. Co-founded in 2015 by Sterling Professor Robert Schoelkopf, Professor Emeritus and Nobel laureate Michel Devoret, and senior research scientist Luigi Frunzio, Quantum Circuits emerged from Yale's leadership in superconducting circuit quantum computing beginning in the early 2000s.

Other quantum labs incorporated aspects of Yale's discoveries, but since no one embraced the Yale approach entirely — particularly the focus on error correction and building better qubits for a more robust and less expensive system — the Yale researchers took matters into their own hands. "We finally decided that maybe the only way we could get our work out there was to do the tech transfer ourselves and start a company," Schoelkopf said.

The acquisition includes plans to double Quantum Circuits' 65-person New Haven workforce. "The success of Quantum Circuits testifies powerfully to Yale's strength in quantum science and engineering, and to the ambition and ingenuity of our faculty," said Yale Engineering Dean Jeffrey Brock. "It also speaks to Yale's commitment to the fundamental research that leads to big technological advances. Yale Engineering is investing in this kind of lab-to-impact technology transfer, and Rob Schoelkopf's triumph proves those investments can be catalytic for New Haven and for society."



## Seeing how cells take shape, with help from a magic carpet

/ In a potentially major advance in tissue engineering, Yale researchers led by mechanical engineering professor Yimin Luo, developed a method to recreate in vitro aspects of morphogenesis, the process in which living organisms take shape. In morphogenesis, cells collectively position themselves in specific ways, leading to the development of tissues and organs. Recreating this in the lab is tricky.

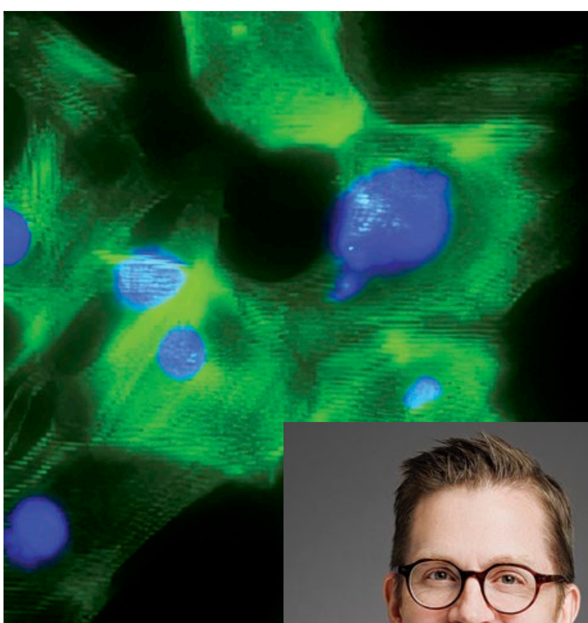
"You can't manipulate where you want them to align," Luo said. "It's quite difficult to get them to align collectively." In her laboratory, Luo and her team created what she calls a "magic carpet." That is, they fabricated a self-organizing, cell-laden environment. They also designed and built what's known as a photopatterning system that they can use to indirectly influence cell alignment, enabling the formation of patterned, tissue-like structures. Cost-effective and versatile, the system is accessible to other laboratories to use and develop their own innovations.

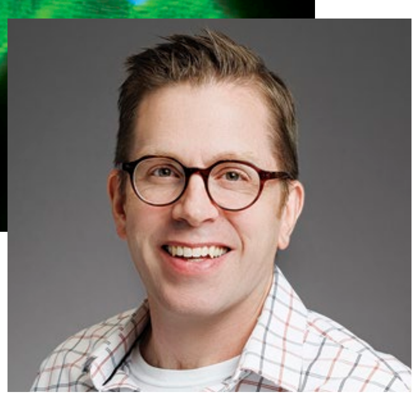
# New technology reveals cancer progression

/ For years, researchers have had to choose: sequence RNA to determine gene activity, or use imaging to identify proteins—but not both on the same tissue sample. Yale researchers have now developed DBiTplus (Deterministic Barcoding in Tissue sequencing plus), a breakthrough technology that enables both analyses on a single sample.

Led by Rong Fan, Harold Hodgkinson Professor of Biomedical Engineering, and PhD student Archibald Enninful, in collaboration with researchers from Yale's School of Medicine and Department of Statistics & Data Science, the team solved a persistent challenge in spatial biology. "For years, imaging-based and sequencing-based approaches have offered complementary but fundamentally disconnected views of tissue biology," said Fan. "Our new approach overcomes this long-standing barrier by preserving tissue integrity while enabling both analyses on the same tissue section. This integration opens many new opportunities for this type of research."

Testing on human lymphoma tissue revealed how cancer cells reshape their environment, potentially informing future cancer treatment and precision medicine approaches across multiple complex diseases.





# A better understanding of two deadly heart conditions

/ Hypertrophic cardiomyopathy (HCM) and dilated cardiomyopathy (DCM) are two common and potentially deadly heart diseases and can be caused by mutations to the same gene. Surprisingly, these two conditions are each associated with very different clinical symptoms.

"This is a question that has intrigued the field for a while," said Stuart Campbell, professor of biomedical engineering. "We want to provide a really sharp picture of what those differences are by studying these two mutations, which are only a few amino acids apart."

Campbell and his research team used engineered heart tissue and computational models to better study these diseases. They were able to pinpoint the biological mechanisms at play in each condition by carefully comparing an HCM-associated mutation and a DCM-associated mutation side-by-side. The study's findings could potentially lead to improving treatments for patients with these conditions.

# Building robots for an unstructured world

## Designing machines that can navigate the messy reality of homes, warehouses, and beyond

/ Robots have long been a major part of manufacturing, especially in such industries as automotive and electronics. That's because they're perfect for work in factories, and other settings that call for very specific actions (eg. "pick up this can, place it here"). The rest of the world, though, is a messy place. Whether it's navigating through a forest or a cluttered living room, robots have a tough go in these unstructured environments. The typical home is one example — things get moved around, people get in the way.

In less structured environments with varied tasks, even seemingly simple actions like grabbing a set of keys or turning a door handle, things get tricky. To succeed in residential settings, robots will need to operate with unprecedented speed, agility, and precision. Yale Engineering's roboticists are working on it. Here's a look at some of their work:

***Right:*** *Tara Boroushaki demonstrates X-AR, an augmented reality headset that fuses radio frequency signals with computer vision to "see" hidden objects inside boxes, beneath piles, and beyond visual obstructions.*

*Photo by Jimmy Day / MIT Media Lab*


signal
kinetic

## Doing more with less

As a popular genre of joke implies, unscrewing a lightbulb should be pretty easy. Don't tell that to robots, though. A big part of the problem has to do with the "wrist" mechanisms robots have to work with; they're often complicated and bulky and struggle with certain maneuvers. A much simpler approach taken by Yale researchers could give robots a way to handle more complicated movements.

Typically, robots designed to manipulate objects are built with a gripper and a wrist with three degrees of freedom. That is, they can move in three independent ways: "Roll" (rotating front to back), "pitch" (side to side), and "yaw" (vertically). But wrists are mechanically complex, and are often located far from the grasped object, requiring the robot to move its entire arm to complete the task. The result is awkward and inefficient movements that require a lot of space.

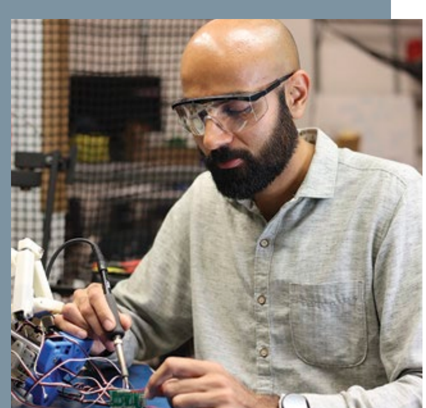
This Yale-designed robotic hand, which the researchers have named the Sphinx, was developed in the lab of Aaron Dollar, the Frederick W. Beinecke Professor of Mechanical Engineering. It features a spherical mechanism that can both grasp and rotate a wide range of objects in all three axes, combining much of the function of traditional wrists and grippers.

"It's not very complex," said Vatsal Patel, a Ph.D. candidate in Dollar's lab, and the project's leader. "It works without any cameras or sensors and things like that. But because of the spherical mechanism, it's always going to roll, pitch, and yaw objects.

"It's a lot more efficient, and you don't need a ton of space. The wrist is able to do these rotations much closer to the object without the burden of moving the whole arm. It works much faster and much more efficiently."

The design also makes it easier for robots to perform tasks within a constrained space, such as screwing in a lightbulb inside a closet. More broadly, it brings the field a step closer to an increasingly common goal of designing robots that work well in homes, disaster sites, and other unstructured environments.

"In these environments, robots don't know exactly where the objects are," Patel said. "They're trying to adapt to the environment, adapt to the objects. That's where robotics in general is moving, and we're trying to solve the same problems."



***Left:*** *The Sphinx robotic hand combines gripping and wrist motion into a single spherical mechanism, allowing robots to roll, pitch, and yaw objects efficiently.* ***Right:*** *Ph.D. student Vatsal Patel leads the Sphinx project, designed to simplify wrist motion and improve dexterity.*

*Photos by Tanner Pendleton (pages 10 & 11)*


***Above:*** *Research in Danny Rakita's lab accelerates derivative computation, enabling robots to move more quickly and gracefully while planning complex motions in real time.*

## Faster, more graceful robots (thanks, calculus!)

Every time a robot intentionally swings its arms, or sways from one side to another, a lot of math went into making that motion possible. In the lab of Danny Rakita, derivatives — a core concept of calculus — figure heavily into some of his devices.

In robotics, derivatives are a mathematical tool often used to ensure that robots move correctly to accomplish a particular goal. A fundamental concept in calculus, derivatives provide information about the rate of change of a function — that is, they allow robots to make adjustments in real time. In an unstructured environment, this ability is crucial.

For a robot, this may mean using derivatives to stay balanced, responding to even the slightest nudge by rapidly recalculating how to shift its weight or adjust its position. Whether that robot can react in time — regaining its balance or falling — depends on how fast it can compute the derivatives. To that end, Rakita has developed a method that dramatically accelerates these derivative calculations, enabling robots to move more quickly, efficiently, and gracefully.

Robots often struggle with inefficient or ineffective motions due to slow derivative computation. "Over the years, doing many problems like this in robotics and beyond, derivative computation was always a pain point," said Rakita, assistant professor of computer science. "Eventually, I just got really determined and thought, 'It's time to finally figure this out.'"

Typically, robots calculate each derivative from scratch, treating every computation as an entirely separate process. But it doesn't have to be that way, Rakita decided. Working with Ph.D. students Chen Liang and Peter Wang, he developed programs in which robots calculate a sequence of derivatives, each one building on the last. One key insight of this work is that derivative computation can be accelerated by reusing information from previous, related calculations — a strategy known as coherence. The team's novel approach, called the Web of Affine Spaces (WASP) Optimization, enables robots to calculate derivatives seven to 10 times faster than traditional methods.

"When you put them side by side, it really feels like the others are stuck in the mud," he said. "They just take a lot longer to converge on good motions in comparison."

The speed-up isn't just a matter of convenience — it fundamentally changes the robot's capabilities. "The robot can now consider more options and plan further into the future," Rakita explained. "If there are obstacles in its path, it can proactively choose motions that gracefully reach around them, something that would be too computationally expensive to consider in real-time with slower methods."


*__Above:__ FuseBot hovers over a cluttered tabletop, using radio frequency signals to locate hidden, RFID-tagged objects beyond the reach of cameras alone.*

*Photo by Jimmy Day / MIT Media Lab*

Rakita notes that WASP derivatives could help robots better reason through the physics-based outcomes of their own motion, such as anticipating when they might knock something over and adjust their movement in advance to intentionally brush the object aside in a controlled way.

"We're only beginning to scratch the surface of where these derivatives can be applied — even within robotics," he said. "They open up new possibilities for robots to reason about how their actions affect the physical world."

## Finding needles in haystacks, with radio frequencies

In warehouses, factories, and other dense or crowded settings, it's not easy to find specific items, especially if they're hidden by many other objects. Even conventional robots aren't much help if the target item is obscured from the robot's camera. Tara Boroushaki is here to help.

As a graduate student at MIT, she developed FuseBot, a robot that uses radio frequency to quickly root out hard-to-find items even when they aren't in plain view. More generally, she develops algorithms and builds robotics and other systems that can interact with the environment more efficiently and capably.

"The majority of my research is about how we can use different types of signals alongside other modalities — like computer vision — to sense the environment in a new way," said Boroushaki, assistant professor of electrical & computer engineering. "For example, what is good about signals like Wi-Fi and Bluetooth is that their signal can go through walls and go through obstacles. That's why you can get Wi-Fi when the router is in a different room."

When items go missing in warehouses, it's a waste of money. Finding these items, even if they're not in the line of sight, is important, and Boroushaki's robot is at least twice as fast as previous work in doing so. "When you scale that to a huge operation, like an Amazon warehouse, the amount of time and money you save is pretty high."

She points out that if you put a normal robot with only cameras in a packed warehouse, it would need to explore the whole pile to find a specific item.

"We showed that if we only use the information from even a couple of items that are tagged with radio frequency identification (RFID), the robot can reason about how much space each of those items will occupy in the structure of the pile," she said. "So if I know there's an iPhone here and this space is the size of an iPhone box, then I know a tablet can't also be here, because physically that's impossible. We're creating this type of reasoning for a robot to be able to understand that. On average, that makes the system twice as efficient."

Radio frequency technology is also key to another of Boroushaki's innovations. The X-AR is an augmented reality headset that employs wireless signals and computer vision to allow users to see things that are hidden — inside closed boxes, under piles, or behind occlusions. The headset uses holograms to guide users toward desired items and verify when they have picked them up. With radio frequency sensing from the antenna and visual sensing from the headset's cameras, it locates radio frequency-tagged objects with an accuracy of 9.8 centimeters or less.

## Robotic acrobats

Using AI to train robots to perform single-task feats of agility, such as handstands or backflips, is impressive. But if you want to train your robot to perform multiple tasks — say, performing a backward flip into a handstand — you'll need more than that.

"We often want to train our robots to learn new skills by compounding existing skills with one another," said Ian Abraham, assistant professor of mechanical engineering. "Unfortunately, AI models trained to allow robots to perform complex skills across many tasks tend to have worse performance than training on an individual task."

To that end, Abraham's lab is using techniques from optimal control — that is, taking a mathematical approach to help robots perform movements in the most efficient and optimal way possible. In particular, they're employing hybrid control theory, which involves deciding when an autonomous system should switch between control modes to solve a task. One use of hybrid control theory, Abraham said, is to combine the different methods in which robots learn new skills. These include, for instance, methods of learning from experience with reinforcement learning, or through model-based learning in which robots plan their actions through observing. The trick is getting the robot to switch between these modes in the most effective way so that it can make high-precision movements without losing performance quality.

"Think of how we learn new skills or play a sport," he said. "We first try to understand and predict how our body moves, then eventually movement becomes muscle memory and so we need to think less."

As a demonstration, Abraham and his research team applied methods from hybrid control theory to a dog-like robot, training it to successfully balance and then flip over.

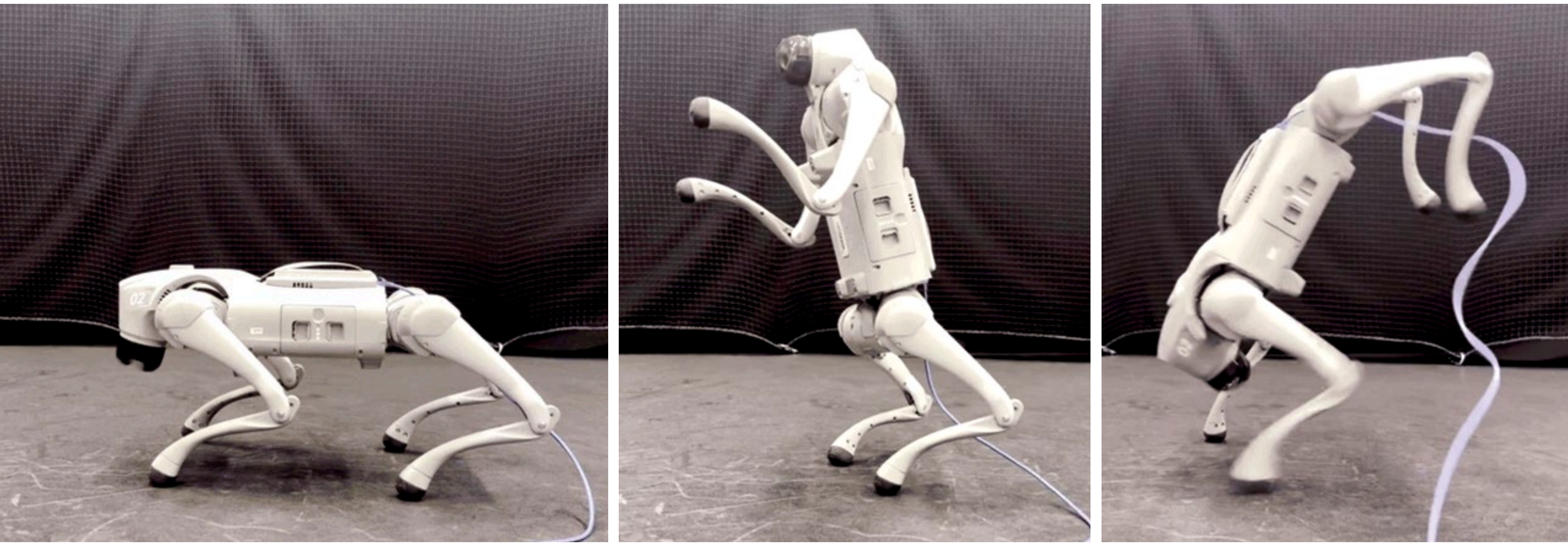
AI methods are used to develop the more challenging motor skills that require whole-body precision. Hybrid control theory is then leveraged to schedule and synthesize the various mechanisms for robots to learn diverse motor skills to gain more complex, compounding behaviors.

Ideally, this could lead to robots working in homes and other unstructured environments.

"If a robot needs to learn a new skill when deployed, it can draw from its arsenal of learning modality, using some level of planning and reasoning to ensure safety and its success in the environment, with on-the-job experience," Abraham said. "Once a certain level of confidence is achieved, the robot can then use the more specialized learned skills to go above and beyond."

*Top:* ***Top:*** *A robotic arm scrubs a bowl, refining precision through hybrid control.* ***Bottom:*** *A dog-like robot executes a controlled backflip, demonstrating how hybrid control theory helps enables smooth transitions between learned motor skills.*

*Photo by Tanner Pendleton (top)*



# Microbes: The invisible inhabitants

## An ambitious study led by Yale Engineering explores how the microbes in our homes shape our health

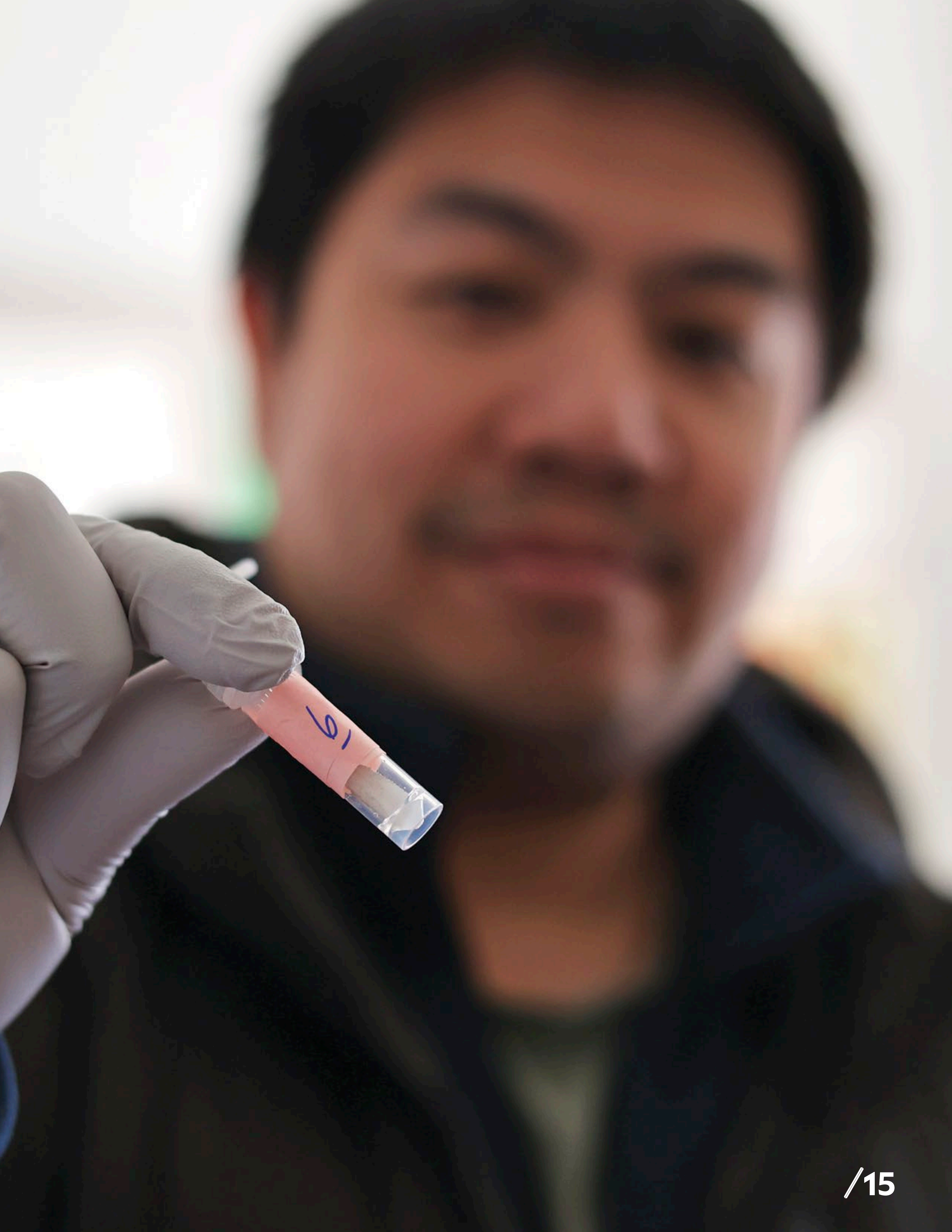
Photos by Amy Levitin Gray

Irvan Luhung, an environmental engineering research scientist, reaches up to swab the upper frame of the closet in the home office of a house in Branford, CT. He then plunges the swab and all of its collected dust into a marked container of solution for later analysis. Then, it's on to the next room to take some more samples.

It's one small part of an ambitious, federally funded project that brings together an interdisciplinary team of researchers designed to provide some insight about when and how microbes in the home help and hurt us. With funding of up to $5 million from the Advanced Research Projects Agency for Health (ARPA-H), researchers from Yale Engineering, the Yale School of Medicine, and the Yale School of Public Health will visit 400 homes in the Southern Connecticut region, take samples of water, dust, and air, and conduct respiratory tests on the residents. One goal of the project is to create what the researchers call a Healthy Building Microbiome Index (HBMI), a quantitative metric that indicates the human health risks or benefits of a home's microbiome. The HBMI could then be used to promote the best approaches for designing buildings for optimal well-being.

"The idea is to identify microbes that are closely associated with healthy and unhealthy buildings," said Jordan Peccia, who's leading the study. "We know all about allergens. We know about pathogens like tuberculosis, and we know about influenza. We don't know about the ones that help to make us healthy."

Studies have shown that the microbes a child is exposed to in the first six months to a year help determine the strength of their immune system. Researchers have also found that living in a home with greater microbial diversity lowers a child's risk of developing asthma.



“We know that there are healthy exposures to microbes”

Jordan Peccia, Thomas E. Golden Professor of Chemical & Environmental Engineering


"We know that there are healthy exposures to microbes," said Peccia, the Thomas E. Golden Professor of Chemical & Environmental Engineering. "This is an attempt to find some associations between buildings where people are healthy and what that microbial ecology or those microbial communities look like in those buildings."

## Making the invisible visible, with sensors and swabs

Data collected from the Branford house, built in the 1880s, won't be part of the study's final results. The research team is using it as a test run — a way to iron out unanticipated wrinkles. For instance, when the researchers sample water from the upstairs shower, it leads to a short debate about whether it would be better to use a funnel or a larger container to collect the water. Considering how many variables there are in a large study like this, it's no wonder that practice runs are pretty common.

A building's design can have a significant impact on its microbial population. For example, better outdoor air ventilation can increase its microbial diversity. Older houses, like the one the researchers are using for their test run, tend to be better ventilated since they were built before construction technology allowed buildings to be so thoroughly sealed. In recent years, the design of housing in the U.S. has focused more on comfort and energy efficiency.

The 400 homes are divided into two groups; about half the buildings are occupied by people with various health issues, and residents of the other half are all considered healthy. The researchers plan to go into homes and sample the buildings' microbiomes. In part, that involves sampling settled dust and different sources of water and then sequencing the DNA in those samples to determine what type of microbes are present. Settled dust is a particularly rich source of information since they can tell a lot about a home's microbial activity over several months. Results from air samples tend to be more immediate.

Drew Gentner and his team will deploy numerous sensors in the homes and analyze a broad suite of chemical signatures that are in the homes.

"I'm really excited about this project," said Gentner, professor of chemical & environmental engineering. "It's a great opportunity to bring together a wide range of expertise that we have across Yale and to think holistically about human health in the indoor environment."

The Yale faculty are working with Neighborhood Housing Services of New Haven, a nonprofit organization that works with housing in southern Connecticut.

"By working with this group, we're able to reach the broader community better and look at a wide range of housing stock to consider how environmental disparities can play into this as well," Gentner said.

The data generated by all of this testing and sampling will be massive. That's where another component of this collaboration comes in. Mark Gerstein, at the Yale School of Medicine, focuses on biomedical data science, and will be making sense of the data.

## Getting the pulse

Researchers at the School of Public Health, led by Daniel Carrion, will help recruit the participants and arrange the home visits. Under the guidance of Sandra Zaeh from the Yale School of Medicine, they will also perform lung function testing on the participants, part of which involves having them blow into a tube so that the condensation from their breath can be then analyzed for various measures of health outcomes.

"One of the things we're exploring is the status of the home and the quality of the home," said Carrion, assistant professor of epidemiology. "I will be interested to see what those relationships are between the home microbiome that Jordan is interested in, the indoor air quality, and the quality of the home, and how those relate to respiratory health."

As part of their practice run at the Branford house, Zaeh runs respiratory tests on one of the home's residents, Allison Beaulieu, a program manager at the Yale School of Public Health and a member of the project's research team. Zaeh uses a portable spirometer, a device to measure how much and how fast someone can breathe. It's typically used to test and monitor for asthma, COPD and similar conditions. Zaeh also surveys Beaulieu with questions about their home and lifestyle.

"There's a couple of different health outcomes that we're looking at," said Zaeh, a medical doctor who specializes in pulmonary and critical care. "One is a survey, and it's talking about general health and lung health and asking a lot of questions, specifically related to pulmonary things. The second is measuring lung function."

Zaeh said she's glad that the Neighborhood Housing Services of New Haven is on board for the project. She's worked with community organizations on previous studies, and said it contributes to a valuable perspective.

"I just think it adds such a different flavor because you actually have a sense of the pulse and of what's going on," she said. "I think we need those partners to do really good, meaningful work on the ground."

*This research was, in part, funded by the Advanced Research Projects Agency for Health (ARPA-H). The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the United States Government.*

# Fluid thinking

# Yale Engineering researchers explore the hidden physics of fluids, from tiny particles to dancing droplets

From the time you wake up in the morning, your day is filled with fluid mechanics. There's the way that toothpaste (a non-Newtonian liquid) flows out onto your toothbrush. That chaotic combining of fluids when you pour cream in your coffee? That's called turbulent mixing. How the air circulates around you, the clouds form above you, and raindrops splay out on your car's windshield are all matters of fluid mechanics. It's a field of research that affects everything from the pharmaceutical industry to predicting the weather to designing motor vehicles and airplanes.

Amir Pahlavan and Bauyrzhan Primkulov, both Mechanical Engineering faculty members, have made fluid mechanics a key focus of their research. The two have collaborated on a number of projects, including those that could advance in-situ mining and geothermal energy.

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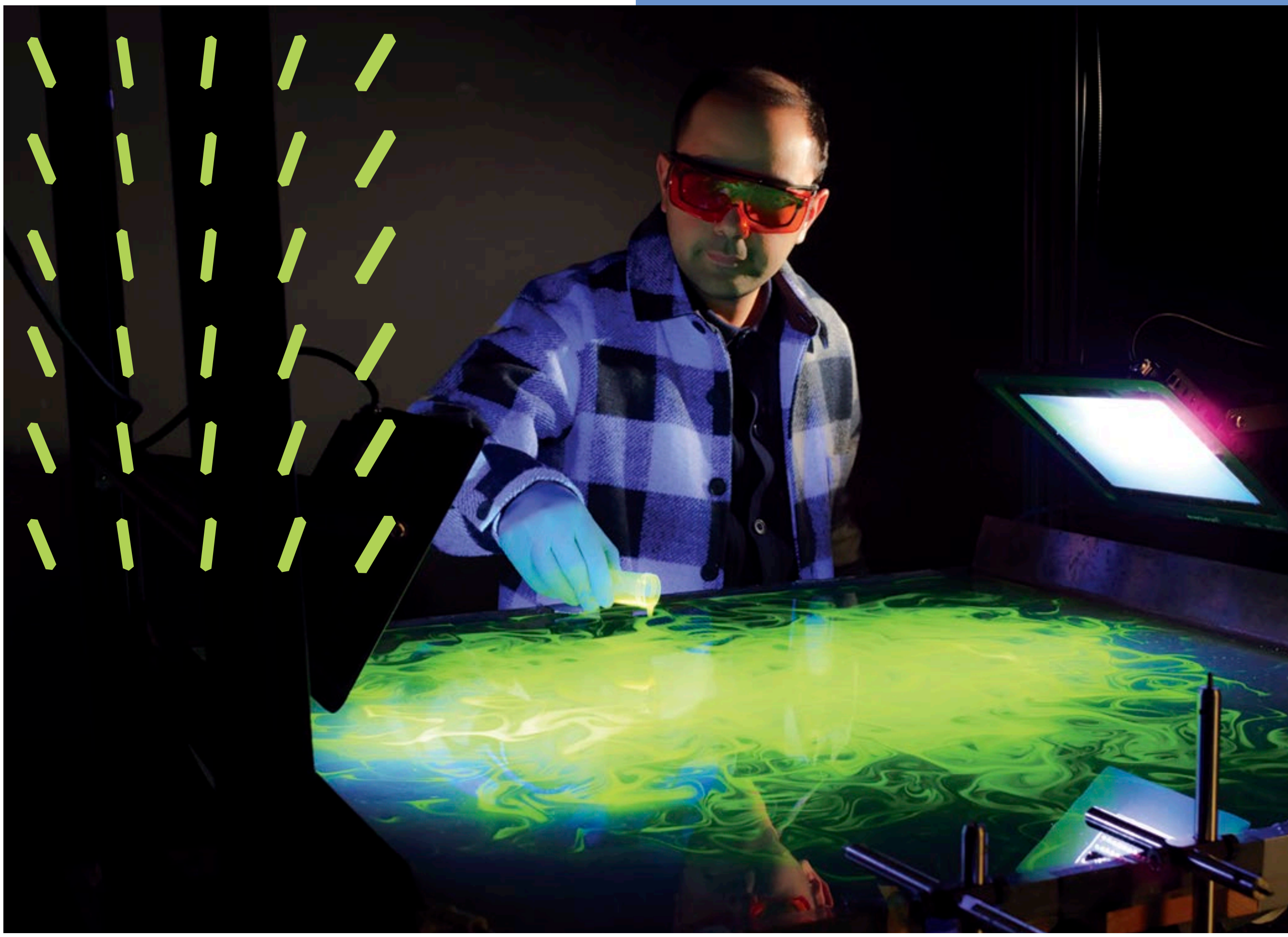
Whether it's within the micron-scale labyrinth of soil or the kilometer-scale swirls of the ocean, fluids carry everything from nutrients and microbes to pollutants, droplets, and microplastics. But in nature, what gets transported often doesn't simply go with the flow. In Pahlavan's lab, the unifying question is deceptively simple: Why don't things go with the flow, and what are the invisible forces steering them?



By combining theory, simulations, and visual lab experiments, his team looks for general rules that connect microscopic mechanisms to large-scale outcomes.

A central theme of the lab is that chemical gradients — variations in salt, nutrients, or other dissolved substances — create "landscapes" that can guide motion of tiny particles known as colloids, and bacteria through complex porous environments such as soils, aquifers, and biological tissue. These gradients may be caused by outside sources such as seawater intrusion, irrigation, or contamination. But they can also be generated internally as the environment evolves: when things dissolve or crystallize in water, by microbial metabolism and secretion that reshape local chemistry, and by freeze–thaw cycles that concentrate solutes and redirect flow pathways.

How chemical gradients influence the transport of colloids and bacteria in porous environments, however, has received little attention.

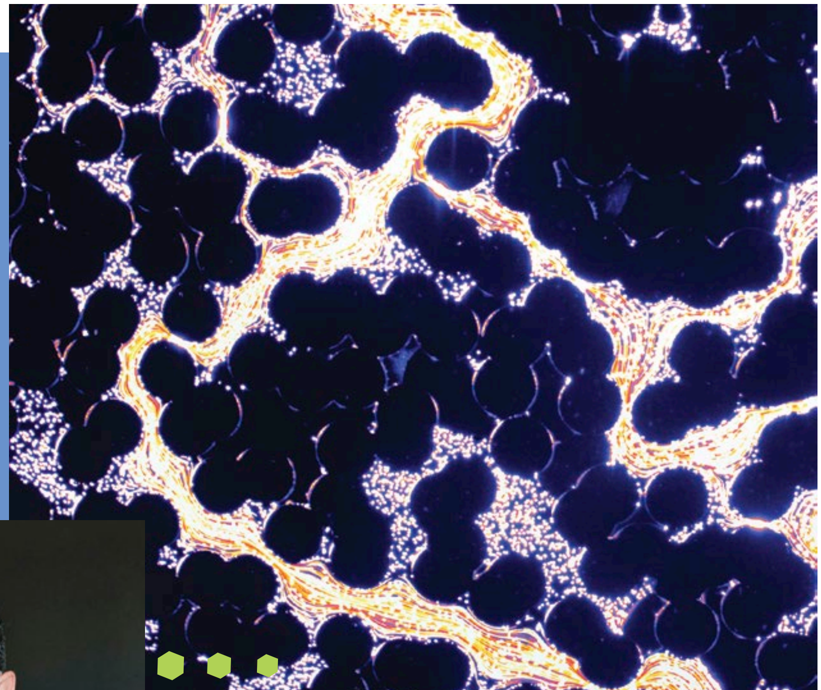
"Colloids are everywhere, from clay particles and microplastics in subsurface environments to synthetic nanoparticles used in drug delivery and environmental remediation," Pahlavan said. "Bacteria are equally ubiquitous, living in the pores of soils and sediments and even within our bodies; their ability to sense and move along chemical cues can strongly shape how they spread, attach, and form biofilms in these complex environments."

## Not always going with the flow

To isolate these effects in a controlled, measurable way, Pahlavan's lab builds miniature porous worlds using microfluidics. They develop small chips patterned with networks of obstacles that mimic the winding geometry of real porous media while allowing Pahlavan and his research team to see what's happening in real time. Within these networks, the lab studies how chemical gradients steer suspended colloids — a process known as diffusiophoresis — and how microorganisms navigate nutrient landscapes via chemotaxis (the way bacteria sense good and bad chemicals in their surroundings and steer themselves accordingly). The goal

***Above:*** *Postdoctoral associate Mobin Alipour pours liquid in the darkened lab to reveal the hidden physics of fluid motion and interfaces.*

*Photos by Tony Fiorini (page 18), and Tanner Pendleton (pages 19 & 20)*



*__Left:__ Drawn to the visual intuition of mechanical engineering, Amir Pahlavan explores why suspended particles deviate from fluid flow in porous environments. __Middle:__ Alipour conducts flow-table experiments to observe how chemical gradients steer particles. __Right:__ Captured under magnification, shifting particle paths expose the subtle gradients that reshape fluid motion.*

*Photos by Tanner Pendleton (left & middle)*

is to develop ways to predict when chemistry acts as an active driver that determines the direction of particles and cells and where they accumulate.

The same "not going with the flow" question also plays out in far larger scales in the ocean. With tabletop models that feature a very thin layer of saltwater, magnets and a small electric current, the researchers create two-dimensional flows that resemble surface ocean dynamics as seen from above. The motion can be chaotic. It stretches and folds material into long filaments, dramatically amplifying spreading even in the absence of turbulence. Pahlavan's group uses laboratory experiments and modeling to explore how particles, algae, droplets, and floating objects move in these flows, and how properties such as inertia and shape determine whether material follows currents, concentrates into patches, or separates into distinct pathways.

A particular focus is on objects that can change as they move. Droplets can break up and coalesce, shifting their size distribution in real time and feeding back on how they spread and where they end up. Floating material can also become collective: in the ocean's marginal ice zone, for example, sea ice can behave like a driven, interacting granular layer — more like a crowd of colliding, jostling pieces than a smooth surface. By treating these systems as coupled problems, the lab aims to identify the mechanisms that set spreading rates, patchiness, and accumulation zones, with relevance to phenomena ranging from microplastic dispersal and algal blooms to ice floe dynamics.

Across porous mazes and ocean-like swirls, the lab's goal is to uncover the hidden rules that govern the movement of particles, large and small. By linking controlled experiments to theory and simulations, Pahlavan aims to make these movements more predictable, and eventually more controllable across the environments that matter most, from the pores of soil and tissue to the surface of oceans.

As a student in Iran, Pahlavan had been encouraged to go into electrical engineering. But something about mechanical engineering called to him.

"It can expose you to many kinds of problems," he said. "For me, it was more natural. And it helps that you can visualize things!"

## Science that looks like art

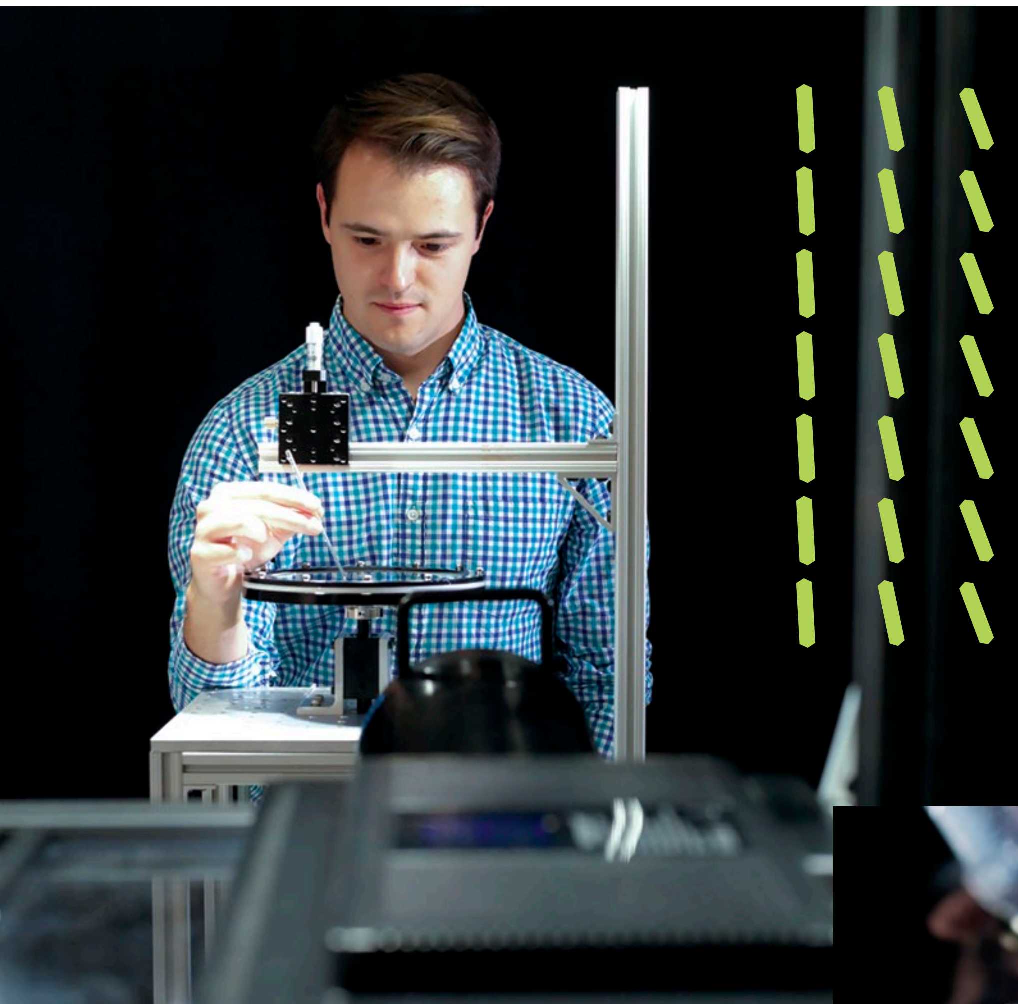
Throughout Bauyrzhan Primkulov's lab in Mason Laboratory are various contraptions that manipulate tiny drops of liquid into countless different states. Drops of water get stretched to their limit, until they inevitably break apart and give way to even tinier droplets shooting in all directions. Elsewhere, drops dance across a vibrating film of liquid, generating dazzling patterns. Slow-motion camerawork captures it all in minute detail.

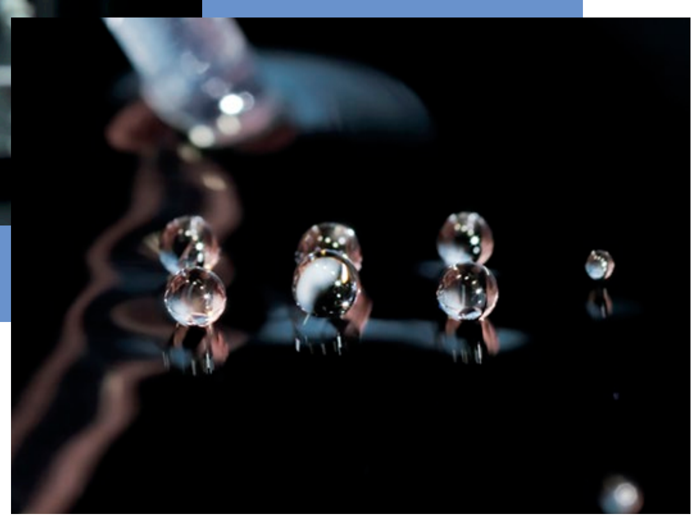
It's all part of Primkulov's mission to shed light on the many mysteries presented by fluid mechanics. This work has the potential to provide technical solutions to current energy and environmental challenges. In addition to that, the experiments are pretty mind-bending. Primkulov, who grew up in Kazakhstan, said he discovered the beauty of fluid mechanics while a graduate student.

"There was the usual fluid mechanics, but then I took another course on fluid mechanics that had to do with interfacial phenomena, where surface tension is important," he said. "You would get very, very visually appealing experiments, something similar to art. You see something, you like it, you're not sure why. There was something aesthetic about these problems that initially drew me in."

Some of his work has clear practical applications, like his research on in-situ mining, in which a solution is pumped underground to dissolve minerals and bring them to the surface. Others tackle fundamental science, asking fascinating questions along the way.

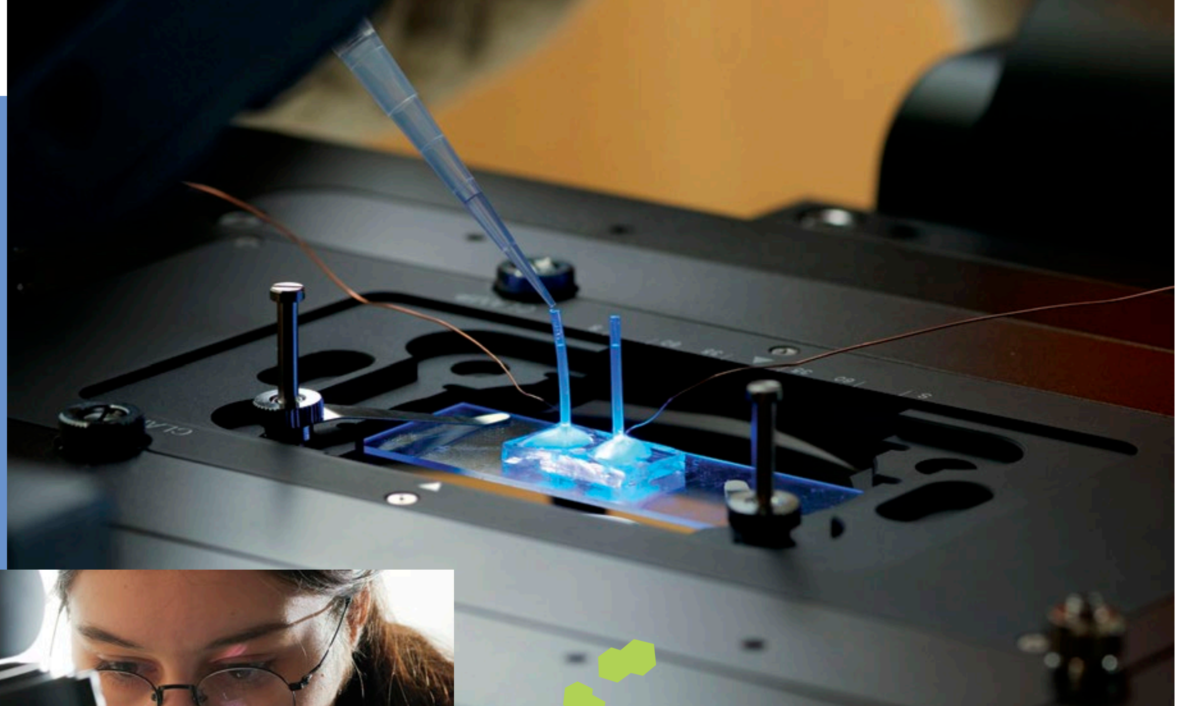
"I try to keep a balance. I think most problems can be interesting if you spend enough time on them. I try to do projects where I clearly see the





***Top:*** *Using a simple click pen, postdoctoral researcher Johnathan Hoggarth generates precise droplets to uncover the physics of fluid motion and surface tension.*
***Bottom:*** *Tiny droplets hover and bounce on a vibrating liquid bath, forming delicate patterns that helps the lab study instabilities, wave interactions, and "walking" droplet behavior..*

*Photos by Tanner Pendleton (pages 22 & 23)*



***Top:*** *A precision pipette introduces liquid to a vibrating surface, where controlled frequencies generate bouncing droplets for study.*
***Bottom:*** *Ph.D. student Zahra Shamsi fine-tunes experimental conditions to investigate how surface waves guide droplet behavior.*

application, but I think it's important to do problems where maybe I don't see the applications yet, but the problem has an interesting feature you don't usually see at this scale."

## Sometimes a click pen is all you need

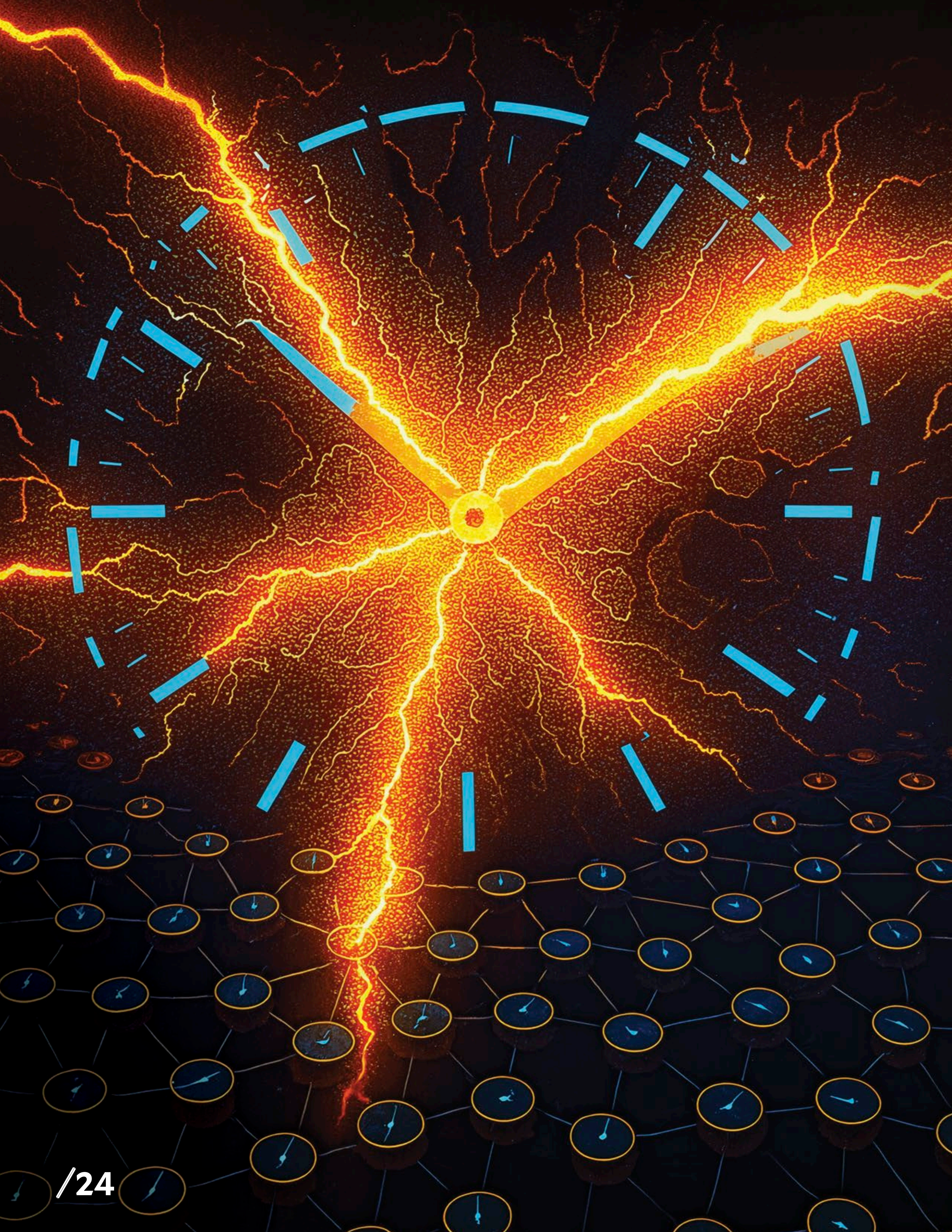
Primkulov said he tends to bounce between experiments and theory, each refining the other until he knows it's right.

"It always starts in the lab — you see something that you can't quite explain," he said. "So then you play around with an experiment, and you start working on the models. You make a guess in your model, then you go to experiment to test it out. Then eventually, you refine the experiment, you refine the model, and then once the two agree, that's a very good feeling. I've been chasing that ever since it happened for the first time."

Recently, his lab demonstrated how liquid drops can overlap with the uncanny world of quantum mechanics. Specifically, they showed how vibrating droplets can serve as what they call a "hydrodynamic analog" of the Kapitza-Dirac effect, a theory from quantum science in which a beam of particles is diffracted by a "grading" made of a standing wave of light. By shaking a thin film of oil with specific levels of vibrations, oil droplets placed on the pool don't merge at first. Instead, they bounce and create waves, which then cause them to "walk" across the liquid. Their own waves are guiding these droplets and can occasionally show statistics very similar to those of quantum-scale particles, Primkulov said.

And what happens if you infuse these droplets with nanoscale particles of iron, and then place them in a magnetic field? His lab is currently working on that also.

In addition to making discoveries like these, Primkulov is making it easier for other labs to make their own. Conventional methods for droplet generation often rely on specialized or costly equipment, which significantly limits accessibility. But Primkulov found an even better way to generate single droplets from a vibrating liquid bath: the humble click pen. With it, they can reliably produce droplets on a stationary bath and then apply them to vibrating baths. By varying the retraction length and pen tip radius, they can control the dimensions of the liquid ligament and access a wide range of droplet sizes. It's an approach that easily allows them to make droplets with tunable sizes and investigate bouncing droplets for a wide range of experiments.



# Scaling intelligence

## A new neuromorphic architecture replaces global synchronization with a local approach inspired by the brain

Photos by Carl Kaufman

Chips that simulate how the brain works have great promise for AI, robotics, and other fields. But making them so that they're scalable while providing repeatable results has proven tricky. Now, a Yale-led team of researchers has put forth a solution.

Neuromorphic chips — custom integrated circuits that mimic how the brain works — are used to study brain computation and develop neuroscience-inspired artificial neural networks. While not exact replicas of the human brain, multiple chips can be interconnected to create large-scale systems with more than a billion artificial neurons. Each of these neurons processes information by "spiking" individually. In doing so, neuromorphic systems use up much less energy due to sparse, event-driven operation and can outperform conventional computing systems on specific types of tasks, such as distributed computing workloads.

There's a randomness to how the brain works, a trait that largely works to its advantage. But randomness can cause some difficulties when it comes to computing. Due to the many variables involved with neuromorphic chips, and depending on how the chip is built, you may or may not get the same result each time you run the same calculation.

"An execution is non-deterministic when you don't know what the output is going to be just based on the input," said Rajit Manohar, the John C. Malone Professor of Electrical & Computer Engineering. "There might be some changes."

The makers of IBM's TrueNorth and Intel's Loihi, two of the best-known neuromorphic chips, added mechanisms to the hardware to ensure that it was deterministic — that is, able to repeat the same results based on the same input. Manohar, who had worked on the TrueNorth chip, said they introduced a new mechanism to make the executions repeatable. Because of this new mechanism, scaling up the system with more or bigger chips means that the system has to work extra hard to perform the calculation.

That's where NeuroScale comes in — a new neuromorphic chip developed by Manohar and his research team.

"The big improvement we made in NeuroScale is that we replaced that mechanism with a new one," said Manohar. "In our implementation, if the system gets larger, the overhead stays fixed. It's constant."

Specifically, the NeuroScale chip doesn't rely on what's known as "global synchronization," as the other chips do. In TrueNorth and Loihi, a global barrier synchronizes all the chips' artificial neurons and synapses. This limits the chips' scalability, partly because having a single synchronization mechanism ensures that the chip can be only as fast as its slowest component. It's comparable to an office where none of the employees can begin their work until all of them have started.

To solve this, Manohar and his team developed their own mechanism for NeuroScale. Rather than relying on a global barrier to synchronize all components, NeuroScale synchronizes individual clusters of neurons and synapses that are directly connected to each other. They recently published the results of their work in *Nature Communications*.

"Our NeuroScale uses a local, distributed mechanism to synchronize cores," said Congyang Li, a Ph.D. candidate in Manohar's lab and lead author of the paper.

The researchers say the main benefit of this innovation is scalability.

"Our approach is only limited by the same scaling laws that would apply to the biological network being modeled," the researchers report.

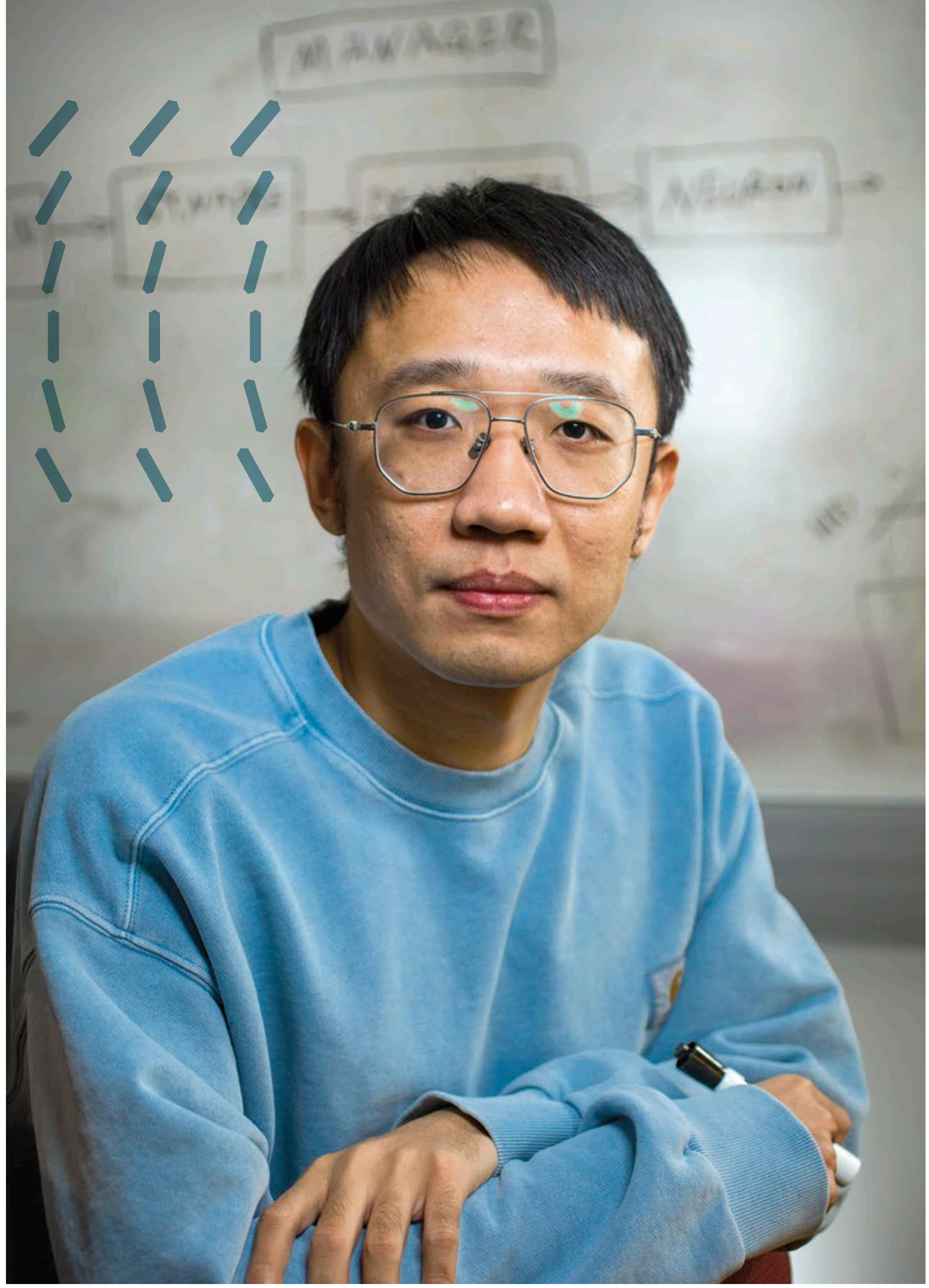
Going forward, the researchers plan to fabricate the NeuroScale chip.

"If you don't understand exactly what's happening and how the brain computes, for lack of a better word, then how can you expect to realize it?"

› Rajit Manohar
John C. Malone Professor of Electrical & Computer Engineering

“Our NeuroScale uses a local, distributed mechanism to synchronize cores.”

Congyang Li
Ph.D. candidate
Rajit Manohar’s lab




“We have a prototype that runs on an FPGA, but we want to make a real silicon prototype to demonstrate the energy efficiency of the architecture,” Manohar said. “An FPGA is a nice proof of concept, but the real efficiency will be evaluated only when we build our own chip to do this.”

While there have been many advances in the field since computer scientists first began seriously considering neuromorphic computing in the 1980s, there’s still much to be done. It’s impossible to know all the potential applications of the technology, but many in the field believe that neuromorphic chips could be a huge boost for robotics, autonomous vehicles, healthcare and cybersecurity.

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Manohar’s work in neuromorphic chips stems from his time at Caltech, where he completed his Ph.D. He was friends with people in the lab of Professor Carver Mead, who coined the term “neuromorphic.”

“People I’d known from Caltech days who had been working on neuromorphic computing for their entire career got in touch with me and said, ‘You should work on this with us because you’re designing asynchronous circuits, and we’re doing neuromorphic — it’s a good match, and we should work together.’ And that’s how I got involved in it.”

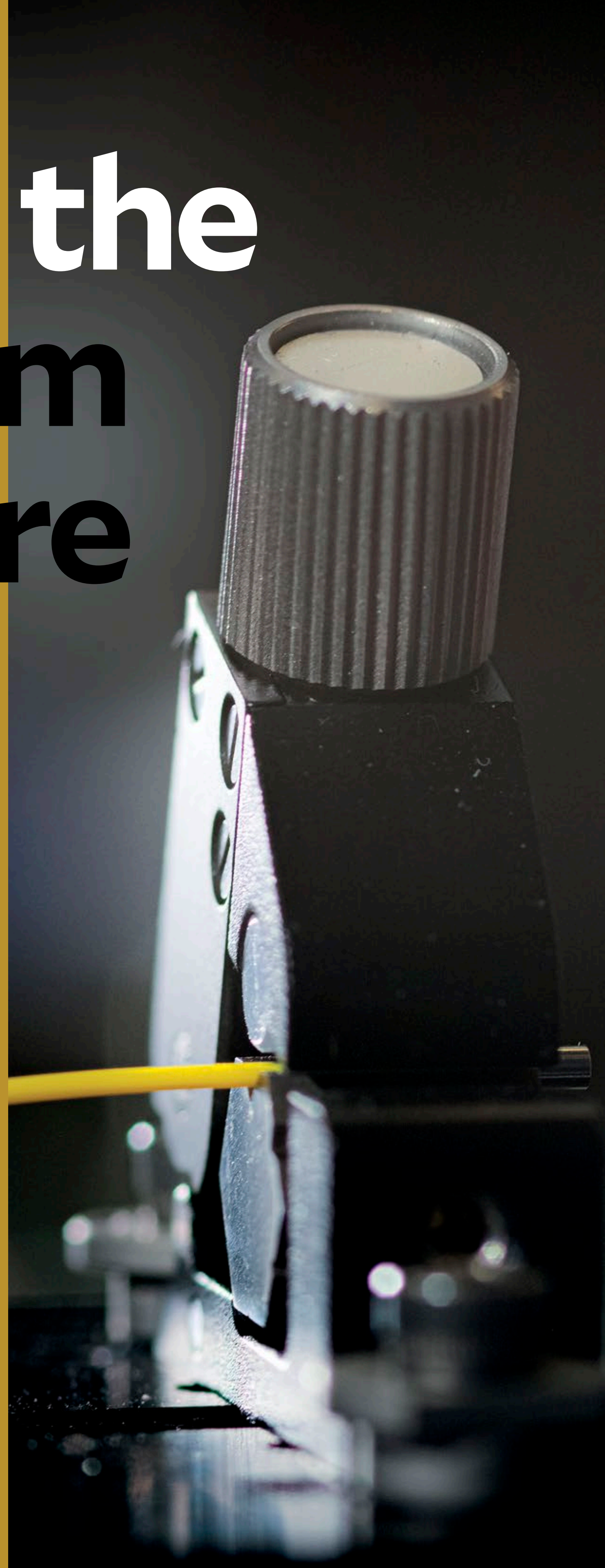
Although neuromorphic chips are inspired by the brain’s workings, Manohar said we’re a long way off from a time when chips truly act like brains.

“I think it does catch the public’s attention, which is both good and bad,” he said. “But we don’t understand many things about the brain. If you don’t understand exactly what’s happening and how the brain computes, for lack of a better word, then how can you expect to realize it?”

That said, the closer we get to a brain-like chip, the greater the possibilities of what we can do with it.

“We know that biology can do certain computations very, very efficiently compared to what we know how to do on a conventional computer,” he said. “The hope is if we can map these computations to a substrate that’s inspired by biology, then maybe we can implement the same computation with much higher efficiency than, say, a CPU or a GPU or other programmable hardware substrates that we have.”

# Back to the quantum future



## Peter Rakich revives a 19th-century device to push quantum technology forward

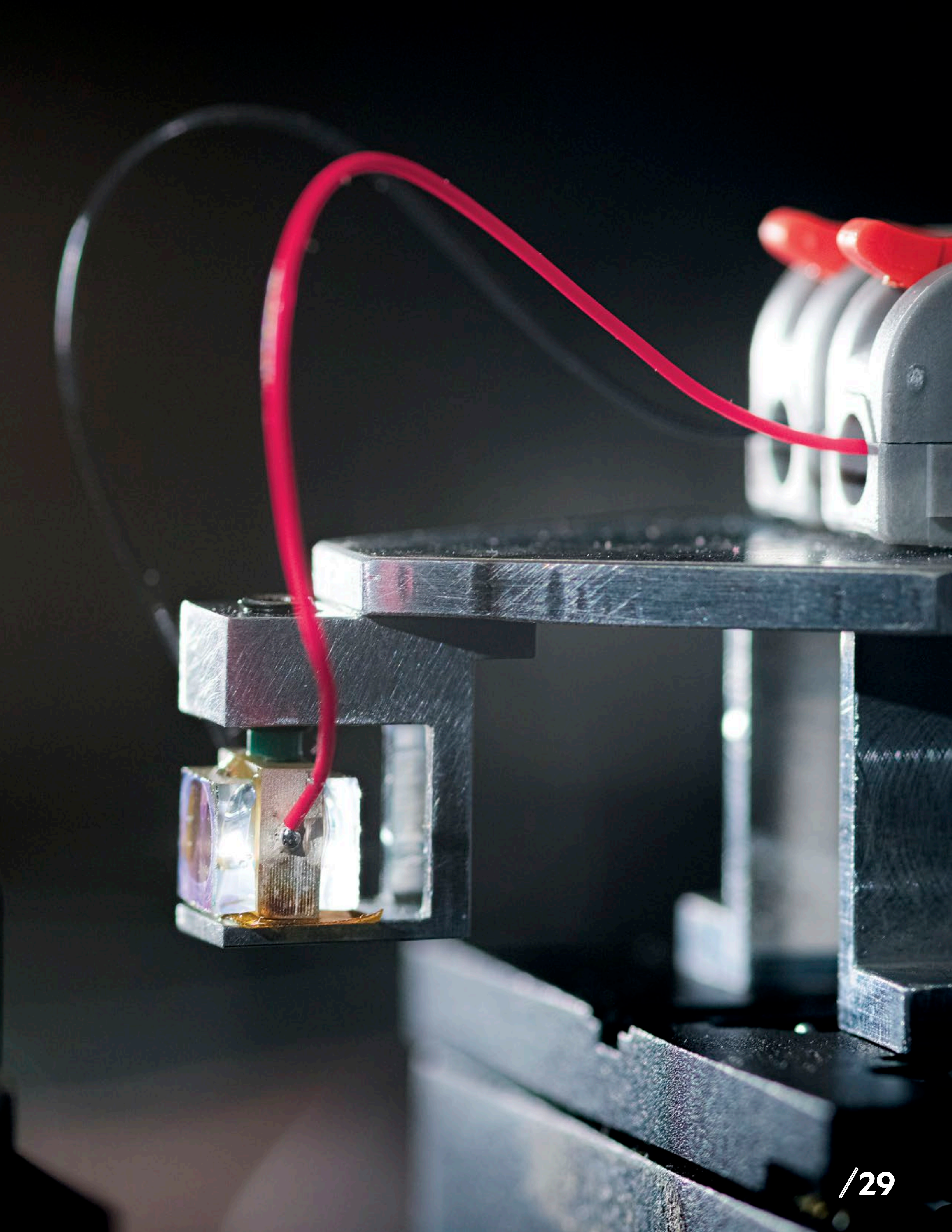
So how does a 19th-century technology built around two mirrors address the very 21st-century issue of advancing quantum technology?

This device, known as the Fabry-Perot resonator, was invented by the French physicists Charles Fabry and Alfred Perot, and is indispensable for optical clocks, quantum technologies, and other applications. It was first used to measure extremely small distances, which proved useful in establishing the standard length of a meter. Among other scientific contributions, it helped bridge the gap between physics and astronomy; measure the energy emitted by the moon, stars, and the sun, and identify the ozone layer.

Today, it's considered a key to ushering in the next generation of quantum communications, computation, and timekeeping technologies. It's a structure that consists of two ›

***Right:*** *The Fabry-Perot resonator — a 19th-century device consisting of two precisely aligned parallel mirrors — lies at the heart of the work, proving key to next-generation quantum communications, sensing, and timekeeping technologies.*

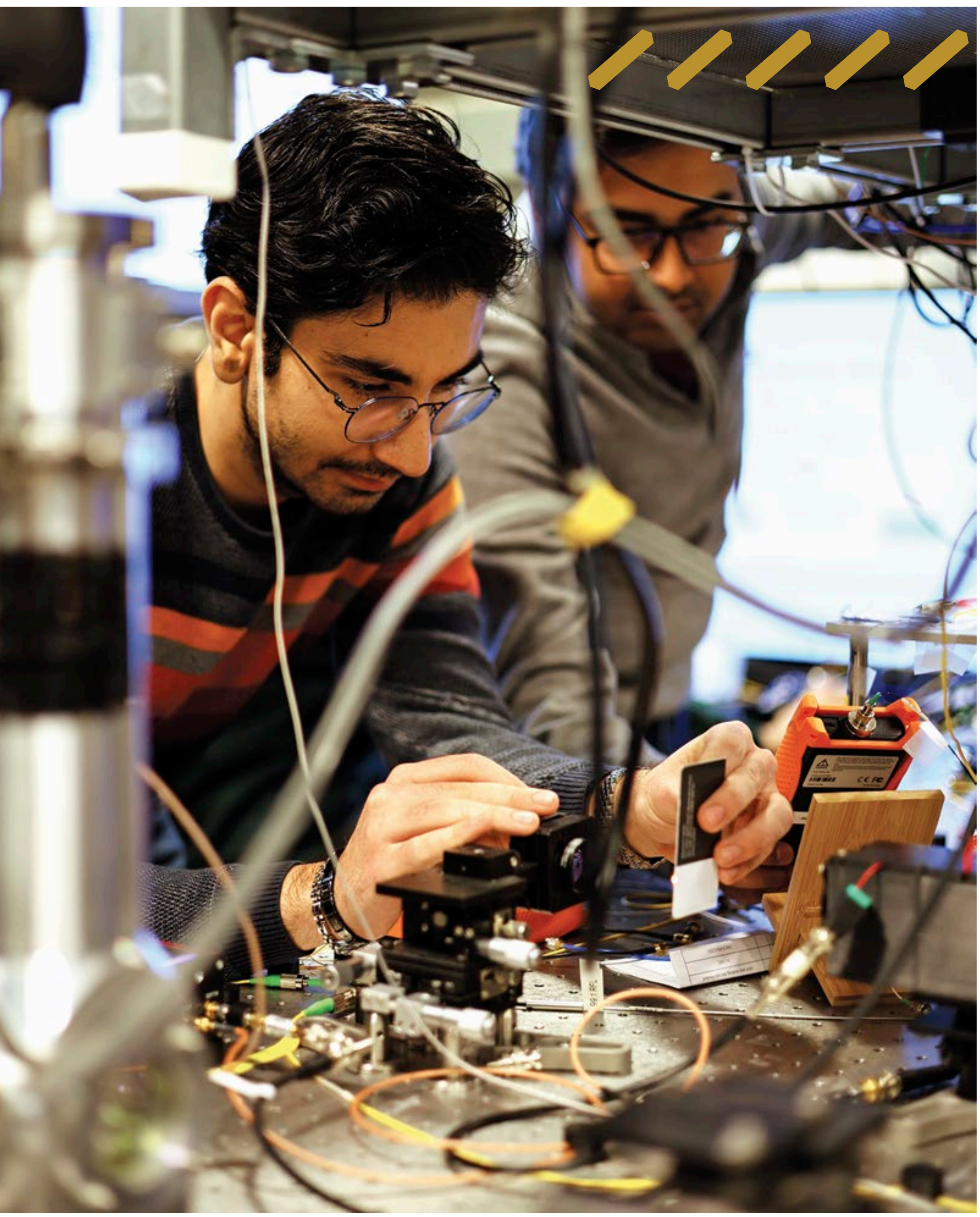
*Photo by Tanner Pendleton*



parallel mirrors precisely placed to reflect light back and forth. Its extreme stability comes from operating in a vacuum. The trick, though, is in finding a way to incorporate these resonators into photonic integrated circuits. These are microchips that use light, or photons, to provide significant advantages over conventional electronics in terms of efficiency, speed, and smaller devices.

The main challenge with incorporating Fabry-Perot resonators is that their strong mirror-like reflections can destabilize or even damage an on-chip laser.

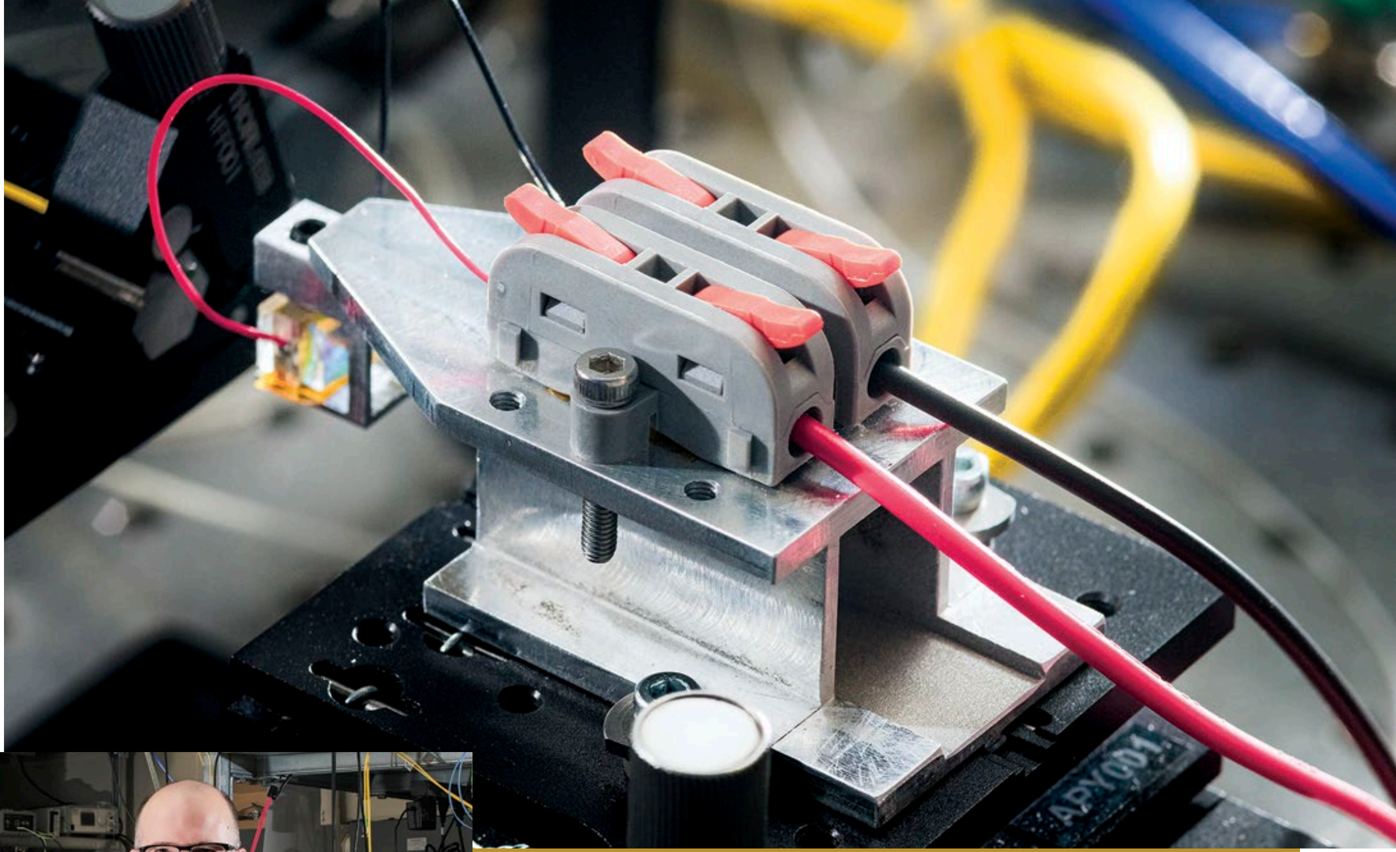
A team of researchers in the lab of Peter Rakich, though, developed an ingenious solution. They introduced what they call "reflection transformation circuits" that essentially transform the light produced by a tiny, millimeter-scale Fabry-Perot resonator and tune it to the frequency of the on-chip laser. In doing so, they demonstrated for the first time an ultra-stable "self-injection" locked laser using a Fabry-Perot resonator. The study's lead author, Haotian Cheng, a former grad student in Rakich's lab and now an optics engineer at Apple, explains that "self-injection" means that a laser can effectively synchronize the laser oscillator with the resonance of this Fabry-Perot cavity, inheriting the remarkable low-noise properties of the cavity.



Through their innovation, they've created a device that produces an unprecedented suppression of fluctuations — or "noise" — in the laser's frequencies. That's important, because a laser with lower noise "gives us the ability to detect smaller signals or to sense motion, vibrations, etc. with

***Left:*** *Researchers carefully align a laser, part of the painstaking work behind the team's breakthrough ultra-stable laser system.*

*Photo by Amy Levitin Gray*



***Above:*** *A lower-noise laser means better ability to detect the position of a vehicle, identify a microwave communications signal, or sense motion in a radar system — all potential outcomes of the ultra-stable laser system developed in Rakich's lab.*

*Photos by Tanner Pendleton*

> "We have developed a very different type of bulk acoustic resonator that permits access to very high-frequency phonons using light."
>
> Peter Rakich, Donna L. Dubinsky Professor of Applied Physics

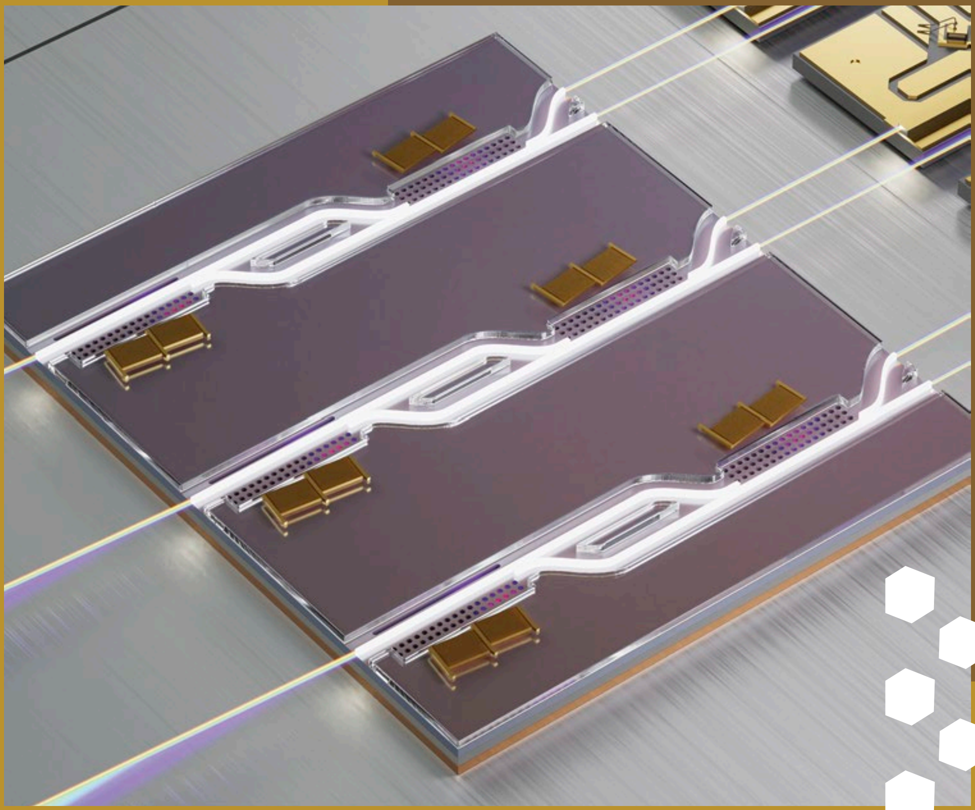
much more precision," says Rakich, the Donna L. Dubinsky Professor of Applied Physics. These features are crucial in that they have potential benefits for communications, sensing, laser radar, and imaging technologies. The laser's low noise means that users can better identify the position of a vehicle, detect a microwave communications signal, or sense motion in a radar system.

Going forward, the researchers plan to use their current ultra-stable laser system as a building block for fiber-optic sensing applications. With a low-noise laser, such a system can sense any vibration in the fiber and detect earthquakes, submarines and other things. The technology also underpins Resonance Micro Technologies Inc., a company Rakich co-founded with Gregory G. Luther, which received a grant last year from the Roberts Innovation Fund — Yale Engineering's accelerator for faculty innovations — to support commercialization efforts.

## Cooling sound

In another study, Rakich and his lab used the same device to achieve another breakthrough. In this case, they developed lasers to cool phonons — or particles of sound — within massive objects to their quantum ground state, the lowest possible energy in quantum mechanics.

"We have developed a very different type of bulk acoustic resonator that



## Guiding the path of light

For another project, Rakich and his team employed a more recently invented device, the optic isolator. With it, the researchers figured out a better way to control the path of light on small chips, a breakthrough that could lead to better and cheaper sensors, smartphones, and other devices.

Photonic integrated circuits (PICs) use light, or photons, to provide significant advantages over conventional electronics in terms of efficiency, speed, and allowing for smaller devices. The ability to generate, manipulate, and detect light using PICs of increasing complexity has opened the door to revolutionary advancements in classical and quantum computation, optical communications, as well as imaging and sensing technologies. Incorporating a component known as an optic isolator into PICs has the potential to make them even more powerful.

"It's an essential component to protect lasers," said Haotian Cheng, who also led this project. "It will let light pass in one direction but block it in the other direction."

The challenge, though, is that optic isolators rely on magnetic materials, which are incompatible with the complementary metal-oxide-semiconductor (CMOS) materials used to make PICs.

"So it's very hard to make that material out of your silicon chip," Cheng said. "We need to find alternatives."

To that end, the researchers made their own alternative by creating a non-magnetic optic isolator that allows for a wide range of light frequencies. Other researchers have demonstrated the use of optic isolators in PICs, but they come with limitations. They can only operate within a few gigahertz of optical bandwidth, for instance, which greatly limits functionality. The Yale researchers demonstrated that their approach allows the system to scale up the optical bandwidth to two terahertz (one terahertz equals 1,000 gigahertz) which means it can operate with multiple colors of light sources.

The system includes two acousto-optic beam splitters, each of which can split light beams and change their directions, creating a system that allows for easy control of the paths of light.

"If we can move everything on chip," Cheng said, it could significantly reduce the cost of optical communications devices and other technologies. It will also make them more efficient and versatile.

"With this building block, we can achieve all the functions in silicon photonic chips," he said. "That will make the industry change from a micro-assembled optical component to a fully on-chip platform, which will dramatically drop the cost."

permits access to very high-frequency phonons using light," Rakich says. They enhanced the interaction between light and the massive phonons using an optical Fabry-Perot resonator. The device's highly reflective mirrors enhance the light field in the crystalline resonator. With this system, they were able to use lasers to cool the phonons within these objects to their lowest state of energy. In doing so, they were able to stabilize the phonons and enhance their quantum properties.

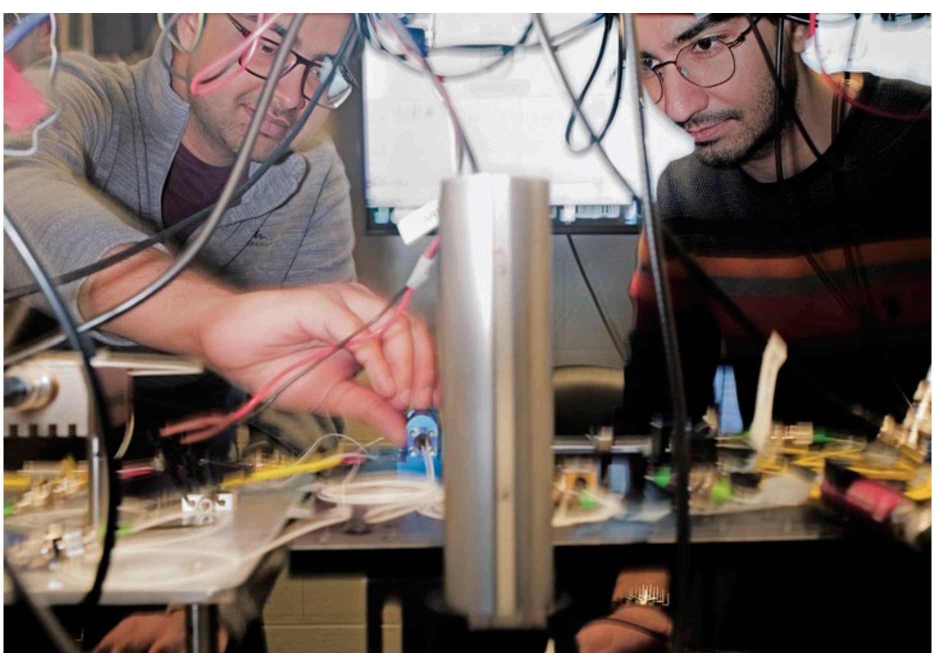
Rakich notes that, in the quantum realm, "massive" is a relative term. In this case, it means 10 micrograms of material in the acoustic wave motion, or an object that's a bit smaller than a grain of sand. At the atomic scale, however, this corresponds to an enormous number of atoms (100 quadrillion) moving in quantum-coherent fashion.

This is a major advance — prior methods of using light to control motion at the quantum level have been limited to objects about a million times smaller. Scaling up to the Rakich lab's system is critical because it allows for longer coherence times — that is, the duration of time that quantum information maintains its quantum properties before decaying.

Increasing coherence times is crucial to advancing quantum science and will be necessary to create practical quantum computers. The increase in size results in longer coherence because a smaller proportion of the atoms resides at the surface, where things can get tricky (even by quantum's very tricky standards). Rakich recalls a quote from the late theoretical physicist Wolfgang Pauli: "God made the bulk; the surface was invented by the devil."


*__Top:__ A cryogenic optical system cools and stabilizes delicate devices, enabling experiments to advance tomorrow's quantum technologies. __Bottom:__ Ph.D. students Sayan Ghosh and Tevfik Bülent Kanmaz fine-tune numerous optical components at the workbench.*

*Photos by Amy Levitin Gray (top), and Tanner Pendleton (bottom)*



"It's notoriously difficult to control various interactions that occur at surfaces," Rakich says. That's why the Rakich lab's approach works so well — by using light to access sound waves within the bulk of a crystal, they greatly reduce surface interactions. This effectively protects the system from unwanted quantum decoherence.

Hagai Diamandi, a former postdoctoral associate in Rakich's lab who headed up the project, noted that the system provides excellent material properties, without many of the drawbacks of conventional methods.

"Having a system that can precisely control phonons while maintaining their unique properties opens up exciting possibilities for advancing the field of quantum research," says Diamandi.

# When machines join the team

## Marynel Vázquez is studying human-robot teamwork — one pizza at a time

**Photos by Tony Fiorini**

It takes some time for any team of workers to get used to each other's habits — their quirks, ways of communicating and work patterns — and become an effective and efficient working unit. But how does that dynamic play out when one of the team members is a robot?

With the rapid advance of both robotics and AI, it's a question that takes on a growing urgency. And it's the crux of a recent collaboration between researchers at Yale Engineering and Tata Consulting Services (TCS), an international technology company based in India.

In Marynel Vázquez's Interactive Machines Group Laboratory, human subjects teamed up with a robot to build a toy pizza: The robot is in charge of passing ingredients to the human, and then the human takes those ingredients and places them on the pizza. It's the kind of task that calls for the same fundamental cooperative skills required in many settings, from homes to factories and restaurants. At first glance, it may look like a game, but it's backed by cutting-edge computer science.

"This is a project about being able to — in a natural and quick way — adapt the behavior of a robot to human preferences during a collaboration," said Vázquez, assistant professor of computer science and Yale's lead researcher on the study. Chayan Sarkar, a senior scientist with TCS, is the study's other co-leader. ›

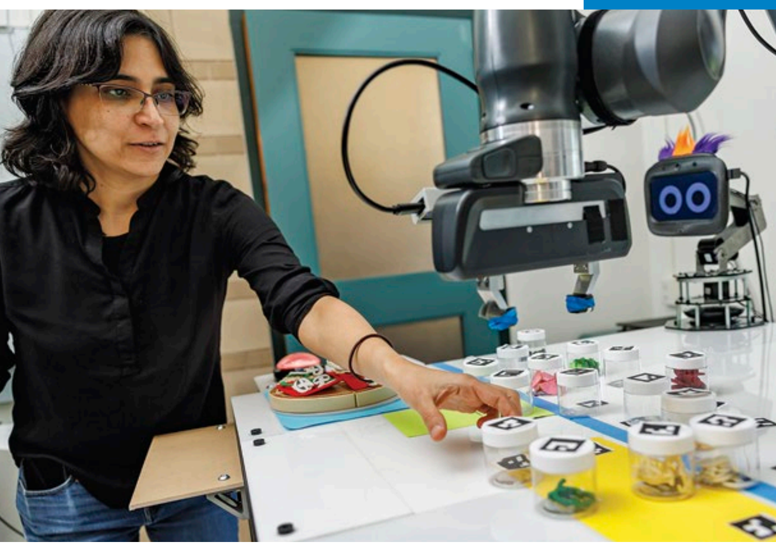
## Teaching robots to adapt

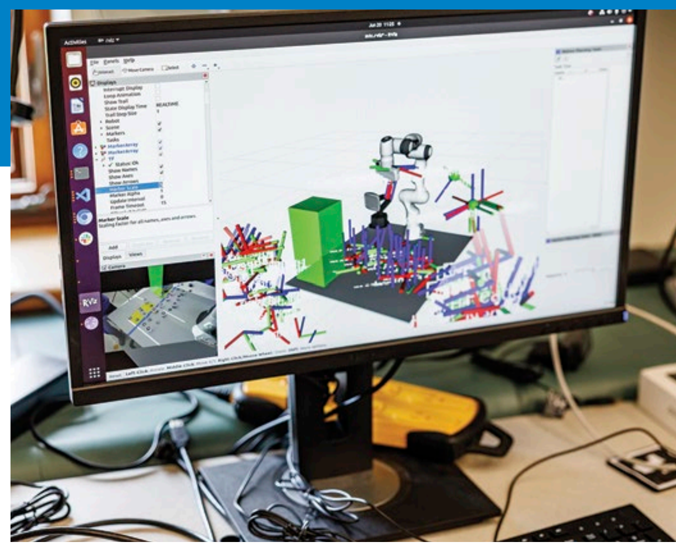
Typically, in establishing a robot-human partnership, the first phase of training involves giving instructions to the robot. Then, in the second phase, the robot and human try to complete the task together. The Yale and TCS researchers wanted to see if they could combine those two phases, with each adapting their behavior as they go along.

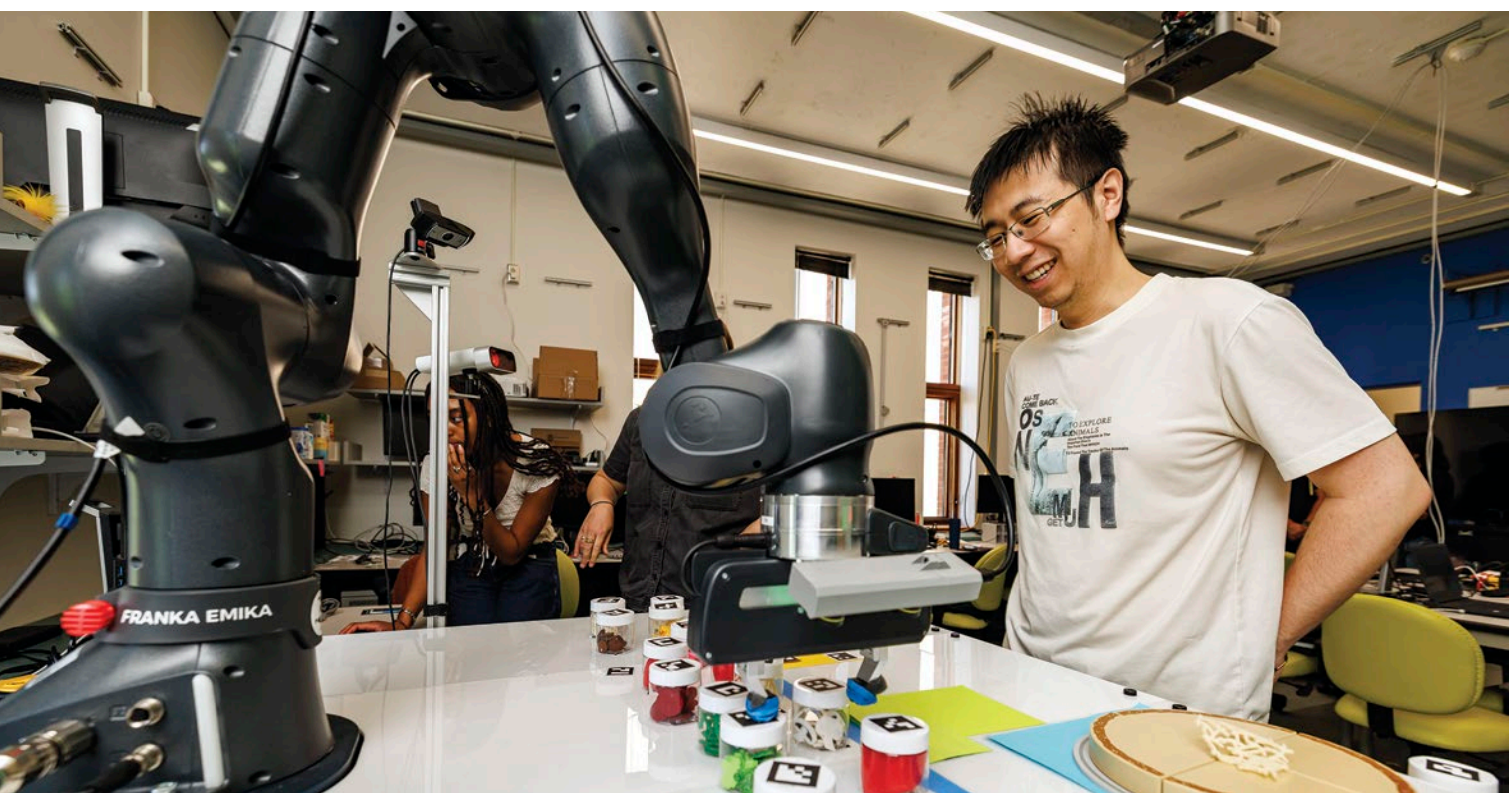
In this case, the humans offer the robot binary feedback by pushing one of two buttons. One button tells the robot it performed a task correctly, the other is pressed to express disapproval. That's the simplest and most explicit form of feedback. But then there's also the unspoken, or implicit, communications that are part of every working team. That could include a smile, a shrug, or a rolling of the eyes. Could robots pick up on that kind of feedback and use it to improve their performance?

"What we're trying to do in this project is see if we can combine those two phases, the explicit and the implicit," Vázquez said. "That's what would probably end up happening in real-world deployments, where someone is working with a robot. The robot would say 'Let me try to adapt my behavior as we're working together.'"

***Top, left:*** *ID tags help the robot track what ingredients it's handling as Vázquez guides it through adaptive training.* ***Top, right:*** *T3D visualization shows the robot's motion planning in action.* ***Bottom:*** *Ph.D. student Qiping Zhang monitors a collaborative robotic arm as it completes a task and adjusts its behavior in response to human guidance.*







***Above:*** *The robot passes a container of "cheese" to its human collaborator — but if the human opts not to use it, the robot takes note and updates its model of their preferences accordingly.*

Both kinds of communication are critical in a human-robot team. Ideally, the workflow will become more natural. As it does, though, it's common for the human to forget to provide the explicit feedback.

"People often forget to press the button because they get engaged in the task," she said. "It's very common for this kind of feedback to kind of reduce over time. But then the robot can use that, and look at what actions the human is taking and infer from that."

For instance, the robot might pass cheese to the human, but the human opts to not use it. "Then the robot thinks 'Hmm, maybe my model that says you want to put cheese first is not accurate. I need to change that.'"

A publication that describes the team's approach to enable robots to reason about explicit binary feedback and human actions during a collaboration appeared in the 2026 IEEE/ACM International Conference on Human-Robot Interaction, in Scotland in March of 2026.

The study also looks at how people's reactions to their robot coworkers change over time as they become more accustomed to the robot's work habits.

"We believe this happens because the person is updating their mental model of the robot," Vázquez said.

It also considers the role of small talk among coworkers. Can robots engage in it? And perhaps, more to the point, should they?

"What do coworkers talk about while working? They can talk about something related to the task. But how long can you really talk about the task?" Sarkar said. "Typically, what people do is talk about other things; they engage in social talk. So a similar thing can also happen with a robot."

Using Large Language Models, the researchers are looking at ways to instill some chattiness in the robots. The challenge, though, is how to make a robot's conversational skills just good enough to keep things interesting without being distracting.

"If it's only social talk, that might be a bit distracting and the work progress might be slow," Sarkar said. "If it is only task talk, then it can be boring. So how can we mix these two kinds of talking styles, and when to switch between them?"

## A look into the workplace of tomorrow

Sarkar said that much of this research can be put to use fairly soon at TCS. "In the near future, we'll have a set-up where human workers and robots will share the space," Sarkar said.

Rajesh Sinha, chief scientist at TCS Research and Innovation, said "this research illustrates how we can create better human-robot collaborative cells within the Industry 5.0 paradigm. The ability of robots to adapt and personalize their behavior to human collaborators is crucial for seamless integration in both industrial and service domains."

Longer term, the researchers note, the generality of the task means that the results of the study can apply to many settings, including home care robots, which need to personalize their behavior to specific individuals. It can also inform the design of service robots in hospitals and other workplaces. If experts' predictions are correct, it won't be long before many of our coworkers are robots. Thanks to the kind of research that Vázquez and Sarkar are doing, we'll be a lot more prepared.

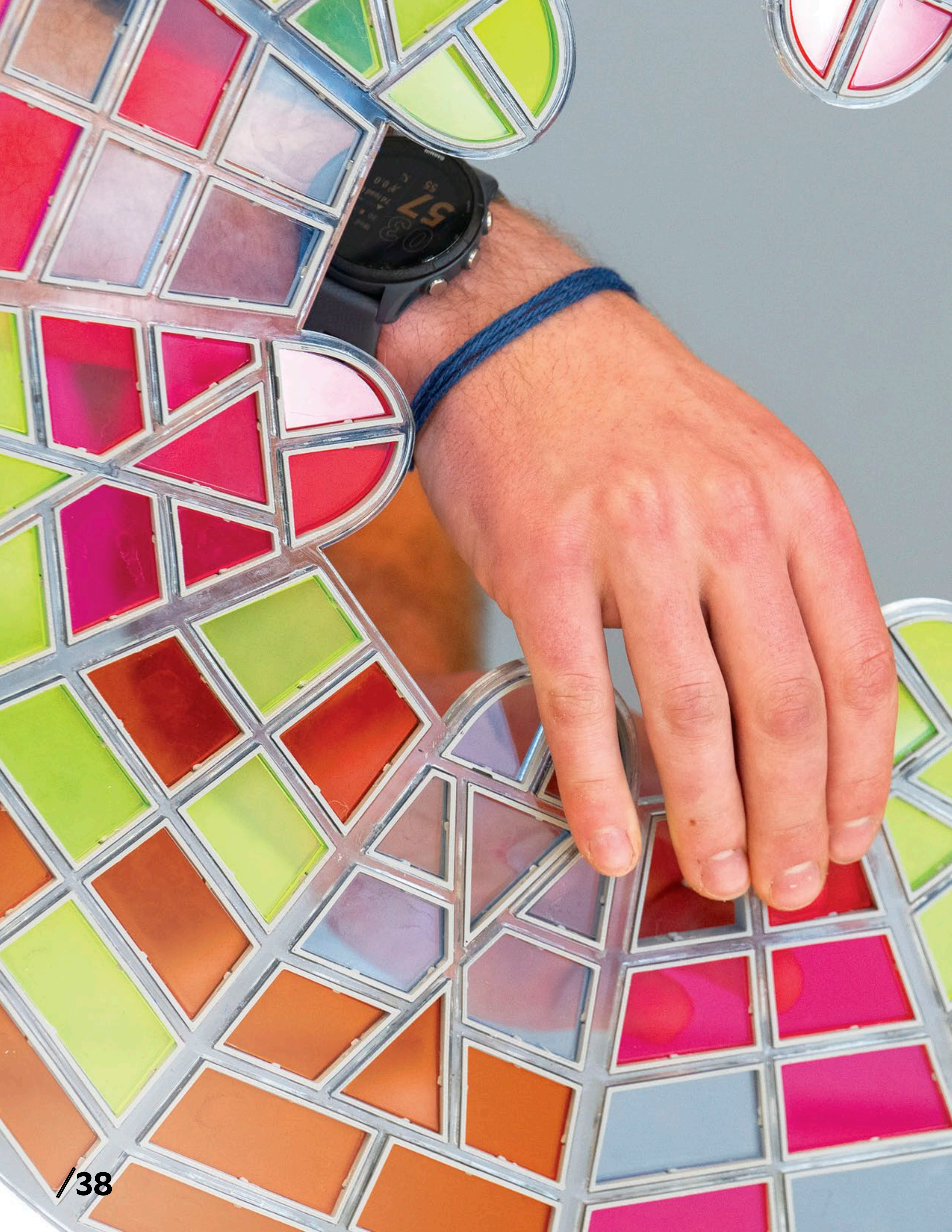


*Photo by Solomon R. Guggenheim Foundation / Filip Wolak*

# Where engineering meets design

## From its wheelchairs to its famous spiral ramp, the Guggenheim teams up with Yale Engineering to rethink the museum experience

The Solomon R. Guggenheim Museum, designed by Frank Lloyd Wright, is now considered an iconic work of 20th-century architecture. Completed in 1959, the art museum's building is known both for its dramatic spiral exterior as well as the "single continuous floor," as Wright described the building's interior ramp.

But in the intervening 65 years, a lot has changed in New York City, in the world, and in museums. So has the way the Guggenheim activates its architecture through exhibitions and programming, cultivates its relationship to the city, and defines its role as a public and civic space.

"We at the museum have been thinking a lot about that intersection of architecture and visitor experience," said Chitra Ramalingam, director of academic engagement at the Guggenheim. "Not just how to realize the museum's potential as an inclusive educational civic space, but as a space of connection and belonging."

As a former faculty member at Yale, Ramalingam was familiar with the Center for Engineering Innovation & Design (CEID). When she moved to the Guggenheim in 2023 to develop new kinds of academic partnerships, CEID Executive Director Joe Zinter, Ph.D., was one of the first potential collaborators she reached out to. Together with Ashlyn Oakes, M.Arch, the CEID's program manager, they began discussing a full collaboration, in which students would spend the semester exploring these big questions at the core of the Guggenheim's spatial and cultural identity. Many of the challenges Ramalingam and her colleagues were wrestling with are just the sort of things considered in "Making Spaces (ARCH 390)," a course that Zinter and Oakes teach. This interdisciplinary course, blending principles of engineering and architecture, invites students to explore how design and technology can enhance museum experiences for a broad public.

Over a period of several weeks, Ramalingam, Zinter, and Oakes worked out a plan for the Spring 2025 course, defining five challenges to spark the students' innovative spirits. The end result, Ramalingam said, was "an incredible success."


Photo by Solomon R. Guggenheim Foundation / Filip Wolak

"The students were so engaged, so thoughtful and creative," she said. "They asked such smart and probing questions. They really got right to the heart of these five different challenges, often in ways that I and my colleagues at the museum hadn't necessarily considered. So I was really, really impressed by that."

An interdisciplinary course cross-listed between Engineering and Architecture, Making Spaces collaborates with clients who work with the students to reimagine a space, often in ways that go beyond simply identifying a technical solution or architectural intervention. It's a complex challenge that requires the students to work across disciplines to develop creative solutions and designs, while considering feasibility, viability, desirability, and other constraints.

In other words, it's the perfect course for considering museum space. Shortly before it closed for renovations in 2020, Making Spaces teamed up with the Peabody Museum. Students worked closely with museum representatives to develop ways for Peabody visitors to experience the renovated galleries. A student project from that collaboration became the basis for a start-up company, Amuse Technologies, which is now the navigation platform being used in the Peabody Museum. In other years, the course has worked with the Smithsonian Arts and Industries Building, for which students developed interactive tours and other innovations.

Working with the Guggenheim proved to be just as fruitful a collaboration.

"As one of the world's most influential and iconic museums, collaborating

***Left:*** *Yale Engineering students gather in the Guggenheim lobby during a site visit, exploring the museum's iconic spaces as part of their interdisciplinary Making Spaces course.*

with the Guggenheim was a very exciting opportunity and the course garnered tremendous interest from students," Zinter said. "The challenges presented by Chitra and her team were multifaceted and nuanced, and they required our students to develop deeply creative and holistic solutions that engaged with the cultural, spatial, and human dimensions of the museum experience."

The students were divided into five teams, each tasked with finding a new way to approach a different aspect of the museum. The class included guest lectures and a tour of the Guggenheim itself.

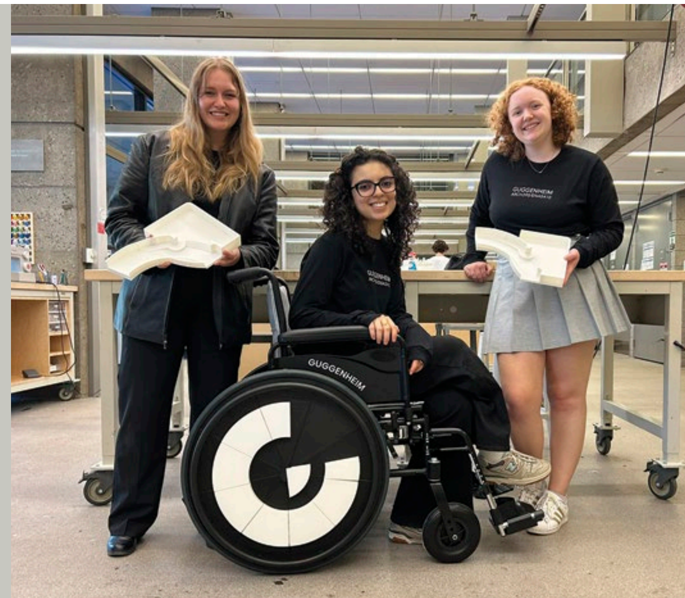
"It was inspiring to work with such a talented and interdisciplinary group of students, whose diverse perspectives led to these creative and innovative solutions," Oakes said.

Here's a look at the five projects that came out of the course:

## Accessibility Team:

**Halyn McKenzie '25, Selma Mazioud '25, Piper Jackman '25, Caleb Nieh '26**

Although the Guggenheim was designed around an icon of accessibility — a ramp — some parts of the building unfortunately remain inaccessible to visitors using wheelchairs. These areas include the High Gallery and the Aye Simon Reading Room. The student team proposed two interventions to support a more inclusive visitor experience at the museum, while preserving the building's architectural integrity.

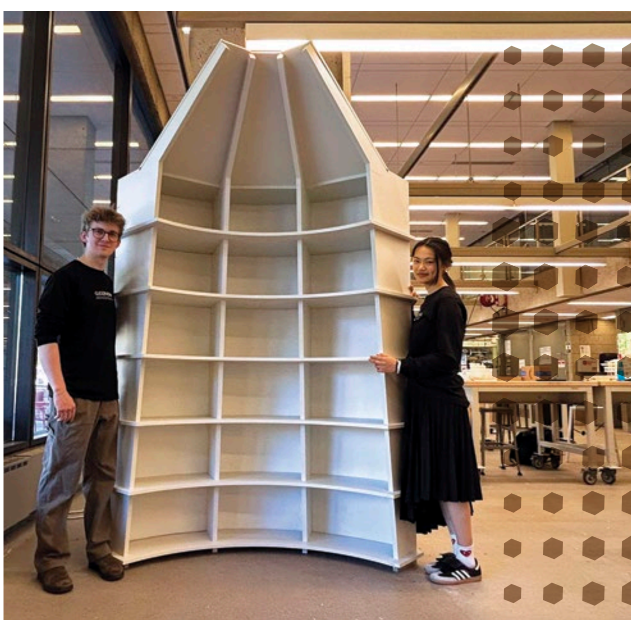



First, they offered two iterations of an intervention to open the stepped entrance into the High Gallery to wheelchair users — one, a more traditional and compact ramp that curves around the central staircase, compliant with the Americans with Disabilities Act; the other, a flat plane extending from the gallery floor, leveraging the existing slope of the rotunda ramp.

The team also reimagined the standard wheelchair the museum currently loans out to visitors, updating it with easily attachable and removable design elements. The redesigned chair features a black powder-coated frame, custom 3D-printed logo wheels, upgraded casters, and integrated storage — offering both enhanced functionality and a refined look to match the aesthetic of the museum.

## Education Center Team:

**Tian Hsu '26, Jason Nuttle '25, Brandon Lin '25**



The team set out to create a suitable storage solution for books, art supplies, and other materials in the museum's Gail May Engelberg Center for Arts Education. Specifically, they wanted to "create a learning space that feels seamlessly integrated with the Guggenheim's architecture — organic, inviting, and reflective of Wright's vision."

That meant helping the museum's art-making and classroom spaces better express the ethos of its programs: to be a place where all visitors, especially children, can feel inspired to learn, play, and engage with art.

"We focused on developing a unique storage solution that bridges aesthetic and functional gaps to make the education center feel more welcome to all," said Tian Hsu '26.

The customized shelving system, like much of the Guggenheim, would be curvy with rounded edges, reflecting the museum's architectural language. The shelf translates the museum's cross-section into a continuous, flowing form scaled to the human body and adapted for practical storage and displaying children's art. The museum plans to install the shelf in the Engelberg Center.

# Its partnership with the Guggenheim is just the CEID's latest collaboration with a prestigious museum.

Here are a few other examples from recent years:

## Protecting ancient artifacts at the Met

**Vibrations in the museum environment can be risky for artwork, particularly when that artwork is thousands of years old. In the course "Introduction to Engineering, Innovation & Design," students were tasked with finding a way to protect the Metropolitan Museum of Art's ancient wooden coffins in the Egyptian Art collection from potentially damaging vibrations.**

**Even mild disturbances from construction, parties, and other nearby events can wreak havoc on the collection's very fragile artifacts. The student team devised a solution that involves a finely calibrated system of springs and polyethylene foam. The springs absorb the vibrations, while the foam prevents the springs from moving and disturbing the coffin. The coffin-and-pedestal model could easily be scaled up to the originals at the Met, and further modified for testing on other items.**

## A contactless microscope

**Working with officials from the Yale Peabody Museum of Natural History and the Smithsonian Institution, students developed a microscope that can be operated without touching it. The museums' officials told the team that they were looking for a microscope that visitors could use without spreading germs. The students developed a sleek device that they dubbed the Hover. Encased in a damage-resistant acrylic surface, it allows users to operate the microscope by holding their hands over different sensors. Depending on where the hands are placed, the microscope lens can go up, down, left and right, as well as diagonally. Hold your hand up high, and the lens travels slowly to its destination. Lower your hand, and it speeds up — but it never gets too fast for novice users to operate or too difficult for people with physical disabilities.**


## Shedding light on an artist's work

**When the Yale University Art Gallery held an exhibition of artist Thomas Wilfred in 2017, it was with the help of two teams of Yale Engineering students. Wilfred, who used light as his medium, was considered a major figure in the art world earlier in the 20th century. His works are rarely displayed today, however, because much of the technology he used is obsolete. The two student groups in the "Engineering Innovation & Design" course found a way to revive the work. They built models of interactive displays related to Wilfred's work for visitors to use at the exhibit, each designed to foster a greater appreciation of the pioneering artist's work.**

## Making art accessible to all

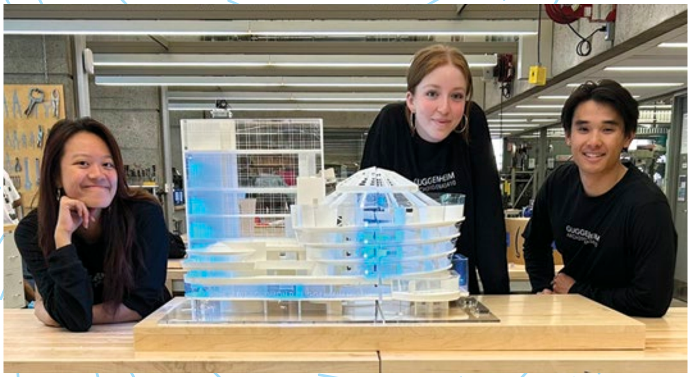
**As part of the Summer Design/Research Scholars Program, a student team collaborating with the Smithsonian Institution explored ways for patrons who are deaf or have hearing loss to experience the emotion of music and sound that are often critical to museum exhibits. For this, they found inspiration in the apps Trope and Bloom, created by ambient musicians Brian Eno and Peter Chilvers, in which users can generate visual patterns that correspond to music. They also drew from the work of filmmaker Oskar Fischinger, known for his abstract musical animations. In the students' plan, users would stand in front of a Kinect, a motion sensor, to create musical and visual pieces. Visitors would also hold a touchpad that simulates heartbeats of various tempos, each one corresponding to a different emotion.**

## Wayfinding Team:

**Nathan Sih '25, Willa Hawthorne '26, Nayan Birnbach '25, Laura Zeng '25**
The team was tasked with enhancing Wright's vision of the building as a space that encourages wandering, but at the same time ensuring that visitors can still find their way around in a space that can be very disorienting.

"I think it's very easy to get lost in the space, but that is also the essential character of the building," Laura Zeng '25 said. "How do you lean into the architecture of the building while also making it easier for people to navigate the space?"

Not wanting to interfere with the architectural character of the building with intrusive lighting or signage, they decided to make a 3D scale model of the iconic building that could serve as a tactile, interactive map. Featuring a 3D-printed interior and laser-cut acrylic exterior panels, the model offers a transparent glimpse into the building's intricate geometry and distinctive architectural character.



"The scale model is often used as an informational tool, but we were really excited about the prospect of using it as a wayfinding tool, specifically," Zeng said.

## Relationship to NYC Team:

**Sityana Abdu '26, Luis Guevara-Flores '25, Jonah Heiser '25, Abby Zheng '26**
This team worked on how the museum could better connect with the vibrant communities that surround it in New York City. Could an intervention on the patio by the museum's Fifth Avenue entrance offer a more inclusive invitation, enhance visitors' first-time impressions, and blur the lines between what's inside and outside the museum?

The Guggenheim, they noted, can seem like an imposing building. "In our design process, we wanted to think about ways to bring something from the inside that made people that are outside feel welcome to go inside," said Sityana Abdu.

They used the building's famous domed skylight, the Lawson-Johnston Family Oculus, as the inspiration for a participatory public sculpture rooted in principles of placemaking and playmaking. This interactive scale model of the Oculus was fitted with individually cut, colorful acrylic pop-out panes. Passersby could interact with the eight-foot-tall structure by spinning it and rearranging the pieces. By inviting the co-creation of ever new versions of the Oculus, the project reinforces the Guggenheim's connection to its community.

*Photo by Solomon R. Guggenheim Foundation / Filip Wolak*

## Sound Team:

**George Ploumis '26, Alina Susani '26, Henry Kaplan '25**
Museums are multi-sensory spaces, and the curved, concrete surfaces of the Guggenheim make it a complex — and sometimes challenging — auditory environment. Rather than seeing its unusual acoustics as a problem, the team embraced them. How could they create a memorable experience for Guggenheim visitors out of the unique sonic character of the space? Their first step was to think of the building as a sonic instrument itself.

This led the three students to design the *Whispering Bench,* an interactive sound installation for the sidewalk outside the museum designed to catch people's attention and then activate as they pass by. Approaching the circular bench, designed to evoke the building's circular form, triggers an audio recording that offers passersby a sensory preview of the reverberating sound within the museum. The team intends the piece to spark curiosity, draw visitors into the museum, and encourage a deeper awareness of how form and material influence sound.

# Under pressure

## A Yale collaboration is repurposing deep-Earth research tools in the search for practical superconducting materials

**Photos by Amy Levitin Gray**

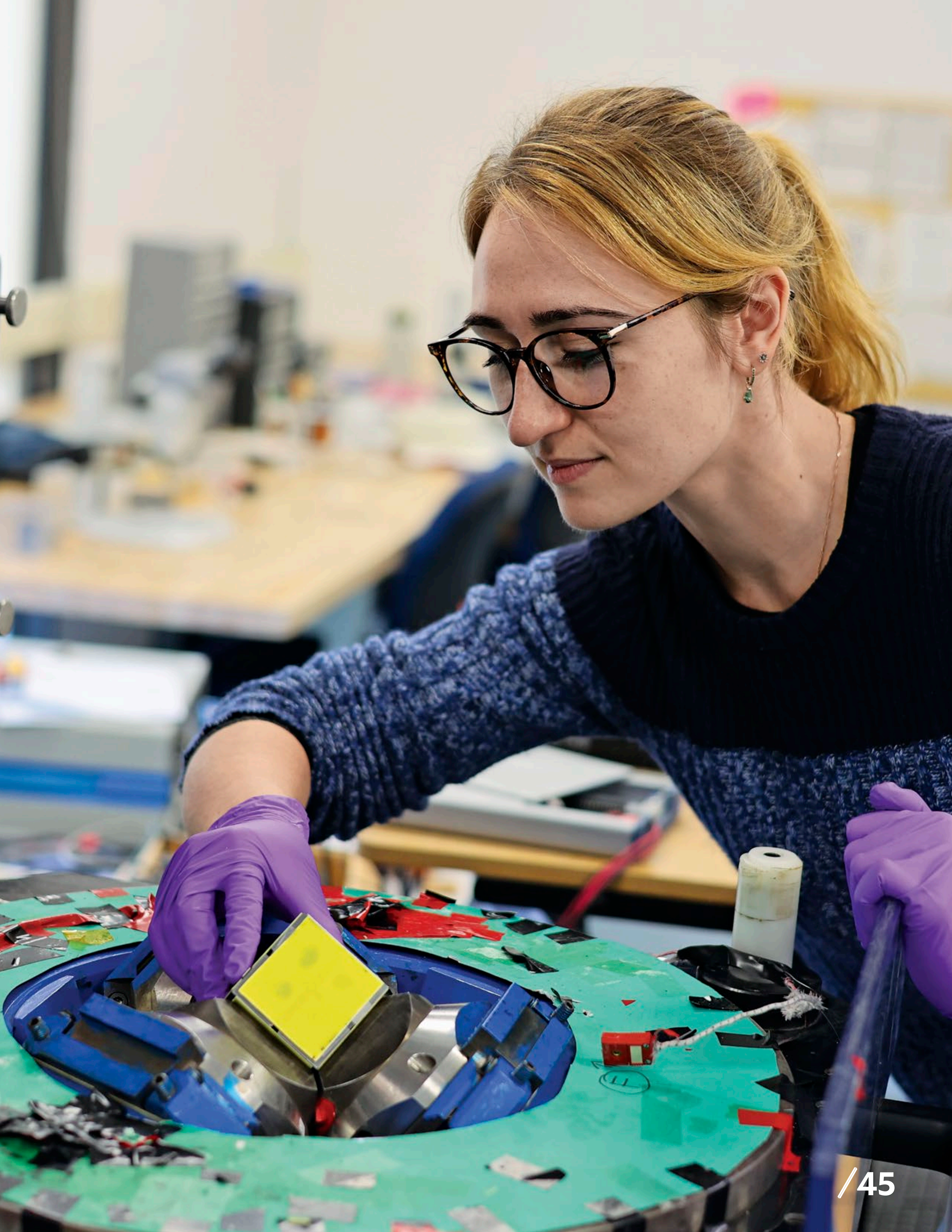
If scientists could find a material that acts as a superconductor — that is, one that transmits energy with zero resistance — at normal pressures and relatively high temperatures, it would open up a massive number of possibilities. These include medical imaging, quantum computing, and numerous other fields. So, yes, it would be a big deal.

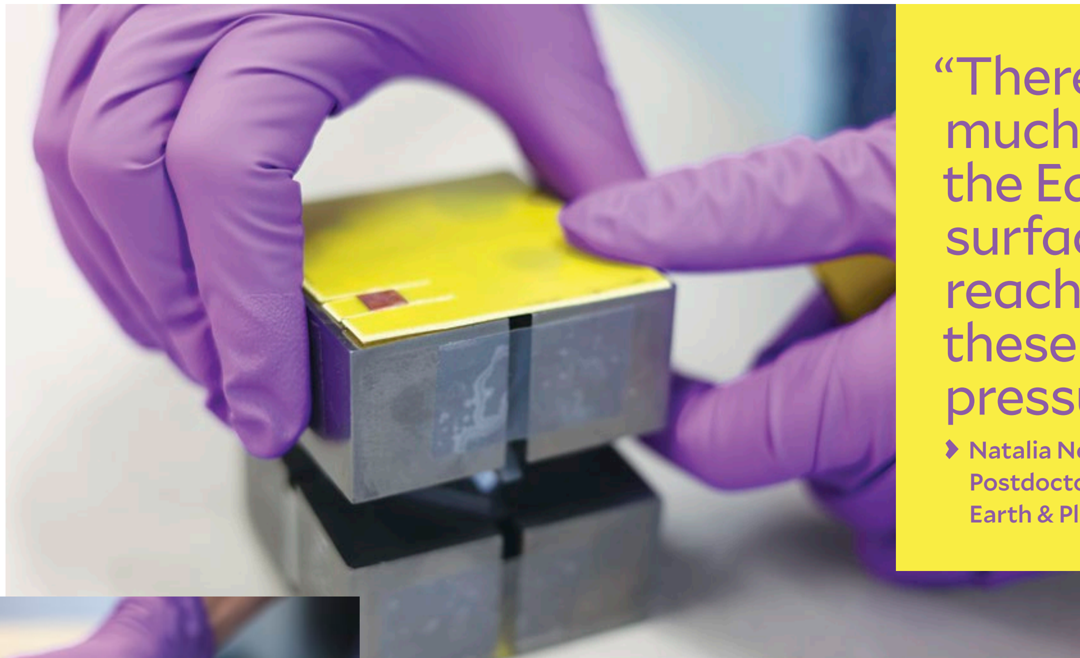
"Right now, almost 50% of the energy in transmission is just heat in copper wires," said Shomeek Mukhopadhyay. "If you can transmit electricity through wires without dissipating energy, that's a huge economic benefit. I would say it's equivalent to having thermonuclear fusion."

Mukhopadhyay, a research scientist in Chemical & Environmental Engineering, is on the third floor of the Kline Geology Laboratory. Nearby, Natalia Nevskaya, a postdoctoral associate in Earth & Planetary Sciences preps a massive device called the Kawai multi-anvil press. The machine is designed to simulate Earth's deep mantle conditions by generating very high temperatures and extreme pressures. Its intended purpose is for studying materials billions of years old, but for the past five years or so, a multidisciplinary group of scientists has been using it to potentially create materials of the future. Heading up the project is Lisa Pfefferle, the C. Baldwin Sawyer Professor of Chemical & Environmental Engineering.

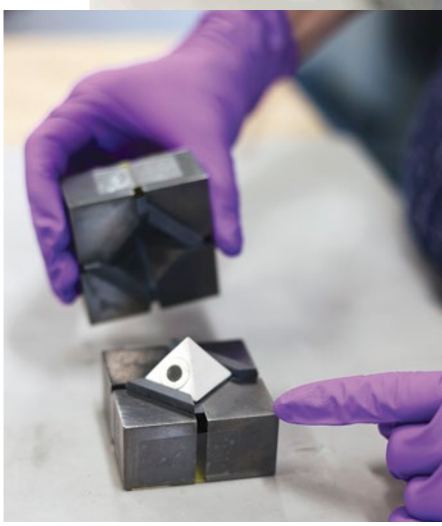
Specifically, they're aiming to create materials that act as superconductors under normal pressure levels and at relatively high temperatures (when discussing superconductivity, "relatively high temperatures" usually means anything above the temperature liquid nitrogen freezes, or about -196 Celsius). Currently, they're focusing on sulfur trihydride ($H_3S$). A close relative of hydrogen sulfide ($H_2S$), $H_3S$ is made up of three parts hydrogen to one part sulfur. It began getting attention a few years ago when scientists found that it acted as a superconductor at higher-than-normal temperatures (about -23 Celsius). The catch is that it did so only under extreme pressures — 150 to 200 gigapascals (the unit of measurement is named for Blaise Pascal, who helped clarify our concept of pressure). That's the kind of

***Right:*** *Natalia Nevskaya carefully positions a sample cube into the Kawai multi-anvil press, preparing to simulate extreme deep-Earth pressures for superconductivity experiments.*





> “There’s not much on the Earth’s surface that reaches these high pressures.”
>
> **Natalia Nevskaya**
> **Postdoctoral associate, Earth & Planetary Sciences**



***Top:*** *Nevskaya secures the lid on the sample cube, ensuring proper confinement before inserting it into the multi-anvil press for superconductivity and high-pressure research.* ***Bottom:*** *A close-up of the sample cube reveals a small white pyramid inside; the core material poised for high-pressure synthesis experiments.*

pressure found halfway to Earth’s core, approximately 3,200 kilometers into the Earth’s interior. Such pressure levels are obviously too high for any practical use, and the superconductivity disappears once the pressure is released.

So the trick then is, how do you get it to stay superconductive after relieving the pressure? And at a temperature high enough to make it practical?

Researchers in Pfefferle’s lab think they may have found a way and have teamed up with researchers from Yale’s Earth & Planetary Sciences and Chemistry departments, as well as the U.S. Navy, to help them achieve it.

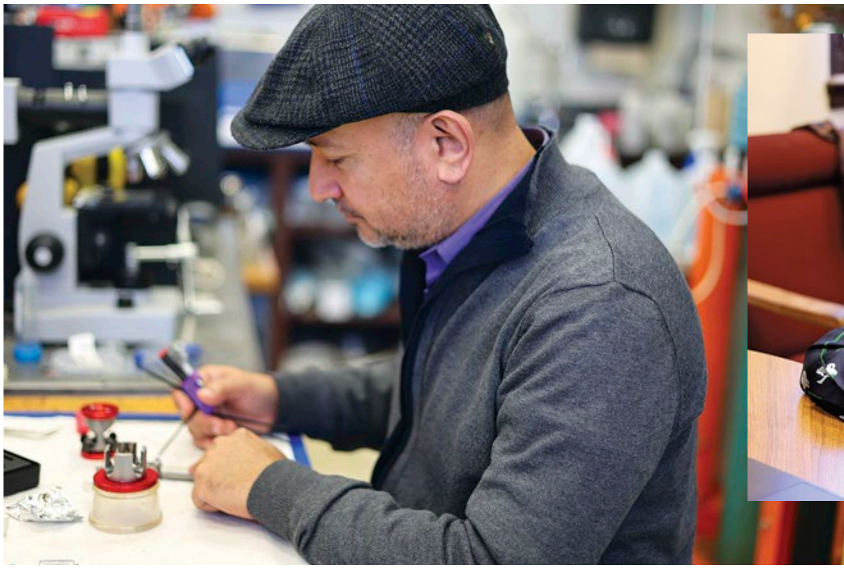
One of the inconvenient things about $H_3S$ is that it’s highly unstable. Under normal conditions, it essentially dissipates. To that end, Pfefferle’s lab has made a significant breakthrough, developing a technique to synthesize $H_3S$ under much lower pressures (about 15 gigapascals), and in a way that it remains stable after the pressure is relieved. As for making it superconductive, they’ve already seen some encouraging results while working with other materials. Last year, they were able to turn platinum into superconductors. Doing so required super-low temperatures (about 2 degrees above absolute zero or 6 Kelvin), “but the interesting thing is that this material, which is never superconducting, can turn superconducting,” Mukhopadhyay said. That is, they were able to “freeze” those materials’ superconductive properties after letting up on the pressure. So the next step is to see if they can freeze the superconductivity of $H_3S$ at both higher temperatures and ambient pressures.

The method they’ve developed for doing so involves placing sulfur and a hydrogen precursor between two graphene sheets with only a few nanometers of spacing. Metal particles are also placed between the graphene sheets to generate strain and induce more pressure. Platinum is the preferred choice of metal particle, as it also works best as a catalyst for the hydride formation. The choice of graphene as a material is important because it’s flexible and does not break under extreme pressure.

“What we have shown is that with this graphene sheet system, we can produce $H_3S$ at lower pressures because constraint — having two walls very close together of the order of half a nanometer — acts like high pressure,” Mukhopadhyay said. “So instead of producing it at pressures found at the Earth’s crust, we can produce it with 10 times less pressure.”

• • • • • • • •

Heike Kamerlingh Onnes, a Dutch physicist, discovered superconductivity in 1911 when he observed that mercury had zero resistance to electricity when it was cooled to a few degrees above absolute zero. Ever since, scientists have struggled to understand the phenomenon, and importantly, find a way to put it to practical use. As researchers searched for ways to harness it for various applications — everything from levitating trains to portable MRIs to quantum computing — the idea of superconductivity proved as confounding as it was



promising. The few times it has been discovered at relatively high temperatures, it has required extremely high pressures.

Pfefferle's interest in this line of research has its roots in her extensive work with nanotubes. Boron nanotubes, it turns out, have superconductive properties. That led Pfefferle to look further into the matter of superconductivity.

"For the past several years, people have been recording higher temperature superconductivity for a number of compounds, especially hydrides, but only when they're at very, very high pressures," she said. "So our work with the geology team was in order to use their different pressurization devices."

Her lab reached out to Nevskaya and Jennifer Girard, a research scientist in Earth & Planetary Sciences. Victor Batista, the John Gamble Kirkwood Professor of Chemistry, has also lent his expertise to the project. Curious though she was about this line of research, Pfefferle wondered what practical benefits there could be if all these materials just lost their superconductive powers once they returned to ambient conditions.

"So I thought, 'OK, strain and confinement are likely possibilities,'" she said. That is, what if they could find a way to apply pressure in such a way that the acquired properties became stable at ambient pressure? "So I put together a model system of $H_2S$ between two graphene layers to test our ideas."

Batista's group modeled this system, showing that the confinement effect could allow formation of the superconducting $H_3S$ phase at much lower pressures; this motivated the Pfefferle lab's experiments.

For the next phase of their work — inducing superconductivity in $H_3S$ — they've received a 5-year grant from the Naval Research Laboratory. Some of that work will take place at Argonne National Laboratory in Illinois. There, they'll make use of high-pressure machines that allow users to see the actual process as it happens. And as part of their collaboration, they'll use the U.S. Navy's Superconducting Quantum Interference Device (SQUID) magnetometer to measure the magnetic fields of the samples. The SQUID is critical to their research because it can pick up on the small samples' very low magnetic fields (about a billion times weaker than those of the Earth). That's crucial, because when a material takes on superconductivity, it expels its magnetic field. Ultimately, they want to hone their methods so that they're reliably reproducible, and viable for industry and military use.

Pfefferle's lab has been working with the Earth & Planetary Sciences department for about five years. In the Kline Geology Lab, they've made good use of the Kawai multi-anvil press, which applies extreme pressure to its sample from all directions. When discussing extreme pressure levels, the researchers tend to identify each level according to its proximity to the Earth's core.

*__Left:__ Shomeek Mukhopadhyay works at his lab bench, manipulating samples and preparing materials for experiments. __Right:__ Lisa Pfefferle's interest in superconductivity grew from her nanotube research, including a key discovery involving boron nanotubes.*

"There's not much on the Earth's surface that reaches these high pressures," Nevskaya explains. "That's why they built this machine. The history of the machine is not superconductivity, it's geology. The idea of the machine is to reach lower mantle conditions, or even beyond. We know a lot about the oceans. We know a lot about space — in fact, we know more about space than about what is actually happening beneath our feet."

As more has been learned about superconductivity and the effects of extreme pressures, Mukhopadhyay notes, materials scientists and geologists have increasingly been teaming up to see what more they can learn.

"The landscape has changed significantly because I think people realize there's a lot of overlap between mineral physics or high pressure, rock studies, and material science," he said.

# A global hub takes shape

## A new Yale Engineering collaboration with South Korea brings researchers and industry together to tackle global technological challenges

**Photos by Tanner Pendleton**

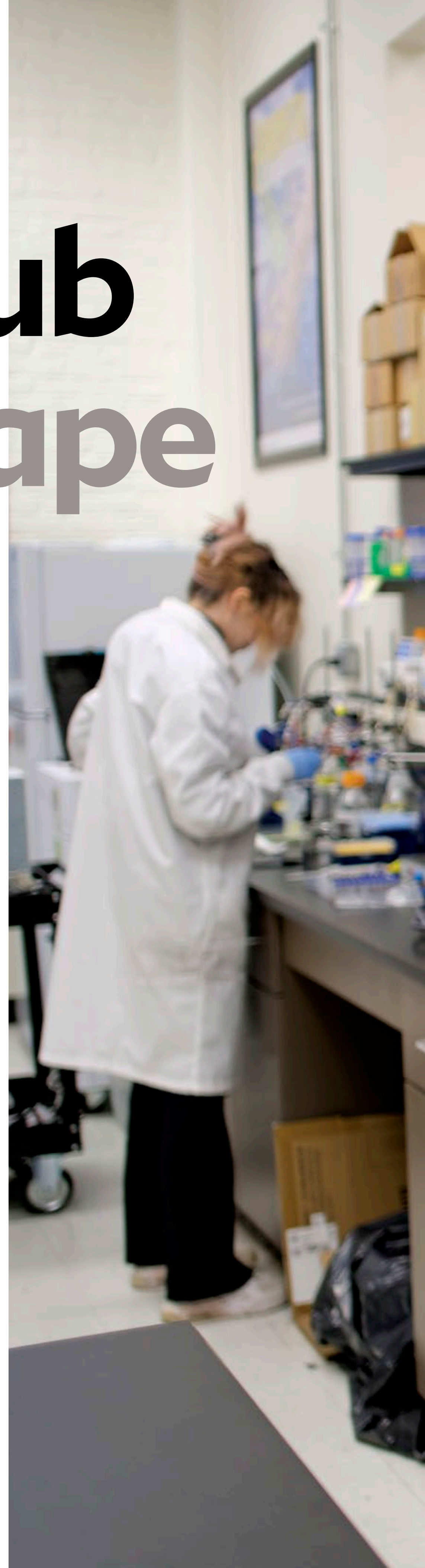
Working with the South Korean government, Yale Engineering has launched a "global industrial technology cooperation center" that provides a platform for developing research and development partnerships between South Korean companies and Yale researchers.

Led by Professor Jaehong Kim, the Korea Center for Industrial Technology-Yale (KCITY) will focus on strategic areas such as robotics, artificial intelligence, and semiconductors and manufacturing processes. Already underway at the center are research projects aiming to purify water, develop new cancer treatments, create low-power gas detectors, and advance robotic grasping.

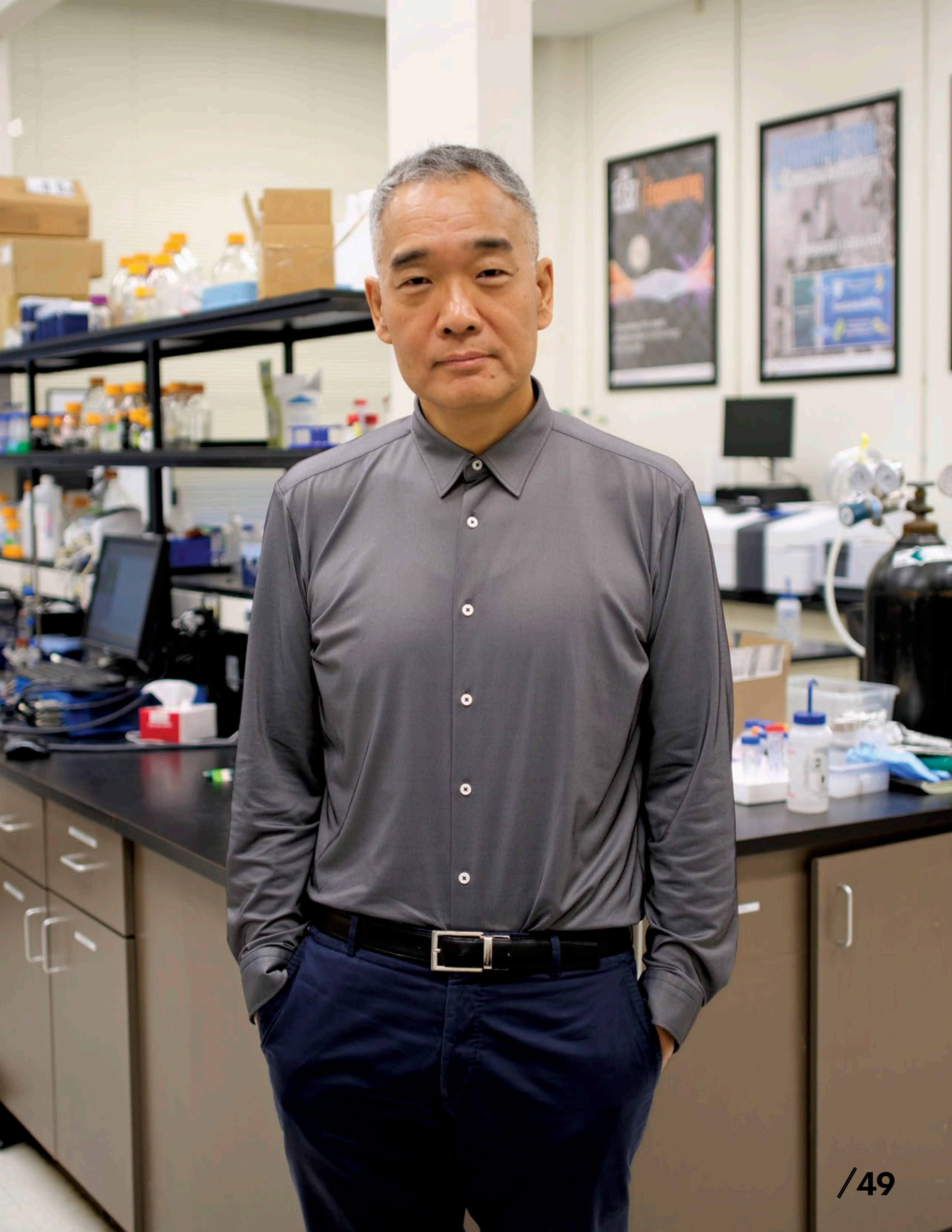
The center's establishment marks significant inroads into many of Yale Engineering's long-term goals, creating new international collaborations, as well as numerous industry partnerships.

Yale Engineering Dean Jeffrey Brock said KCITY's goals align closely with the School's.

"This is an exciting opportunity to extend Yale Engineering's international collaborations, and we look forward to providing an exceptional cooperative research environment for Korean researchers and industry partners," Brock said. "Even more so, we look forward to the impactful innovation that will come out of this partnership and their work on some of today's most pressing global challenges."



***Right:** Jaehong Kim stands in his lab, overseeing experiments that highlight KCITY's collaborative work in robotics, artificial intelligence, and semiconductor research.*




***Above:*** *Jaehong Kim and Mingjiang Zhong are developing new approaches to make ultrapure water — a critical resource in semiconductor manufacturing — more sustainable.*

Kim, the Henry P. Becton Sr. Professor of Chemical & Environmental Engineering, said KCITY provides a vibrant hub for Yale Engineering faculty to work with Korean companies on joint research and development projects. In partnership with the Korea Institute for Advancement of Technology (KIAT) and the Ministry of Trade, Industry and Energy (MOTIE), KCITY also provides administrative support for research partners and visitors from Korean companies, government, and organizations.

KIAT has also established similar partnerships in the U.S. with Purdue, Johns Hopkins, Georgia Tech, and MIT.

“The Yale center is different from other centers in that we are very broad — we are cross-disciplinary,” Kim said. In addition to the four ongoing projects KCITY also has several more proposed projects from a wide array of fields that may receive funding. “This is an important accomplishment, because it’s probably the first time that we’ve formed a cross-disciplinary team this size. It’s a large number of people who are involved.”

**The center currently has four research projects in the works:**

## Producing ultrapure water sustainably

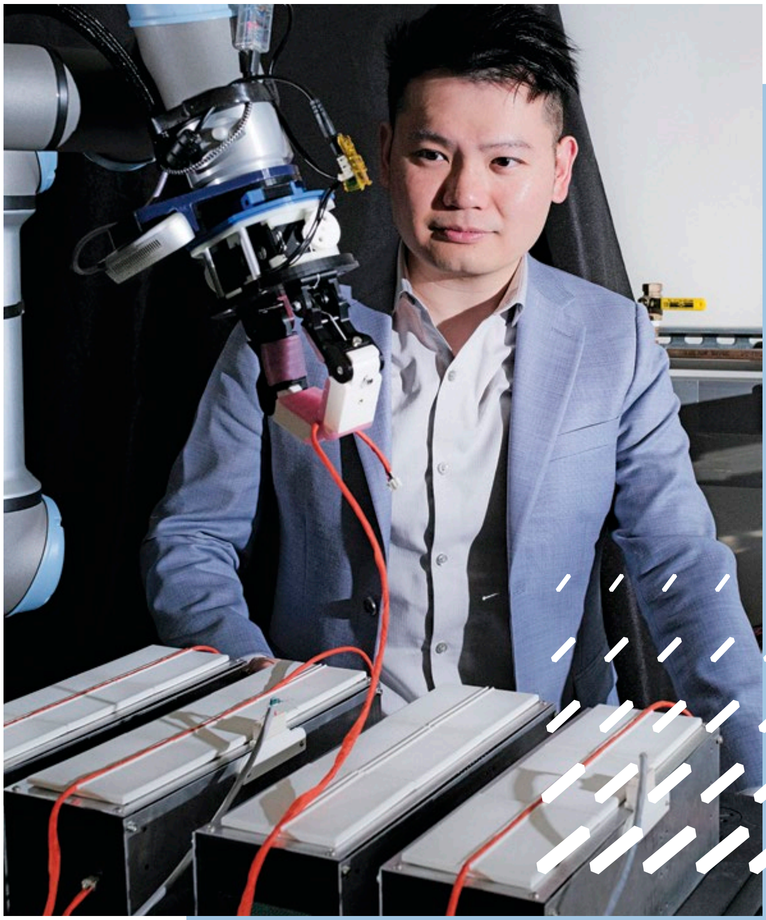
Ultrapure water is used in numerous phases of semiconductor development and requires the highest grade of water purity. And the amount of water needed for these processes can be staggering. It is estimated that over 1.8 million gallons of source water needs to be treated to produce ultrapure water required for a single 12-inch wafer. Despite Korean companies leading the global market in semiconductor manufacturing, they still depend on imported materials and technologies for ultrapure water production.

“If the semiconductor industry requires tons of water starting from fresh water, that means it's a water resource distribution problem," Kim said.

To that end, he and collaborator Mingjiang Zhong, associate professor of chemical & environmental engineering, aim to create technologies that can utilize alternative water sources such as saline or reuse water to produce ultrapure water. To do so, they will optimize ultraviolet oxidation based on extensive computer simulation and bench-scale demonstration. They will also develop a high-efficiency reverse osmosis membrane process.

## Treating cancer with nanoparticles

Mark Saltzman, the Sterling Professor of Biomedical Engineering, is working with Ingenium Therapeutics in Korea to create technology for producing anti-cancer CAR-NK cells directly in the body. CAR-NK cells are used in a form of cancer therapy in which immune cells known as natural killer (NK) cells attach to a type of engineered cell known as chimeric antigen receptors (CAR). The CAR cells essentially direct the NK cells to cancer cells. The NK cells then attach themselves and destroy the cancer cells.



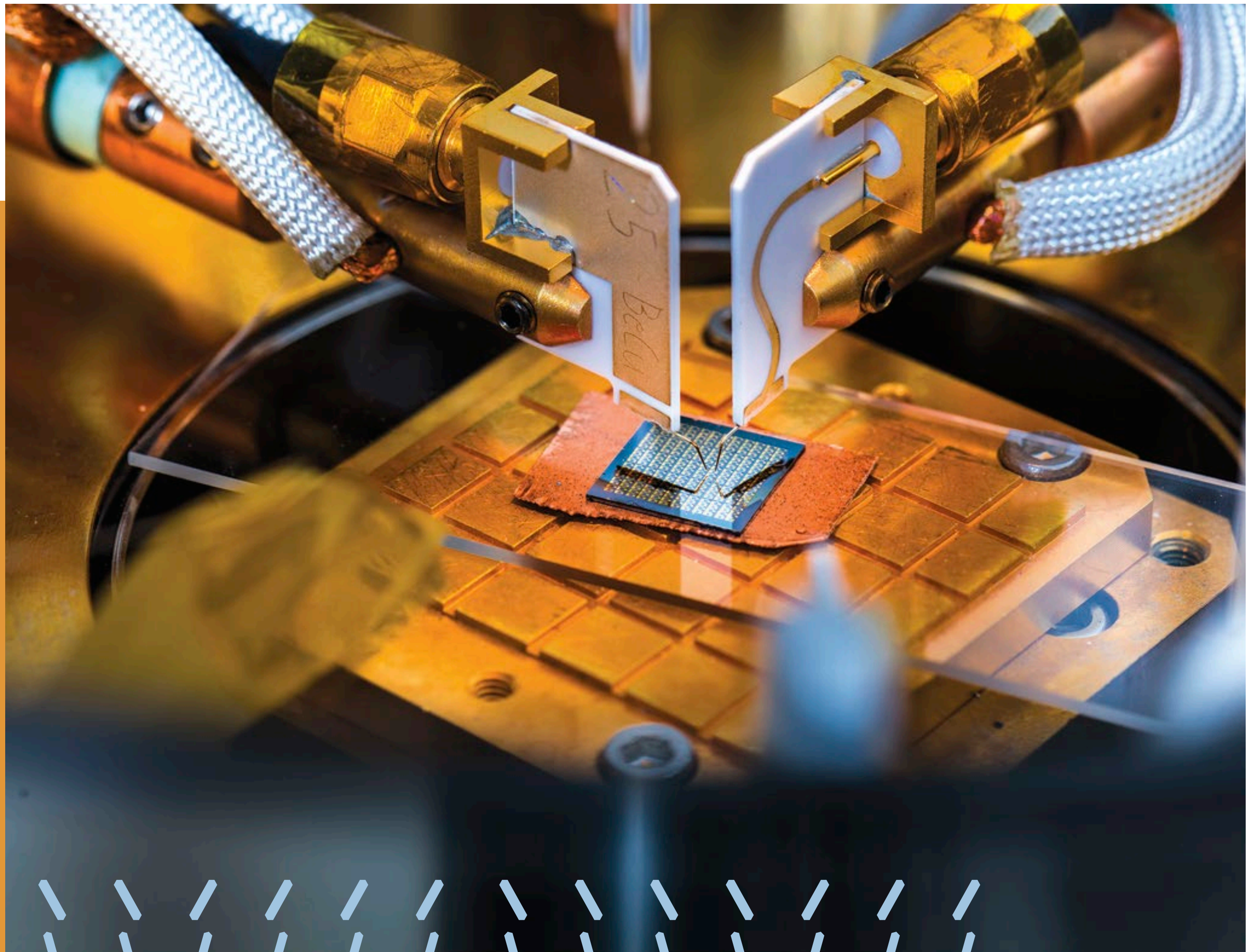
"Part of our role in the project involves packaging the messenger RNA for the chimeric receptor in a targeted nanoparticle that will then deliver it to the NK cells," Saltzman said. His lab has developed an approach in which they assemble proteins on the surface of the nanoparticles in a way that causes them to accumulate at a higher level in tumors.

## Improving robotic grip

This collaboration unites Alex Wong's Vision Laboratory and Aaron Dollar's GRABLAB at Yale with Korea's ATEC and THOTH to enhance robotic perception and dexterity for tasks such as battery pack recycling and disassembly. They're focusing on developing an innovative gripper for the dexterous

***Top:*** *Mark Saltzman is designing nanoparticles for CAR-NK cell therapies aimed at delivering targeted cancer treatment directly inside the body.*
***Bottom:*** *Alex Wong is developing advanced robotic perception and dexterity systems to enable safer battery pack recycling and disassembly.*

*Photo by Tony Fiorini (top)*



handling of delicate components in unstructured environments. It leverages multi-modal 3D perception and task planning learned by optimizing it through a simulation environment.

Disassembling battery packs presents some specific challenges for the system — both for gripping and perceiving the very small objects.

"We're essentially trying to scan these objects and see if we can actually capture them in high fidelity with a laser scanner," said Wong. "The problem is that you have these tiny wires, so there's some difficulty in reconstructing the actual thing [with typical sensors]."

To address this, they're developing new perception models that combine multiple sensors to reconstruct these thin objects with high fidelity, using the scanned objects as supervision.

"We've taken some of these thin objects that we've scanned and imported them into a simulation environment," he said. Dollar's lab then designs control algorithms to try to grasp and interact with them.

## A better gas detector

A team that includes the lab of Fengnian Xia, the Tso-Ping Ma Professor of Electrical & Computer Engineering, aims to develop ultra-low-power, high-reliability gas sensor technology capable of detecting carbon monoxide, carbon dioxide, and methane gases. This technology uses lasers that pass through the air.

***Above:*** *Precision probes interface with a photodetector chip designed to enhance gas sensing performance by combining photon and thermal detection mechanisms.*

*Photo by Carl Kaufman*

Certain gases absorb certain wavelengths of the light. Xia's lab is focusing on the photodetector needed to detect the intensity of the light in different conditions.

The researchers innovatively combine photon and thermal detection mechanisms to enhance photodetection performance within this specific spectral range. The approach is the first to use both detection mechanisms simultaneously.

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