Less Wattage, More Brain Power

SEAS teams with the Medical School to deliver faster, more capable brain-implanted device to treat multiple disorders

From Projects to Products

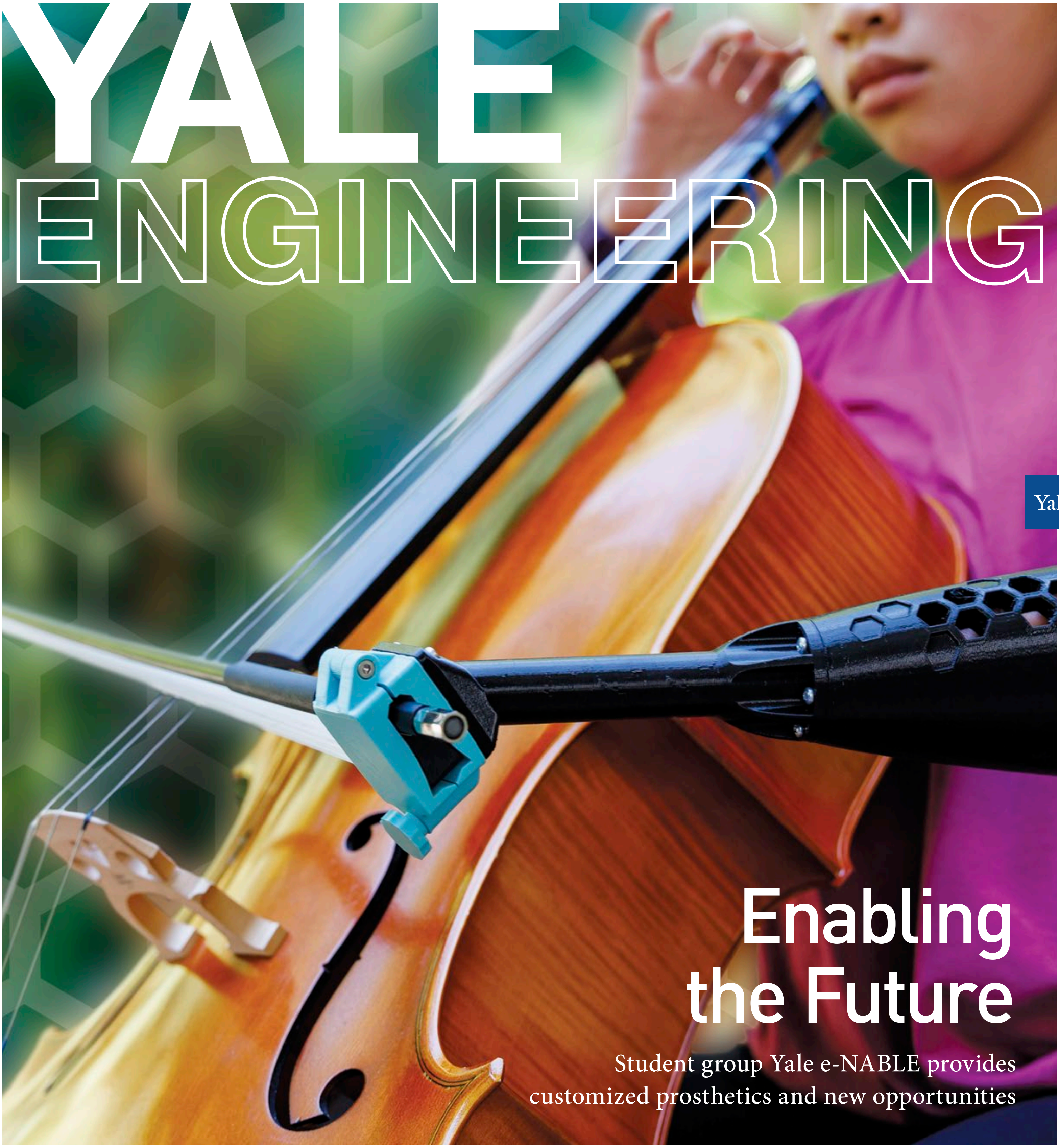
Students learn the process of launching a business, from conception to market

True Colors

Ted Kim shows that representation in animation is not skin deep

2021-2022

YALE ENGINEERING



Enabling the Future

Student group Yale e-NABLE provides customized prosthetics and new opportunities

Yale

The Publication of Yale's School of Engineering & Applied Science

In This Issue

YALE ENGINEERING 2021-2022

Front Cover: *Thanks to the help of student group Yale e-NABLE, 11-year-old Emily Reid can now play the cello comfortably and at the right angles.*

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Message From the Dean

If you were fortunate enough to watch the recent launch of Yale's "For Humanity" campaign, it should come as no surprise that SEAS was prominently featured throughout. Engineers inherently serve at the forefront of innovation and implementation, solving problems and breaking ground to put technology to work for people. And here at SEAS, we collectively bring our culture of innovation to bear on the problems that matter most, alongside colleagues in every discipline, to the broadest benefit of humanity.

As you'll read in this year's edition of *Yale Engineering,* our faculty are collaborating with colleagues from the Medical School to create an innovative brain-implanted device to treat multiple disorders. We're creating new kinds of lasers for better cybersecurity, bioimaging, and a myriad of other beneficial applications. And our faculty are tackling tough questions about how to develop computer animation technology that truly represents our diverse world.

Our students are also finding a higher purpose for their work. A team of SEAS undergraduates designed and created a bespoke prosthetic limb that allows a young girl to play the cello. Others are utilizing technology to not only preserve history, but also help provide Afghan women a better chance to earn a livable income.

Proudly, the humanitarian spirit that SEAS instills in its students doesn't end at graduation. You'll also read about three recent enterprising alums who launched successful start-ups based on innovations they created while at SEAS. Two of these ventures can improve the lives of those who suffer from skin disorders and scoliosis, the third provides a quick and accurate way to detect bacteria and viruses.

The greater sense of purpose our community brings to societal issues inspires me daily, and I am proud to share these stories with you.

Jeffrey F. Brock
Dean, School of Engineering & Applied Science
Dean of Science, FAS
Zhao and Ji Professor of Mathematics

Year in Review

A look back at some of the news stories from the Yale School of Engineering & Applied Science over the last academic year

Sept. 2020

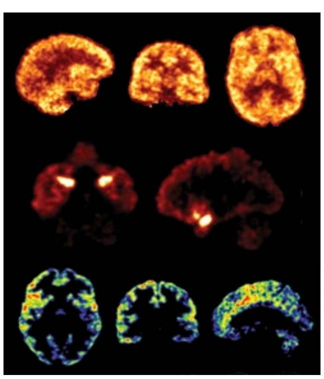
Anjelica Gonzalez, New Tsai CITY Faculty Director

The Tsai Center for Innovative Thinking at Yale (Tsai CITY) named Anjelica Gonzalez, associate professor of biomedical engineering, as its new faculty director. Tsai CITY, which launched in 2017, is designed to inspire students to innovate solutions to real-world problems. Gonzalez, who has focused on the development of biomimetic materials for use in the investigation of immunology, inflammation, and fibrosis, will help advance Tsai CITY's vision. Yale provost Scott Strobel noted that Gonzalez's approach to innovation makes her appointment a great fit for Tsai CITY, stating her work "exemplifies the creative, collaborative approaches Tsai CITY aims to foster in its growing community."

Yale

Oct. 2020

State-of-the-Art Brain Imaging

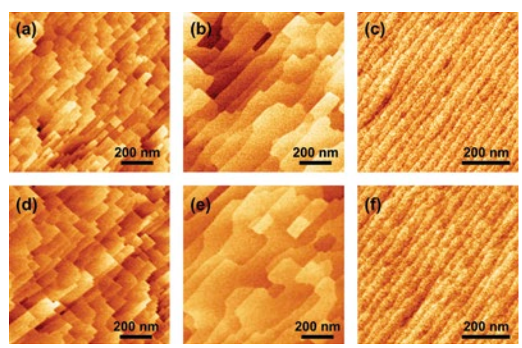


The Yale PET Center's HRRT system, previously the highest resolution brain scanner in the world, was replaced by the NeuroeXplorer, providing much greater sensitivity than the HRRT scanner to produce much higher quality images. These improvements will lead to dramatic expansions in the scope of brain PET applications for the study of the healthy and diseased brain. "The new system will give us the ability to measure very small nuclei in the brain and very small signals in the brain with remarkable precision," said Richard Carson, professor of biomedical engineering and radiology & biomedical imaging and director of the Yale PET Center.

Nov. 2020

A Very Detailed Replication

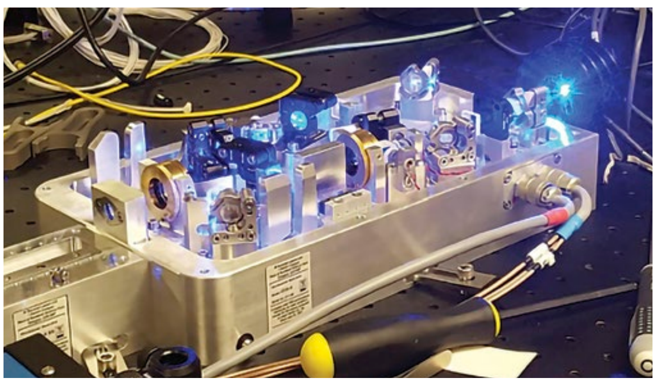
The ability to replicate materials at the atomic level has gained significant attention in the field of materials science. Although various factors limit the current technology, Udo Schwarz, professor of mechanical engineering & materials science and department chair, showed in a study that when working with metallic glasses, there's virtually no limit to the accuracy that you can achieve when replicating surface features. In *APL Materials,* he demonstrated a process that can replicate a surface's features to details of less than one ten-billionth of a meter, or less than 1/20th the diameter of an atom.



Dec. 2020

Big Potential for a Small Chip

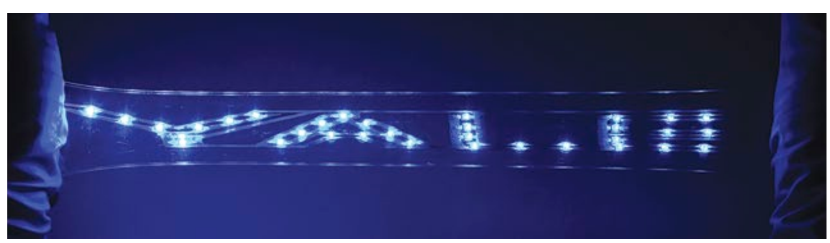
Researchers, led by Hong Tang, the Llewellyn West Jones, Jr. Professor of Electrical Engineering, developed a first-of-its-kind chip that could pave the way toward more accurate clocks, the discovery of exoplanets and improved GPS systems. The chip entails a single laser that is shot through a microscopic comb, which splits into a rainbow of colors. It all happens in a highly controlled manner on a tiny photonic resonator.



Jan. 2021

A Closer Look at How Immune Cells Work

Researchers in the lab of Kathryn Miller-Jensen, associate professor of biomedical engineering and molecular, cellular & developmental biology, used single-cell RNA sequencing to get a closer read on how individual macrophages — immune cells that both fight infections and fix the damage they cause — react to different stimuli. They found that while these cells tend to be multitaskers, some are more inclined toward responding to certain cues than others. The discovery could provide critical clues in understanding how the body responds to disease and advance our treatment of it.



Feb. 2021

The Future of Electronics is Stretchy

A team of researchers in the lab of Rebecca Kramer-Bottiglio, the John J. Lee Assistant Professor of Mechanical Engineering & Materials Science, developed a better material and fabrication process for making stretchable electronic circuits. A major challenge for this area of electronics is reliably connecting stretchable conductors with the rigid materials used in commercially available electronics components. The Yale researchers created a stretchable circuit board assembly that performs as well as a conventional one, even under high levels of strain. It opens up opportunities for applications such as soft robotics and wearable technologies.

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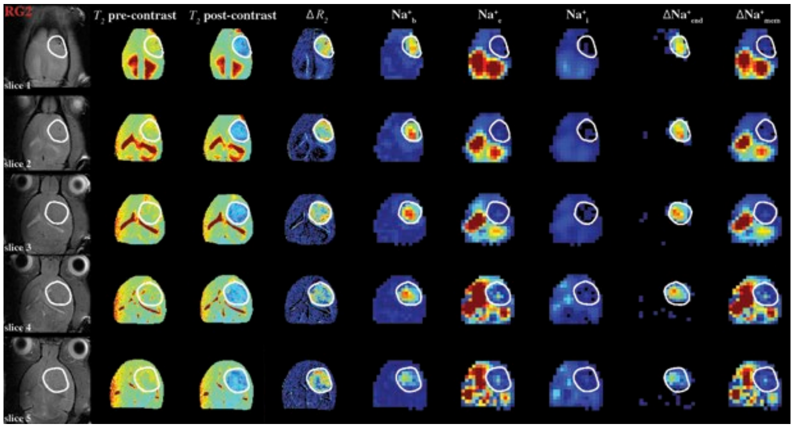
Year in Review



March 2021

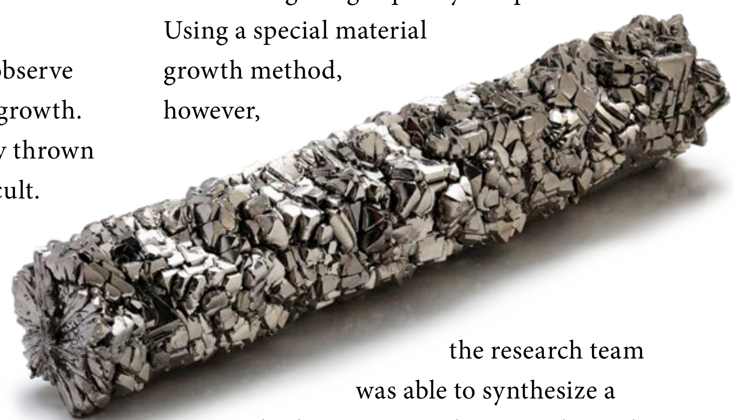
A New Way to Detect Early-Stage Brain Cancer

A team of Yale researchers developed a non-invasive way to observe changing salt levels in the brain in the early stages of cancer growth. When cancer invades the brain, normal salt levels are quickly thrown off-kilter, but detecting this change in patients has been difficult. This new method, developed in the lab of Fahmeed Hyder, professor of biomedical engineering and radiology & biomedical imaging, could lead to several new directions in treating cancer — from earlier diagnoses to new drugs for targeting cancer cells.

May 2021

New Clues About an Elusive Material

A research team in the lab of Charles Ahn, the John C. Malone Professor of Applied Physics, synthesized high-quality Titanium monoxide (TiO), a material that has eluded close study by physicists. One reason TiO hasn't been studied more is because it's so difficult to get high-quality samples. Using a special material growth method, however, the research team was able to synthesize a high-purity sample. From there, they were able to study the material, which they found that at very cool temperatures acted as a superconductor — a material that can transport electrons with no resistance.



April 2021

Professor Elected to National Academy of Sciences

Hui Cao, the John C. Malone Professor of Applied Physics, Electrical Engineering, and Physics, was elected to the National Academy of Sciences in recognition of her distinguished and continuing achievements in original research. Cao is among 120 new members elected to the academy, which is one of the highest honors that can be bestowed on a U.S. scientist or engineer. Cao has been a Yale faculty member since 2008; her research is focused on understanding and controlling quantum optical processes in nanostructures.

NATIONAL ACADEMY OF SCIENCES

June 2021

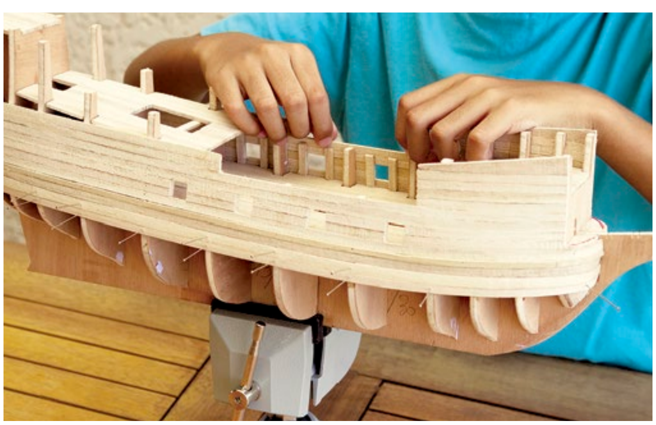
A Self-Updating Robotic Hand

To capture the sophisticated mechanics of in-hand manipulation, a team of researchers in the lab of Aaron Dollar, professor of mechanical engineering & materials science, designed a robotic system that relies on its ability to map out how it interacts with its environment to adapt and update its own internal model. To give the hand precise control, the researchers derived algorithms for the system to self-identify necessary parameters through exploratory hand-object interactions. To demonstrate the results, the researchers had the hand perform a number of tasks, including cup-stacking, writing with a pen, and grasping various objects.

July 2021

STEM Challenges for Students

Working with Connecticut governor Ned Lamont, the state Office of Workforce Strategy, and the Connecticut Conference of Independent Colleges, SEAS co-launched the Governor's Summer STEM Challenge. The statewide initiative presented students in grades 3 through 12 with a

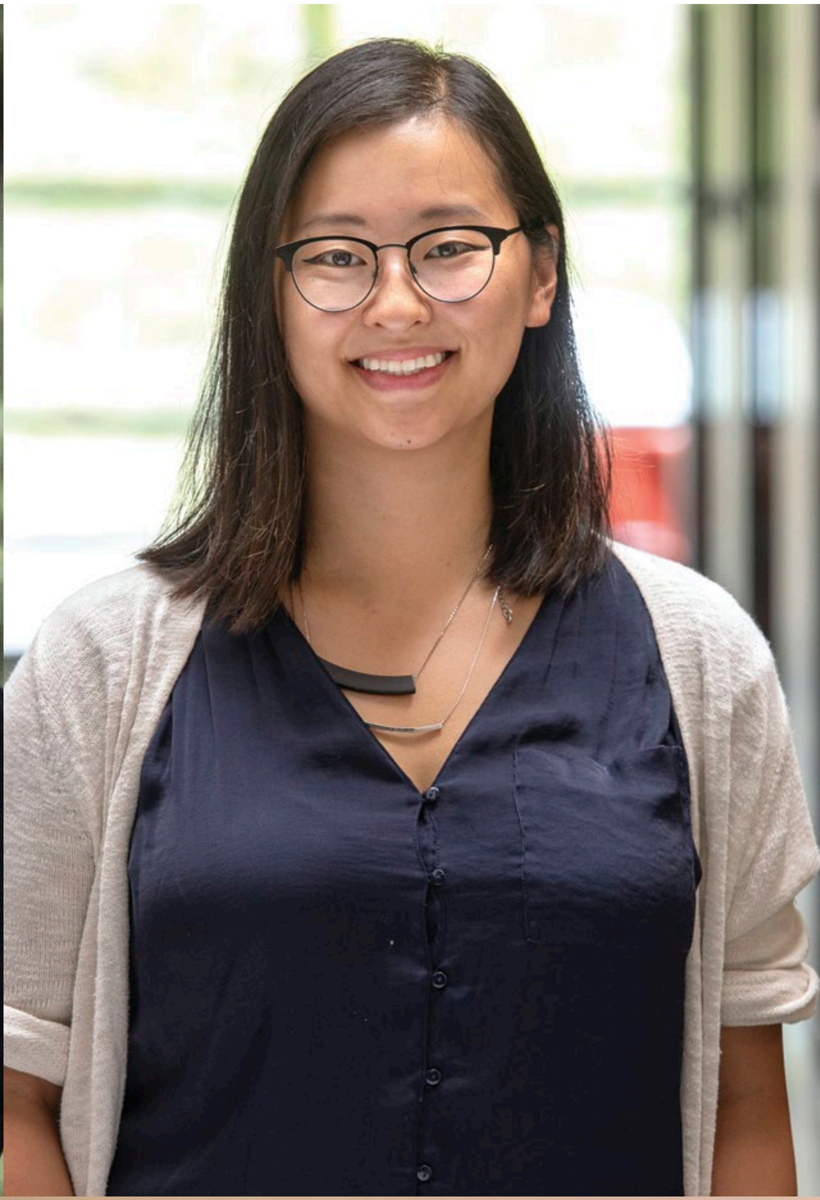


series of hands-on design projects designed to hone high-quality STEM skills for the future. Weekly challenges, presented by six SEAS student groups, introduced students to virtual instruction with Yale student organizations and building projects with everyday materials.

August 2021

Life-Saving Efficient Buildings

Drew Gentner, associate professor of chemical & environmental engineering and the environment, worked with researchers at the School for the Environment to develop two building-efficiency improvement scenarios that they estimate could prevent thousands of premature deaths in the U.S. caused by harmful emissions. Buildings in the U.S. are responsible for 40% of the country's total energy consumption. By improving the energy efficiency of new and existing buildings, the emissions generated from heating and cooling them could be dramatically reduced, according to their study, published in *Science Advances*.



Innovative Students Turned Thriving Entrepreneurs

Three innovative alums discuss their time at SEAS, launching start-ups, and offer advice for aspiring entrepreneurs

Left to Right: *Elizabeth Asai, Ellen Su, and Monika Weber*

With so much innovation at SEAS, it's no surprise that numerous students have gone on to form their own startups, some even while they were students at Yale. Here, we talk with three of those enterprising alums — Elizabeth Asai, Ellen Su, and Monika Weber — about how they got their start and what advice they have for any aspiring entrepreneurs.

An Up-Close Exam from Afar

It was while working on a different project that Elizabeth Asai '13 and Elliot Swart hit upon the idea for 3Derm Systems, the startup they founded while students at Yale. The 3Derm platform allows patients to take high-definition, standardized images of skin abnormalities and upload them to a telemedicine portal. Dermatologists with access to the portal can then assess the images and get a sense of whether the patient needs a referral for an in-person visit, and if so, how urgently the patient needs to be referred.

With advice from their Yale mentors, and a prototype that they developed for $400 using a 3D printer, they soon had the basis for their company. Within a few years, they had raised more than $5 million. Fast forward to 2020 and 3Derm was acquired by Digital Diagnostics, an Iowa-based company specializing in autonomous AI systems for healthcare, where Asai now works as Vice President of Dermatology and Swart is Chief Architect.

Did you come to Yale with the goal of starting a business?
I think the world has changed a bit since I was in college, and a lot more people are going to college thinking they want to launch a startup. But I definitely was not in that camp. Elliot was — he came from Palo Alto, so everyone he knew already had a startup by the time we graduated from college [laughs]. I thought I was going to med school or into the healthcare business, which

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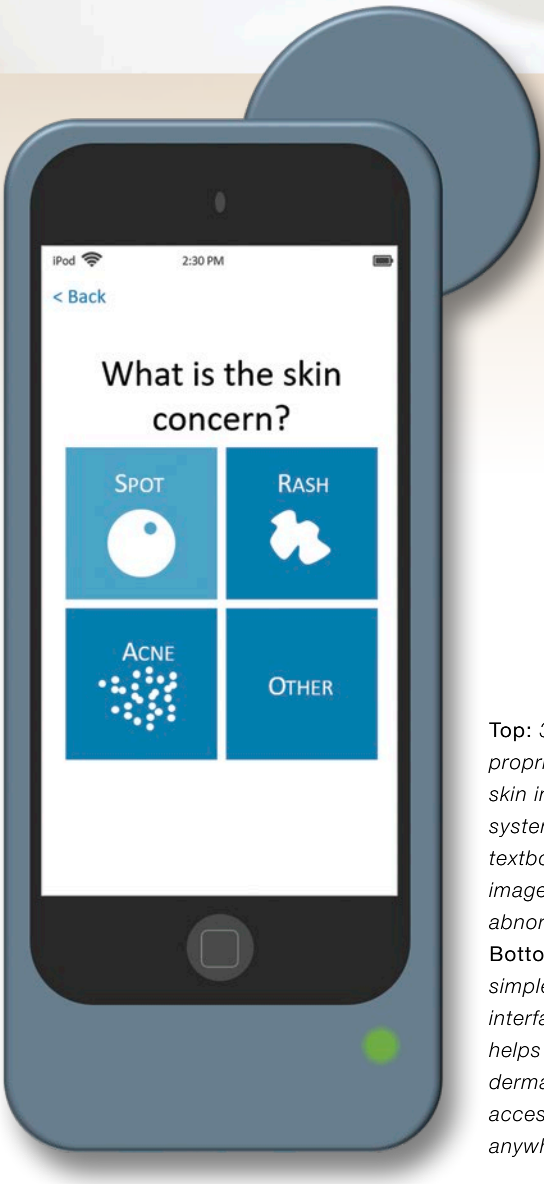


Top: *3Derm's proprietary skin imaging system captures textbook quality images of abnormalities.* Bottom: *Its simple user interface helps provide dermatology access from anywhere.*

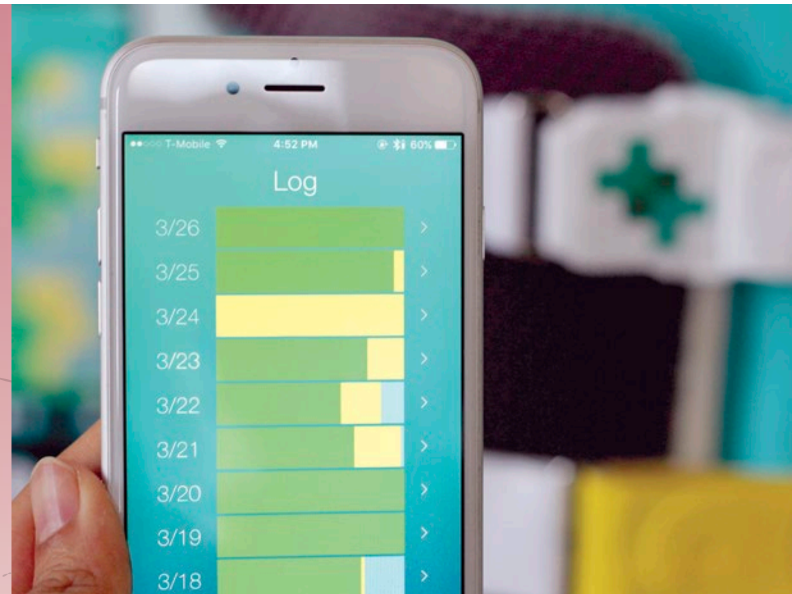
I guess is where I ended up. But I didn't think I would do something as risky as this.

When did you realize this could be the basis of a startup?
We had a lot of really good feedback early on from people who mattered a lot. We were meeting doctors and different engineers — people from the healthcare world who seemed to really get behind this idea. They were telling us, 'You're onto something — this is a big issue.' That kind of feedback from people who were way smarter than we were was good validation.

You majored in biomedical engineering, and Elliot was electrical engineering and computer science. How important was having that combination?
That was huge. Between the two of us, we covered most of the base technical knowledge we needed to get started. As most people in the startup world will tell you, hiring tech talent is really hard early on because you're competing with all of the other cool stuff that engineers can go work on, and engineers are really expensive. So, the fact that we could prototype and get stuff out there on our own was a game changer at the beginning. Then, the key pieces missing were on the business side and anything to do with commercialization. But that's where we found a ton of really good mentors.

You got a lot of support from Yale, including SEAS, the Department of Dermatology and the Yale Entrepreneurial Institute.

That was really nice. I don't know how many other schools do anything like what Yale did for us in the early days. They saw promise in this and wanted to see if this could work, so people opened doors for us. We were the youngest people to get the National Science Foundation's Small Business Innovation Research program. We had three tenured professors who had gotten tons of these grants over their careers, and they read our application and gave feedback. People who are mid-career applying for these grants would kill to have that kind of access. We were 20 years old and didn't know how lucky we were.



Launching Business a "Cinch"

Ellen Su '13 was still a Yale student when she founded Wellinks with Levi DeLuke '14. The startup focused on "Cinch," a smart strap for scoliosis braces aimed at giving its users, especially children, a greater sense of independence. With a Bluetooth connection to a smartphone app, the strap collects data for the patients, their guardians, and their doctors on how the brace is being worn and whether it's adjusted correctly. In early 2020, Fairfield-based Convexity Scientific acquired Wellinks and hired Su as its Chief Product Officer. Convexity, now known as Wellinks, created a portable nebulizer that aerosolizes medication for people with chronic obstructive pulmonary disease (COPD) and asthma.

Looking back, what were some key decisions that you made?

I would say one of the biggest influences was getting involved with Design for America, cofounding the Yale chapter, and learning more about human-centered design. That really inspired all the work that came after that—learning about the design process, about human-

Continued →

Top: *Data is continually collected to determine if the brace is being worn correctly.* Bottom: *Su credits human-centered design as one of her biggest influences.*

centered empathy processes, and it really spoke to me in terms of how I approach problem solving and how I approach the world. Also, the fact that you could use a very broad skill set. Understanding technology is great, but it's not the same as being able to think creatively and make creative applications from those things.

Yale

The second thing that really helped us was the Center for Engineering Innovation & Design (CEID) Summer Fellowship — that opportunity to spend 10 weeks over the summer full-time on a self-directed project — that was something we just didn't have the luxury to do during the school year. I'm also just a big proponent of people being in New Haven over the summer — I think it's a very different learning experience.

What advice do you give undergraduates considering a startup?
My general advice for any student I talk to is to reach out to people. Just go and spend as much time as you can learning from people in the field. People are very willing to help and are open to sharing what they do. For me, that was incredibly valuable. Send emails, talk to people, reach out on LinkedIn — the worst thing that can happen is that people don't respond to you.

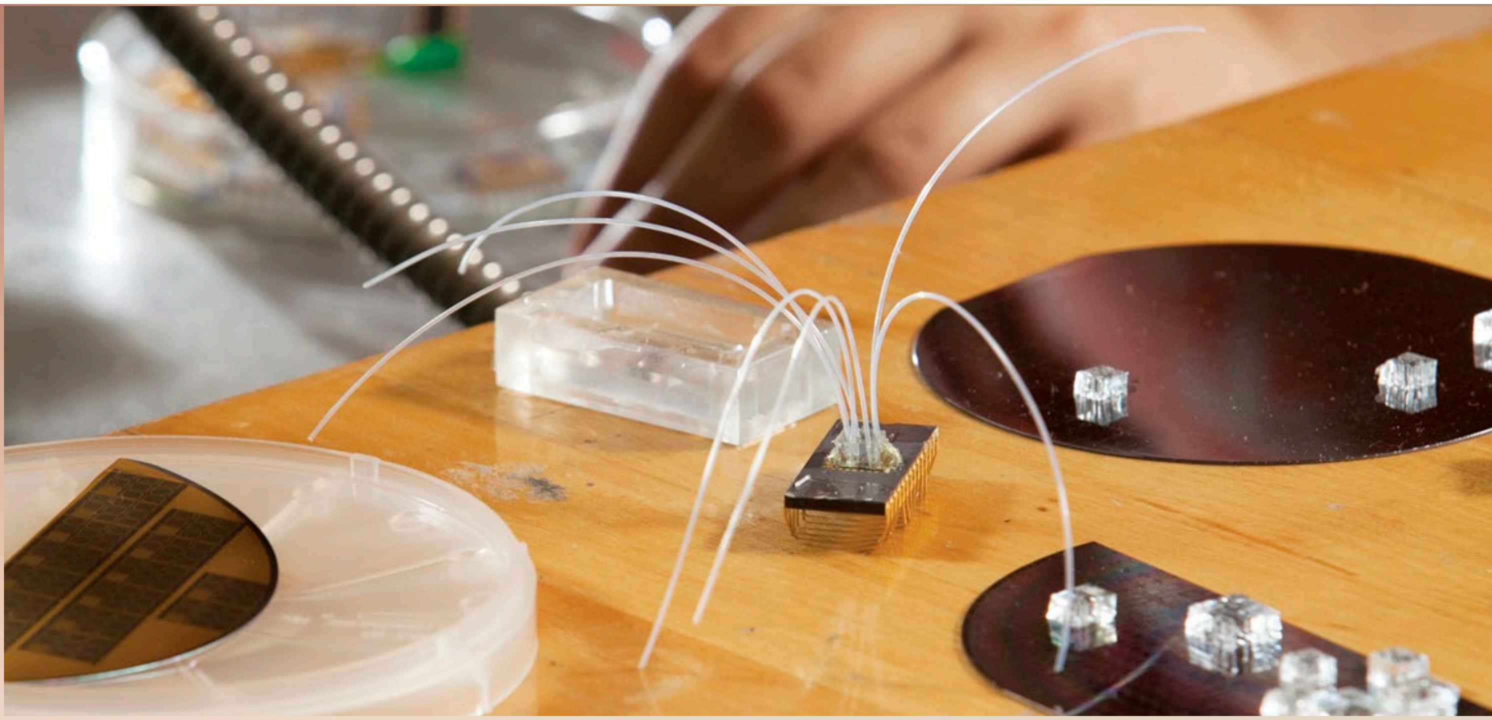
The second bit of advice is to take advantage of the Yale resources as much as you can. A lot of people are open to help as long as you ask and as long as you keep up with them — things like getting a mentor at Tsai CITY, going to specific talks. I never did as much of that as I could have, and that's one of the things that does go away — you don't have a second chance to do those things once you graduate, so take advantage of those resources while you can.

It seems one of your strengths was being open to going in entirely new directions.
I was never one who had a career planned out and it was always very stressful to me when someone asked, 'What do you want to be when you grow up?' That was never a question I knew how to answer. I still don't have a good answer for that. The answer I found is more about, 'What kind of work do I want to do and what environment do I want to work in?' That's more important than the title or specific place where I end up.

Detecting a Need

Dr. Monika Weber, CEO and founder of Boston area-based Fluid-Screen, co-invented the bacterial and virus detection and identification technology that her company is based on while still a graduate student in Electrical Engineering at Yale. The Fluid-Screen platform allows users to place a sample directly on a microchip, bypassing the time-consuming step of culturing samples on a Petri dish. The biosensor can detect bacteria in liquid samples in a matter of minutes, with an accuracy greater than 99%.

The company, founded in 2015, is currently working with several major pharmaceutical companies and preparing to send its first prototype to numerous experts, who will use the technology and provide feedback.



Above: *The Fluid-Screen platform allows users to place a sample directly on a microchip. It can detect bacteria in liquid samples in a matter of minutes, with an accuracy greater than 99%.*

When you came to Yale, did you have plans to eventually start your own company?
Yes, I was very excited about the entrepreneurial mindset and that is one of the reasons I came to the U.S. I really wanted to be at the intersection of cutting-edge science, technology, and commercial applications.

When did you know that your work could be the basis for a start-up?
It started in 2011 when there was the outbreak of *E. coli* contamination in Europe. There was *E. coli* in the food supply, and by time the produce arrived, there were still no test results. Thousands of people got sick, and over 50 people died because they were not able to test and contain the contaminated produce.

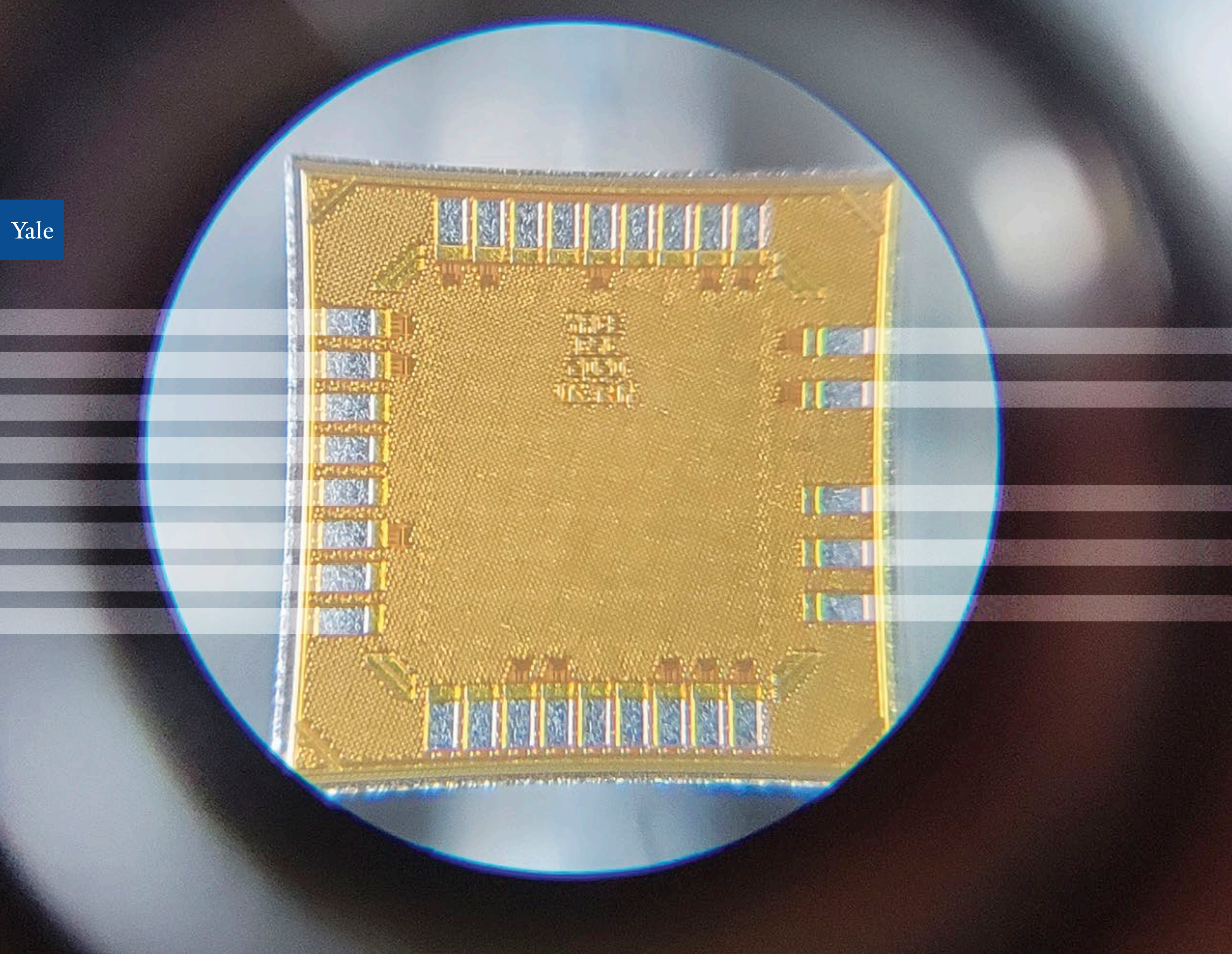
I already had some background — I took some classes, including a medical design class where my colleagues and I designed the first concept behind Fluid-Screen. It was a device that would detect the bacteria in meat. When the outbreak in Europe happened, we had already been thinking about it, and I realized that there was a huge need, and we had this solution.

What advice would you give students with similar ambitions?
I would say that the key thing is people. Find people who would be supportive — that matters a lot. And teammates who want to see the idea through to fruition. I'm really grateful to [SEAS Deputy Dean] Vince Wilczynski, who was really one of the first people who supported me and really helped me get on the pathway from a scientist to becoming an entrepreneur. And I really want to thank my early investors in Fluid-Screen whom I met during my time at Yale through the Yale Alumni Association. And of course, Dr. Jim Tyler '65, who was the main founder of the CEID, is also a Board Director and an investor in Fluid-Screen, so I have this amazing opportunity to work with him to learn from him, and hopefully replicate his success in the business world. David Cromwell, who was a finance professor at the Yale School of Management and the first Board Director at Fluid-Screen, helped me get the company off the ground and was a much-valued mentor.

You took part in the SEAS Advanced Graduate Leadership Program (AGLP) — how did that help?
I loved it — as part of AGLP, I took classes. It was one of the reasons I was able to take classes at the School of Management. Then I encountered some wonderful mentors, and the program also provided lots of coaching, so both AGLP and the CEID were very instrumental for me at a very early stage of starting a venture.

Less Wattage, More Brain Power

SEAS teams with the Medical School to deliver faster, more capable brain-implanted device to treat multiple disorders



Since they came into use by physicians and researchers, Brain-Computer Interfaces (BCIs) or Brain-Machine Interfaces (BMIs) have provided ways to treat neurological disorders and shed light on how the brain functions. As beneficial as they've been, BCIs have potential to go far beyond the technology's current capabilities. In a collaboration between SEAS and the School of Medicine, a team of researchers are looking to break through these limitations.

"The goal is to build a class of ultra-low-power devices that are safe for chronic implantation in humans," said Abhishek Bhattacharjee, associate professor of computer science. "Chronic implantation opens the door to a number of clinical uses, ranging from implants to treat epilepsy and movement disorders to designing assistive devices for patients with paralysis, as well as many research uses."

Chronic implantation is the practice of placing a device in the brain of patients, who then go about their daily lives, albeit with regular check-ins with their doctors. At SEAS, Bhattacharjee has been working on this with Rajit Manohar, the John C. Malone Professor of Electrical Engineering and Computer Science, and Anurag Khandelwal, assistant professor of computer science. Their collaborators at the Medical School are Dennis Spencer, the Harvey and Kate Cushing Professor Emeritus of Neurosurgery, and Hitten Zaveri, assistant professor of neurology.

The research team's work is part of a larger effort to push the potential of BCIs to accomplish things that once seemed the stuff of science fiction. A video of a monkey playing Pong with the help of a neural interface created by Elon Musk's company, Neuralink, has been viewed by millions. The same company has raised hundreds of millions of dollars for the technology. And it's more than just buzz fueling the interest. Synchron, Inc. received permission from the FDA earlier this year to begin human testing for a brain implant designed to treat paralysis.

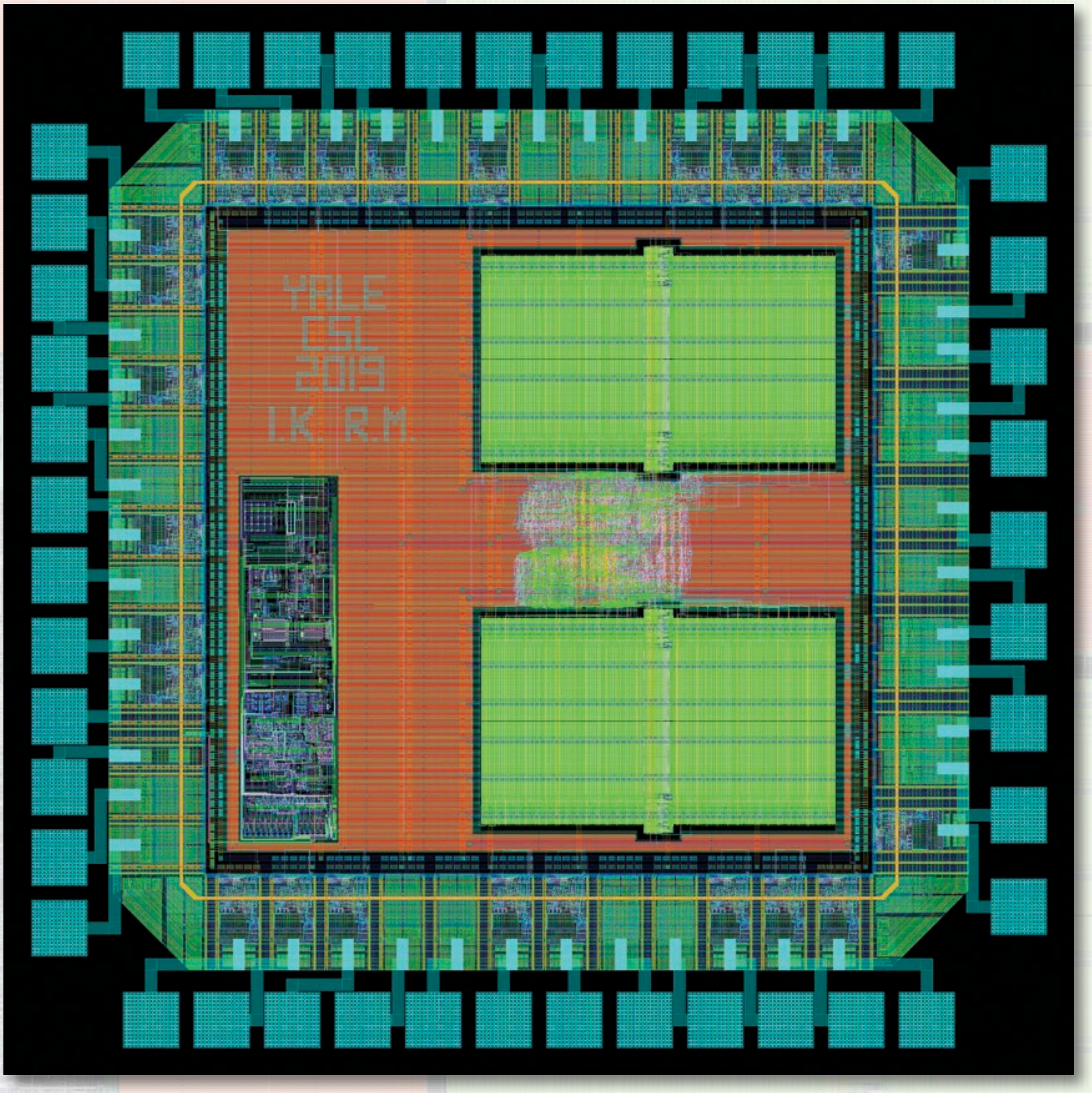
The BCIs that epilepsy surgeons Spencer and Zaveri commonly use are implanted in the brain just below the skull — it's small and you typically wouldn't know that someone has one. The device continuously monitors the patterns of the patient's brain, detecting any anomalies as a way to predict an oncoming seizure. When it does so, the device sends an electrical stimulus to specific regions of the brain to disrupt those patterns. At this point, it's used only for patients who are resistant to drug treatment. Spencer said most epilepsy patients using BCIs see their seizures decrease by at least half after 18 months. While it's been effective enough to become very popular for patients with limited options, Spencer and Zaveri are looking toward a technology that could prevent all seizures. A BCI with considerably enhanced capabilities such as the Yale solution, they said, could bring about that result.

Continued →

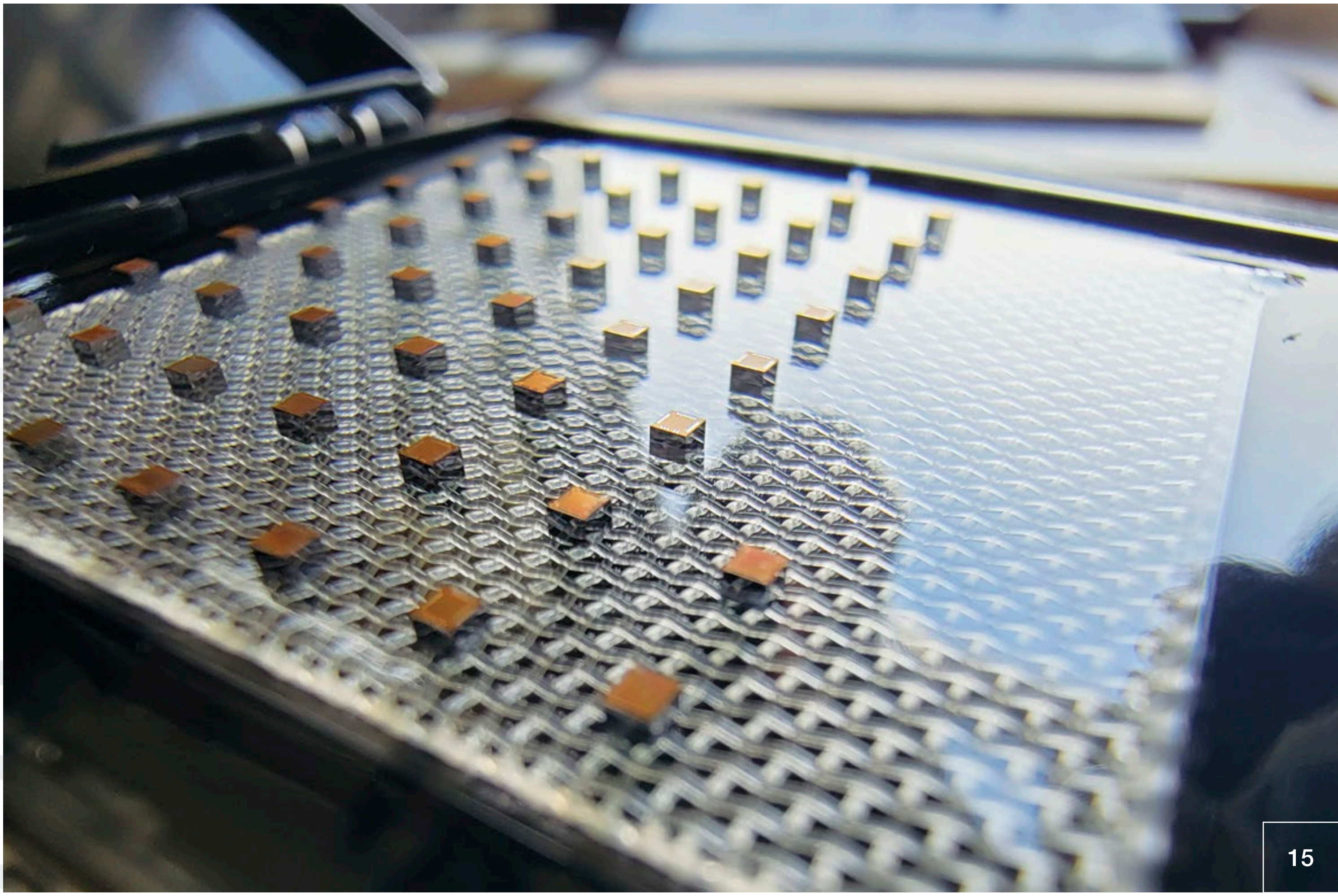
The tricky part about this goal is that these implantable BCIs are limited by how much power they use. Federal and international guidelines state that BCIs must not use more than 15 to 40 milliwatts of power, depending on the depth within the brain tissue that the BCI is implanted. Anything beyond that is unsafe for chronic implantation in humans. Excessive power dissipation causes the devices to overheat, which brings the risk of damaging the cellular tissue of the brain. The SEAS researchers' task, then, is broadening the potential of these devices while staying within a very constrained power limit. They're limiting the power of their own device to 15 milliwatts, which would allow it to be placed deeper into the brain, where power constraints are more stringent.

"So, it's power-constrained, but at the same time, there are some serious computation needs here - you need to be able to read and perform fairly sophisticated signal processing on more and more data from the brain for these devices to be more useful," Bhattacharjee said. "How you do all of this under really tight power budgets of 10 to 15 milliwatts is a wide-open question."

To that end, they've developed HALO (Hardware Architecture for Low-power BCIs), a general-purpose architecture for implantable BCIs. The technology allows for the treatment of various conditions, and records and processes data for studies to advance our understanding of the brain. The technology includes a chip and sensors and allows for



Left: *An early version of the team's chip diagram.*



a microelectrode array that reads roughly 50 megabits per second from 96 distinct parts of the brain. And unlike other BCIs, which are designed for one specific purpose — treating epilepsy, for example — the HALO technology can support numerous tasks. This is all achieved while operating within the team's strict power budget.

The initial HALO concept was detailed in a recent paper, "Hardware-Software Co-Design for Brain-Computer Interfaces," authored by the Yale researchers in collaboration with scientists at Rutgers and Brown University. It was published at the flagship conference for computer architecture, the International Symposium on Computer Architecture, and was selected for inclusion in IEEE Micro's Top Picks in *Computer Architecture* magazine as one of the top computer architecture papers published in 2020.

"One of the things that I'm particularly excited about in our research is that it shows that if you build BCIs that can balance specialized hardware with general purpose hardware in a principled way, you can actually be under

Above: *Unlike traditional BCI's, the team's technology can support numerous tasks and expand potential treatments.*

the power limit, while supporting a much broader class of computational functionalities than what existing devices support," Bhattacharjee said. He also believes that the results point to a broader question beyond BCIs, particularly because the waning of Dennard scaling (the principle that as transistors get smaller, their power stays constant) "poses questions about how best to determine what to build hardware accelerators for, how to integrate these hardware accelerators seamlessly, and how to enable a modular platform that can naturally slot in new accelerators. HALO is an exemplar of these research questions."

The lead graduate student on the HALO project, Karthik Sriram, said he became interested in the field of BCIs as an undergraduate. "I wanted to see how we can bridge this gap between the human brain and our attempts to analyze it — and how to integrate that with computer systems that we have come to

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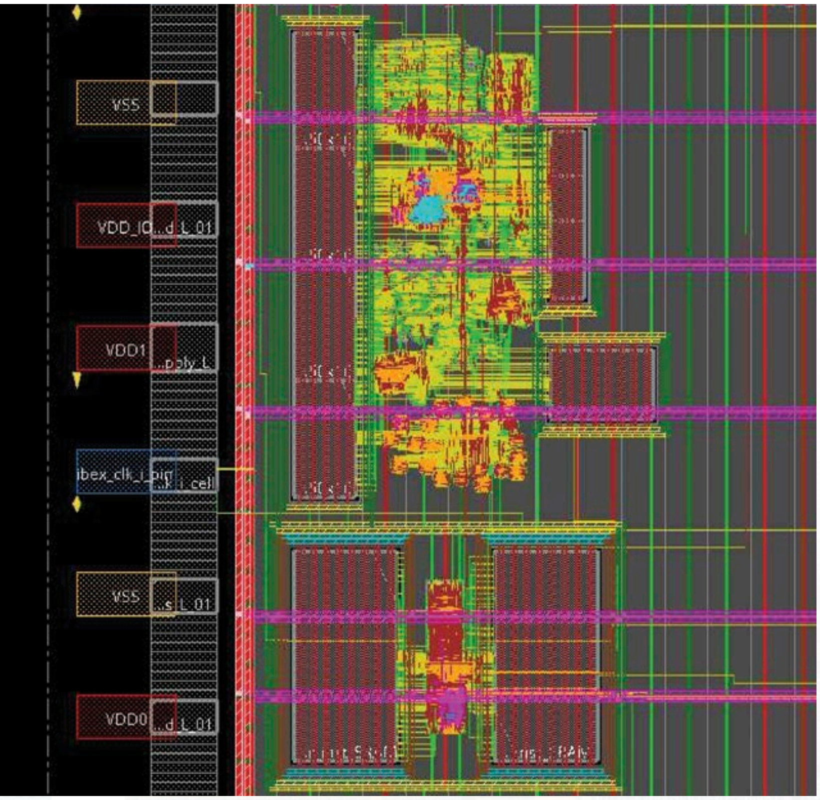
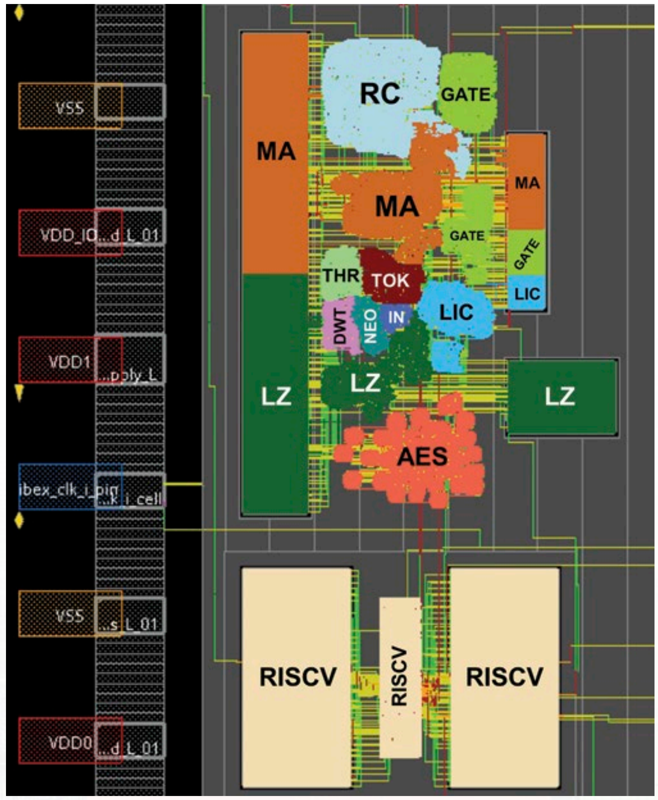




Above: *An updated chip diagram with the various components of HALO labeled to show their relative complexity.*

be more comfortable using," said Sriram, a Ph.D. student in Bhattacharjee's lab.

The work they've done at Yale is just the beginning, he said.

"HALO is a working demonstration that we can get a more flexible architecture that can do a lot more than current BCIs and support a much higher data rate," Sriram said. Beyond that, he said, the research could lead to some exciting possibilities, such as creating a network of BCI devices that record from multiple parts of the brain.

"Neuroscientists are interested in that because they're looking to analyze the brain like a bunch of graph connections — especially for something like seizures," he said. "They're starting to analyze it as a more graph-based problem, rather than a single-source localized problem."

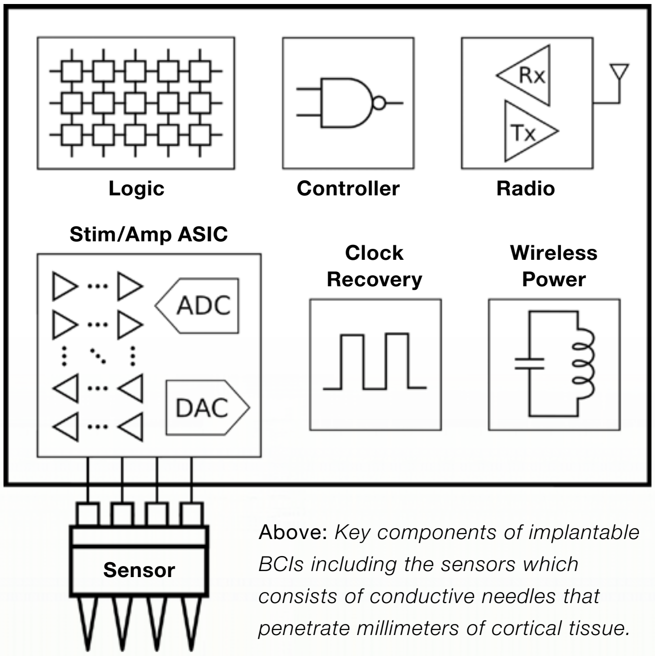
Manohar's role on the team is taking the design for HALO and building chips to create a physical device. He worked on the chips with postdoctoral associate Ioannis Karageorgos and graduate student Xiayuan Wen. The researchers figure it could be a few years before they have a prototype for human trials.

"It takes effort to do a good job, like everything, and as we learn more and more about the problem, we're building it in steps, we're starting with the core of its architecture and adding to it," Manohar said. "And we're designing the architecture to make it relatively modular and easy for us to extend it."

Khandelwal has lent his expertise in distributed systems to the project. His first goal, with Bhattacharjee, is finding a way to increase data storage in BCIs while working within the power limitations. Currently, researchers conducting a longitudinal study on a patient with an implanted BCI would need to bring the patient into the clinic to collect the data from the implant. It's cumbersome and limits the amount of data that can be collected.

"What we are essentially looking for is something where the BCI upstreams the data to another device in the patient's home, or somewhere near it," he said.

More ambitiously, he wants to improve the communication between the different components of a BCI to reduce latency. In a system that's designed to detect and ward off oncoming seizures, or in a brain-controlled prosthetic limb, speed is critical.



Above: *Key components of implantable BCIs including the sensors which consists of conductive needles that penetrate millimeters of cortical tissue.*

A major part of this project is the fact that implantable BCI technology has a broad range of use. In addition to epilepsy, prosthetic limbs, and research purposes, the devices have been used to treat people with conditions such as Parkinson's disease, schizophrenia, or elevated levels of anxiety. So not only do the researchers want to extend the capabilities of these devices, but they also want to design them in a way that allows them to be adapted to changing needs.

"This is a field where new things are being discovered continuously and the field evolves and you don't want to have to build a new device every time different groups decide they want new functionality," Manohar said. "We're trying to address a much broader range of possibilities with a single device."

And that, Zaveri said, is crucial to expanding the range of patients who are eligible for BCIs.

"The Yale team's work allows us to draw from a larger set of application areas and patients because they're not making what we call an ASIC — an application-specific integrated circuit — they're making a powerful general-purpose solution on which you could run different algorithms," Zaveri said. "So, you could have a version for epilepsy, and another version for patients who are paralyzed - the hardware could be the same, though."

Zaveri said the SEAS researchers' work has great potential for both clinical and research applications. Having technology that can run very powerful algorithms in real time to interact with the brain would open up numerous research applications.

"We're currently collecting data and processing it offline, so this development enables studies and therapies that aren't possible at present," he said.

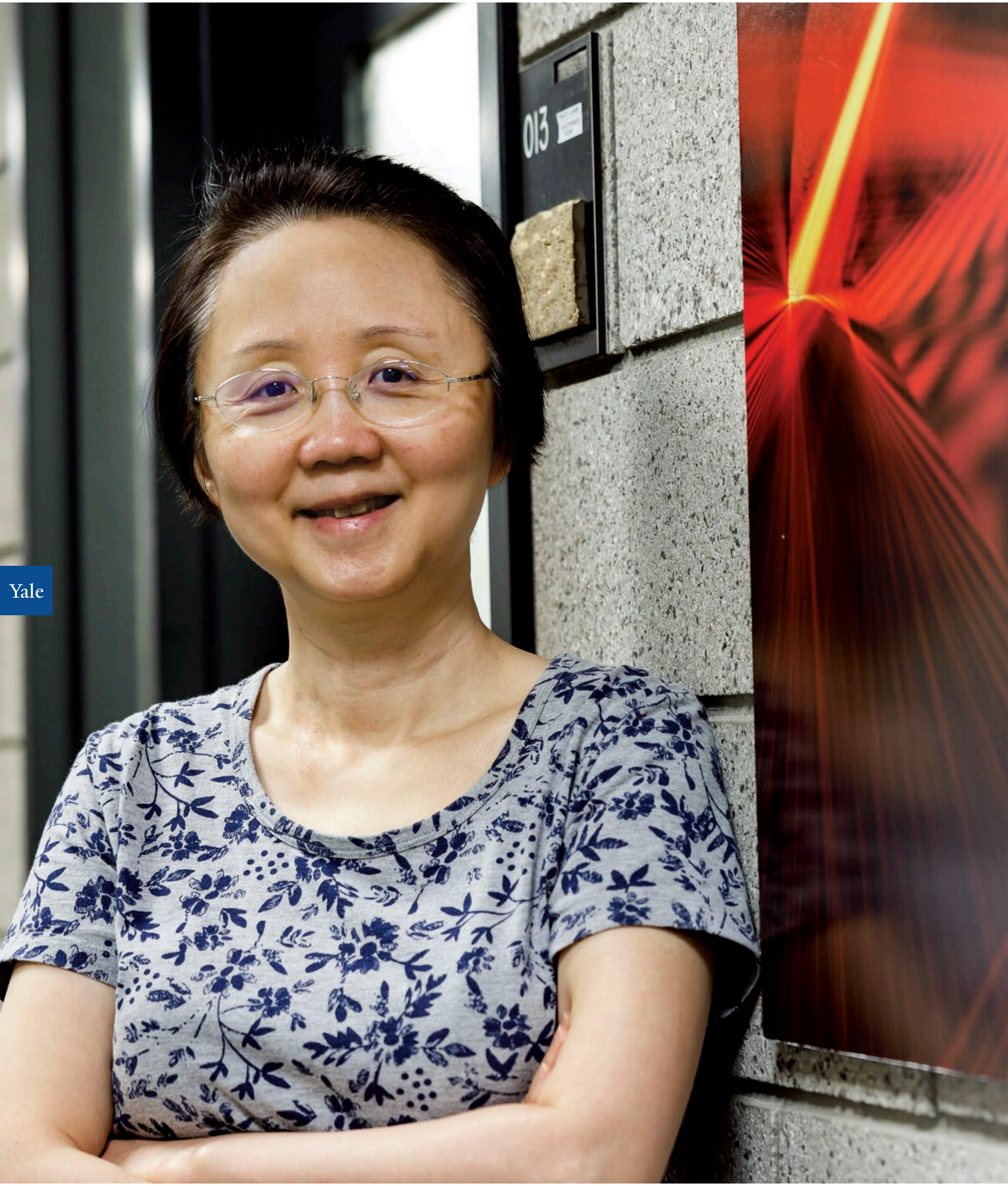
For instance, he said, a device that allows clinicians to monitor the brain of an epilepsy patient and detect aberrance in an epilepsy network in real time and can modulate that network increases the possibilities for treatment. It also expands what disorders can potentially be treated, such as depression and other neuropsychiatric disorders with a broader, more diffuse manifestation in the brain.

Nicholas Turk-Browne, a professor of psychology at Yale, has also talked with the SEAS researchers about applying their work to his own research.

"One application they're doing is clinical, but another is to study brain function with precision and then to use those signals for neurofeedback-type applications," said Turk-Browne, director of the Wu Tsai Institute. "Both require expertise with designing cognitive tasks and psychological experiments, which is the expertise that I bring — how to measure and quantify human behavior and brain function with respect to cognition. So, I've had a lot of conversations with them about that."

Spencer noted that this work is in the spirit of Yale's collaborative environment.

"This is the beauty of cross-disciplinary research," he said. "I am a clinician and throughout my career I have presented problems to those who are smarter than I am technologically. And those researchers may be working on something more theoretical or on something in a different field, when something lights up and they say, 'That problem may have a solution in what we're doing.' The chips they are developing just unlock a whole new world for those of us who are asking questions about how to deconstruct brain function into parcels that can then be reconstructed as a meaningful network for study and modulation."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Shedding Light on Lasers' Powers

Hui Cao keeps finding new ways for lasers to improve our world

When the laser was invented, the fundamental science behind it astounded the physics community. On the other hand, many in the field wondered what it could be used for. Even one of its inventors called it "a solution in search of a problem." Today, of course, the list of laser applications is a long one and continues to grow. Lasers are now used for everything from manufacturing to surgery to home electronics. Indeed, lasers are such a ubiquitous part of our daily lives that some might suspect that there's not much more to discover about these intense beams of light.

Not Hui Cao, who continues to invent new types of lasers, and find new ways to put them to use. Conversely, sometimes her lab explores practical applications, which then leads to new insights about the fundamental physics of lasers. She has pioneered the use of random lasers in biomedical imaging. She has figured out how to stabilize chaotic lasers by using chaotic cavities, that is, "fighting fire with fire." Her work has earned her a place in Photonics Spectra's "History of the Laser," as well as numerous awards and honors. This year, she was elected to both the American Academy of Arts & Sciences and the National Academy of Sciences.

Her curiosity began with a comment from her father.

"When I was very young, my father told me the thing that moves the fastest in the world is light," said Cao, the John C. Malone Professor of Applied Physics, Physics, and Electrical Engineering. "So I was always intrigued by light — why is it so special? Why can it generate all these different colors? So that's how I got into optics."

From there, studying lasers was the logical next step. She got hit with the bug while in college when she discovered how powerful lasers were and all the ways that they could be used. And since then, the number and diversity of those applications has increased at a tremendous rate. After coming to the U.S. in 1990, Cao recalled, she would call her parents in China on the telephone at a cost of $1 per minute.

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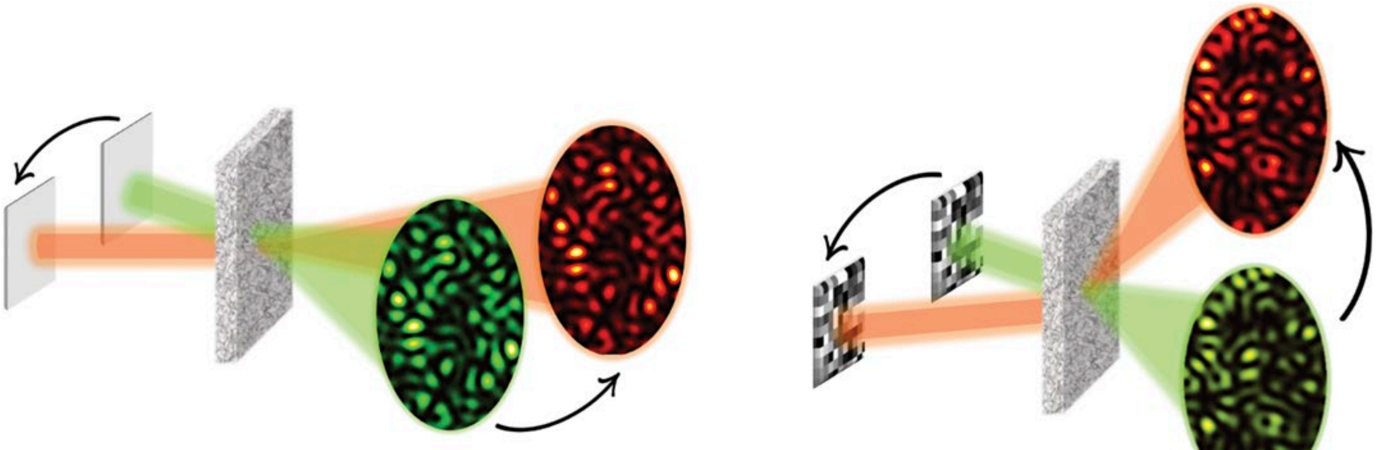


a) Conventional angular memory effect **b) Customized angular memory effect**

Above: *Cao developed a way to significantly increase the memory of speckle patterns, the very complex patterns that result from shining a laser light onto an opaque sheet, such as paper, biological tissue, or fog.*

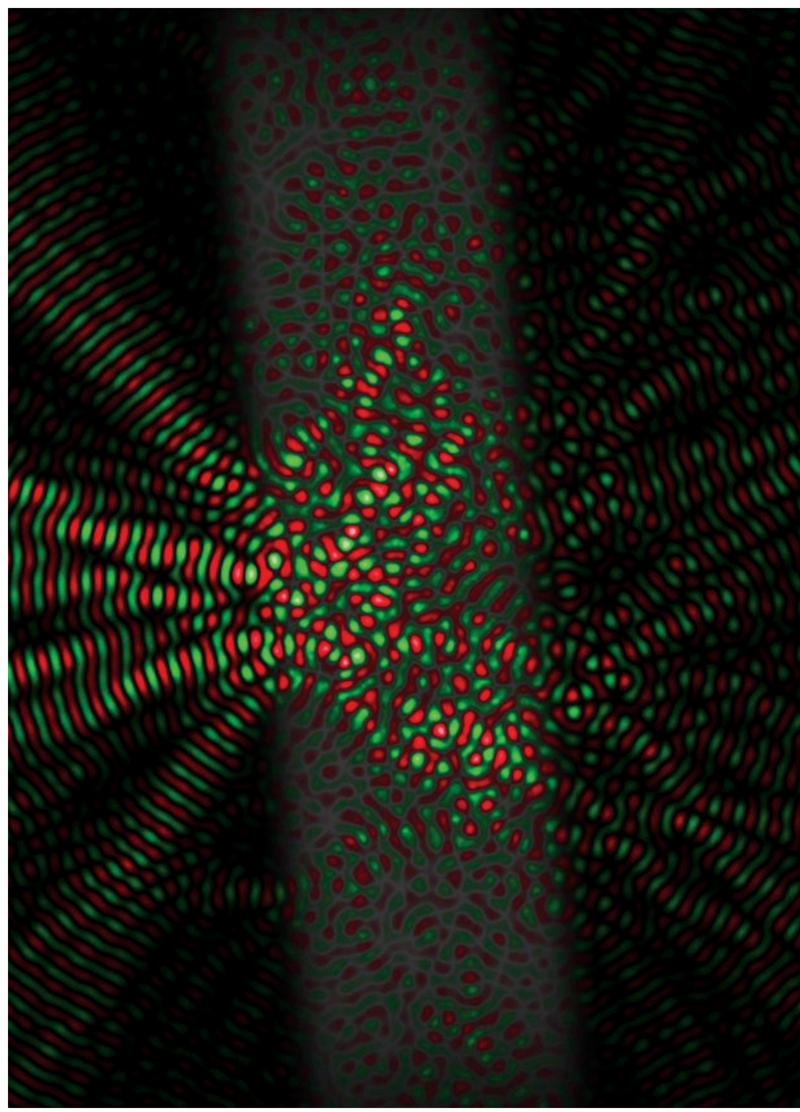
“Nowadays we will pay nothing for a video talk,” she said. “That is because of optical telecommunications, and because we have fiber optics technology, lasers, amplifiers and photodetectors. We use lasers in our daily life, everywhere. That is a complete revolution, I would say.”

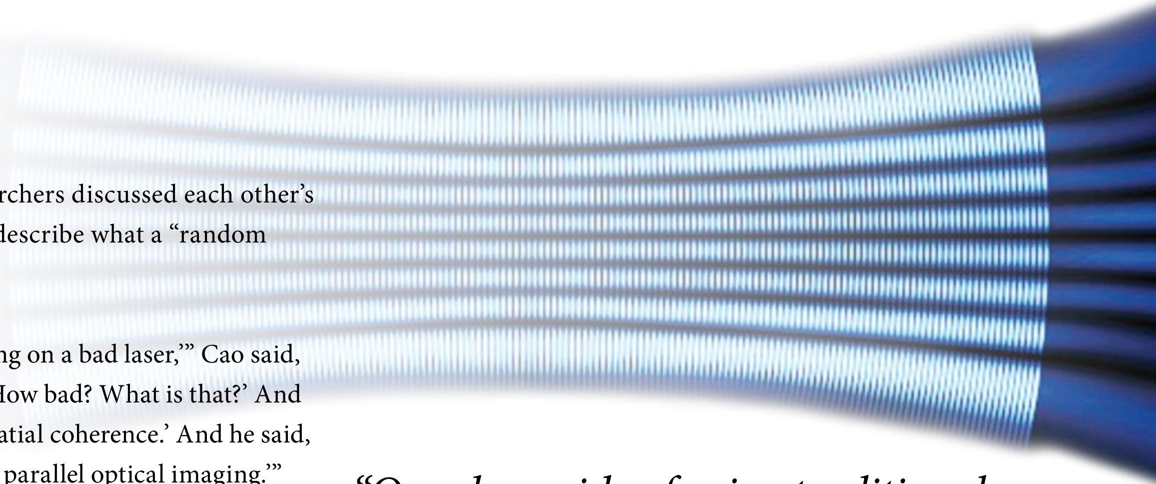
The first laser was built in 1960 by Thomas Maiman for Hughes Research Laboratories in California. More than 60 years later, lasers still have new properties to show us, and Cao has been instrumental in finding many of them. It was while she was working in a lab at Northwestern University, checking the optical properties of a new semiconductor material, zinc oxide, when she discovered the random laser. There was interest at the time in making ultraviolet lasers from zinc oxide, but making laser cavities with such material was tricky.

“But I saw something lasing and I just could not understand how it can happen, because there is no cavity to support lasing,” she said. Initially puzzled, she figured out that the laser cavities can be “self-formed” in disordered structures. And, it turned out, creating such a random laser was easier than making conventional ones.

“We didn’t really think that we were going to find this, but sometimes we saw something intriguing in the lab, and we just pursued that,” she said. “These kinds of surprises or unexpected discoveries are really an exciting part of the research.”

But the random laser became much more than just a curious phenomenon after a chance encounter with Michael Choma, then a faculty member at the Yale School of





Medicine, when the two researchers discussed each other's work. She wasn't sure how to describe what a "random laser" was.

"So, I just told him, 'I'm working on a bad laser,'" Cao said, laughing. "And then he said, 'How bad? What is that?' And then I said, 'It just has a low spatial coherence.' And he said, 'That is exactly what I need for parallel optical imaging.'"

From there, Cao and Choma would go on to demonstrate how the random laser could potentially have clinical applications. By using these random lasers as a source of illumination in medical imaging equipment, clinicians could get faster

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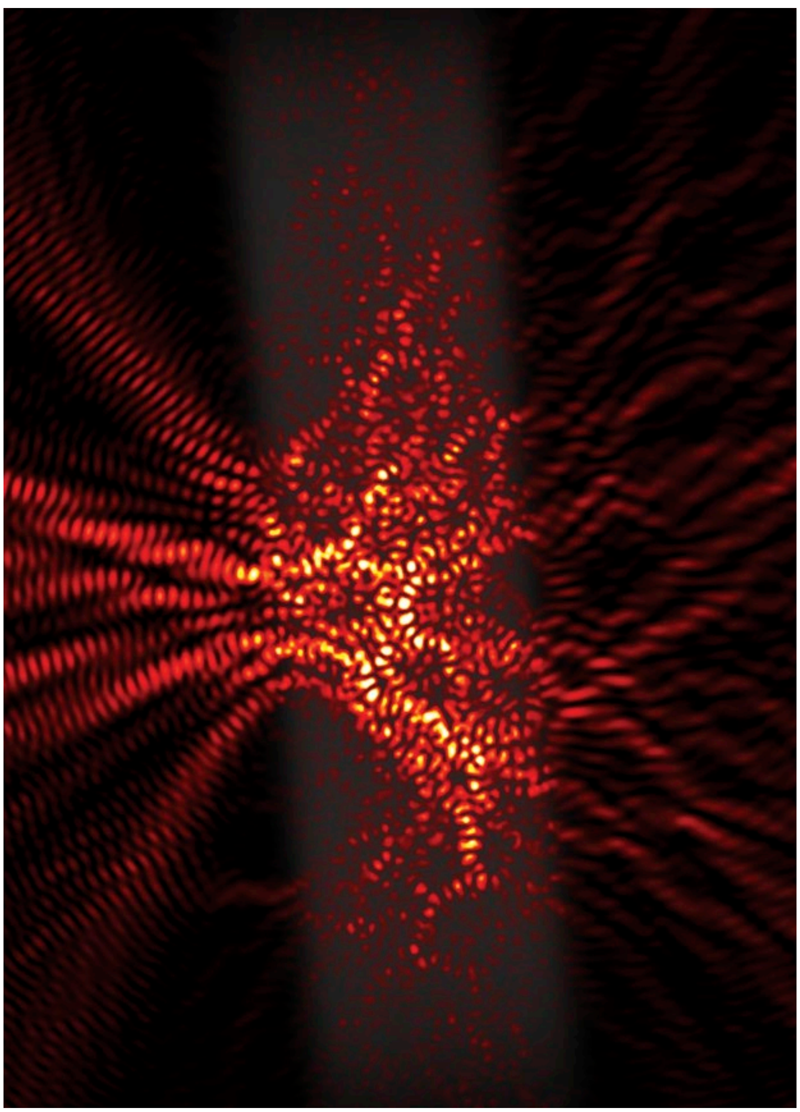
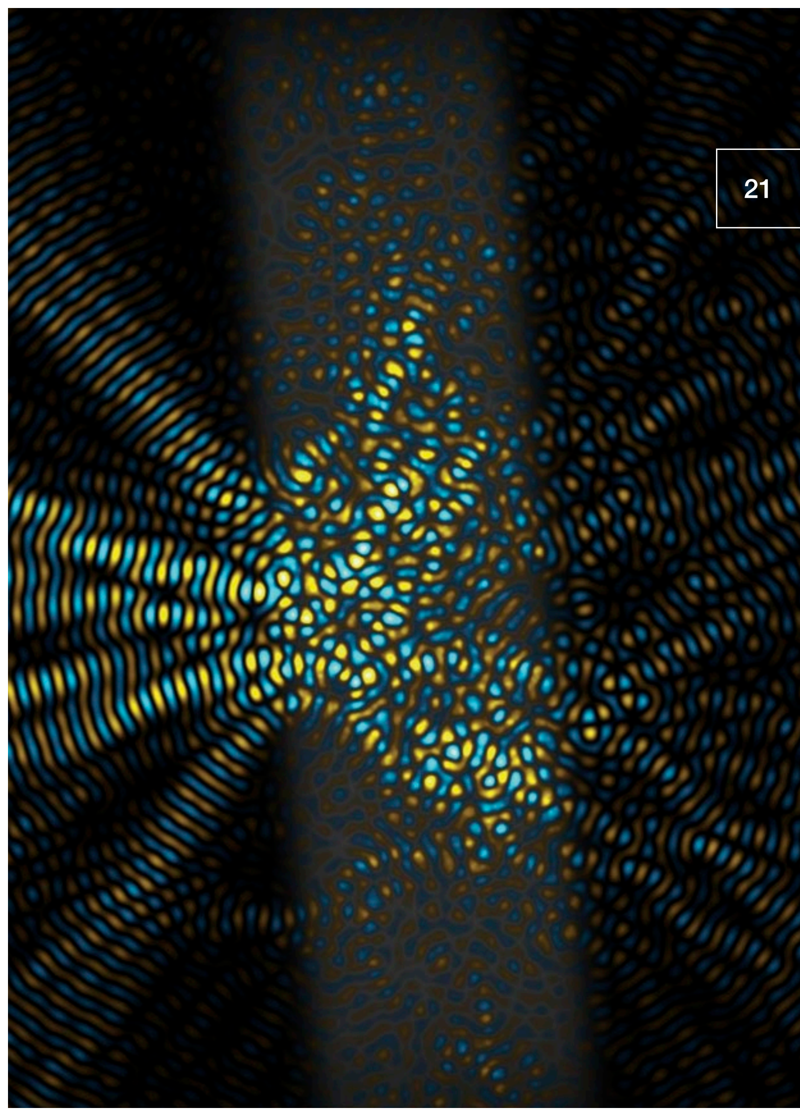
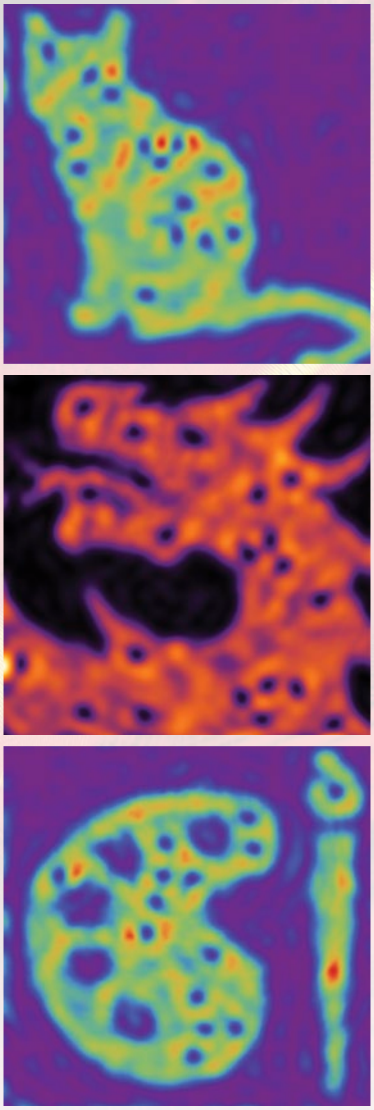
"One downside of using traditional lasers in imaging systems is something known as 'speckle noise,' a grainy pattern that can diminish the quality of the images."





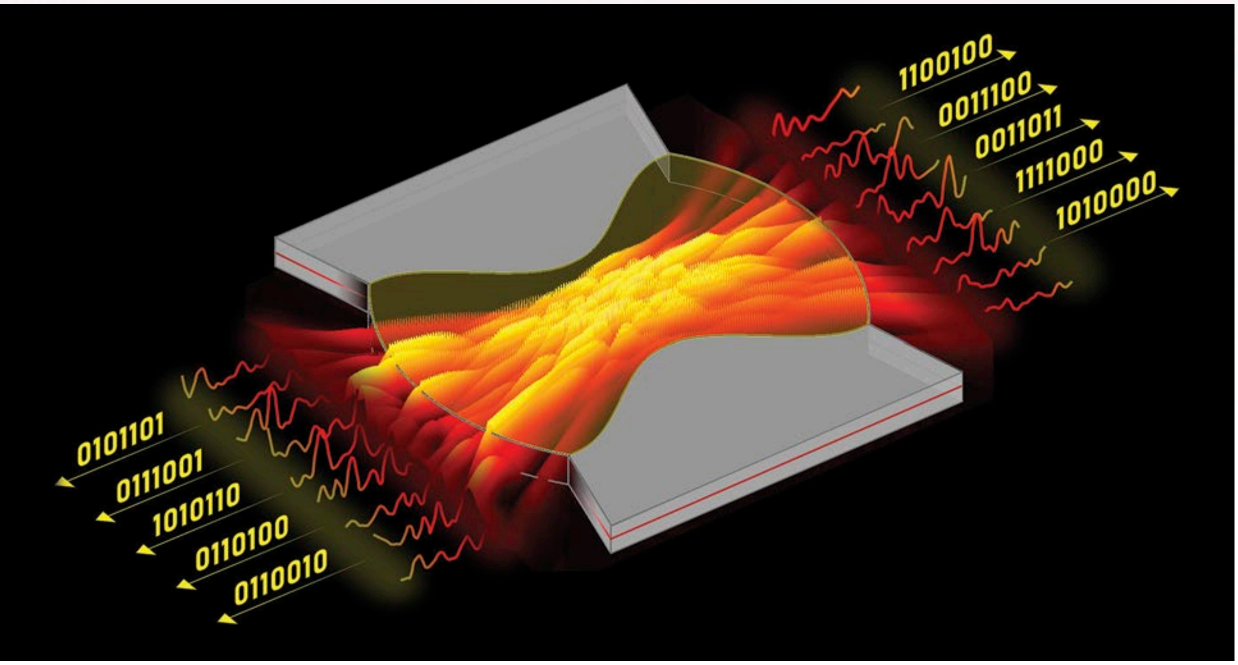


processing and greater clarity of their images. One downside of using traditional lasers in imaging systems is something known as "speckle noise," a grainy pattern that can diminish the quality of the images. The random laser, though, doesn't produce the speckle noise. And because they help generate the images faster, fast-moving phenomena like the movements of embryo hearts can be better captured in those images.

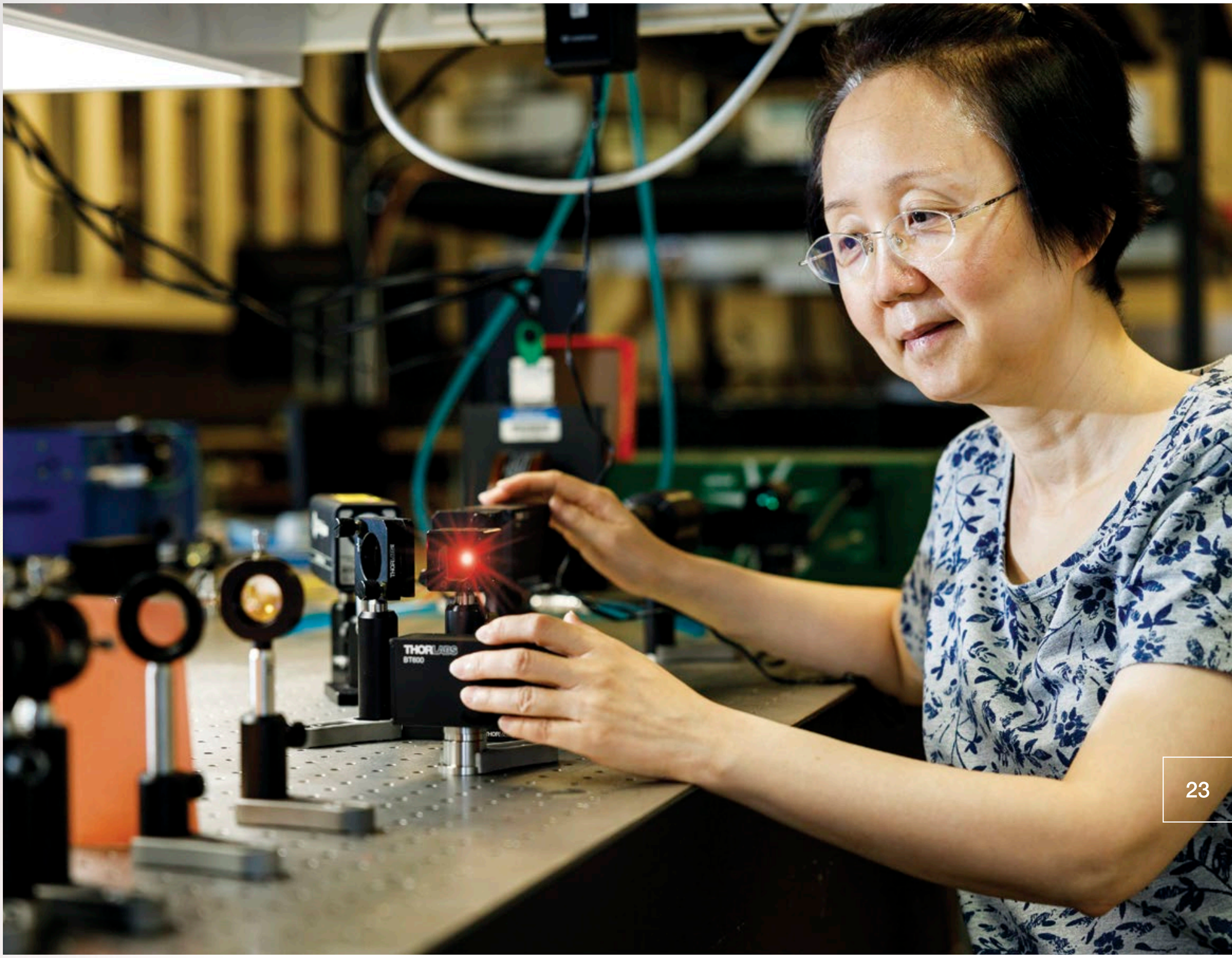
From Medicine to Computers

In one of her more recent studies, Cao demonstrated how a small laser — by quickly generating random numbers — can help bolster cyber security. As we become more digitally connected, computer systems need to generate sequences of random numbers to foil would-be hackers. Producing them fast enough, though, is a challenge. To speed things up, Cao led a team of researchers in developing a compact laser that can produce these random numbers one hundred times quicker than the fastest, current systems. The research team designed the laser cavity to amplify many optical modes simultaneously. These modes will interfere with each other to generate rapid intensity fluctuations that are recorded by a high-speed camera. These fluctuations are then translated to random numbers.

Cao compared the hourglass-shaped device to a violin that's designed specifically to amplify sound and resonate with many acoustic frequencies. Similarly, the new laser cavity acts as a resonator for optical waves and amplifies many modes of light. The result is a system that can generate about 250 terabits, or 250,000 gigabits, of



Bottom: *A chip detects laser fluctuations to generate random numbers. The result is more than two orders of magnitude higher than the fastest current systems.*



random bits per second — more than two orders of magnitude higher than the fastest current systems. It's also energy-efficient and can be scaled up significantly. She published the research this year in *Science*.

"This is a really exciting period for lasers, for optics, and also more generally, for applied physics. We are going back and forth between physics and engineering, and I really enjoy that. I think there's a lot of things we can do."

› Hui Cao

"It really opens a new avenue on how to generate random numbers much faster, and we have not reached the limit yet," she said. "As to how far it can go, I think there's still a lot more to explore."

Cao is convinced that lasers have a lot more secrets to reveal. One of her ongoing research projects is finding a way to use the coherent control of lasers to be able to penetrate deeper into biological tissue for noninvasive imaging. But tissue changes very quickly, so "the burning question," she said, is finding a way to adapt the laser to quickly find the way into the tissue.

"This is a really exciting period for lasers, for optics, and also more generally, for applied physics," she said. "We are going back and forth between physics and engineering, and I really enjoy that. I think there's a lot of things we can do."

Leveraging Yale's Strengths to Advance AI

SEAS faculty take lead roles in two NSF-funded institutes focused on optimization and edge computing

With such tools as facial recognition, voice assistants, and drones, artificial intelligence (AI) is poised to transform society — in industry, government, and among individuals. It will affect how we drive, interact with each other on social media, stay informed, conduct business, and learn. By capitalizing on its strengths, Yale is set to play a key role in ensuring that transformation is for the better.

One of the most immediate steps toward doing so is SEAS' participation in two AI institutes, funded by the National Science Foundation (NSF), with faculty taking leadership positions in each. Taking advantage of the wide array of AI expertise at Yale, one will focus on optimization, and another is dedicated to edge computing and computer network systems. Eight Yale scientists in total are members of the institutes.

"Taking AI into its next phase means tackling questions that lie at the intersection between fields — often disparate ones — both from a technical and a cultural perspective. Yale's interdisciplinary character puts us in a unique position to do that," said Jeffrey Brock, dean of the Yale School of Engineering & Applied Science, and dean of science for the Faculty of Arts and Sciences. "Yale's researchers, who already work in an environment that encourages impactful, cross-disciplinary collaboration, will surely have many valuable contributions to both of these institutes."

The two institutes were among 11 that the NSF is funding with an investment of $220 million, each receiving $20 million over five years. The 11 institutes are focused on AI-based technolo-

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gies poised to produce a range of advances, from helping older adults lead more independent lives, to improving agriculture and food supply chains, to increasing equity and representation in AI research.

Nisheeth Vishnoi, the A. Bartlett Giamatti Professor of Computer Science, is co-principal investigator for the Institute for Learning-Enabled Optimization at Scale (TILOS). Partially funded by Intel, TILOS aims to "make impossible optimizations possible" by addressing the fundamental challenges of scale and complexity. Led by the University of California San Diego, TILOS partners also include the Massachusetts Institute of Technology (MIT), San Diego-based National University, the University of Pennsylvania, and the University of Texas at Austin. Yale professors Daniel Spielman and Amin Karbasi will serve with the institute's "Foundations" team, with Vishnoi as the team's co-lead.

Lin Zhong, Professor of Computer Science, is co-principal investigator for the AI Institute for Edge Computing Leveraging Next-generation Networks (also known as the Athena Institute). Yale professors Abhishek Bhattacharjee, Wenjun Hu, Anurag Khandelwal, and Leandros Tassiulas, are also institute members. With Duke University as the lead

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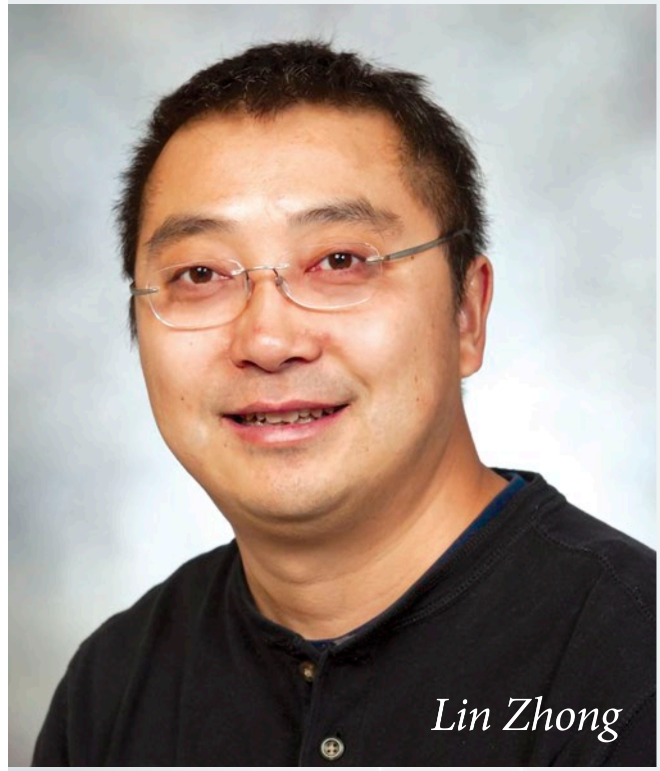


Lin Zhong

"AI has Great Potential to Solve Numerous Real-World Problems."

Leading the Computer Systems thrust and Yale's participation at the Athena Institute is Lin Zhong, professor of computer science. At Yale, Zhong leads the Efficient Computing Lab, designed to make computing and communication more efficient and effective. An experimental computer scientist, he builds systems as a way to validate research hypotheses.

Zhong said that the Athena Institute treats AI as a tool that is both powerful and in need of development for significant advancement in numerous fields, ranging from agriculture, to chemistry to physics.

“AI has great potential to solve hard problems in real-world,” he said. “Applying AI to these problems also contribute new insights that advance AI itself; the Athena institute embodies this partnership.”

In addition to Zhong, Yale researchers in the institute are Abhishek Bhattacharjee, associate professor of computer science; Wenjun Hu, assistant professor of electrical engineering & computer science; Anurag Khandelwal, assistant professor of computer science; and Leandros Tassiulas, the John C. Malone Professor of Electrical Engineering & Computer Science.

By taking on “some really hard problems,” Zhong said the Athena Institute is set up to explore how AI can transform computer and network systems. These problems include those in the field of cloud computing. Typically, cloud computing data centers are based in rural areas, often near a power plant. That allows for lower electricity costs, but there are also drawbacks.

“For your data to do computation using that center, you suffer the long latency,” he said. One solution is to bring the cloud closer to the user with what’s known as “edge computing” — that is, a system of distributed computing that decreases response times by bringing computing closer to the data. It’s driven by the exponential growth in data that is collected by the internet-of-things and the massive number of mobile devices. Edge computing has the potential to provide computing that’s faster, cheaper, more secure and more efficient. Making it viable, though, requires efficient and reliable data centers and networks.

Zhong’s focus at the Athena Institute is AI-powered computer systems for edge computing. That involves designing next-generation edge data centers. Many larger tech companies are already increasing their number of data centers, particularly in large population centers. But the effort needs to go further, Zhong said. For instance, there should be edge data centers in smaller municipalities like New Haven. That would improve not only everyday computing tasks, but also augmented reality, virtual reality, autonomous vehicles, and drones — all of which have critical latency requirements. It would help the individual consumer, as well as level the playing field for newcomers into mobile network business and allow start-ups to better compete with the large operators.

“Now, you must deploy a nationwide network to be competitive — a major capital investment upfront,” he said. “But if what we are envisioning happened, there would be more startups, because you could just rent from the tower companies, and buy time from edge data centers. There is no need to build a national infrastructure yourself. You can just pay per use for the infrastructure already there to set up a cloud-native mobile network. We think this should transform the national infrastructure for cloud computing and mobile networking.”

Zhong acknowledges that it’s an ambitious plan.

“There's a lot of technical challenges, of course, but this institute is about tackling the technical challenges of this vision,” he said. “It’s about tapping into the power of AI, and finding and taking on new challenges.”


Nisheeth Vishnoi

Yale

"We're No Longer Working in the Normal Space — We're Working in Some Complicated Geometry."

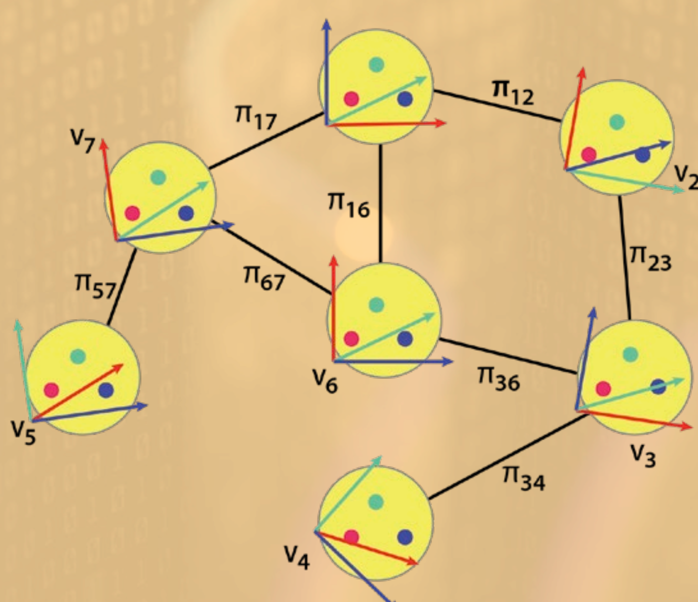
Nisheeth Vishnoi, the A. Bartlett Giamatti Professor of Computer Science, is leading Yale's participation in the Institute for Learning-Enabled Optimization at Scale (TILOS). His research spans foundations of computer science, machine learning, and optimization. He also explores issues that arise in nature and society from the viewpoint of theoretical computer science. His current focus is on natural algorithms, emergence of intelligence, and questions at the interface of AI, ethics, and society.

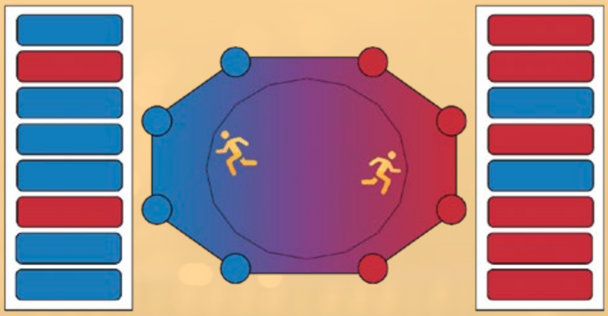
The institute's foundational research will drive its efforts to advance chip design, robotics, and communication networks. Vishnoi is the co-lead for the "Foundations" team, which also includes Daniel Spielman, the Sterling Professor of Computer Science, Statistics and Data Science, and Amin Karbasi, associate professor of electrical engineering & computer science. The team will explore five directions: interactions between discrete and continuous optimization; distributed and parallel optimization; optimization and sampling on geometric spaces; sequential learning and decision making; and optimization in deep learning. Vishnoi is involved in all five, while Spielman will work on discrete and continuous optimization, and Karbasi is part of the distributed and parallel optimization team.

The conventional approaches to optimization, Vishnoi said, are no longer adequate given the current technology. For instance, a typical household may have several computing devices, such as cell phones and tablets. Tech companies are learning from this data, but it's data that's happening in a very distributed manner. Traditional algorithms assume all the data is in front of you. In today's world, though, the data is all scattered around — phones are on and then shut off; sometimes users intentionally tweak their data out of privacy concerns.

"So doing optimization in the presence of all of these different nuances, which have risen quite rapidly, has become challenging," Vishnoi said. "What we've been doing in the last decades is independently pushing and trying to double up optimization methods in a variety of different settings that tackle this problem of scale."

Below: *Visualization of the semidefinite programming gap example for Unique Games constructed by Vishnoi.*





Above: *An illustration of the algorithmic framework to control polarization in personalized feeds introduced by Vishnoi.*

And scale is only one of the challenges. The general complexity of networks is another.

"With traditional optimization, you take a straight line and that's the shortest path," he said. "But now people are including things like manifolds, which are complicated surfaces. So now, it's no longer clear how you go from one point to another point. You have to design new optimization algorithms for that."

TILOS will also be exploring sequential decision making. Vishnoi compares it to playing chess, in which the factors that decisions are based on consistently change. This kind of adaptation is particularly important in robotics.

"A robot or a drone tries to navigate in an environment, so it's constantly interacting with the environment," he said. "It is changing the environment and the environment is changing itself. So once again, the data is reviewed sequentially, and not all at once. These may seem like nuances, but these are major, major areas inside machine learning and AI, and traditional optimization methods are insufficient."

He compares the new technology landscape to being in a mountain range versus flat land. Moving forward requires entirely new approaches.

"We're no longer working in the normal space — we're working in some complicated geometry," he said. "So, you need new algorithms, you need new models. So that is the overarching goal of this institute — to push the frontiers of optimization."

institution, other partners are MIT, Princeton University, University of Wisconsin, University of Michigan, and North Carolina A&T State University. It is partially funded by the U.S. Department of Homeland Security.

NSF officials noted that the AI institutes are composed of researchers from 37 states, and that they are looking to expand into all 50 states.

"These institutes are hubs for academia, industry and government to accelerate discovery and innovation in AI," NSF Director Sethuraman Panchanathan said. "Inspiring talent and ideas everywhere in this important area will lead to new capabilities that improve our lives from medicine to entertainment to transportation and cybersecurity and position us in the vanguard of competitiveness and prosperity."

At TILOS, Vishnoi said, the goal is "to push the mathematical frontiers of optimization into the next century." While decades of work in optimization have driven technology in chips, networks, and robotics, the demand on optimization models and methods from these areas has become much higher with today's technology.

"In the last few years, the scales of these problems have gone berserk," said Vishnoi. "The size of optimization problems that arise in these application areas have really gone out of bounds for traditional optimization methods.

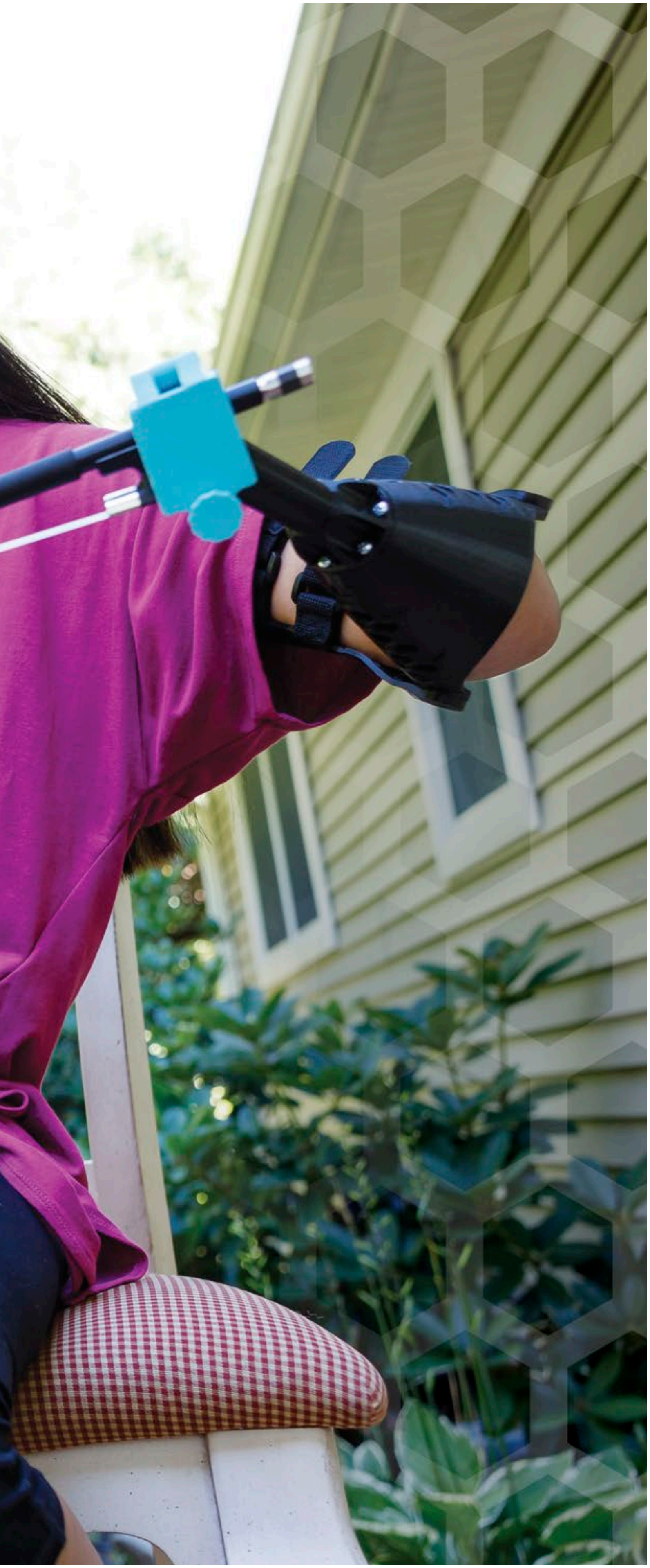
The Athena Institute aims to advance AI technologies to develop Edge Computing — that is, computing done at or near the source of the data instead of relying on a distant data center.

Zhong said the two institutes showcase two of Yale's strengths when it comes to AI. While TILOS focuses on the mathematical foundations of AI, he said, Athena is concerned with AI's potential impact on computer and network systems.

"One is mathematically driven, and the other is more empirically driven," he said. "So they are very complementary, the two institutes that Yale now plays a role in."

Enabling the Future

Student group Yale e-NABLE provides customized prosthetics and new opportunities



For 11-year-old Emily Reid, playing the cello with her standard prosthetic was cumbersome. Heavy and rigid, it caused her to overextend her arm to get the right angles — all of which would take a toll on her shoulder. With the help of the new student group Yale e-NABLE, though, she now has a new prosthetic for her lower arm. It's lightweight and porous, both of which are important for long sessions of cello-playing. And because it's easy to make, the student group can make different versions without much trouble.

It's the first major project for Yale e-NABLE, a group founded last year by Grayson Wagner '23. It's a chapter of the international group e-NABLE, made up of volunteers who use their 3D printers and skills to create free prosthetic limbs for those in need. They focus on helping people who are missing fingers, hands, or arms below the elbow. The 3D-printed devices are especially helpful for children who don't have the option of a traditional prosthetic device, either due to cost, time, or to the uniqueness of their limb difference. The Yale chapter focuses on reaching the broader New Haven community.

Wagner had been thinking about starting a chapter since high school, when she worked on a project involving 3D-printed prostheses.

"I thought it was incredible that e-NABLE is able to give these devices for free all over the globe, and also in fun colors," said Wagner, who is majoring in biomedical engineering. "You see kids picking up water bottles and Barbie dolls for the first time, and it's just really inspiring."

Once she put the word out about Yale's chapter, a team of students assembled pretty quickly. At about the same time, Guy and Linda Reid of Cheshire, CT, were looking for a way to help their daughter, Emily, play the cello. Born with a left arm without the hand and wrist, Emily wanted a customized prosthetic that was better suited to the specific mechanics of playing a cello.

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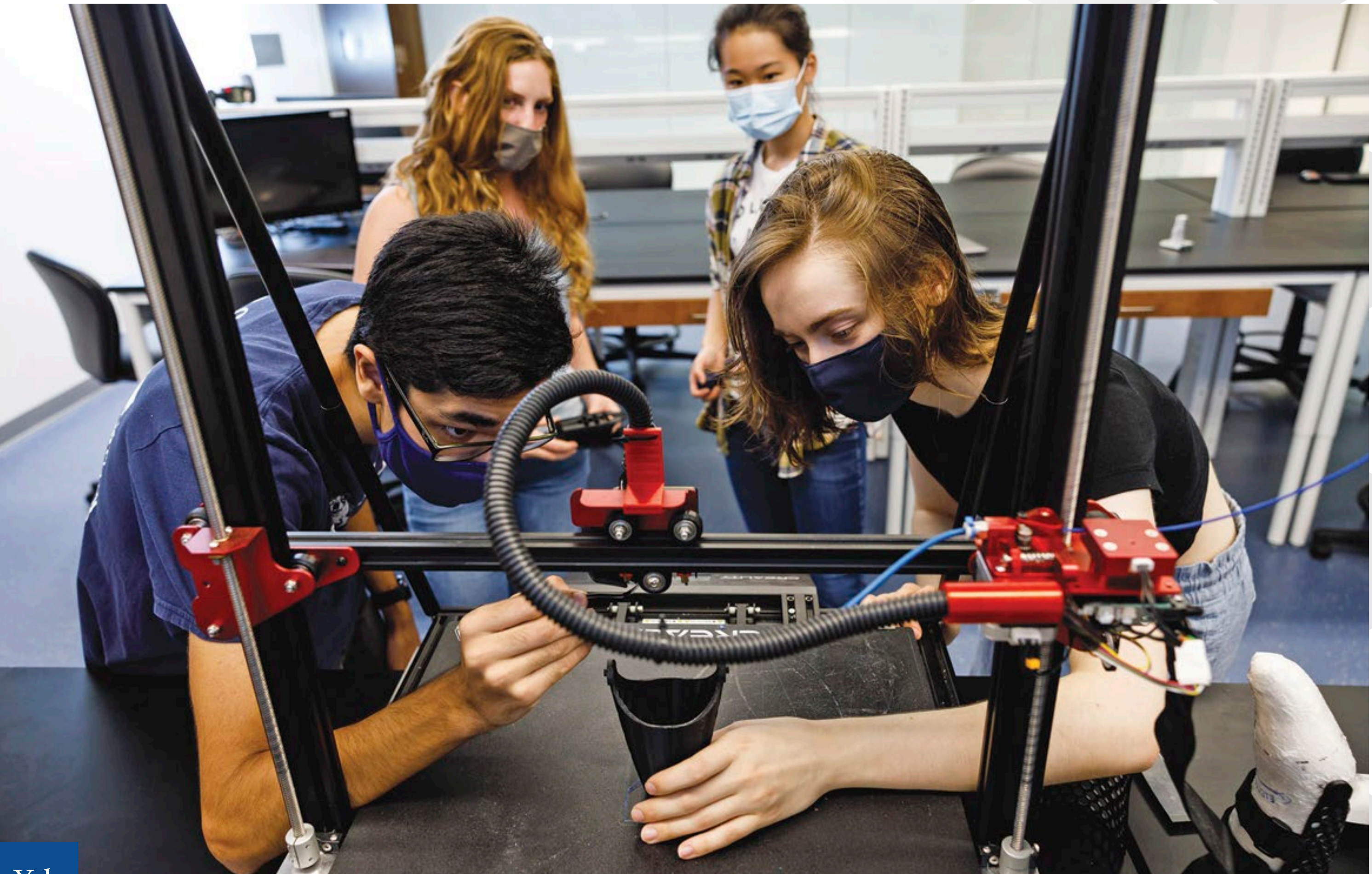


Above: *Yale e-NABLE members use their 3D printers and skills to create free prosthetic limbs for those in need, focusing on helping people with missing fingers, hands, or arms below the elbow.*

"We're very close to Yale, and I thought they've got to have some pretty smart engineering students," Guy Reid said. "So, I sent an email."

That email found its way to Deputy Dean Vincent Wilczynski, who then referred the Reids to Yale e-NABLE. The student team met with the Reids over Zoom, analyzed Emily's playing method, and got to work.

"I think the first thing was figuring out the right angles for the bow clamp, because we didn't want to hinder her development by having her start playing in an improper way and then continuing that further down the road," Wagner said, adding that they recruited a Yale student who plays the cello to offer some guidance. "Then we sent Emily three or four pieces, each with different angles on them, until she found which one suited her best."

Left: *The prosthetic is lightweight and porous allowing for extended use.*

It was an ambitious start for the group, especially since most of the work was done remotely from various locations across the U.S. The group now has a printer at the Yale Center for Engineering Innovation and Design (CEID), but for much of its first year, members printed parts in their own homes and consulted with each other from across the country, due to COVID.

"We were virtual, so it was a bit all over the place," Wagner said. For the group's Build A Thon, an annual event in which new members develop their skills by trying to build a wrist-actuated prosthesis for the hand, Wagner sent out packages to students who were dispersed around the U.S. with printed parts in them that they could assemble at their own homes. When it came time to work on the project for the Reid family, it again meant shipping out parts and molds to members' homes.

Above: *The device intentionally bends allowing Emily to comfortably place her bow at the right angles on the cello.*
Below: *The group consulted a Yale student that plays the cello to ensure the bow clamp was designed so Emily learns the proper way to play the instrument.*

To help them with the design, the Reid family made their own plaster mold of Emily's arm, and then sent it to the student team.

"We had two really talented designers, Audrey Whitmer '23 and Zubin Kremer Guha '24, who have been working on this and they have put so much effort into it," Wagner said. "So it's really rewarding to see their design coming to fruition and to see how Emily's using it."

For Whitmer, who's been making small toys and geometric shapes since high school, joining Yale e-NABLE was a good fit — and a bit of a challenge.

"Making prosthetics was an aspect of 3D printing I've always been interested in, but designing for a human is very hard," she said. "The organic shape of the arm is very different from anything I've designed for before."

It took some trial and error, but it wasn't long before they had a prosthetic device that Emily could use. Emily said she noticed a big difference once she began playing the cello while wearing the Yale e-NABLE device.

"I thought that it was way easier to play with since it bends and now I have the

Continued →

right angles, so I'm not struggling to place my bow in the right spot on the cello and making my arm uncomfortable," she said.

The low-cost of 3D printing is also a major benefit. The Yale e-NABLE prosthetic was free for the Reid family. Insurance will cover costs for conventional prosthetics, although there are still deductibles and co-pays. It gets really pricey when you look for customized prosthetics for specific activities. Those can run thousands of dollars. There aren't many companies that make them, and insurance companies rarely cover their costs.

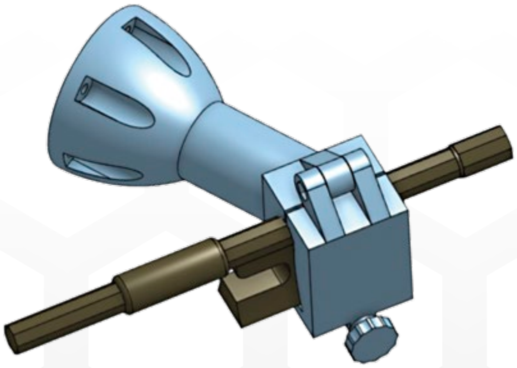
Drs. Lisa Lattanza and Daniel Wiznia, both orthopedists at the Yale School of Medicine, are the faculty advisors for Yale e-NABLE. Lattanza was already familiar with the use of 3D printing to make prosthetics, having done some work with it before she came to Yale. She said the student group is

> *"It was nice for her (Emily) to get some special attention and to have an opportunity to play an instrument that may have been more difficult without this."*
>
> › Linda Reid

getting in on the ground floor of a field that's likely to take off dramatically over the next few years. Besides being lightweight and less expensive, she said, 3D-printed prosthetics are much easier to customize to the specific patient.

"I've been aware of 3D-printed prosthetics for probably five or six years, and it continues to be honed," said Lattanza, chair of the Department of Orthopaedics and Rehabilitation. "And 3D printing has become so much more commonplace — some people now have the printers in their homes or offices — and it's just a lot more accessible. So I think it's going to really catch on with the folks who do traditional prosthetics and orthotics."

Below: *Members of the Yale e-NABLE group: Zubin Kremer Guha '24, Tenzin Kunsel '23, Grayson Wagner '23, Christy Zheng '23, and Audrey Whitmer '23.*



Emily has two older siblings who both have leg prosthetics. Lower limb amputations tend to get more attention from the prosthetics community, Linda Reid said, so it was great to see that e-NABLE focuses on the upper limbs.

"It was nice for her to get some special attention and to have an opportunity to play an instrument that may have been more difficult without this," she said.

The ease and low-cost of 3D printing allows for multiple iterations, so even after Emily was fitted with a working prosthetic, e-NABLE will continue to tweak the design to get it perfect. Part of that is the color scheme. Emily requested a teal and black design, so that will be coming up soon. The Reids said they'll spread the word about e-NABLE to other families with limb differences. Prosthetic adaptations for playing music, sports, and other activities can make a huge difference in kids' lives, Guy Reid said. Too often, though, families don't realize what resources are available.

For their part, the success of the first project has emboldened the e-NABLE group to seek out new projects. Beyond their time at Yale, both Wagner and Whitmer are both considering careers that involve 3D-printed prosthetics. As vice president of the group, it was Christy Zheng's job to organize and coordinate meetings and communications — not an easy task while working remotely. She said all the work was worth it, though, when the Reids sent a video of Emily playing the cello with the Yale e-NABLE device.

"We were overjoyed," she said. "It's amazing, and that project inspired me incredibly, because the orchestra teacher at my high school has a prosthetic device, and he's a world-renowned violinist. I think nothing is impossible."

From Projects to Products

Students learn the process of launching a business, from conception to market

Back in 2018, a team of students in the Yale Center for Engineering Innovation and Design (CEID) demonstrated a prototype of a device that guided exercisers in performing perfect squats and push-ups. A few years and many iterations later, that device has made its way around the continent for real-world testing. And soon, it could be at your own gym.

That device and a contactless microscope designed specifically for museums are just the first endeavors of Projects2Products (P2P), an undergraduate student program that gives hands-on experience in turning student projects into commercial products.

The program is supported by the CEID, the Tsai Center for Innovative Thinking at Yale (Tsai CITY), and the SEAS Greenberg Engineering Teaching Concourse (GETC). Besides sharing the ingenuity of Yale's students well beyond campus, P2P gives students a chance to work on all angles of entrepreneurship — product design, manufacturing, and marketing.

In designing the program, Deputy Dean Vincent Wilczynski said he had President Peter Salovey's concept of Yale's "Innovation Corridor" in mind — that is, the combined forces of the CEID, Tsai CITY, and GETC, and its promise "to enhance our city's reputation as a center for technology and innovation."

"This is a program that comes from the community of Yale — Yale Athletics, Yale students, and Yale Engineering — to create a learning environment for students to experience an idea in the full-scale development of a commercial product, which includes manufacturing and engineering," Wilczynski said. The program has been working with leaders in Yale's Cooperative Research and General Counsel offices on trademarking and other details.

The Bulldog RepBox™, a device to assist workouts, and the Hover, a microscope that users operate without touching are well underway in the P2P process. Also in the early stages is a balancing board to help medical professionals assess the recovery process of brain injury patients. The scope and aims of each project are flexible. The RepBox could eventually be a consumer project, for instance, while the Hover may be limited to museums and other institutions.

Clare Leinweber, executive director of Tsai CITY, said P2P is a great example of the kind of collaboration at which Yale excels.

"I was so glad when Vince reached out to talk with me about his idea for the Projects2Products initiative," Leinweber said. "It lends itself well to the kind of collaboration that CEID and Tsai CITY seek with each other, and which students value. I'm looking forward to the next steps, and exploring new ideas."

The Bulldog RepBox™

The RepBox provides users with a high-tech assist with push-ups, sit-ups, squats, and other workout staples. These exercises have been around for centuries, but there's still no exact way to make sure you're doing them the right way. With the RepBox, though, everyone from average gym rats to pro athletes can perform them with complete consistency.

The RepBox project originated in the course Engineering Innovation & Design (ENAS 118) in 2018, when students worked with Thomas Newman, then Yale's director of sports performance and innovation, on designing a device to help users perform squats properly and consistently. A key component of the design is its time-of-flight sensor, which measures the distance between the athlete's body and the floor. The RepBox uses this continually monitored signal to alert an athlete when the proper exercise height has been obtained.

Continued →

With the basic concept and prototype worked out in ENAS 118, the device then went to CEID Design Aides, who designed a printed circuit board to house the electronics and honed the overall design. Led by former CEID Fellow Antonio Medina ’19, the team at the CEID developed a design process to manufacture the devices using the CEID’s fabrication and assembly equipment. This phase also involved making the device more user-friendly, refining how it feels and sounds, and making it more durable. A major goal was making sure that it fit in well with a gym or physical therapy environment.

“We wanted to give it a little more of an ergonomic feel, making it a size that's comfortable and portable, but not so small that you can lose it,” said Medina, now a graduate student in design at Stanford University.

Also important was creating an interface — including buttons, display, and sounds – that are familiar and easy to use. Even simple things, like adding rubber feet to keep it from slipping around on the gym floor, go a long way toward making the device market-ready.

“It's a great lesson in how long things take to refine things and understand what the client or consumer would really want,” Medina said.

With some tweaking, such as figuring out the best way to fit the device's electronics, the team was able to streamline the manufacturing process, which paid off in a smaller and less expensive RepBox. The original design was brick-sized, weighed a couple pounds, and cost about $100 to make. The CEID team’s 3D printed iteration weighs less than a pound and now costs $40-$50. It’s even outfitted with a sleek logo designed by Jacob Payne, a member of the student team, who majors in architecture. So far, they’ve made about 50 of the devices which have been deployed for market testing.

They’re now working with a manufacturing company in China founded by SEAS alum Gordon McCambridge ’16 to explore mass-producing the device.

Above: *The RepBox brings science and consistency to workouts and can be used by pro athletes and casual exercisers.* Below: *Creating iterations allowed the group to refine and perfect the product to meet the needs of consumers.the Rep Box iterations.*

Yale

Right: *The RepBox provides users with a digital assistant to aid with push-ups, sit-ups, squats, and other workout staples.*

"They have a lot of experience with this kind of thing, especially small enclosed electronic devices," Medina said. "So it's right up their alley to take a look at our design and see if they can refine it a little further."

Tsai CITY Innovation Fellow Matt Gira is heading up the marketing aspect of the project. Gira recognized the device's potential as soon as he saw it.

"The big question I had right away was, 'What's the price point?' — all the typical business questions," he said. "The entrepreneur in me came out really quickly — price point, market, where do we start? I had a billion questions that came through."

To get some impartial, non-Yale feedback, they've sent the devices to numerous university trainers, physical therapists, and strength coaches. These include University of Florida, the University of Kansas, and Notre Dame. The Municipal Police Training Committee (MPTC) in Massachusetts is also evaluating the device. Newman visited MPTC on one of the days they were incorporating the RepBox into their training regimen.

"They used it for push-ups, and it was bullet-proof. It was great," Newman said.

With a lot of innovations, new ways to use them become apparent once they're out in the real world. That's been the case with the RepBox. Though originally designed for squats, testers used it to also standardize their push-ups and sit-ups. Coaches at the University of Kansas even used it to verify depth of motion for basketball shots. As part of the market research component of P2P, the original and more specific name of "SquatBox" has been altered to the wider-encompassing "RepBox."

The feedback they've gotten so far includes some helpful suggestions, like making the audio signal louder and adding a repetition counter. They've also gotten a lot of rave reviews, which doesn't surprise Newman. It's the era of the tech-savvy athlete, but judging push-ups and squats has long been very subjective and based on very inexact methods. The RepBox brings science and consistency to these exercises.

"It is really accurate and it's really reliable," Newman said. "It's really cool, and it solves a problem. It's an example of something that's a testament to practical design and product development."

The Hover

The Hover, the second major P2P effort, is a contactless microscope that's being tested for use in museums, and potentially wider uses. The first clients for the Hover are the Yale Peabody Museum of Natural History and the Smithsonian Institute — both of whom have worked with the CEID on previous projects. The Hover project began in the 2020 fall semester in ENAS 118, when the student team of Alexa Loste '24, Mikiala Ng '24, Avery Long '24, and Erick Marroquin '24 were tasked with developing a microscope that can be operated without the user touching it.

David Heiser, director of student programs at the Peabody, told the team that he was looking for a microscope that could be used by

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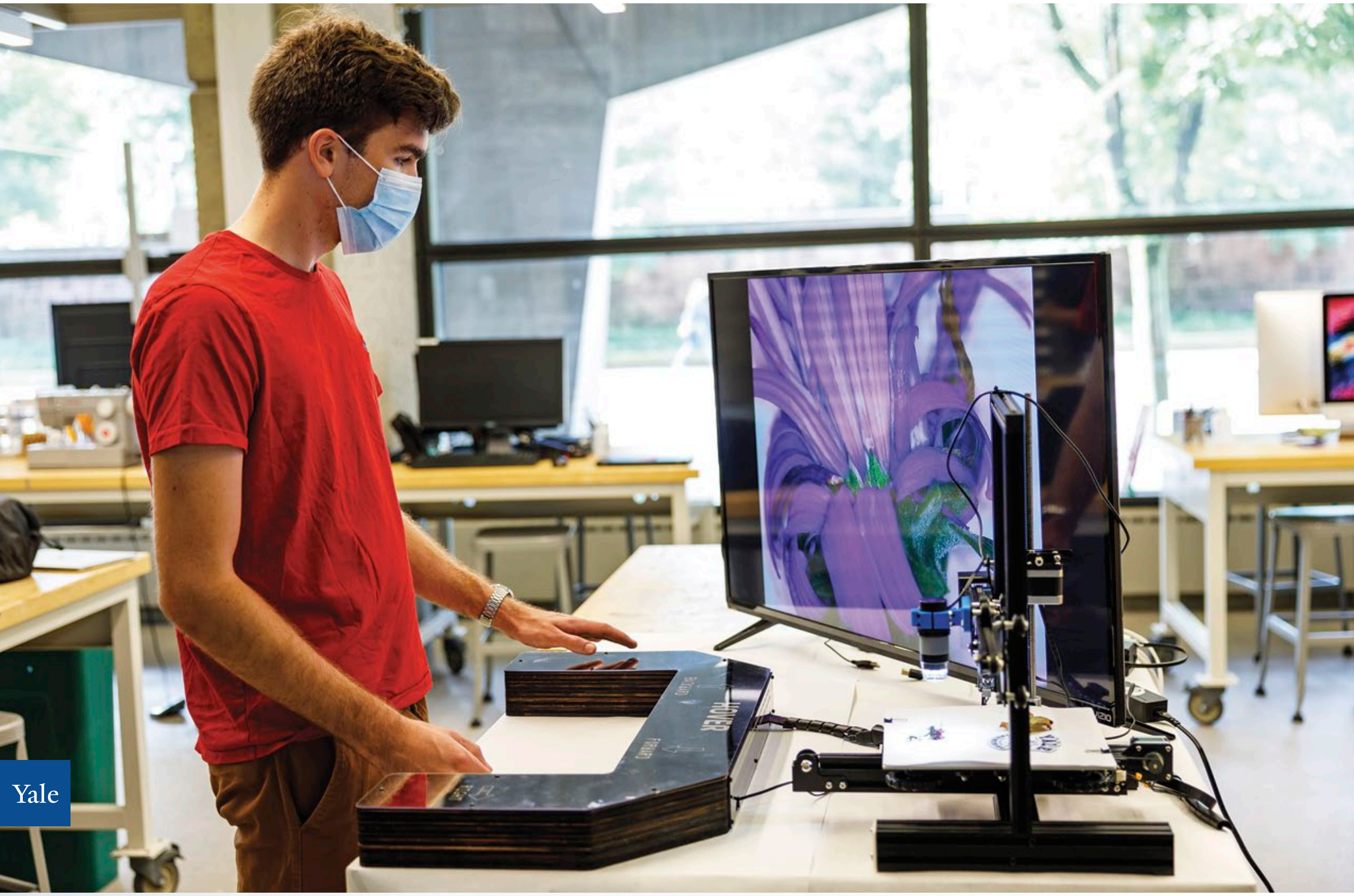


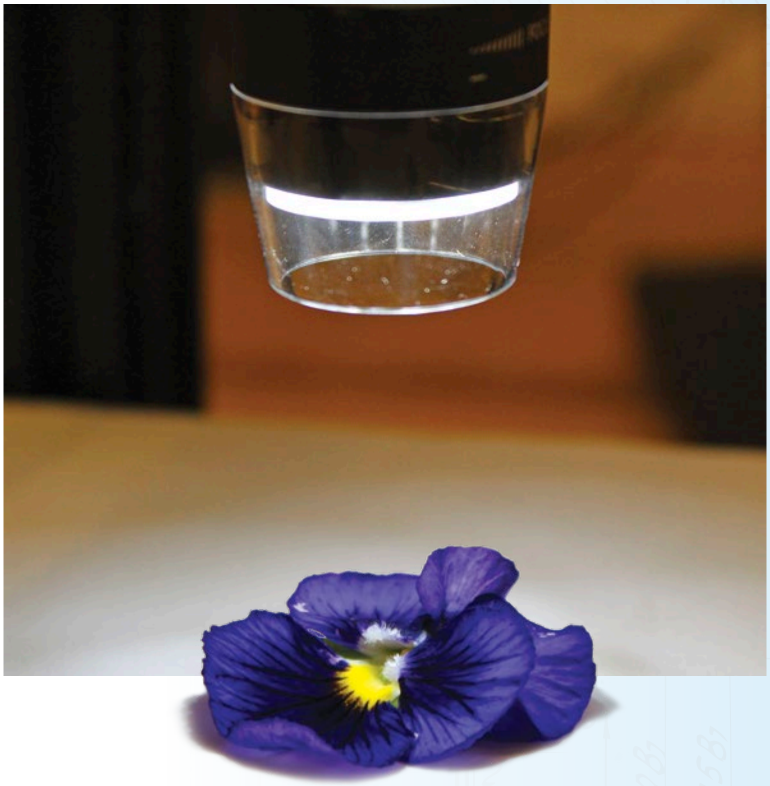
Above: *Ted Wayland ’24 utilizes the Hover to zoom in on an item by placing his hand over the device’s sensors. The group is exploring ways to implement the Hover at Yale’s Peabody Museum of Natural History and the Smithsonian Institute.*

visitors to the museum that wouldn’t spread germs, be durable, easy to use, and educational. By end of the semester, the team had developed a working prototype, which went through a second iteration process at the CEID with students and staff honing the device. Officials at the Smithsonian Institute were also brought onto the project, and they offered their own suggestions and goals for how a contactless microscope could enhance exhibits at several Smithsonian museums.

For the third phase of the project, students Lily Dorstewitz ’24 and Kayla Morgan ’24 took on the job of further advancing the microscope as part of the 2021 CEID Summer Fellows program. Taking the feedback from the Smithsonian and Peabody officials, they developed a sleek device that they dubbed the Hover. Encased in a damage-resistant acrylic surface, the Hover 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.

The team demonstrated the device for both the Peabody and the Smithsonian at the end of the program. It was a hit.

“This is really exciting, to see what’s possible — It’s really clever to repurpose the guts of a 3D printer to get the 3-dimensional motion of the scope — I just think this has real potential, not just for the Peabody, but potential for the field,” Heiser said. “This is something other museums and science centers would be very interested in.”



Left / Right: *Items such as a flower petal become much more vibrant when displayed on the large, connected screen.*

Heiser added that a number of features in particular impressed him. For instance, the large stage of the microscope means that visitors won't have to ask museum workers to switch out samples for examination.

"With this nice big stage, which is different from the limited stage of a traditional microscope, you could have seven or eight things on it and then people could literally move the stage all around and see each one of those things."

As a bonus, the team also outfitted the Hover with a game in which users can test their prowess with the device by zooming in on specified items. It also has a large monitor that allows others, who aren't using the microscope, to also see what's being examined in vibrant, high-definition detail.

"I see this as something for public discovery and for the examination of things — it's great for that," Heiser said. "With it connected to a screen, it becomes an exhibit, so that others in the room standing by the person see the same thing. It becomes sort of a social thing."

Smithsonian officials were also impressed.

"There's a lot of practical uses that we could make of this, and it's just another tool that we can use when we're trying to come up with mechanical interactives to be used in a really engaging way for working with visitors in different museums," said John Powell, a developer of exhibits for the Smithsonian. "We could use it in a variety of museums."

One idea, he said, is that it could potentially be used in the Smithsonian American Art Museum, which has a conservation lab open to the public.

"They're trying to reinterpret it to give more direction for visitors, so with something like this, you can imagine zooming in on an artwork and being able to see the tiny details that conservators have to repair or restore when they're working on a painting or some other artwork," Powell said. "From that, to science museums to air and space, there's so many different applications that we can use it for."

Juanita Wichienkuer, chief of design for the Smithsonian, suggested that the Hover could allow visitors a new way to look at rare artifacts. Because they're so valuable, the museum can't allow visitors to touch these artifacts, but simply keeping them encased in glass creates a certain distance between the exhibit and the visitor. The Hover could help them resolve this conflict.

"But letting them scan it in this way might be more engaging than just having detailed shots of it that are already done for you," she said. "We're always looking for ways to engage people in a way that's not just reading another text panel."


Yale

True Colors

Ted Kim shows that representation in animation is not skin deep

Shortly after arriving at Yale, Theodore Kim was invited to give a guest lecture on the history of computer-generated imagery (CGI) for a Film and Media Studies class.

"While I was assembling the materials, a pattern became clear to me," he said. That is, the degree of bias that exists in computer graphics technology toward the features of white people. He met with the professor of the course, John MacKay, who confirmed that the pattern was real — and deep-seated in film history.

"He introduced me to the book 'White' by Richard Dyer, which described how similar biases pervaded film technology in the analog era," said Kim, associate professor of computer science. "From there, it became clear that there was a whole body of scholarship on this topic, but its coverage of the digital age is still ongoing, especially with movie CGI."

In recent decades, the technology of computer graphics has made remarkable progress. However, when it comes to matters of race, and the means to depict characters of different ethnic backgrounds, the field remains very much in the past. Kim, who co-leads the Yale Computer Graphics Group, is among those who are trying to change that. He's seen the issue from the perspectives of both the industry and academia. Before coming to Yale, he was a senior research scientist at Pixar, where his work can be seen in such movies as *Cars 3, Coco, Incredibles 2,* and *Toy Story 4.*

From the ground up, computer graphics technology has been developed with the notion that the skin and hair of white people are the default when it comes to depicting humans. For instance, articles in computer graphics journals often include only computer-generated images of white people when discussing skin rendering, even when the topic is broadly claimed as "humans." And many of the lighting techniques used in computer graphics are based on guidelines for film lighting developed before the 1940s — long before the modern computer — and specifically designed for white skin.

It's a problem that severely limits what computer graphics artists can do, and how wide of an audience they can reach.

"We're supposed to be the leaders in storytelling," said Kim. "There are lots of stories out there and we haven't told a bunch of them, so let's go tell these stories."

Thanks in part to the efforts of Kim and others in the field, there's more awareness about the issue. Because racial bias is so deeply baked into the technology, though, there's no quick fix. For instance, early in the development of models for human features, computer graphics turned to the medical literature for guidance. Despite having the imprimatur of "hard science," Kim notes, it turned out that much of the literature was made with the same biases, with Caucasian skin and hair being treated as the standard.

"We thought we were doing the right thing by going to the medical literature, but instead we inherited all the same things," Kim said. "Everybody needs to be more careful about this stuff and think a lot harder about what we're doing. We're trying to develop technology that we claim is for all of humanity."

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The first step is getting a substantive discussion going in the community.

"At the very least, we're locating people who actually care about it," he said. "From there, it's a community-building exercise. There are people who care about it, but we need to form a community."

A big step toward that goal happened after Kim published an article about the issue in *Scientific American* magazine in 2020. From that article:

> *Today's moviemaking technology has been built to tell white stories, because researchers working at the intersection of art and science have allowed white flesh and hair to insidiously become the only form of humanity considered worthy of in-depth scientific inquiry. Going forward, we need to ask whose stories this technology is furthering. What cases have been treated as "normal," and which are "special?" How many humans reside in those cases, and why?*

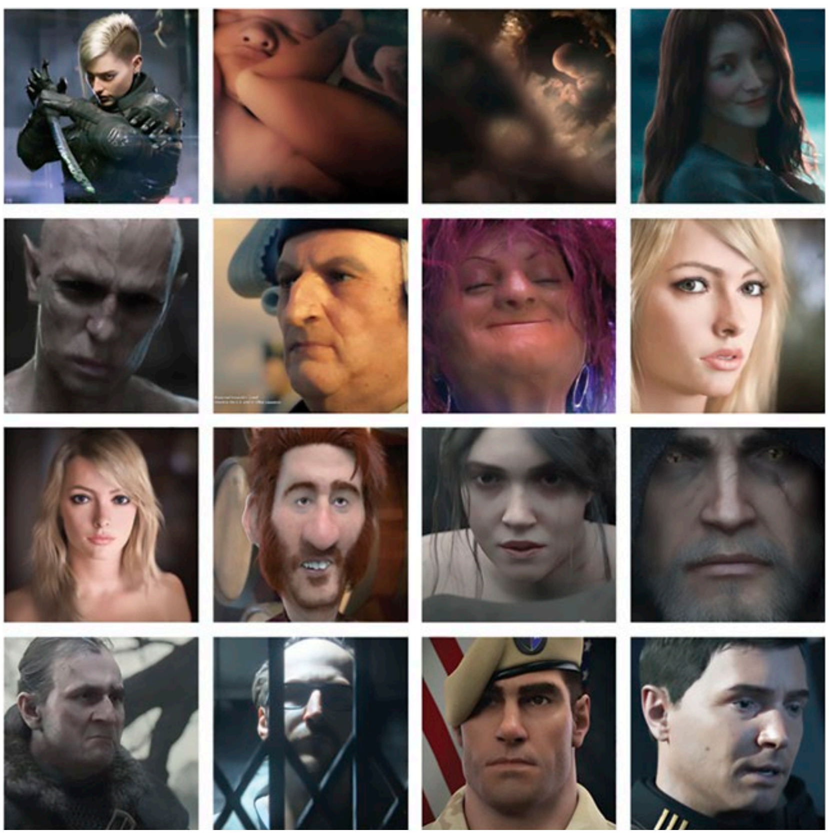
Yale

That article got the attention of many others in the field with similar concerns. Kim and an "all-star cast" of co-authors that includes fellow Yale computer science professors Julie Dorsey and Holly Rushmeier submitted an extended abstract to SIGGRAPH 2021, a prestigious conference for computer graphics and interactive techniques hosted by the Association for Computing Machinery.

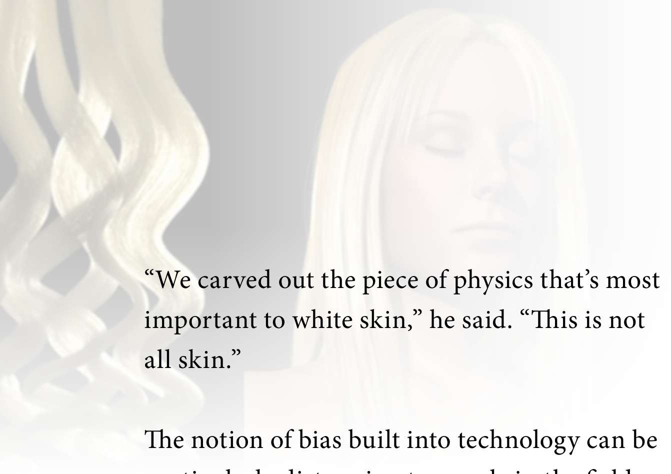
"You never know what's going to happen when issues are this controversial or hot-button," Kim said. "And what happened was we got seven reviews, which is usual. Five were extremely positive, one was neutral. And one was virulently negative, and in fact contained coded racist messages, and this person forced it to get rejected."

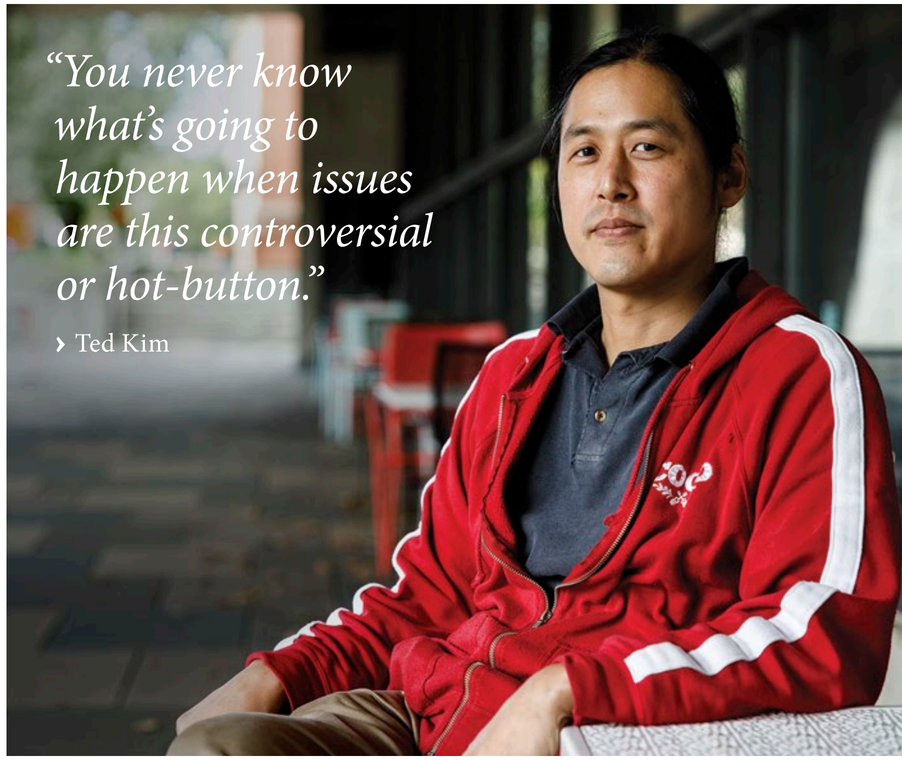
But Kim was invited to be the opening speaker for the event's Diversity, Equity, and Inclusion Summit to give his talk, "Anti-Racist Graphics Research." He and Rushmeier also led a town hall-style gathering, otherwise known as a Birds of a Feather, titled "Countering Racial Bias in Computer Graphics Requires Structural Change." The goal was to get others interested in joining them in submitting a broad range of extended abstracts for SIGGRAPH 2022. The rejection of the previous submission, Kim said, made it clear that it was a "numbers game."

In his talk, Kim discussed a common lighting technique in computer graphics known as subsurface scattering, which creates a glowing effect. It adds realism to white skin, but is much less important in darker tones. While there are ways to add pigment to the default white skin to make darker skin, details are lost in the process. The technique is even codified in elaborate mathematical equations, creating the sense that rigorous science is behind it.



Left: *Gallery of user-generated character examples from the Arnold website. Commercial rendering programs like Arnold lack the full spectrum of human skin shades and hair types.*





"We carved out the piece of physics that's most important to white skin," he said. "This is not all skin."

The notion of bias built into technology can be particularly distressing to people in the field who are used to thinking that "math is math."

"That's what attracted many of us to research to begin with," he said. "We get to look at these clean, neutral problems all day don't get all tangled up in the ugly politics of the real world."

Raqi Syed, one of Kim's co-authors, said she noticed the problem while working on a project in 2018, and "trying to make a character look like me."

"I became aware that if I wanted to tell stories that reflect my experience and use the tools that I understand from working in visual effects, then that's going to be really challenging, because these tools aren't designed to do that," she said.

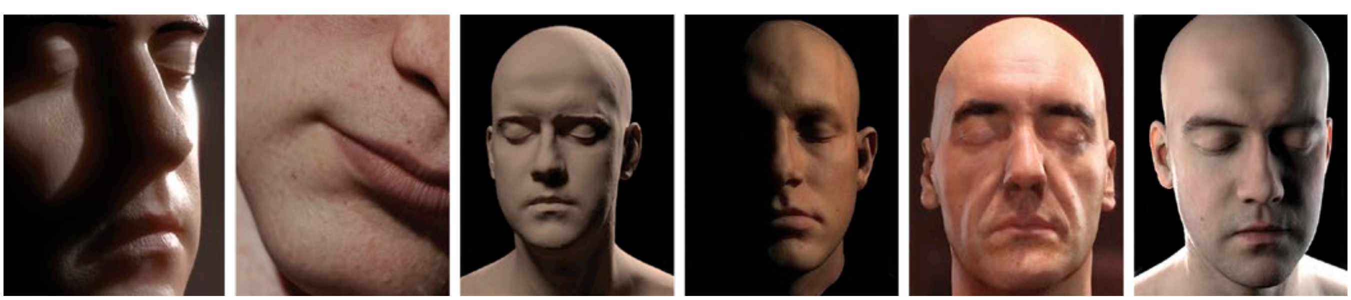
A.M. Darke, another co-author of the paper, encountered the results of anti-black bias in graphics technology while creating a virtual reality space called "In Passing," a 3D media project about how people navigate public spaces. When developing the avatars for Black characters, she found a very limited range of hairstyles that she could use. This prompted Darke to create the Open Source Afro Hair Library, which gives users a wider choice of hairstyles to choose from for their characters. When Darke tweeted about an award for the library, it went viral — a sign that this issue resonates well outside just the computer graphics community.

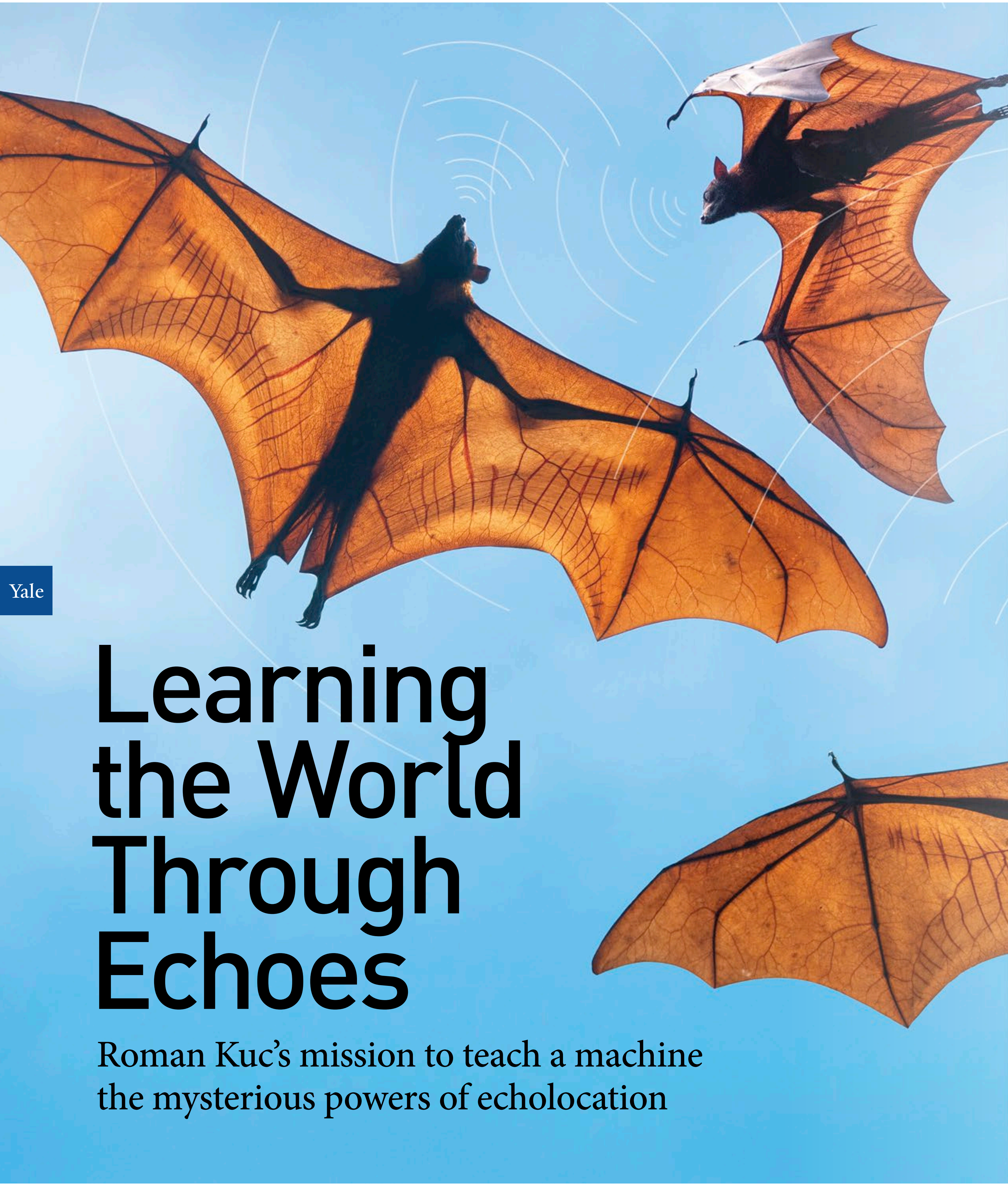
"The response was really positive because this was something that had already been understood tacitly in a non-specialist community," said Darke, an assistant professor at the University of California, Santa Cruz, in the department of Performance, Play and Design.

Spreading that awareness to the community of specialists is the next important step.

"The way we solve these issues is collectively, by opening up a dialogue," Darke said. "The aim of what we did at SIGGRAPH was to encourage others in this community to write and research and go down this line of inquiry, so that this knowledge and expertise can be made available, and so this community can be amplified and heard." 

Below: *The history of representation in animation is problematically narrow. Numerous academic papers highlighting "skin" use the same white characteristics, and in many cases, the same person.*





Learning the World Through Echoes

Roman Kuc's mission to teach a machine the mysterious powers of echolocation

Inside the lab of Roman Kuc, an experimental system teaches itself the details of its surroundings by emitting sounds and then picking up the echoes that bounce off nearby objects. Built in 2017, the device — a biomimetic sonar with five degrees of motion — plays a big part in Kuc's ongoing quest to figure out how bats, dolphins, and some visually impaired people use sound to "see."

Echolocation — locating objects with reflected sound – is an area of research that could lead to better self-driving cars, assistive wheelchairs, and improved biomimetic sensors. Over the last several years, it has evolved significantly for Kuc, a professor of electrical engineering. Recently, he presented a talk at the International Conference on Intelligent Data Acquisition and Advanced Computing Systems Technology and Application on an echolocation system that can discern between the leaves of different plants. Modeled after the human brain and how it processes new information, the system was inspired by YouTube videos of human echolocators.

Kuc didn't originally set out to unravel the mysteries of echolocation. After getting his bachelor's degree from the Illinois Institute of Technology in Chicago, he went to work for Bell Laboratories and focused on digital signal processing on speech. When Bell created a program for employees to get advanced degrees, Kuc sought a Ph.D. from Columbia University. Unable to decide on an area of study that worked both for Columbia and his employer, Kuc took a leave of absence from Bell.

"That meant that my research topic could be just wide open," Kuc said. "One professor told me if you're going to work on something, make sure you work on something that impresses your neighbors, so you can talk to them about it."

The medical field intrigued him, specifically the use of diagnostic ultrasound to image internal organs. His thesis was on diagnosing diffuse liver disease using reflected signals. After coming to Yale, where he did some collaborations with the School of Medicine, he decided to shift his research to something more technology-based.

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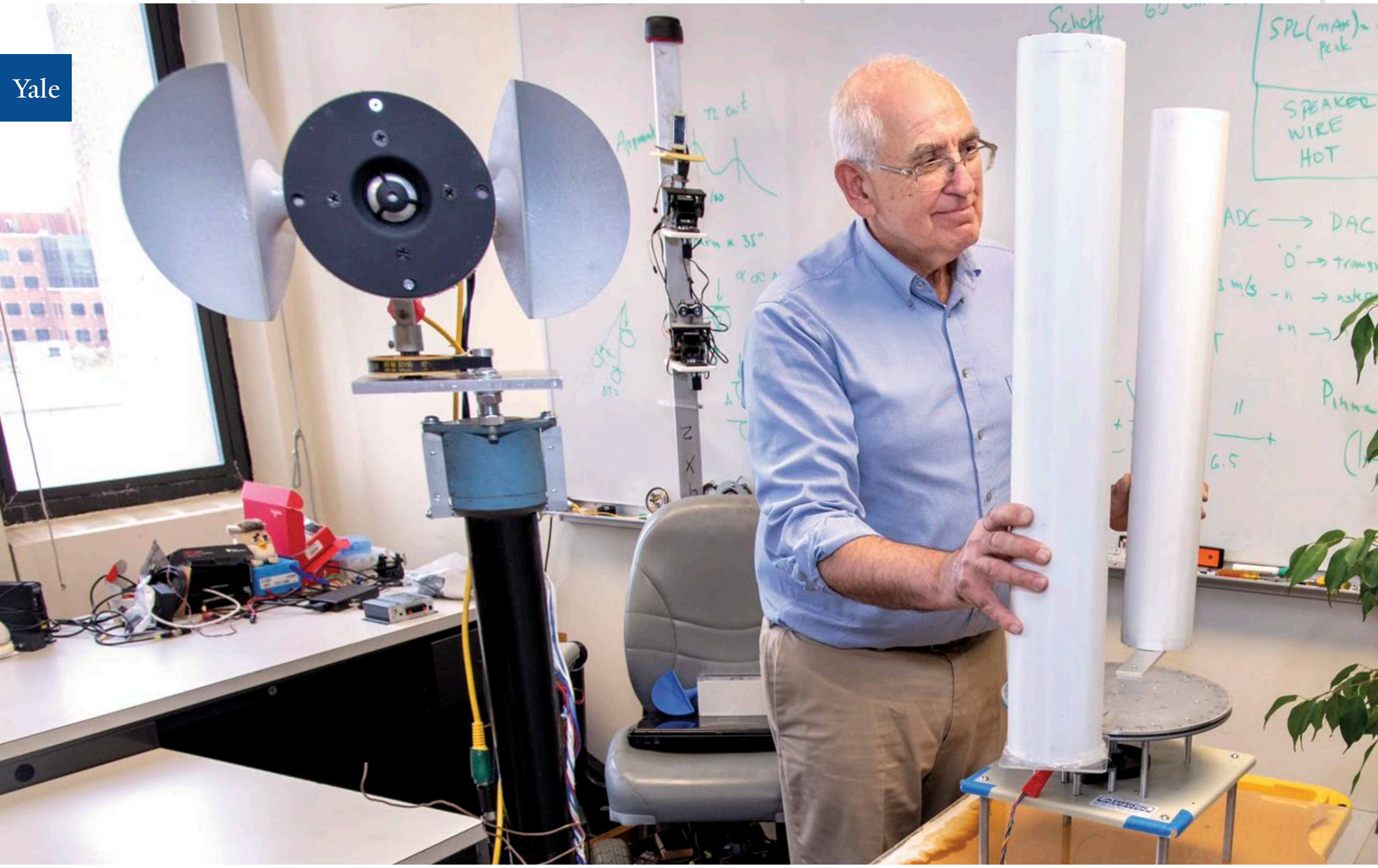
"I said 'OK, what technological field uses this type of processing?' And it turned out that mobile robots with sensors use sonar for obstacle avoidance and for navigational purposes. So I started doing that, and it turns out that I could drive the sensor to produce the same kind of waveform as a diagnostic ultrasound signal."

From the Medical Field to the Animal World

"How do you know what sonar does?" Kuc said. "You look at animal models that use it, like bats and dolphins. For many years, we've been trying to understand how bats and dolphins use sonar."

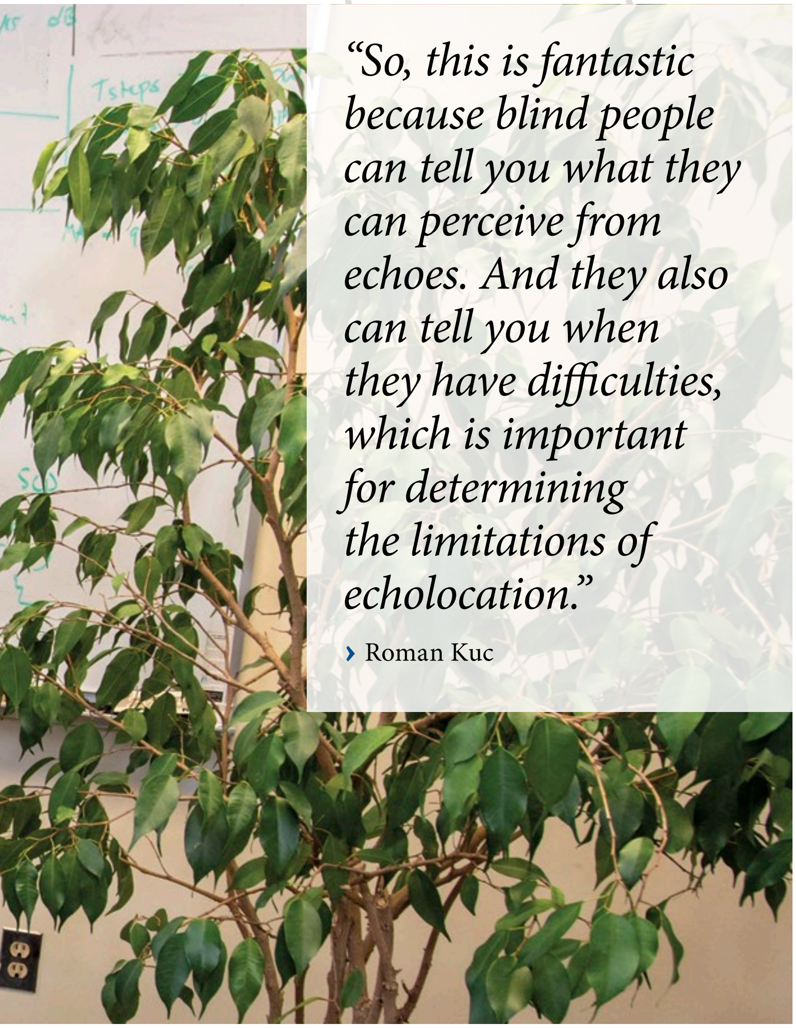
Although they have decent eyesight, dolphins have also developed a keen sonar to help them navigate the waters. Jacques Cousteau was one of the first to extensively study their use of sonar. Several decades since, researchers still don't fully understand it, but they know that dolphins emit a series of high-frequency clicks. The sound waves from these clicks, which travel particularly fast underwater, bounce off surrounding objects. These echoes come back, and the dolphin's brain interprets them. Like dolphins, bats also have vision but rely heavily on echolocation. The less heralded oilbirds and swiftlets also display an impressive ability for echolocation.

With these animals as inspiration, Kuc published numerous papers on echolocation, many in the *Journal of the Acoustical Society of America.* Among them was a study



that showed how turbulence from bat wings move the air in a way that ruffles the wings of insects — just enough so that bats could detect these motions and catch their prey. To do so, Kuc — working with his frequent collaborator and son, Victor Kuc — viewed a high-speed camera film of a bat homing in on a dragonfly. A slow-motion replay showed the subtle movement of the dragonfly wings. Even more remarkable, the study revealed that the bat could tell the difference between the wings of his prey within nearby leaves.

Bats, however, aren't always a convenient study subject — they need upkeep, and there's a limit to how much they can communicate regarding their actions. More recently, Kuc has turned to the phenomena of echolocation by blind people.



"So, this is fantastic because blind people can tell you what they can perceive from echoes. And they also can tell you when they have difficulties, which is important for determining the limitations of echolocation."

› Roman Kuc

"So, this is fantastic because blind people can tell you what they can perceive from echoes. And they also can tell you when they have difficulties, which is important for determining the limitations of echolocation," he said.

And there are numerous videos of visually impaired people demonstrating this skill on YouTube. One is of a blind man, Brian Bushway, who uses echolocation by making clicking sounds with his tongue — known as "palatal clicks." He's so proficient at it that he can use the technique to accurately describe an abstract sculpture as he walks around it.

"I've watched that video about a hundred times looking at the strategies and procedures that they use," Kuc said. Based on those observations, he created a device that models human echolocation with a biomimetic sonar that uses a speaker to produce audible clicks. Two small acoustic antennas act as a pinna — the part of the ear that funnels sound into the ear canal. It's also binaural, mimicking the way humans have two receivers for sound to perceive the echo's direction.

"So now I can model things that they do, like characterize targets from the echoes."

There are two kinds of targets that Kuc focuses on. One is known as "surface reflectors," which include various man-made objects, such as lamp posts. The other target is known as "volume scatterers" — plants and other natural objects. Although human echolocators have been able to detect differences in plants and other fine details, Kuc said it's these that have

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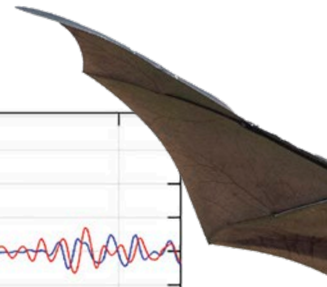
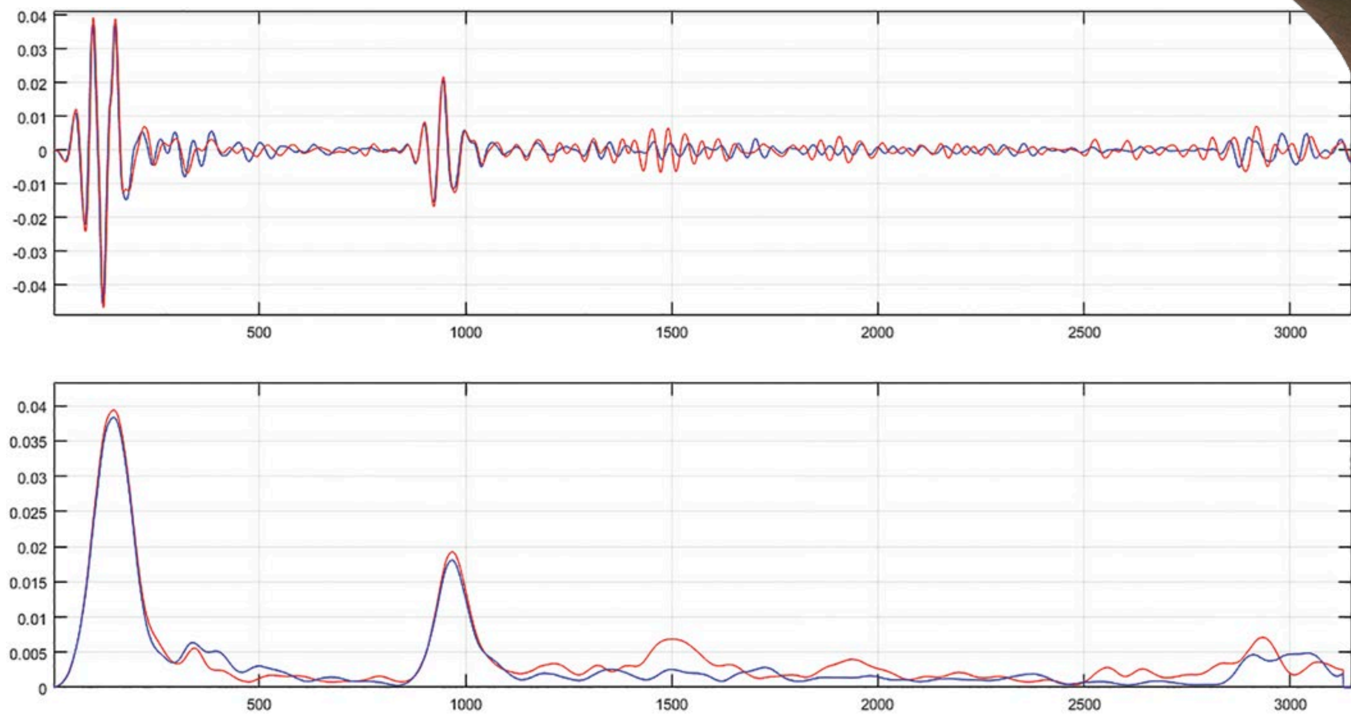
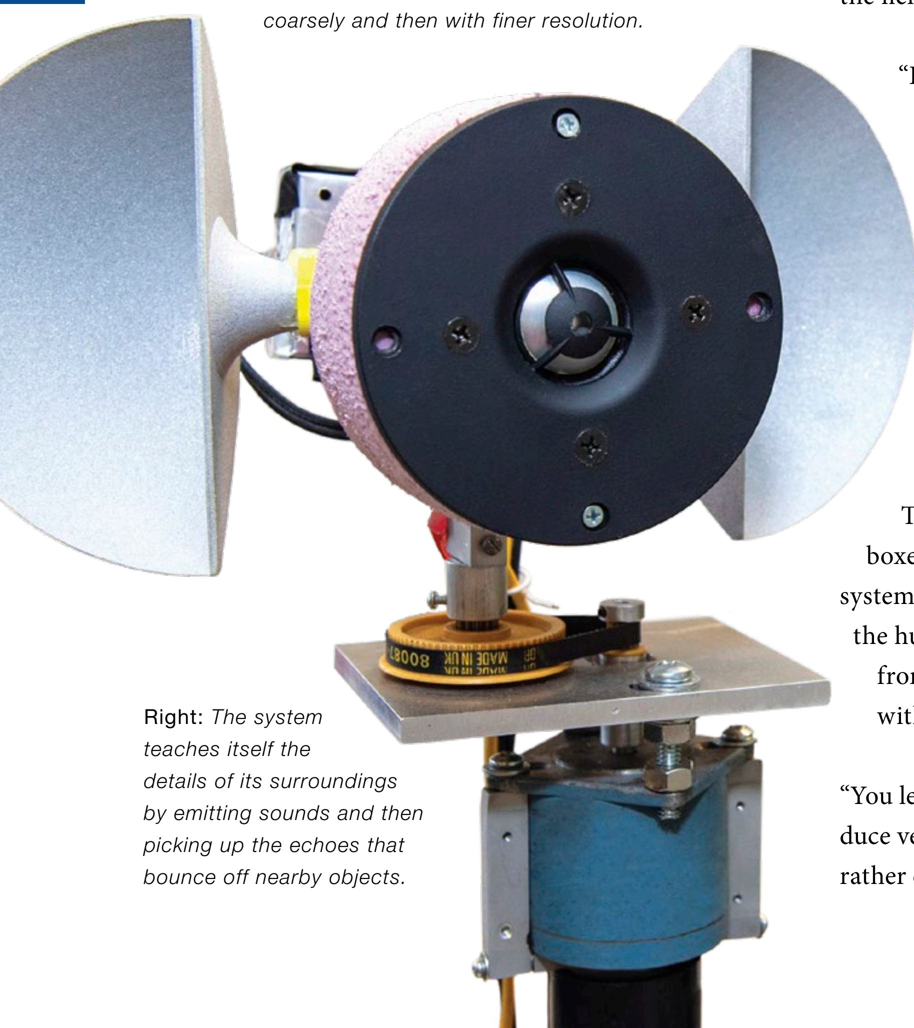




Above: *Kuc's "brain-based system" classifies targets from echo spectrogram features, first coarsely and then with finer resolution.*



Right: *The system teaches itself the details of its surroundings by emitting sounds and then picking up the echoes that bounce off nearby objects.*

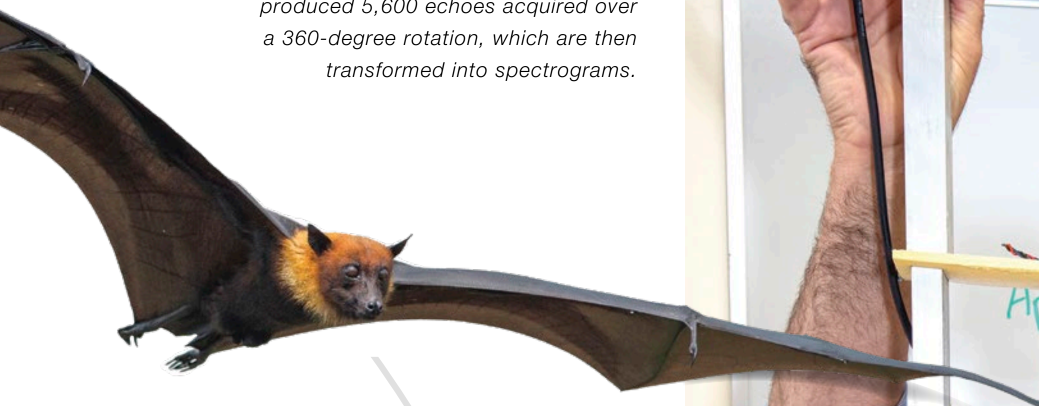
proven particularly tricky for him and other researchers in the field.

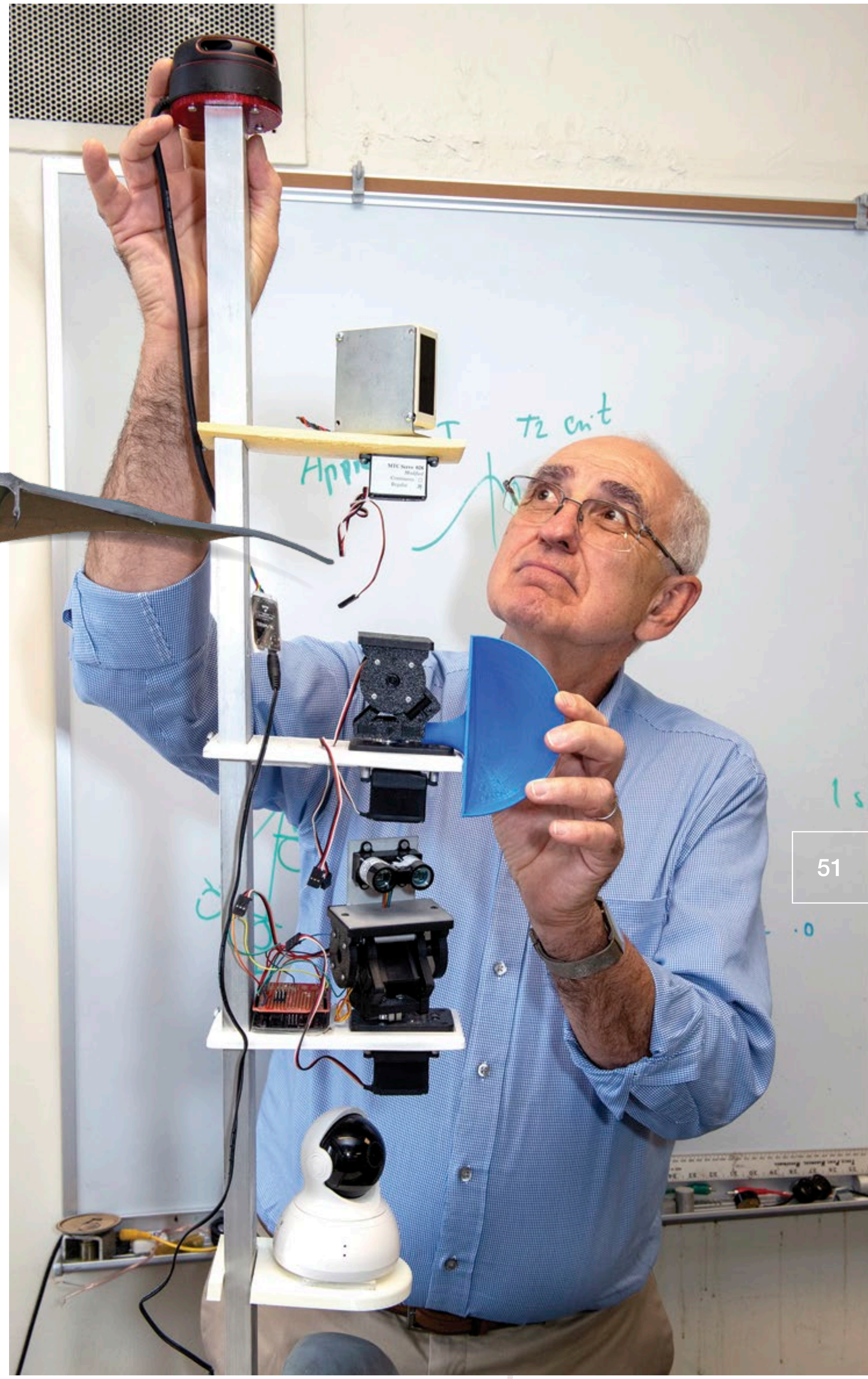
"But then along comes artificial intelligence and neural networks," he said. "What neural networks can do, is they're able to pull out features from spectrograms, which are sort of images of how the frequency of the echo energy varies with time. Typically, they were used for speech sounds, but they're also commonly applied to sonar."

Conventional neural networks are limited, though, in that they can perform functions but understanding how they do so is difficult. That's why they're sometimes referred to as "black boxes." Kuc developed what he calls a "brain-based system" — that is, it's designed to process the echoes as the human brain would. For instance, it classifies targets from echo spectrogram features, first coarsely and then with finer resolution.

"You learn typically by perceiving target groups that produce very different echoes — you can classify the groups rather easily," he said. "We can tell apples from oranges

Right: *With Kuc's system, each target produced 5,600 echoes acquired over a 360-degree rotation, which are then transformed into spectrograms.*





rather easily. But now, if we want to classify apples, we need to know additional features that differentiate apples. That's exactly what our brain-based system does."

A key part of the system is that it relies on a sequence of echoes — it's one of the takeaways from watching the videos of human echolocators, who scan their targets while producing the series of palatal clicks. With Kuc's system, each target produced 5,600 echoes acquired over a 360-degree rotation, which are then transformed into spectrograms.

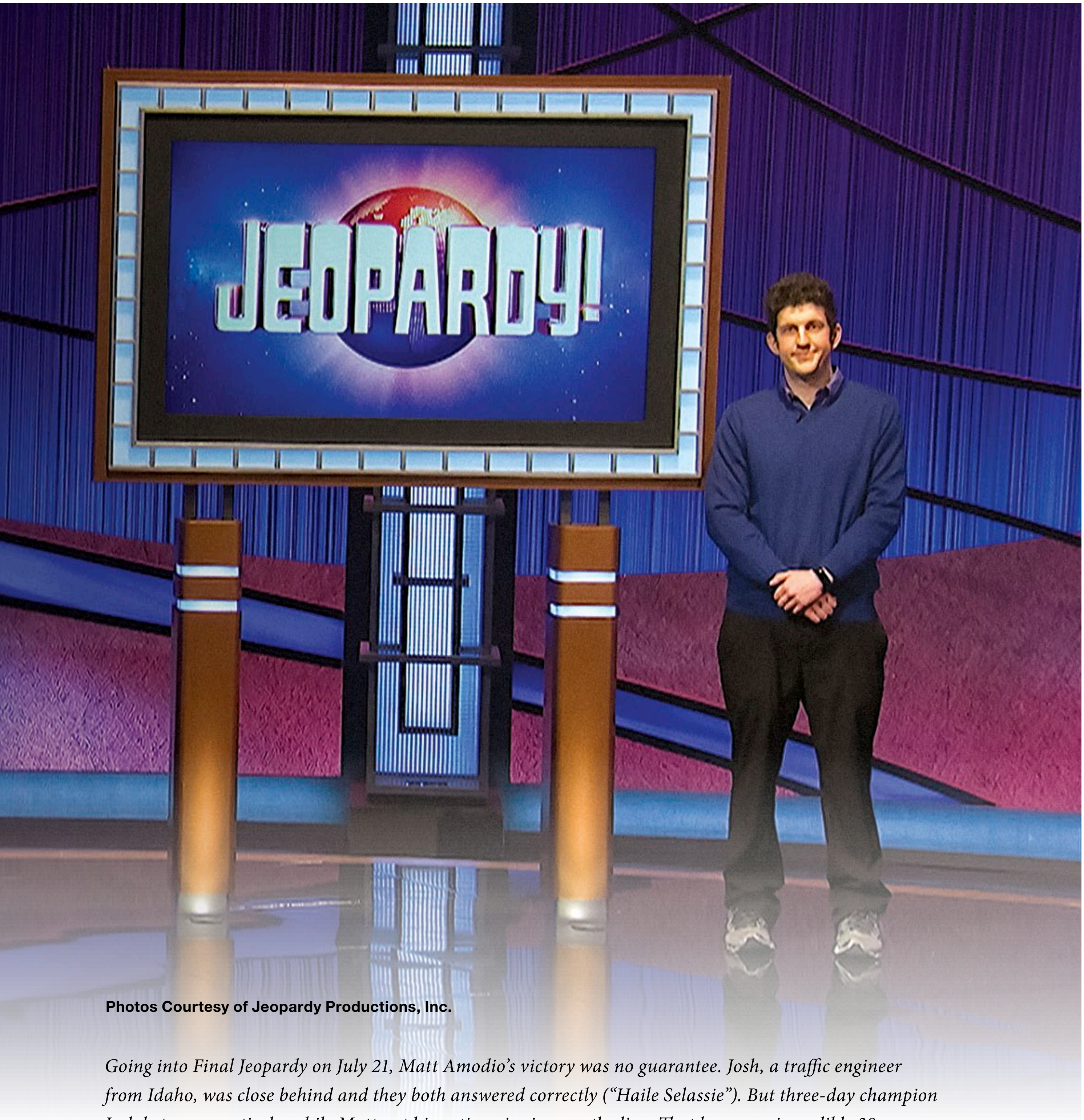
"When you use a sequence of echoes, you get much better accuracy, because some echoes from surface reflectors and volume scatters look very much alike," he said. "As you move around, echoes come from different structures. Basically, by feeling around, you get these unique views that give you really good classification."

The next step, he said, is to put the audible sonar onto a mobile robot and let it try to navigate with it. This will even more closely model the way people learn things. He compares it to the way people drive to work — rather than looking for every landmark, they look out specifically for certain ones that give the needed information. He added that it's likely that we'll never fully understand the human brain and its neurons. It's like building a computer from knowing how a transistor works.

"But I also predict that we can make a functional model of how the brain works, using the clues that neuroscientists give us and observing biological echolocators," he said. "These open small windows to the way the brain works."

"What's Amodio?"

This Yale Computer Science graduate student won $1.5M — and the hearts of viewers — to become the second highest winner in *Jeopardy!* history



Photos Courtesy of Jeopardy Productions, Inc.

Going into Final Jeopardy on July 21, Matt Amodio's victory was no guarantee. Josh, a traffic engineer from Idaho, was close behind and they both answered correctly ("Haile Selassie"). But three-day champion Josh bet conservatively, while Matt put his entire winnings on the line. That began an incredible 38-game winning streak, a record second only to his idol Ken Jennings. Almost daily, Amodio set new milestones — among them, he had the third-highest winnings ($1,518,601) and was first in the number of hosts he played under (six). Since his first appearance on the classic game show, the SEAS social media department worked overtime to make sure that our community stayed up-to-date on all things Matt.

His Jeopardy! *run has been so historic, he's poised to become his own* Jeopardy! *category. In preparation for that day, we offer a primer on this remarkable "Ph.D. student from New Haven, CT."*

Continued →

HOW MATT ENDED UP AT YALE

Amodio is a fifth-year Computer Science Ph.D. candidate in the lab of Smita Krishnaswamy, assistant professor of genetics and computer science.

"I definitely took a circuitous route," he said. "Other people might prefer more direct routes, but I certainly recommend mine to anybody who asks. I did my undergraduate at Ohio State, and I was in financial math. I'm a polymath — I like all subjects — but math was and is something that always particularly stood out to me."

He was lured away by a course in statistics, which played to his interest in sports, and he ended up with a master's in statistics. He got a job in data science, only to find that it wasn't really his thing. In 2017, he decided to pursue a Ph.D. in computer science.

"One of the places I applied was Yale. I saw the opportunity to work with Smita Krishnaswami here, who was generous enough to invite me on board. And I said, 'Yes, that looks like a good fit.'"

Even though it didn't work out the way he planned it, Amodio is glad for the two years of work between his master's and Ph.D. program.

"I think because of that, it's easier for me to appreciate the greater freedom and the greater intellectual challenge that academic research presents," he said.

HIS RESEARCH FOCUS

Amodio focuses on generative neural networks, which he describes as a "sub-niche" of artificial intelligence and deep learning. He applies it to biomedical data in the Krishnaswamy lab, which works at the intersection of computational biology, biology, and computer science.

One way to apply this science, Amodio said, is to use it to transfer sets of data. Suppose researchers are working with

two sets of data, and one happens to be genomic and the other is of protein surface markers. They're both measures of the same underlying system but provide two different ways to look at it. Collecting both sets of data, though, isn't so easy. Instead, you can use domain transfer methods to map one kind of data into the data of another model.

"One of the great things about working in the kind of applied computer science areas like biomedical data is that new problems are being generated on the biological side all the time," he said. "So we're not solving the same computational problems that people have been doing since Turing's day. There are new problems that are created by new technology on their side, and that constantly makes new challenges for us on the computer science side to solve."

HOW TOUCANS AND PENGUINS FIT INTO THIS

One of Amodio's favorite studies that he's worked on was a CycleGAN, which deals with image-to-image translation. It's the visual version of translating the two types of biomedical data.

"It's just a lot of fun to work with ImageNet and I was doing things like turning pictures of toucans into pictures of penguins," he said. "I confess that I spent way more time than I needed to just looking at the examples of output of my model because it was very silly and I often smiled."

ON WHETHER STUDYING GENERATIVE NEURAL NETWORKS MAKES HIM A BETTER *JEOPARDY!* CONTESTANT

"My snarky answer is that I think that I work with neural networks enough to know that they aren't going to be good at this." He's intrigued by the idea of working on a

next-generation Watson, the IBM computer that famously competed — and won — on *Jeopardy!* (between his research and his Jeopardy! experience, is anyone else more qualified for such a job?). But Amodio said human contestants need to find their own strategies of playing.

"I think it's just a completely separate way of going about it. These neural networks are very good when they have perfect access to gigabytes and data. But since our brains can't do that, we have to go about it a different way. I think studying social science — good ways of studying and good ways of retaining — has been far more helpful than anything in my home field of computer science."

SO, HOW DOES HE KNOW SO MUCH?

Regular *Jeopardy!* viewers soon found that is wasn't uncommon for Matt to sweep certain categories, especially those related to history. But his knowledge appears to have no bounds — he seems

Continued →

as equally versed in the founding fathers as he is with the Beatles, Greek mythology, and geography.

"You know, I read a lot — I have to credit my love of reading. I spend most nights starting somewhere on Wikipedia — reading everything there, but also getting 10 or 15 links from that article to other things that I'm interested in. That cascades to more and more and more, and before I know it, the night's over and I still have thousands of things I still want to read, and it just starts over the next day."

Yale

But he is human, and there are a few weak spots in his armor of knowledge. Mostly, it's any pop culture that's happened in his lifetime. For that, he put in some intense time studying TMZ. It's paid off, but it wasn't easy. "When I see things like celebrity marriages, I cringe a little bit."

FRIENDS, FAMILY, AND LAB MATES CELEBRATED HIS RUN— TO AN EXTENT

"They're just extremely happy," he said. "I've heard from people I haven't heard from since graduating from high school, maybe even middle school — just being very nice, sending congratulations. My parents are getting stopped just walking around the city. My mom, who was in the doctor's office, was getting stopped by nurses who weren't even her nurse, saying 'Are you Matt's mom?' It's just been a treat."

His lab mates have followed him on Slack, sending messages of encouragement. "They were a little more fast and furious in the beginning, and then I think they started to realize 'Oh, this might go on for a while.' They've been very supportive."

HE'S ALSO A WIZ AT SOCIAL MEDIA

Amodio is always quick with a fun tweet to his more than 28,000 followers, and has even traded good-natured barbs with fellow *Jeopardy!* hall of famer James Holzhauer. And he's funny:


Matt Amodio
@AmodioMatt

I've felt such tremendous support from the #Jeopardy community, I feel like we're on this run together as a team. Thank you! ❤️

(...but no, I'm not splitting the 💵 amongst us all a million ways, sorry about that...)

5:57 PM · Sep 25, 2021 · Twitter Web App

97 Retweets 18 Quote Tweets 4,167 Likes

BUT NOT ENTIRELY WITHOUT CONTROVERSY

Rather than beginning each answer with "who is" or "where is," as is the traditional *Jeopardy!* way, Matt began every response with "what's" regardless of whether it's a person, place, or thing. Self-appointed arbiters of *Jeopardy!* etiquette cried foul. But *Jeopardy!* producers had Matt's back and clarified that the rules allowed it. It's a strategy he says, that eliminates unnecessary mental labor and allows him to focus on the answer.

"That's the kind of thing we do in computer science all the time," he said. "You have a section of your program, and it does 'A' or it does 'B' and it has to decide which. Then you realize 'Wait, we never actually need to do 'B,' so you cut that off and just leave a smaller bit of program. It's cleaner, and where there are fewer things moving, there are fewer things that can go wrong."

WHEN DID HE REALIZE HE WAS *JEOPARDY!*-READY?

"They have an online test that they offer a couple times a year," he said. "I took it not because I thought I'd get chosen but because my dad was pestering me – 'You're smart, you can do it,' and I said 'No, I'm not going to do it.' He says, 'Just do it — for me!' So finally, I took the online test just to satisfy him and never expected anything of it. And I don't think I heard anything the first time, but the second time I took it, I got invited to an in-person audition. I definitely have to tip my cap to my dad on that one — you're right, I'm glad I did that!"

Preventing Dyes, and a Cultural Tradition, from Fading

Technology designed to preserve artwork can also help Afghan rug makers

Every artwork comes with its own set of challenges for conservators and curators, not least of which is curbing the effects of time. To that end, a device known as a microfading tester (MFT) gives art stewards a much better sense of where and for how long they can safely display a particular work before irreversible fading occurs. At Yale, researchers are working to make this technology not just more accessible to museums everywhere, but as a means to preserve cultural heritage in other parts of the world.

Developed by Paul Whitmore, the now-retired director of the Aging Diagnostics Lab at Yale's Institute for the Preservation of Cultural Heritage (IPCH), the MFT device helps predict how fast colorants, such as pigments and dyes, will fade under normal gallery display conditions. Using fiber optics, the device shines an intense beam of light on a microscopic spot of a material, measures the reflected light, and triggers the photochemical reactions that would cause light-sensitive colors to fade. Every minute the light shines on the material is equal to about one year of aging. Researchers typically use it for up to 5 minutes at a time, allowing them to see five years into the material's future.

“The MFT allows us to monitor dye or pigment fading in real time, predicting fading behavior in gallery conditions,” said Katherine Schilling, associate research scientist in chemical and environmental engineering and associate conservation research scientist at the IPCH. Because the microfading test essentially leaves no trace of altered color, objects can be quickly screened for their lightfastness – that is, how long dyes can resist the effects of fading. This helps determine future storage or exhibition requirements.

With the MFT, researchers can get information about the light sensitivity of everything from sloth fur to bird feathers to paintings, drawings, photographs, and textiles. Most recently, IPCH has been using the technique to test dyes used in rugs originating from an indigenous weaving community in Afghanistan, in support of a collaboration between Yale researchers and a non-governmental organization (NGO) that supports Afghan artisans, primarily women. (Due to the political instability in Afghanistan, a representative requested that the NGO's name not be used).

The project aims to help Afghan weavers find the best possible colorants, partly to preserve a centuries-old tradition, but also to give Afghan women a better chance to earn a livable income. Prior to the August 2021 takeover by the Taliban, there were known to be about 1 million rug weavers in the country. Even under the best of conditions, weaving is not an easy way to make a living.

“We partnered with a dynamic organization with the capacity to work directly in regions where weaving and other traditional artforms have been decimated by commercial or political interests, and now war and famine,” said Alison Gilchrest, the director of applied research and outreach for the IPCH. “These are communities where skills and methods have been passed through families for generations, and they deserve an opportunity to thrive.”

The NGO's representative noted that exporting handmade products has become a significantly growing industry, in part because people are increasingly buying with sustainability in mind.

“We work with a lot of retail partners who know their customers, and know exactly what sort of styles they like,” she said. “We have to make sure that we can present a product to them that works, based on their very serious commercial standards, and one of those concerns is fading. It happens in carpets and textiles through light and through touch. If you're going to create high-value jobs for women in rural Afghanistan, you better be able to create a product that doesn't fade.”

At the IPCH laboratory on Yale's West Campus, the researchers work with a large dye sampler rug provided by the NGO. In a grid of 190 squares, the sampler features patches of all the dyes used by the weavers.

“We're working through the sampler systematically to arrive at recommendations for which

Continued →

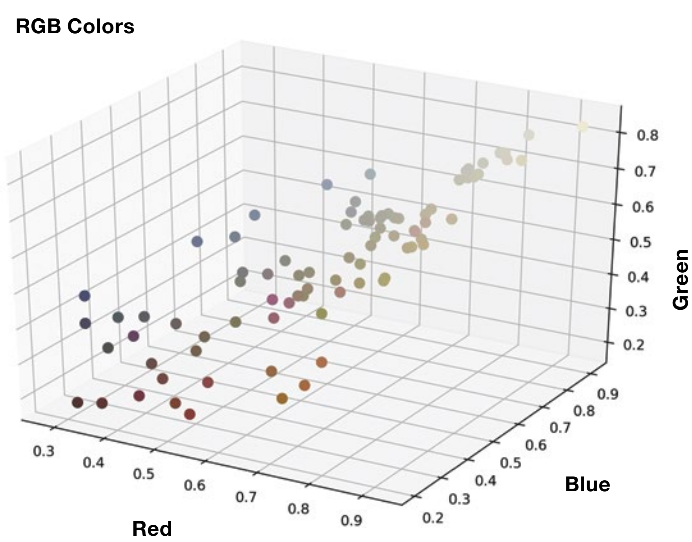
Above: *Vanessa Lamar '23 utilizes the MFT device to predict how fast colors in a given material will fade.*

colors are more prone to fade," Schilling said. "Given the range of options, the weavers can then make substitutions and hopefully still achieve a similar aesthetic effect."

Contributing to the Afghan rug project are two students, Vanessa Lamar, a physics major, and Daniela Flores, a chemical engineering major. Schilling prepared the students for this work by creating an independent study of the photochemistry of colorants during the spring semester. Using the MFT instrument, they measured various materials' lightfastness. Lamar said there was a bit of a learning curve in working the microfading device, but her physics background was a big help. At the end of the semester, she decided to continue with the project through the summer.

"I never thought that I'd be able to do something that combines my interest in art and humanities with science, and this position gives me an opportunity to explore that world," she said. "Even though I usually work with numbers and machines, it's good to know that the work I'm doing has a human impact."

The IPCH researchers also plan to broaden the use of the MFT- a goal that calls for a redesign to make it less costly and more usable for museums around the world. The lab contains a few versions of the MFT that were made since Whitmore invented it in the 1990s. It's time, the researchers said, for a more extensive reworking.



Above: *Distribution of the RBG colors from early testing data of Afghan rugs dyes.*

Background: *The dye sampler rug provided by the organization consists of small squares colored with different dyes, each one commonly used by Afghan weavers.* Above: *An assortment of external fabrics and colors are also tested to inform the lifespan of a certain material.* Left: *The software can measure how long specific dyes can resist the effects of fading.*

"The best way to honor the legacy of the project is to build on its success," Schilling said. It's an ingenious device, but it can be tricky to use, even for other scientists. It's also pricey - creating a new one could cost up $30,000, depending on the components. Several research teams in the U.S. and abroad, including the cross-disciplinary team at SEAS and IPCH - are working to bring the cost down to about $6,000.

"Our goal is to figure out how to make this technology accessible and transferrable at a lower price point," Schilling said. "We want to simplify the instrument design and software so that our partners and collaborators around the world can have access to the same powerful method."

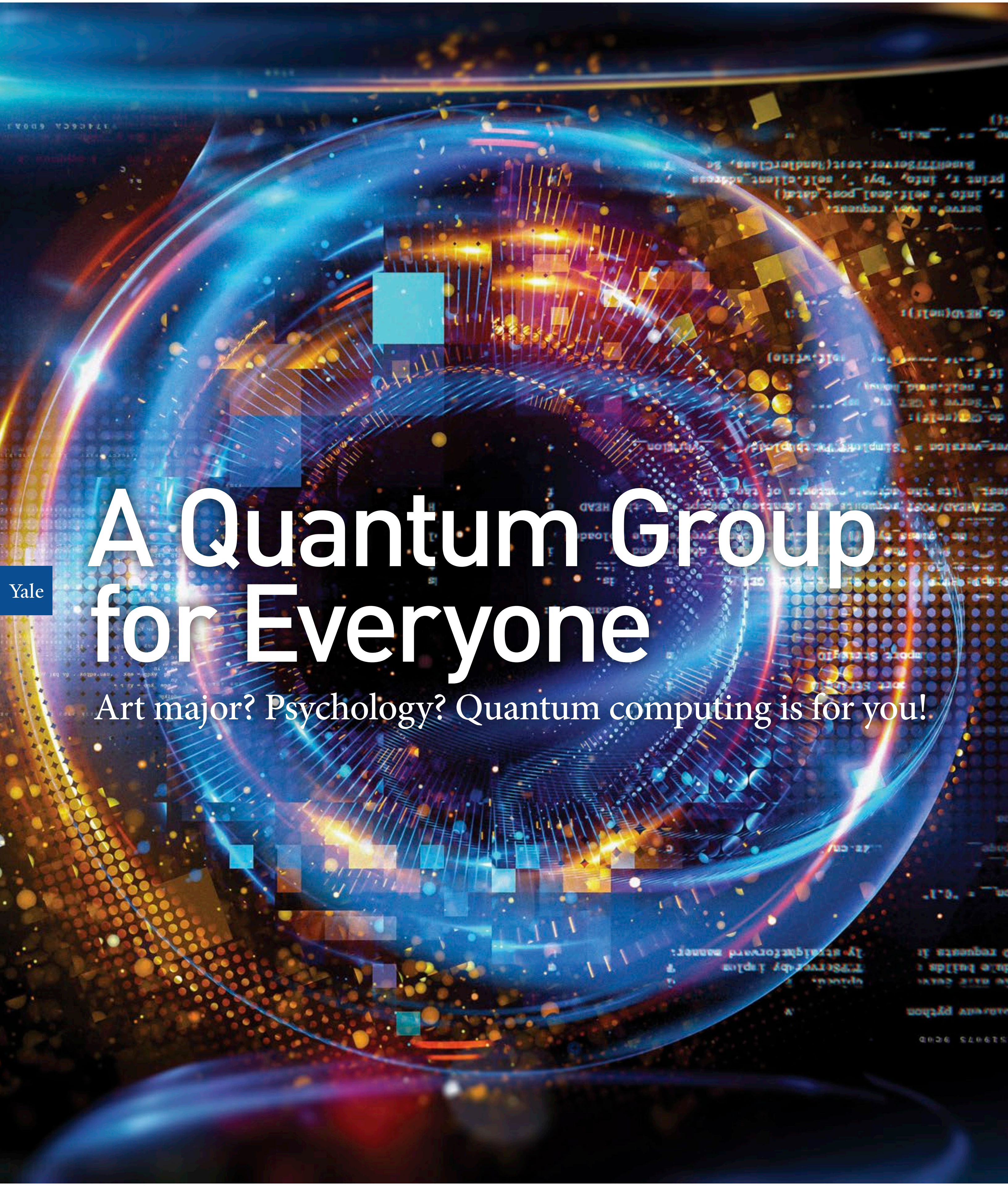
The more broadly the microfading technique is used, the more useful it becomes.

"If we can make the device and the method more accessible, then the global heritage community starts to build larger bodies of predictive data," Gilchrest said.

Adding to the research was Arizona high school student Ella Wang, who worked with the MFT as part of MIT's Research Science Institute program, which recruits top high school students from around the world for immersive science and engineering research during the summer. Working with Schilling and SEAS Deputy Dean Vincent Wilczynski, she used color maps and fading simulations to model the fading effects of UV rays.

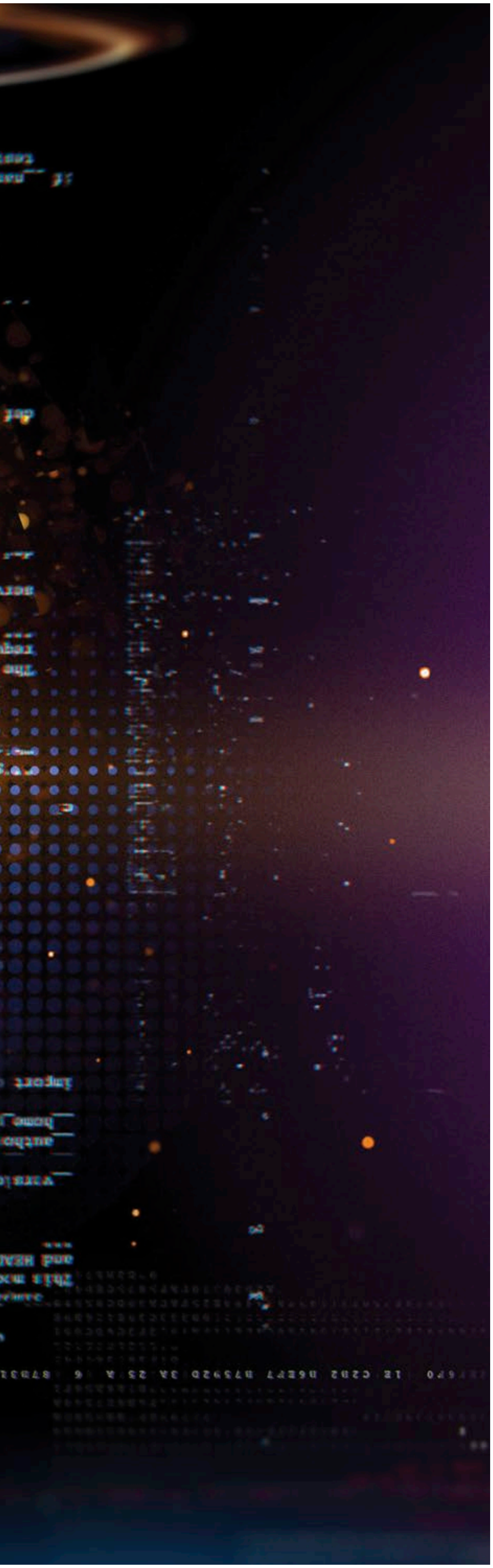
When the researchers finish collecting data for the Afghan rug project, they'll provide their research to the NGO, which will use it to help the rug weavers get the best quality materials for their craft. "It's a small project with potentially far-reaching impact," Gilchrest said. Besides getting valuable scientific research out of it, she said, it's a chance to make a difference for a particular community at a time when it most needs help.

"There's a pressing need to support these endangered and under-resourced communities in documenting and preserving their heritage," she said. "And with our deep and integrated science and art capacity at Yale, embodied by IPCH, it is incumbent on us to continuously question what more we can be doing on a global stage."



A Quantum Group for Everyone

Art major? Psychology? Quantum computing is for you!



Quantum science can be a little intimidating — even Einstein once called it "spooky." So it makes sense that it has developed a reputation as an all-or-nothing kind of commitment. Dabblers needn't apply.

But a new student group is looking to change that. The Yale Undergraduate Quantum Computing (YuQC) group was founded by Shantanu Jha, a math and physics major who graduated in December. Thinking of all the ways that quantum computing can be applied to other fields, Jha said he was inspired to engage a broad spectrum of other students with the emerging field.

"I did a lot of quantum engineering research at Yale, and I had a group of friends who were interested in this stuff — that really kindled my interest in the field," he said. "I wanted to build a community, and I realized that a lot of people are interested in quantum computing who don't come from the traditional background that you might associate with quantum computing."

Since it formed in the fall of 2020, the group has hosted social hours for its members, organized a quantum computing hackathon, and developed its Invited Speaker Series, which included presentations from YuQC advisors, Steven Girvin, the Eugene Higgins Professor of Physics, and Michel Devoret, the Frederick W. Beinecke Professor of Applied Physics.

Key to the group's success is the diversity of the members' backgrounds, said Nikhil Harle '23, a YuQC board member and one of the group's earliest members.

"I think a big misconception about this field is that you have to have the 'right' background or the 'right' degree to be able to contribute something," Harle said. "And through our programming, we've been working to challenge that."

In October, they held a meeting to gauge the level of interest. It turned out that there was a lot. More than 80 people signed up, from about 20 different majors. Some of these majors were the expected ones — physics, computer science, and math — but there were also those from economics, philosophy, psychology, literature, and others. Further, many of these students from non-traditional majors signed up for leadership positions in the group.

Continued →

> *"We just wanted to show people that you don't have to be an expert — you can come in and learn."*
>
> › Nikhil Harle '23

For a student group just getting off the ground — and primarily working remotely — the YuQC managed to quickly rack up some major successes. Working with a quantum student group at Stanford, they created the Quantum Coalition, an international network of university students that works to promote quantum information science across the world. It was through this partnership that they organized the Quantum Coalition Hackathon (QC Hack), an event that attracted 2,100 entrants from 80 countries. The event was sponsored by 10 company sponsors and included challenges proposed by five companies, each of which were to be solved in a 24-hour period. About half were technical, and half were more creative. The winning teams for each would present their projects, walking the audience through their process.

Besides attracting much more interest — and from a wider range of students — than they had anticipated, the organizers said the event went a long way to advance its goal of opening up quantum computing beyond those in the core fields of research.

"All of this was expressly open to beginners, and we tried to be very clear that you don't have to have any experience to be part of this, and we ended up having a lot of beginners joining," Harle said. "We just wanted to show people that you don't have to be an expert — you can come in and learn. I think we proved that with the hackathon."

YuQC's current co-presidents, Ayelet Kalfus '24 and Allen Mi '22, said one of their goals is to keep building on the group's momentum — including expanding the reach of the Quantum Coalition, and building on QC Hack.

"We're deeply excited about having all of our members on campus this semester," said Kalfus. "Many of our members had never met face to face and we think it will be awesome to continue our projects and talk in person as much as possible."

They're also continuing the group's interdisciplinary focus. The more students of varied educational backgrounds study quantum computing, Mi notes, the quicker the field can advance. For example, he said, if you want to build a quantum computer, you have to know about designing integrated circuits so that you can send pulses to the device. You also need some specific engineering knowledge because you want to build a dilution fridge that can keep the device very cool, about 70 millikelvins.

"Quantum computing is one area that would benefit a lot from interdisciplinary studies," Mi said. "For one thing, it's very new — there hasn't been a specific discipline invented for it. And the other is that it really draws from the best of all kinds of technologies."

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