Yale CHIMEs In

A health crisis sparks fast action and teamwork across the Yale campus

A Quantum Leap: Applied Physics Joins SEAS

The union helps advance the university's goals for science and engineering

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An overlooked structure in the foot could be key to long-standing questions about evolution

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YALE ENGINEERING

Solutions in Sewage

How researchers are predicting COVID-19 outbreaks from wastewater

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

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Front Cover: *By testing sludge from various Connecticut wastewater treatment plans for SARS-CoV-2, the virus that causes COVID-19, Yale researchers are able to predict outbreaks approximately five days in advance.*

COVID-19 · EDUCATION · INTERDISCIPLINARY · MEDICAL INNOVATION · SUSTAINABILITY · TECHNOLOGY

YALE ENGINEERING 2020-2021

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Message from the Dean

A family is a circle of strength — every crisis faced together only makes the circle stronger. When our community faced a challenge unlike any we have seen in our lifetimes, I was privileged to witness the power of our family circle and be a proud member of the tight bond we share here at Yale.

As COVID-19 spread throughout the region, the resilience of our SEAS community set the tone for Yale's response — our creativity, our innovative spirit, and our roll-up-your-sleeves approach to urgent problems brought the campus together to focus on immediate solutions. From faculty, students, researchers, staff, and alumni, ours was an all-hands-on-deck mobilization.

As you'll read in these pages, we brought our individual strengths to bear in our response to this crisis. In doing so, we forged new and deeper connections across our Yale community. Helping our community take urgent action in the face of an incipient pandemic was both humbling and inspiring.

Among these efforts is a faculty-led collaboration with State of Connecticut epidemiologists to study RNA in wastewater to predict COVID-19 outbreaks days in advance — an innovation that's proving to be a critical public health tool as we make our way through yet another surge. SEAS also led a University-wide team to address local shortages of medical equipment such as masks, respirators, and other personal protective equipment, as well as new methods for "multiplexing" ventilators so our doctors can serve more of the sickest patients.

In the spring, to engage our researchers who had ramped down their labs in the shutdown, we organized a series of workshops focusing on applying data science to the complex issues of COVID-19. These workshops brought researchers from across our science, engineering, and public health community to share their expertise and discuss how new collaborations could help understand and mitigate the pandemic.

Also crucial to the effort were SEAS undergraduate students, who took on numerous COVID-related projects. These include increasing safety for train passengers; assisting the nation of Colombia on face shield guidelines; and devising a system to help the City of New Haven keep track of PPE supplies. They also looked out for each other in these trying times, with one team developing technologies and a peer network to help alleviate anxiety among students.

I take deep pride in our response. As you read these stories, I hope you share the same sense of pride in our SEAS family.

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

2019: September

Understanding, and Treating, Addiction

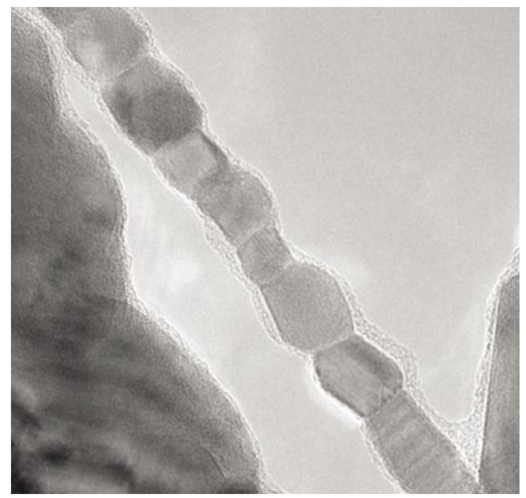
To better understand opioid addiction, Yale and the University of Pennsylvania created a neuroimaging center that focuses on opioid use disorders and finding new treatments for them. Richard Carson, professor of biomedical engineering and radiology & biomedical imaging is leading Yale's effort. "This partnership takes advantage of the combined and complementary expertise at both universities to both develop new imaging technologies, and to address important questions in an area of high clinical need," said Carson. The center is funded by a 5-year, $8.9 million grant from the National Institute on Drug Abuse.

2019: October

Where the Makers Unite

iSAM 2019

For three days, makers from around the world gathered at Yale for the 4th International Symposium on Academic Makerspaces. There, they talked shop, traded notes, and heard from leaders in the growing multi-disciplinary field. The annual event is the result of the partnership between Yale and six other universities. "A strong message of the symposium was that by providing access to all, you provide opportunities to all," said SEAS Deputy Dean Vincent Wilczynski, and director of Yale's makerspace, the Center for Engineering Innovation & Design.



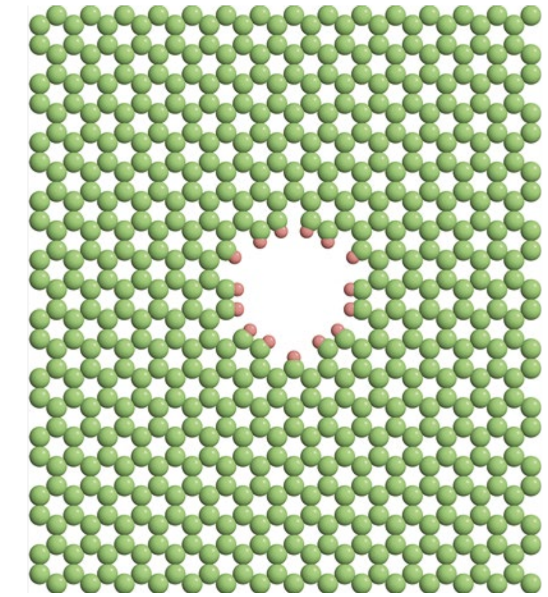
2019: November

Controlling Unpredictable Materials

The field of quantum materials is still in its earliest stages but shows great promise for numerous breakthroughs. Greater control in how these materials are synthesized would be a huge step forward for the field. That's what Judy Cha, the Carol and Douglas Melamed Associate Professor of Mechanical Engineering & Materials Science, is working on with a $1.7 million research grant she received from the Gordon and Betty Moore Foundation. "It's about knowing the ingredients and the knobs I need to tune for my materials, and that means we need to understand how these materials are synthesized and the methods for doing so," she said.

2019: December

The Tricky Science of Membranes



Controlling what passes through membranes is crucial to numerous applications, from water filters to developing new medicines. It relies on semipermeability, the ability to let some things pass while blocking others. But designing membranes to do exactly what you want is tricky. Using a recently-developed technique, known as "jumpy forward flux sampling," Amir Haji-Akbari, assistant professor of chemical & environmental engineering, developed a way to allow researchers to accurately account for the progress of an ion or solute, even though the patterns of the movements can change significantly over a short period of time.

2020: January

Protecting Ancient History

Vibrations in the museum environment — construction or loud sounds, for instance — can be particularly risky for artwork that's thousands of years old. With this in mind, students in Introduction to Engineering, Innovation, and Design (ENAS 118) worked with the Metropolitan Museum of Art to keep the famed museum's Egyptian Art collection lasting for many more millennia. Working in the CEID's Klingenstein Lab, the four first-year students built a scaled-down mock pedestal and coffin and devised a finely calibrated system of springs and polyethylene foam to absorb the vibrations.

2020: February

Recognition for an Innovator

Cited for her contributions to research in cardiovascular tissue engineering, lung regeneration, and biomedical imaging, Laura Niklason, the Nicholas M. Greene Professor of Anesthesia and Biomedical Engineering, was elected to the National Academy of Engineering. Niklason's research is focused on creating engineered blood vessels and lung tissue using bioreactors, with the eventual goal of providing new ways to treat patients, including those with kidney failure, heart disease, or in need of certain organ transplants.

Continued →

Year in Review

2020: March

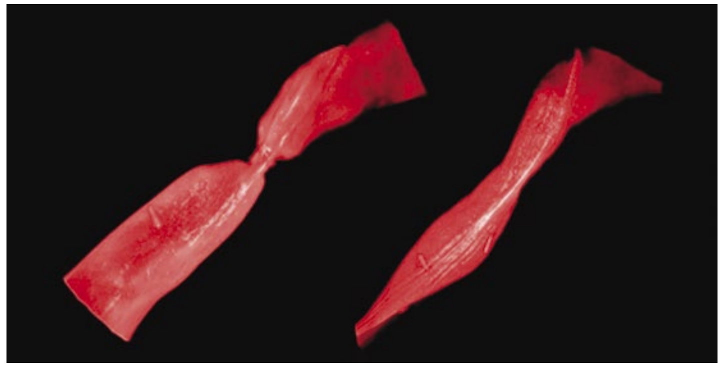
Clearing the Air on Third-Hand Smoke

It turns out that third-hand smoke — the residual effects of cigarette smoking that stick to walls and other surfaces — can travel from one location to another. The finding is the work of a team of researchers led by Drew Gentner, associate professor of chemical & environmental engineering and the environment. They showed for the first time that even if someone is in a room where no one has smoked, exposure to many of the hazardous chemical compounds that make up cigarette smoke is still possible, depending on who else has been in the room.

2020: April

Saving a Potentially Life-Saving Technology

A computer model developed in the laboratory of Jay Humphrey, John C. Malone Professor and Chair of Biomedical Engineering, helped save a promising medical technology. The tissue-engineered vascular graft (TEVG) was designed to help children with congenital heart defects, among the most common of all birth defects. Early evidence of problems with the TEVG, however, brought a clinical trial of the device to a premature end. The computer model simulations, however, showed that the narrowing of the TEVG would reverse itself in a short period of time and work as designed. With some additional testing, the trial resumed.



2020: May

Environmental Testing Made Easy

With the Fresh Air wristband, Krystal Pollitt, assistant professor of epidemiology and chemical & environmental engineering, developed a lightweight, wearable air pollutant sampler. During initial testing, the device reliably collected and retained air pollutant molecules over time, allowing for easy analysis to monitor large segments of a population. It was initially designed to detect air pollutants, but Pollitt is also exploring its use for monitoring small airborne pathogens such as coronavirus, and is working with Yale's Jordan Peccia in chemical and environmental engineering on a field test with the help of health care providers at Yale-New Haven Hospital.

2020: June

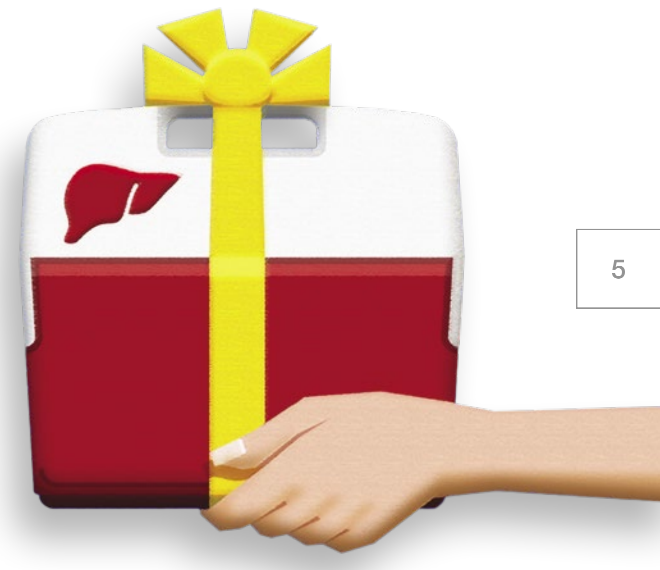
Robots Connecting Friends

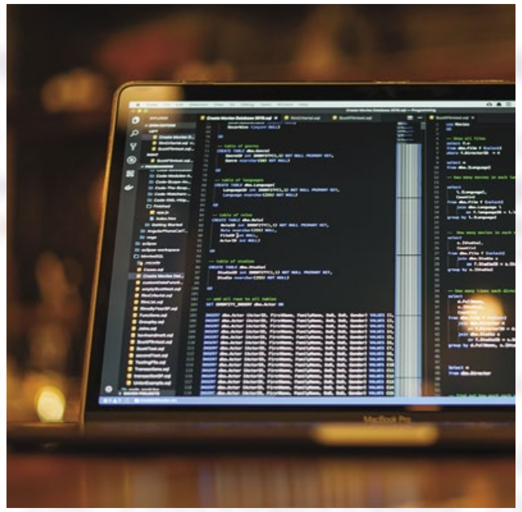
A team of roboticists used their skills to make social distancing a little easier for elementary school-age children. Students in the labs of computer science professors Brian Scassellati and Marynel Vazquez developed an app, VectorConnect, that allows kids to use robots to interact with their friends in separate homes. The free app works with a commercially available robot and allows the user to control the robot in the other person's home. With help from a generous donation from Evren Bilimer '00, a limited number of robots were distributed to families in the New Haven area for free.

2020: July

Repairing Organs for Those in Need

More than 93,000 people currently await kidney donation, but many donor organs are deemed unsuitable. A new procedure pioneered by Yale and the University of Cambridge could make rejected kidneys fit for transplant. Working with human kidneys deemed unsuitable for transplant, the researchers identified why they were poor candidates. Using a process they developed, the team was also able to reinvigorate and qualify them for clinical transplant. The researchers plan to launch a clinical trial at Yale in early 2021.





2020: August

Meeting a Demand

As demand for computer programming skills continues to increase in a broad range of fields, Yale began offering its first Certificate in Programming this semester. While not as extensive as a Computer Science degree (one of the most popular majors at Yale), it provides a short path to programming literacy and prepares undergraduate students to program computers in support of work in any area of study. Zhong Shao, the Thomas L. Kempner Professor and Chair of Computer Science, said the department is "really excited about offering this new Certificate in Programming to all Yale students."

Yale CHIMEs In

A health crisis sparks fast action and teamwork across the Yale campus

In March, days after Yale and most of Connecticut went into lockdown to curb the spread of COVID-19, there was an increasing concern that hospitals might run out of supplies critical to fighting the disease.

In response, Yale faculty and staff from a wide range of disciplines quickly pooled their skills and resources to come up with solutions. This group, the Coalition for Health Innovation in Medical Emergencies (CHIME), brought together engineers, physicians, nurses, and many others to identify the most crucial shortages facing healthcare workers — and then, ways to increase those supplies. This included expanding access to personal protective equipment, ventilators, respirators, and nasopharyngeal swabs. Organized by the staff at the Center for Engineering Innovation & Design (CEID), rapid progress was made on a number of projects, from the creation of a device and a protocol for measuring the reliability of non-certified respirators, to work on the design of ventilator systems that treated more than one patient at a time.

"We've seen as our faculty turned on a dime to take projects they were working on that were non-COVID-19-critical and repurposed them — repurposed their labs, and repurposed the work they were doing — to address what could have a tremendous and important impact on the outcome of the pandemic," said Jeffrey Brock, Dean of the School of Engineering & Applied Science.

The coalition was formed to take advantage of Yale's culture of collaboration, and its diverse range of expertise which includes specialists in engineering, public health, nursing, medicine, and design. The coalition also leveraged Yale's significant fabrication resources, such as those at the Wright Laboratory, the School of Architecture, the Neurotechnology Core at Yale's medical campus, and the CEID.

"Innovative output requires diverse input, so we convened a multidisciplinary team that could look at problems from fresh perspectives," said Joe Zinter, assistant director of the CEID, who helped coordinate CHIME's efforts.

"Giving us More Options"

At a time when many hospitals were running low on personal protective equipment, a Yale-built system that tests non-certified respirators and masks opened up valuable new options for healthcare workers. Typically, hospitals have a steady supply of respirator masks certified by the National Institute for Occupational Safety and Health. At the height of COVID-19 cases in Connecticut, though, a shortage of these masks made finding suitable alternatives a must. Many non-certified masks in circulation, however, are of unknown quality and safety. To identify the most suitable products, Yale researchers developed a system to test the quality of these respirators. This solution to an unprecedented situation was made possible by the collaboration of researchers in different fields.

"Testing for masks on your medical campus isn't normal, but it's necessary right now — like many things we're doing now in the state of COVID-19, it's all about what we need to do for patients and our frontline healthcare workers," said Dr. Lisa Lattanza, chair of Orthopaedics & Rehabilitation at Yale's School of Medicine. "We want to protect our frontline heroes from getting sick, and the ability to test on campus just gives us more options to do that in the time of a really tight supply chain."

Stationed at the CEID, tests of the masks are run on the device and determine how well the respirators filter out aerosols, as well as how well they allow

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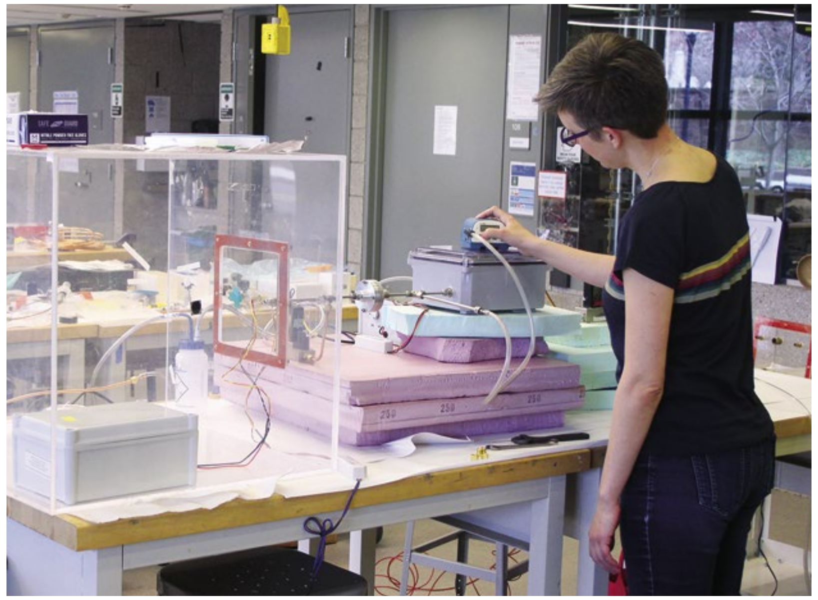


Senior research scientist Lawrence Wilen (left) and associate research scientist Katherine Schilling (right) conduct tests on the quality of non-certified respirators.

their wearers to breathe. They're conducted by senior research scientist Lawrence Wilen, associate research scientist Katherine Schilling, and CEID design fellow Antonio Medina, with guidance from Drew Gentner, associate professor of chemical & environmental engineering and the environment.

The results showed a wide range of quality and were shared with Lattanza and Yale Environmental Health & Safety, which conducts its own tests on how well the masks fit. Wilen said the tests at the CEID provide data that allow Lattanza and her colleagues to make informed decisions.

"We see this as sort of a pipeline — in the end, they're trying to come to some decisions about which ones have the best chance of being the highest quality," he said. "With this information, they can come up with a priority list, and if they start at the top and go down, it optimizes their chances of doing better."

Under the unique conditions, a lot of creativity and fast-thinking was required to build the device. Without the immediate use of an atomizer to generate an aerosol, they used incense instead. In the SEAS Machine Shop in the basement of Dunham Laboratory, research support specialist Nicholas Bernardo "scrounged up some materials" to fashion from scratch a new filter holder made out of aluminum (existing models are made out of Teflon, which wouldn't work for this device). He made the first component in six hours.

"It's was a time when we were all feeling unique pressures, but also finding unique solutions," said Vincent Wilczynski, SEAS Deputy Dean and the James S. Tyler Director of the CEID.

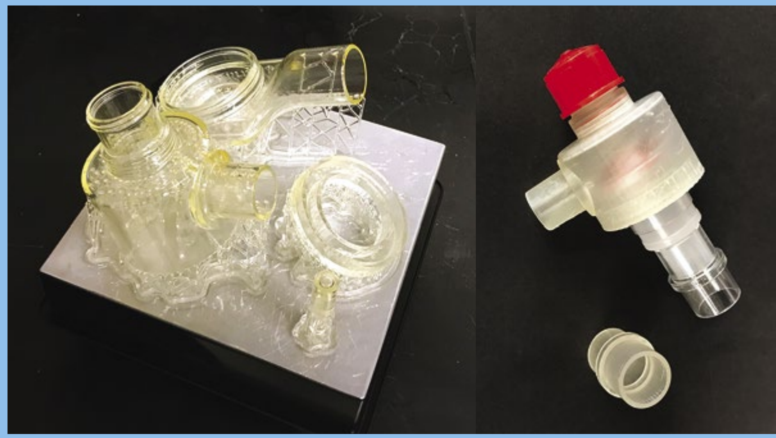
Continued →

Above: *In the SEAS Machine Shop, research support specialist Nicholas Bernardo creates a new filter holder made out of aluminum to aid in respirator testing.*

Other CHIME-Associated Projects Include:

Moldable Face Shield Design

A partnership between Cisco Research Center, the Yale School of Nursing (YSN), and the department of computer science resulted in the creation of 1,000 injection-molded face shields. John Marshall, distinguished engineer at Cisco, said his team started work on the moldable face shield design and created a new design that allowed the use of alternate materials for the elastic strap as well as simplified construction to facilitate efficient injection molding. YSN Dean Ann Kurth said the face shields would be critical in supporting the personal protective equipment needs of students at clinical sites.

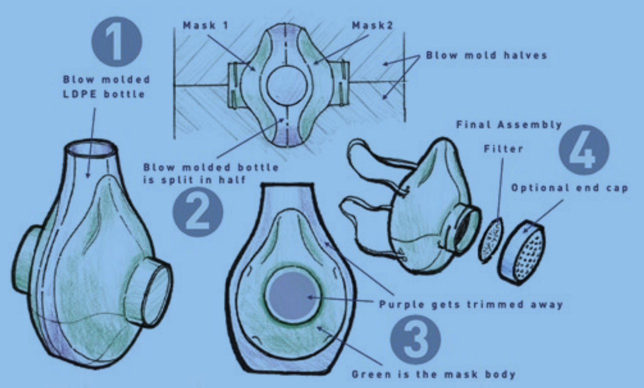


Single-use Ventilator Components

In addition to a shortage of ventilators, single-use parts for ventilators such as tubing and connectors ran low in hospitals at the peak of COVID-19 cases. To relieve this shortage, Dr. Daniel Wiznia, assistant professor of orthopaedics and rehabilitation and mechanical engineering & materials science, worked with James Nikkel, associate director for instrumentation and education at the Wright Laboratory. After identifying eight ventilator parts as being in particularly short supply, the researchers used 3D printers to create prototypes of these parts.

Local Industry Respirator Design

In another effort to increase access to face masks, staff and faculty at the School of Medicine, the CEID, and Yale Environmental Health & Safety, worked with Unilever to produce alternative respirators made with two distinct high-volume production methods: blow-molding and injection-molding.

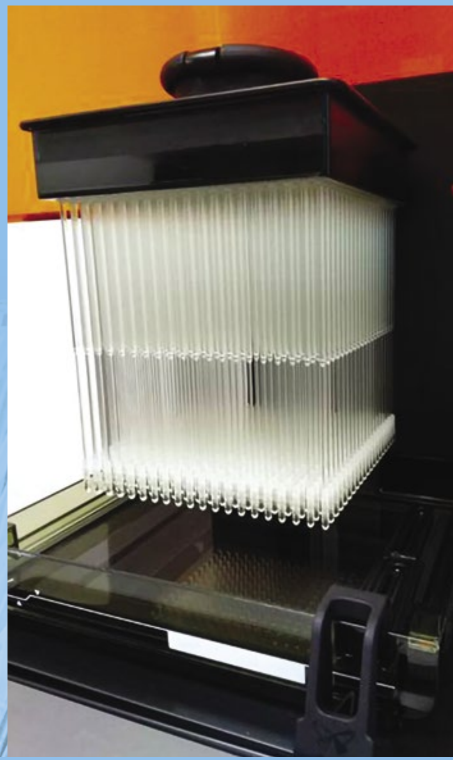


Testing Mask Reuse with Computer Simulations

To help hospitals make the most of what supplies they have on hand, Yale alums and CEID staff developed computer simulations to predict the mechanical properties of single-use face masks when they're reused — a possible necessity due to shortages. The team's computer simulations took into account various failure modes of masks, such as contamination, strap breakage, and filter efficiency to determine the average number of hours a given mask can survive in a hospital.

Printing NP Swabs

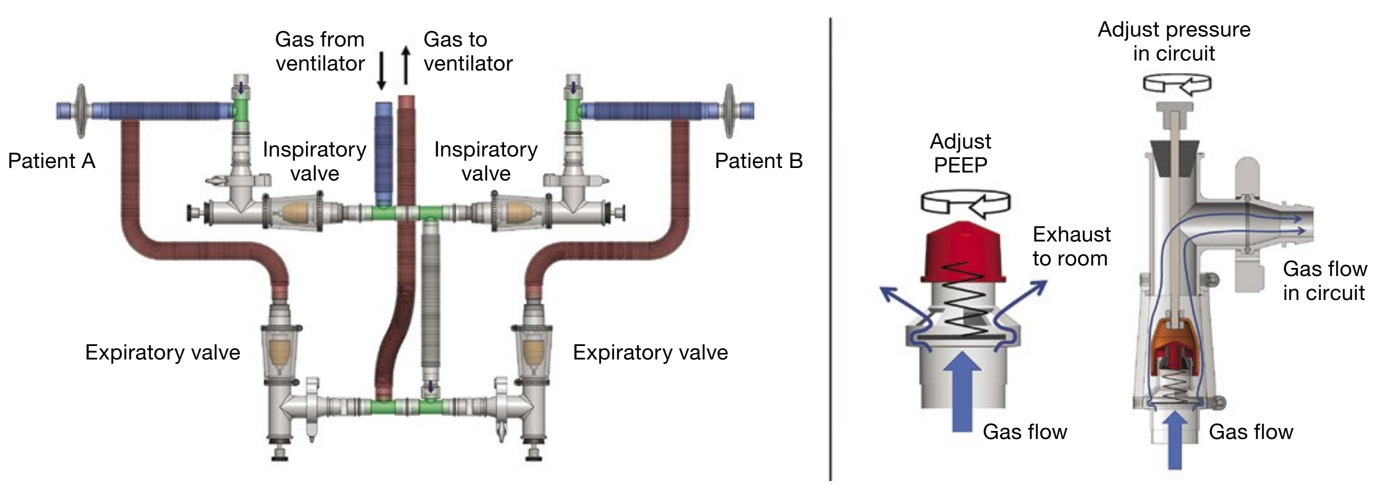
COVID-19 testing led to an urgent need for nasopharyngeal (NP) swabs, used to collect samples from patients. To alleviate the shortage, faculty in the departments of endocrinology, pathology, and biomedical engineering partnered to establish a local mechanism for 3D printing swabs based on an FDA-approved process. After local manufacturing in the department of endocrinology, the NP swabs were autoclaved, packaged, and then added to the hospital's inventory.



Ventilator Innovations

As COVID-19 cases rose, there were concerns that hospitals wouldn't have enough of the ventilators needed for the most severe cases. Rather than building new ones, which would take too much time and resources, some CHIME members focused on finding ways to modify existing ventilators. Because COVID-19 patients vary in their physiological and immunological profiles, though, simply dividing a ventilator's capacity between two patients isn't sufficient — a setting that stabilizes one patient could make another patient far worse. The problem called for a more nuanced solution.

One of these projects came out of the laboratory of Dr. Laura Niklason, the Nicholas Greene Professor of Anesthesiology and Biomedical Engineering. Their system, known as the Pressure Regulated Ventilator Splitting (PReVentS), allows one ventilator to not only treat two patients simultaneously, but in a way that fits both patients' physiological needs. While the PReVentS splitter is designed for simultaneous use by two patients, a study published by the team shows that the system could possibly allow a single ventilator to be used by up to four patients. The researchers note, though, that treating multiple patients with one ventilator would be for emergency situations only.

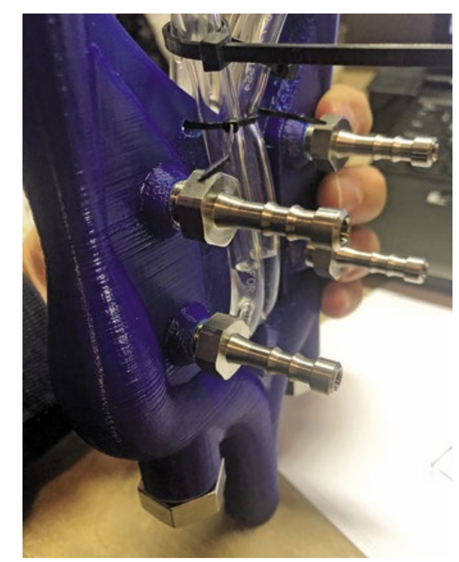


As COVID-19 cases rose, a shortage of ventilators become a critical concern for hospitals. The laboratory of Dr. Laura Niklason created a system that splits an existing ventilator to treat up to four patients simultaneously, but adjustable to fit all patients' physiological needs.

Left: *Sam Brickman Raredon, a member of the Niklason Lab, illustrates how PReVentS can treat multiple patients at the same time.* Middle: *PReVentS being tested and analyzed.* Top Right: *A design that was easy for hospital staff to quickly assemble in a high-stress environment was critical.* Right: *CHIME members also designed an adapter to convert an off-the-shelf positive end-expiratory pressure ventilator valve element into a device that can be used in the vent-splitting circuit.* Bottom: *An alternative multiplexing design that incorporated Venturi-based pressure measurements for each air pathway.*

Working with the Niklason group was Yale alum Joe Belter, director of actuator engineering with ClearMotion, who said they were aiming for a design easy for hospital staff to put together and use in a very high-stress environment. After creating some computer-aided designs, the team printed out prototypes at the CEID, the Wright Laboratory, the School of Architecture, and even Belter's home office. Those were then handed over to the Niklason group so they could review it and work through some of the layouts.

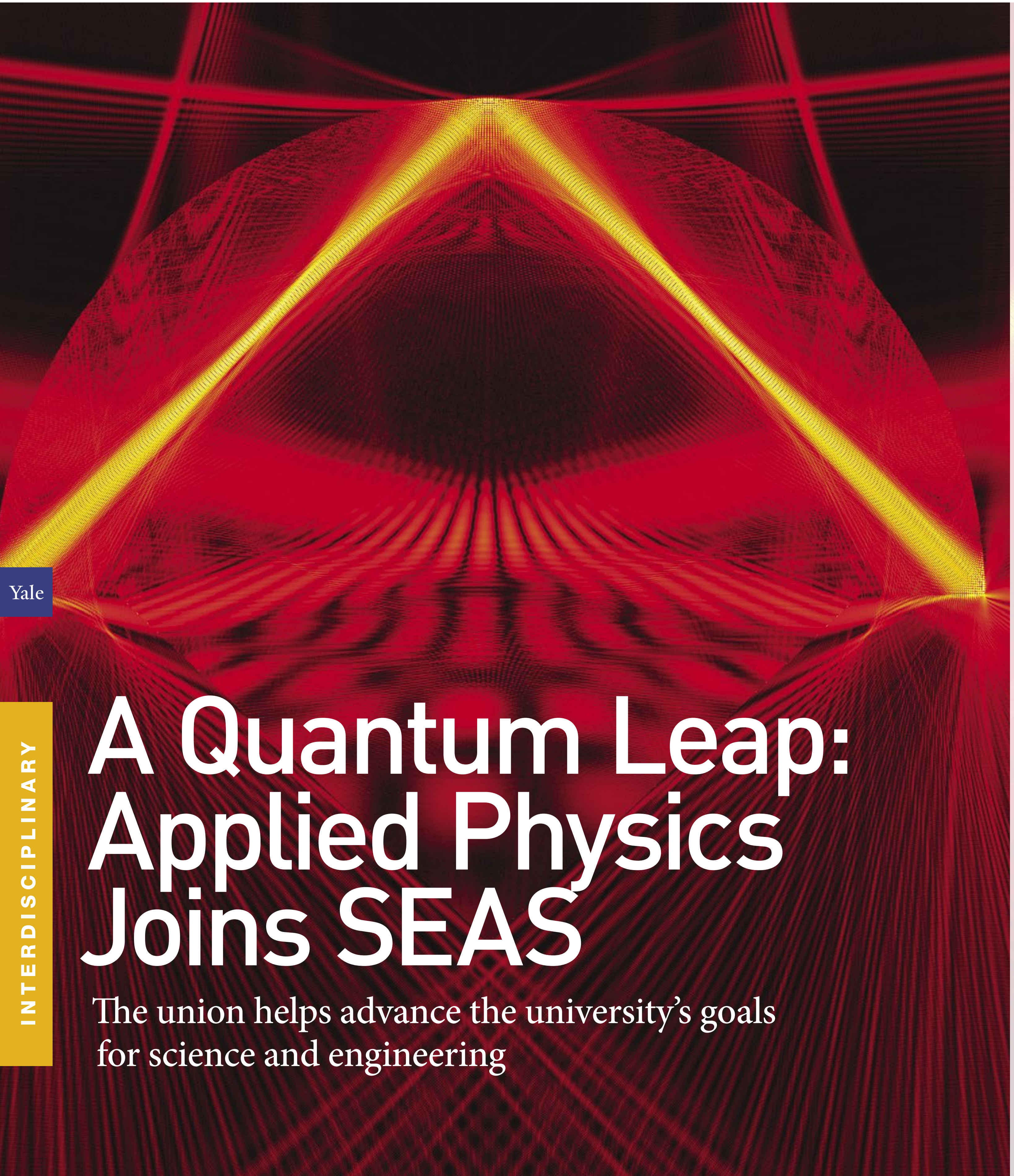
Belter and others at CHIME worked on a separate ventilator project, in which they looked into ways to design a device that can be 3D-printed, added to a standard ventilator, and allow for the ventilation of multiple patients while still independently controlling the air flow to each. When putting together some prototypes, a major part of the process involved consulting with another Yale alum, Becky Robinson-Zeigler, deputy chief regulatory officer with Advanced Regenerative Manufacturing, to advise on certifications and tests pertaining to the work.



"We're fortunate to be at a place like Yale, which maintains such strong connections to former students that they're willing to stop what they are doing to help out in a crisis," Brock said. "From alumni, to staff, and to faculty, it's been all hands on deck."

Yale

COVID-19



Yale

INTERDISCIPLINARY

A Quantum Leap: Applied Physics Joins SEAS

The union helps advance the university's goals for science and engineering

The field of applied physics seeks solutions to critical problems through the study of nature's laws and by the application of technology. So, when it was announced in July that the Department of Applied Physics (AP) would be joining SEAS, Yale officials agreed that it was a perfect fit.

"This is a great move for the School of Engineering & Applied Science, Applied Physics, and the university," said SEAS Dean Jeffrey Brock. "AP is a crucial link between physics and engineering. By bringing AP back into SEAS, that link becomes even more pronounced, and collaborations will surely be all the more fruitful and better resourced."

AP and SEAS researchers share a long history of working together, and the merging of the two will only emphasize that spirit of collaboration. Michel Devoret, the Frederick W. Beinecke Professor of Applied Physics & Physics said that rejoining SEAS has been a "longstanding collective wish of the department in general" since 2010, when AP left the school as part of a restructuring.

"My group is already collaborating with professors in Electrical Engineering, such as [Llewellyn West Jones, Jr. Professor of Electrical Engineering, Applied Physics & Physics] Hong Tang, so that will definitely be easier," Devoret said. "I think the most important element is that we're sharing the whole infrastructure, so it's much better to be part of the same school."

Sohrab Ismail-Beigi, professor of applied physics, physics, and mechanical engineering & materials science, said that the focus of AP research is fundamental science "near the border between science and engineering, but somewhat on the science side of the line."

"This is why research collaborations with SEAS faculty are potentially so beneficial, since the more engineering-oriented researchers can help transform successful basic science demonstrations into more practical real-world applied devices or inventions," he said. And with more efficient use of resources and space for future research, teaching, and hiring, he said, even more ambitious efforts will emerge.

In recent years, faculty from SEAS and AP have collaborated on numerous research projects, including one that focuses on finding new materials for the hardware of quantum computing. Selected and funded by the U.S. Department of Energy, the ongoing project seeks to develop the core quantum computing and networking components that would make the uncanny world of quantum physics realistic for computing. Another collaboration could lead to important insights about gene regulation and the genome, as well as cancer and other diseases. That project, led by researchers in SEAS and AP, is supported by a National Science Foundation program that focuses on interdisciplinary approaches to studying chromatin and epigenetic engineering.

Other SEAS-AP collaborations have emerged out of several interdisciplinary research programs, such as the Center for Research on Interface Structures and Phenomena, an interdisciplinary materials research center that was funded by the National Science Foundation; the Yale Quantum Institute, which facilitates the research and teaching of quantum science on campus; and the Yale Institute for Nanoscience and Quantum Engineering, which focuses on nanoscale research and applications and brings together researchers in the physical sciences and engineering with those in the fields of medicine and biology.

Continued →

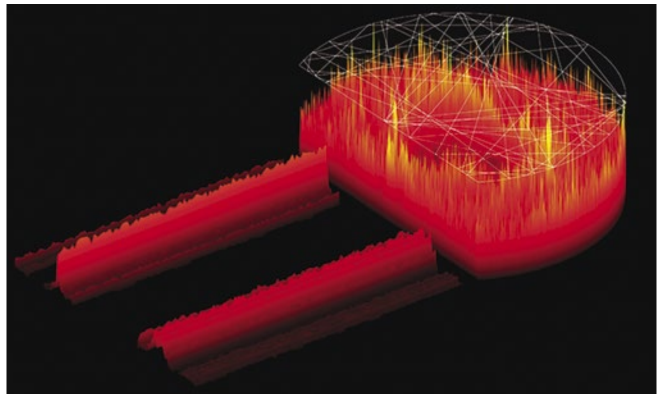
Quantum Leaders

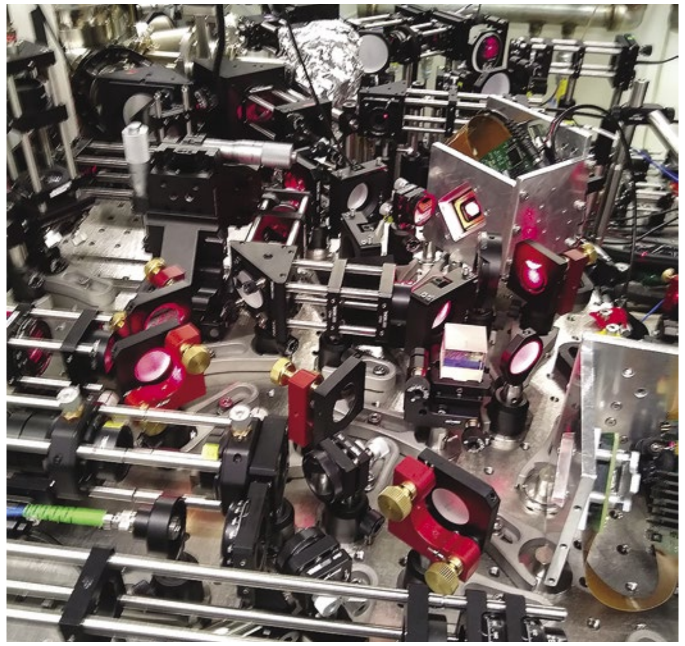
In recent years, Applied Physics at Yale has been one of the leaders in the field of quantum technology, which takes advantage of the properties of electrons, photons, and atoms to develop computers powerful enough to process a massive amount of information. Quantum science has benefited significantly from the work of Yale researchers. The first all-electronic quantum processor was invented at Yale about 10 years ago. Yale researchers are also world leaders in advancing quantum error correction and fault-tolerance — something that's a challenge for traditional computer systems, and even more so in quantum systems.

"The Yale team has contributed several out-of-the-box ideas to address these challenges and was the first to succeed in using error correction to extend the lifetime of quantum information," said Steven Girvin, the Eugene Higgins Professor of Physics & Applied Physics at Yale.

Given Yale's contributions, it's no wonder that the University is a principal player in two major quantum research centers, each announced within weeks of each other (see below for more details on the centers).

AP joins SEAS at a pivotal moment in Yale's history as the university carries out a set of large-scale strategic investments in science and engineering. The move also brings the university one step closer to fulfilling its strategy for the sciences and engineering. The Report of the University Science Strategy Committee (USSC) noted that Yale has "great potential to be the first institution with a comprehensive, university-wide research and education program in Quantum Science, Engineering and Materials." Such a





Top Left and Right: *A look inside some of Yale's quantum labs, including quantum information processing experiments and an optical table for allowing precise experiments in the field of quantum many-body.* Bottom Left: *The D-shaped cavity produces quantum chaos within the cavity, resulting in a more stable laser, from the lab of Prof. Hui Cao.*

Yale

INTERDISCIPLINARY

Two Major Quantum Research Centers

Weeks after Applied Physics officially joined SEAS, several AP faculty became partners in two major quantum research centers.

On August 26, the White House and the United States Department of Energy announced that Steven Girvin, the Eugene Higgins Professor of Physics & Applied Physics at Yale, will serve as director of the Co-design Center for Quantum Advantage (C^{2}QA). Led by Brookhaven National Laboratory, it launches with funding of $115 million over five years. Besides Girvin, the center will include many prominent Yale researchers, including Robert Schoelkopf, Charles Ahn, Michel Devoret, Leonid Glazman, Peter Rakich, and Hong Tang. Girvin will have a dual appointment at Yale and Brookhaven's Energy and Photon Sciences Directorate.

In all, two dozen institutions will participate in C^{2}QA, which will bring together scientists and engineers from a variety of backgrounds with the goal of dramatically advancing the state of the art in quantum information processing and communication.

In addition to Girvin's role, other SEAS faculty will play key roles in the new center:

- **Robert Schoelkopf** (applied physics) will lead the devices group, seeking to dramatically improve the performance of quantum bits (qubits) and related hardware.
- **Hong Tang** (electrical engineering) will lead the devices sub-group on transduction of quantum signals between the microwave domain, where the computers and superconducting qubits work, and the optical domain where optical fiber can be used for quantum networking.
- **Peter Rakich** (applied physics) will design hybrid optical/mechanical systems for signal transduction.
- **Michel Devoret** (applied physics) will lead the devices sub-group on quantum error correction.
- **Charles Ahn** (applied physics/mechanical engineering & materials science) will synthesize and characterize new materials for quantum devices.

"The mission of our center is to carry out the fundamental interdisciplinary research that will break us out of the current era of noisy, intermediate-scale quantum computers and lead the way forward into the era of practical, large-scale quantum computers that will offer a large computational advantage over traditional computers," Girvin said. "We will also focus on key quantum communication technologies needed to network clusters of quantum computers."

The center will focus on research aimed at harnessing the full power of quantum science.

"If we can build practical, large-scale quantum computers, we hope to be able to design new catalysts for energy-efficient synthesis of chemicals such as fertilizers, design new drug molecules that will bind to specific targets, and rapidly solve complex optimization problems of great commercial and scientific importance."

In addition to the C^{2}QA, Yale researchers also became partners of the new Center for Quantum Networks (CQN), funded by the National Science Foundation (NSF).

With the University of Arizona serving as the lead institute and host, the center will be funded with an initial five-year, $26 million grant from the NSF, with an additional five-year $24.6 million option. In addition to Yale, partners include Brigham Young University, Harvard University, Howard University, the Massachusetts Institute of Technology, Northern Arizona University, University of Chicago, University of Massachusetts Amherst and University of Oregon.

The center is part of the NSF's Engineering Research Center (ERC) program, which supports education, technology translation and research at U.S. universities designed to have strong societal impacts. Although they're initially funded by the NSF, ERCs are expected to be self-sustaining within 10 years.

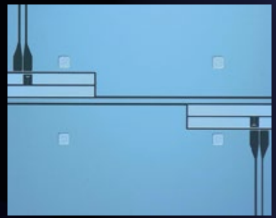
CQN aims to lay the foundations of the quantum internet — a communications network that would be more secure and could work with the next generation of computers. CQN will also investigate the impact of a future quantum internet on education, workforce development, innovation, and society.

Yale's participation in the center is led by Leandros Tassiulas, the John C. Malone Professor of Electrical Engineering & Computer Science; Hong Tang, the Llewellyn West Jones, Jr. Professor of Electrical Engineering, Applied Physics & Physics; and Michel Devoret, the Frederick W. Beinecke Professor of Applied Physics & Physics.

Tassiulas said his role will be in developing network level protocols for this new interconnection infrastructure — analogous to the protocols realizing today's Internet. Tang and Devoret will focus on the hardware of quantum technology.

Continued →

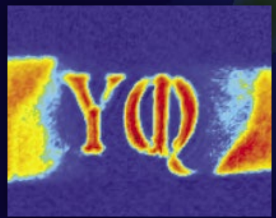
AP Milestones Through the Years



2010 Entanglement, a tenet of quantum mechanics, links two or more objects such as photons so that measuring certain properties of one object reveals information about the other — even when they're separated by thousands of miles. A team led by Yale researchers harnessed this mysterious property and achieved the entanglement of three solid-state qubits, or quantum bits, for the first time. Their accomplishment was a crucial step towards quantum error correction, a crucial aspect of future quantum computing.

2012 AP researchers collaborated with biomedical engineering to develop a special type of laser called a random laser, which generates and emits light differently from traditional lasers. It improved upon conventional lasers in medical imaging by not producing unwanted visual byproducts that mar the final picture. Researchers said it also has the potential to improve processing time of the images.

2014 Teaming up with the department of ecology and evolutionary biology, AP researchers changed the color of butterfly wings, effectively producing the first structural color change in an animal by influencing evolution. Although researchers have studied such mechanisms extensively, little is known about how structural colors in nature evolved. The discovery may have implications for physicists and engineers trying to use evolutionary principles in the design of new materials and devices.



2015 The Yale Quantum Institute (YQI), a state-of-the-art research hub aimed at revolutionizing how digital information is stored, processed, and safeguarded, opened in October. With Robert Schoelkopf leading as its director, the institute brings together researchers and staff from around the university, including leading physicists, mathematicians, computer scientists, and engineers. YQI occupies one floor of 17 Hillhouse Avenue, with space for seminars, events, and classes. Ongoing research continues in laboratories across campus.

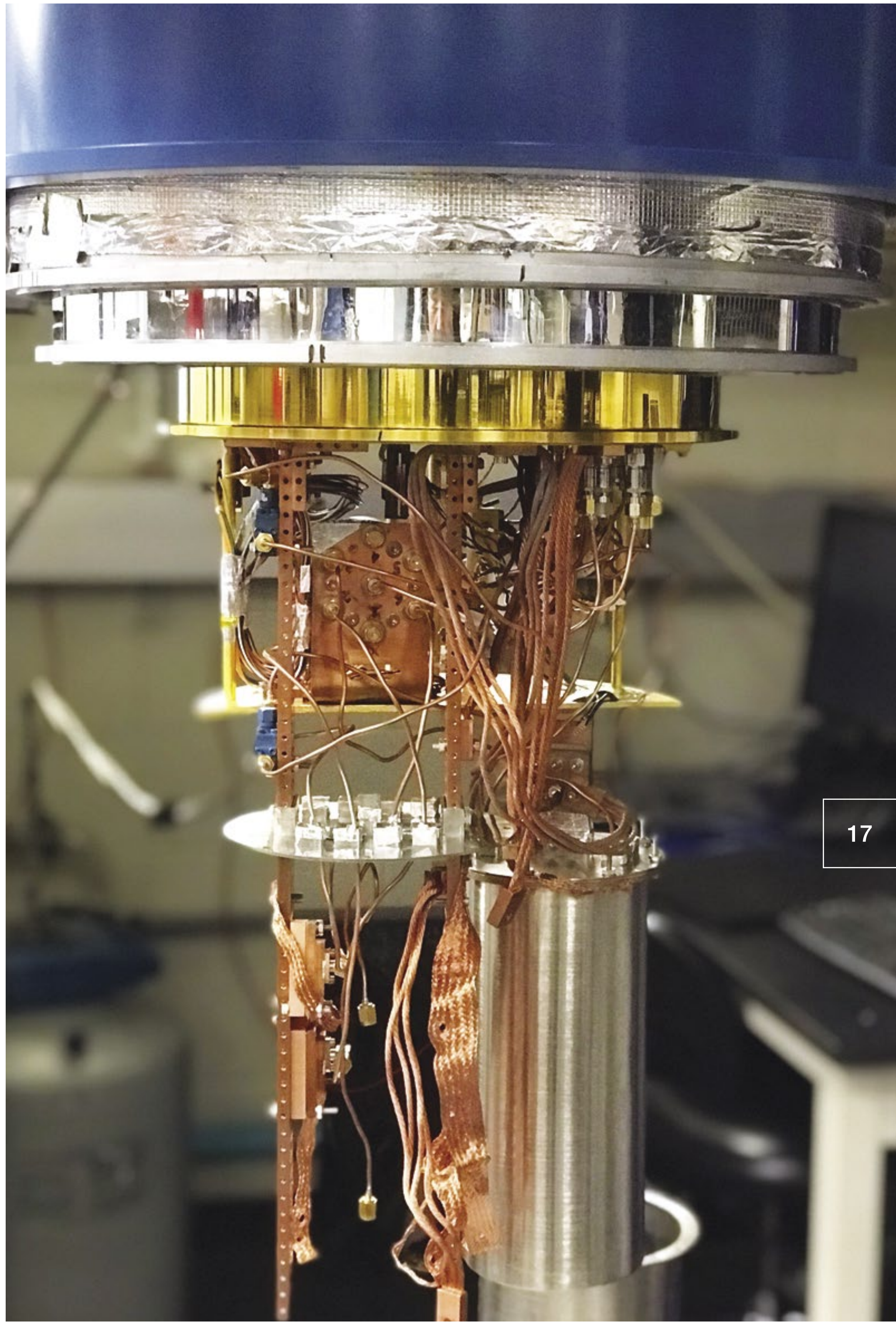
2017 Quantum Circuits Inc. (QCI), a startup founded by Yale scientists Michel Devoret, Luigi Frunzio, and Robert Schoelkopf, raised $18 million in venture funding to build and sell the first practical and useful quantum computers. QCI focuses on building a modular quantum computer that can be reconfigured and reprogrammed, with initial applications to address drug design for biotech, improved processes for industrial chemicals, financial technology, machine learning, and energy. In 2019, the company opened a facility with 6,000 square feet of state-of-the-art laboratories and in-house manufacturing.

2018 With a $16 million grant from the U.S. Army Research Office, Yale researchers got a boost in their work on the next wave of quantum computing research — specifically on their goal of building a "nearly perfect quantum computer out of imperfect parts." The four-year grant helps fund the work of dozens of faculty members, graduate students, and postdoctoral researchers affiliated with the Yale Quantum Institute. The grant also helps pay for a variety of specialized technical gear, including electronics and cooling equipment.

2020 Yale physicists have developed an error-correcting cat — a new device that combines the Schrödinger's cat concept of superposition (a physical system existing in two states at once) with the ability to fix some of the trickiest errors in a quantum computation. The breakthrough is a step toward the researchers' effort to master and manipulate the physics necessary for a useful quantum computer: correcting the stream of errors that crop up among fragile bits of quantum information, called qubits, while performing a task.

Yale

INTERDISCIPLINARY



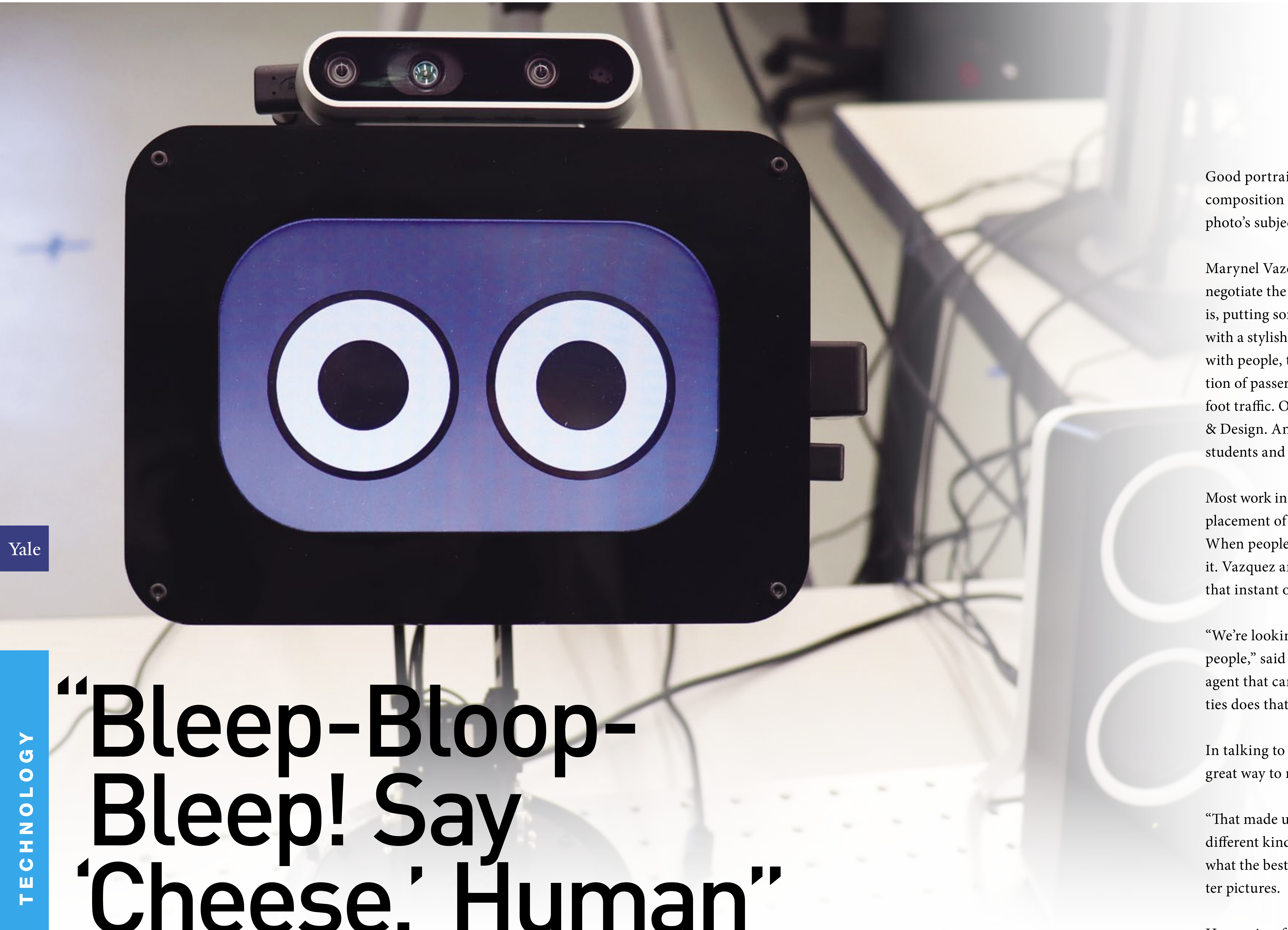
Right: *Once all the cans from the dilution fridges are removed, the superconductive devices are visible. To perform quantum operation, the qubits need to be cooled to almost absolute zero.*

> *"By leveraging our strength in quantum science, engineering, and materials, SEAS can build a foundation for excellence and new models for how Yale can engage with the fundamental problems confronting society."*
>
> › Jeffrey Brock

program would advance the frontiers of knowledge, train the next-generation workforce for this field, and serve as a valuable meeting ground for students and faculty.

It also comes shortly after the announcement of plans for a new state-of-the-art building intended for quantum science, engineering, and materials research. Plans for the building were a priority outlined in the USSC Report as a way to bring together the research strengths in Physics, Applied Physics, and other SEAS departments. The move into SEAS will allow AP to play an integral role in the development of SEAS' new strategic vision for the future, also called for by the USSC Report.

"We're embarking on a new trajectory for SEAS," said Brock, "one characterized by embracing our leadership role in innovation and entrepreneurship, in broad collaboration, and in how applied science can drive new developments in technology. By leveraging our strength in quantum science, engineering, and materials, SEAS can build a foundation for excellence and new models for how Yale can engage with the fundamental problems confronting society. The addition of Applied Physics to SEAS puts us in a far more competitive position to begin that process."



Yale

TECHNOLOGY

"Bleep-Bloop-Bleep! Say 'Cheese,' Human"

A robot photographer learns to capture the moment

Good portrait photography is as much art as it is science. There are technical details like composition and lighting, but there's also a matter of connecting emotionally with the photo's subjects. Can you teach that to a robot?

Marynel Vazquez wants to find out. She and her research team have built a robot designed to negotiate the quick but very complex interactions between photographer and subject — that is, putting someone at ease and drawing out a genuine smile, all in a matter of seconds. Built with a stylish retro-futuristic look, including "eyes" on a touch screen programmed to interact with people, the robot photographer — they call it Shutter — is designed to catch the attention of passers-by. Vazquez has a few places she'd like to station it, all of which have good foot traffic. One is in the John Klingenstein Lab at the Center for Engineering Innovation & Design. Another is the corridor between Becton and Dunham Labs, a spot teeming with students and faculty as they pass to classes.

Most work in robot photography has homed in on the technical side of things — focus, lighting, placement of subject. But as professional photographers will tell you, that's only half the job. When people in a photo look glum or expressionless, all the compositional details won't save it. Vazquez and her team are focusing on the special ability of good photographers to spark that instant of joy and capture it in a photo.

"We're looking at what the robot photographer can do to get more positive reactions from people," said Vazquez, assistant professor of computer science. "Now that we have a social agent that can engage people and change what they're doing, we can ask, 'What opportunities does that open for taking photos?'"

In talking to human photographers, a common theme that came up was that laughter is a great way to make people comfortable in front of the camera.

"That made us interested in how to make the robot humorous," she said. "We've been trying different kinds of humor that the robot photographer can use. We're not really going after what the best joke is, but how we can use this humor to elicit smiles and use that to take better pictures.

Humor is, of course, subjective, and one person's comedy gold could leave another audience cold. To that end, Tim Adamson, a Ph.D. student in Vazquez's lab, programmed Shutter to have a wide range of funniness. These include a GIF of a dog sticking its head outside a car window at high speeds, audio samples of children laughing and goats bleating, and a meme of a man making a face at the camera with the quote "If Monday had a face... This would be it." And if all else fails, there's the classic "Say cheese!"

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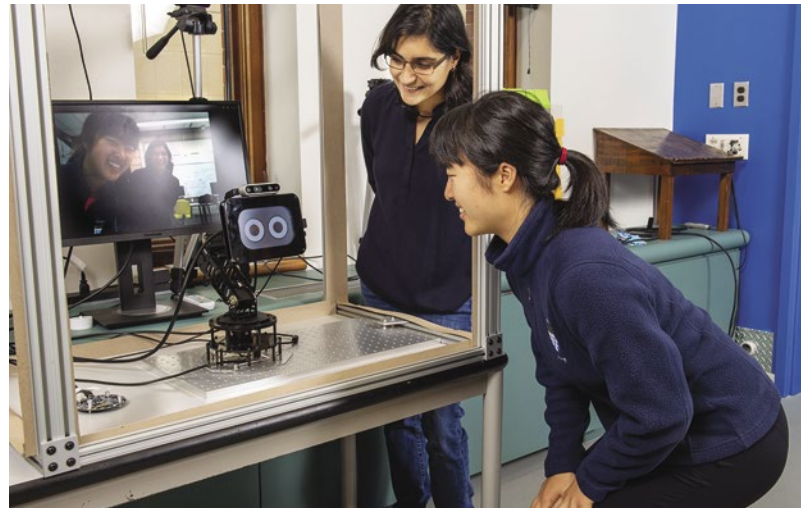
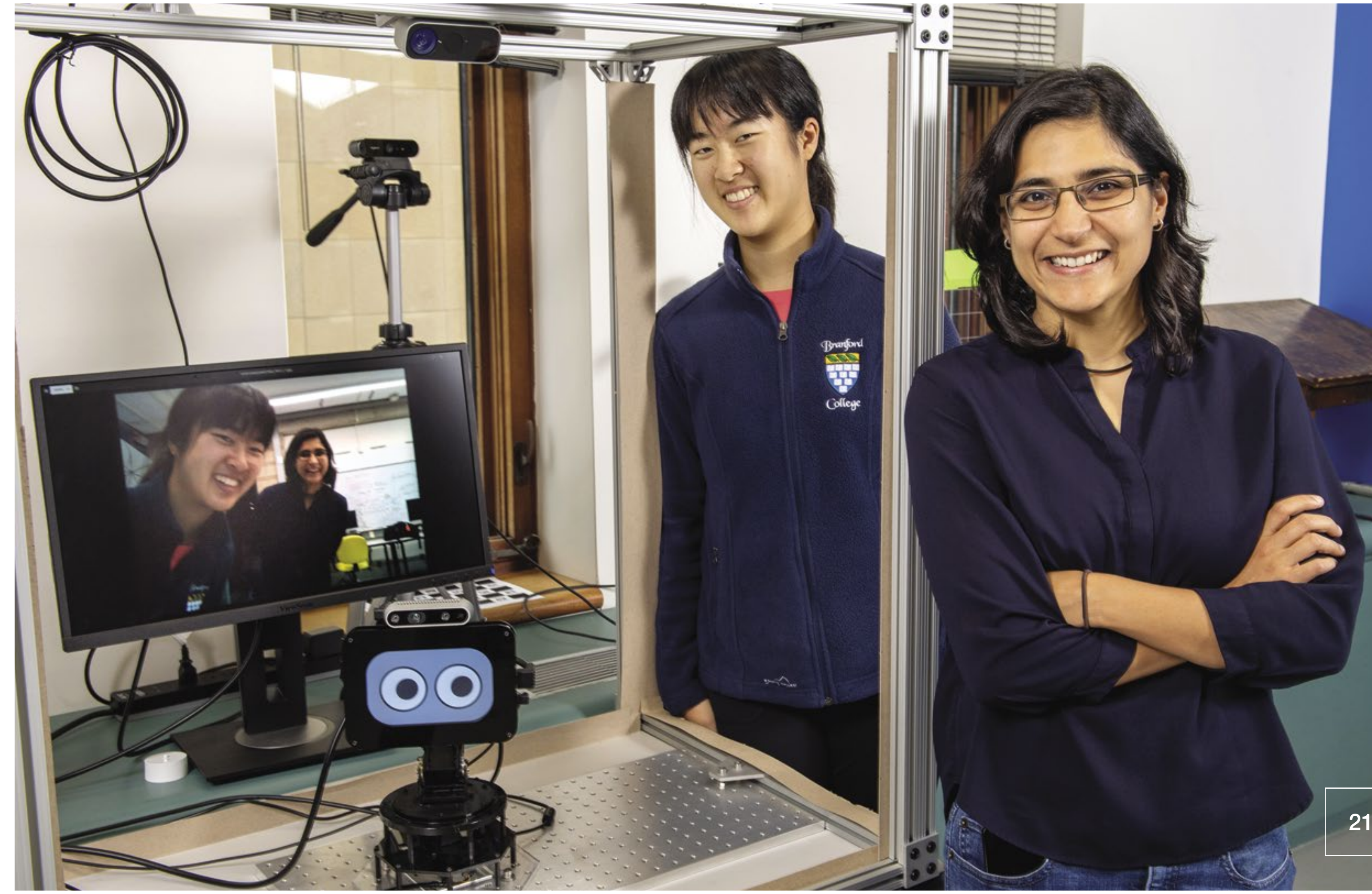




The Big Picture

Top Left: *An early prototype of Shutter where various jokes were tested.* Top Right: *Vasquez and undergraduate student Annie Gao test the next generation of Shutter.* Bottom Right: *Shutter is tested in the lab in its final form — on a cart that can be publicly deployed.* Bottom Left: *Just one of the many images Shutter displays to capture an instant of unexpected joy in a photo.*

Photography seemed to Vazquez an ideal intersection to study human-machine interactions in general — which is all part of the overall mission in Vazquez's laboratory.

"In today's world, you can imagine that robots will be out there — some already are, with Roombas and robots in some factories and warehouses," said Vazquez. "As a community, we've started to realize that it's important to study human-robot interaction in public environments. Our efforts here at Yale with this robot is a first step in getting out of the lab to study more complex interactions with social robots."

A lot of research in the field has dealt with one-human-to-one-robot interactions, but Vazquez is also interested in group settings, a particularly complex human environment. More specifically, they want to help robots understand social contexts, get better at recognizing emotional statements and decision-making — all of which helps them act autonomously.

Vazquez's lab has taken on a number of projects, from working with Disney's research team while she was a Ph.D. student at Carnegie Mellon University to her recent work with students on remotely controlled robots for homebound children during the coronavirus lockdown. At the center of all this research is a deep dive into how humans work with robots. Part of her lab has a space sectioned off by large LEGO-like blocks, forcing humans in the room to figure out how to negotiate the space they're sharing with the lab's robot population. She can then compare those interactions to the human-to-human interactions in the same space.

The initial results of the research team's work with Shutter were detailed in a paper that appeared in March at the 2020 ACM/IEEE International Conference on Human-Robot Interaction. In a more recent paper, they focused specifically on how people perceive Shutter's robot gaze. The perception of how a robot is "paying attention" is a critical part of human-robot interaction. When the subject of inventory-taking robots that roam the aisles of a particular grocery store chain comes up in conversation, Vazquez sighs. On one hand, she said, it's great that the company decided to outfit their robots with eyes, which go a long way to humanize them. Unfortunately, though, the eyes are the googly kind that don't correlate to anything in their sightlines.

"Gaze is something that people are naturally attracted to, and our robot has eyes that help convey its attention to users," she said.

One example of this showed up in their research for Shutter. "We had two people approach the robot photographer, and it looked at only one of the people, so the other person moved away, even though in reality Shutter could have taken a picture of both of them." The subtle move of the robot's eyes immediately shifted the situation to make one person a participant and the other a bystander.

Unexpected encounters like that help make the research exciting, she said, and the more sophisticated Shutter becomes, it's likely they'll see more. Ideally, Vazquez said, Shutter could be located somewhere on campus where students pass by frequently but far enough from classrooms to allow for lively human-robot encounters. She also welcomes the possibility that some passers-by will act out in ways that they wouldn't with a human photographer.

"You might wonder what crazy things people might do when it's out there," she said, with a laugh. "My hope is that if crazy things happen, it's an opportunity for us to study them."

Yale

COVID-19

Lost Summer? Not at SEAS

A first-of-its-kind program keeps students innovating, even in lockdown

Like many college students at Yale and throughout the U.S., Marley Macarewich ’22 suddenly found her summer plans in disarray.

“I was originally in the last rounds of interviews for internships related to patent law,” she said. “But all the internships dropped their interview processes. Then I was going to work at a Wild West-themed summer camp as a camp counselor that I grew up going to — but that also got cancelled.”

Rather than giving into the circumstances, Macarewich continued to look for ways to make it a productive summer. Fortunately, there were plenty of opportunities in SEAS, including the new SEAS 2020 Summer Design/Research Scholars. Created by the SEAS Dean’s Office, the summer program was designed specifically around the unique circumstances that students are faced with this year. SEAS Deputy Dean Vincent Wilczynski said the aim of the internship program was to counteract some of the loss of this year’s internship, research, and academic opportunities.

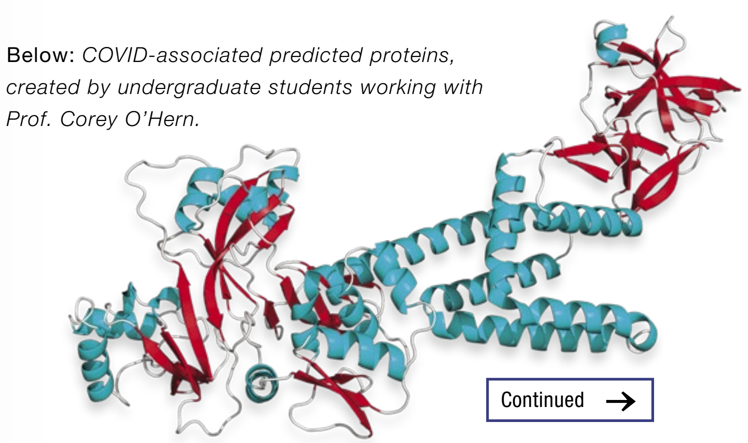
“Thanks to the support of the Yale Engineering faculty, staff, and supporters, the School of Engineering & Applied Science — in partnership with the Office of Career Strategies — was able to quickly find opportunities for students to pursue research and design projects when previously scheduled internships and fellowships were canceled due to the pandemic,” he said.

The program enrolled more than 60 students, working remotely in the labs of numerous faculty members. Projects included evaluating airflow on Connecticut passenger trains, designing exhibits for the Smithsonian Institute for visitors with disabilities, and assisting with a medical software design textbook.

Corey O’Hern, professor of mechanical engineering & materials science and applied physics, said he usually has one or two undergraduate students working in his lab over the summer; this year he had eight. He noted that the summer program allows rising sophomores and juniors to be paid for their research through Yale’s Domestic Summer Award (DSA) funding, as well as obtain course credit toward the Mechanical Engineering major. Most upperclassmen, however, have already applied for a DSA over previous summers (only one DSA is available per student).

“Because a lot of them lost their internships, they need summer funding to pay their expenses during the academic year or provide funding for their summer housing and food,” O’Hern said. So, he used funds from Yale’s National Science Foundation-funded Research Experiences for Undergraduates Site Program to support the additional Yale students in his lab. Students working with O’Hern this summer helped identify the structure of several of the proteins associated with the COVID-19 virus; studied the fluid-driven erosion of granular beds; and in collaboration with Jan Schroers, professor of mechanical engineering & materials science, explored the crystal structure of high entropy alloys.

Below: *COVID-associated predicted proteins, created by undergraduate students working with Prof. Corey O’Hern.*



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Yale

COVID-19

Making Trains Safe

In Macarewich's case, she joined the program and teamed up with Nathan Pharr '22 (his summer architecture-related internship was canceled) to work with the Connecticut Department of Transportation (DOT) on ways to curb the spread of COVID-19 on train cars. Assistant Dean for Science & Engineering Sarah Miller was the students' mentor for the project.

"We came in not knowing anything about this, really, so there was a lot of background reading, reaching out to professors and experts in the field regarding aerosols and infectious diseases, and then seeing how all this could be applied to the railcar itself," said Pharr, who majors in environmental engineering.

DOT officials provided the students with background information on the railcar layouts, the HVAC system, and the electrical wiring that goes throughout the layout of the car itself. One of the first things the students learned was that the issue is a lot more complicated than it initially appeared.

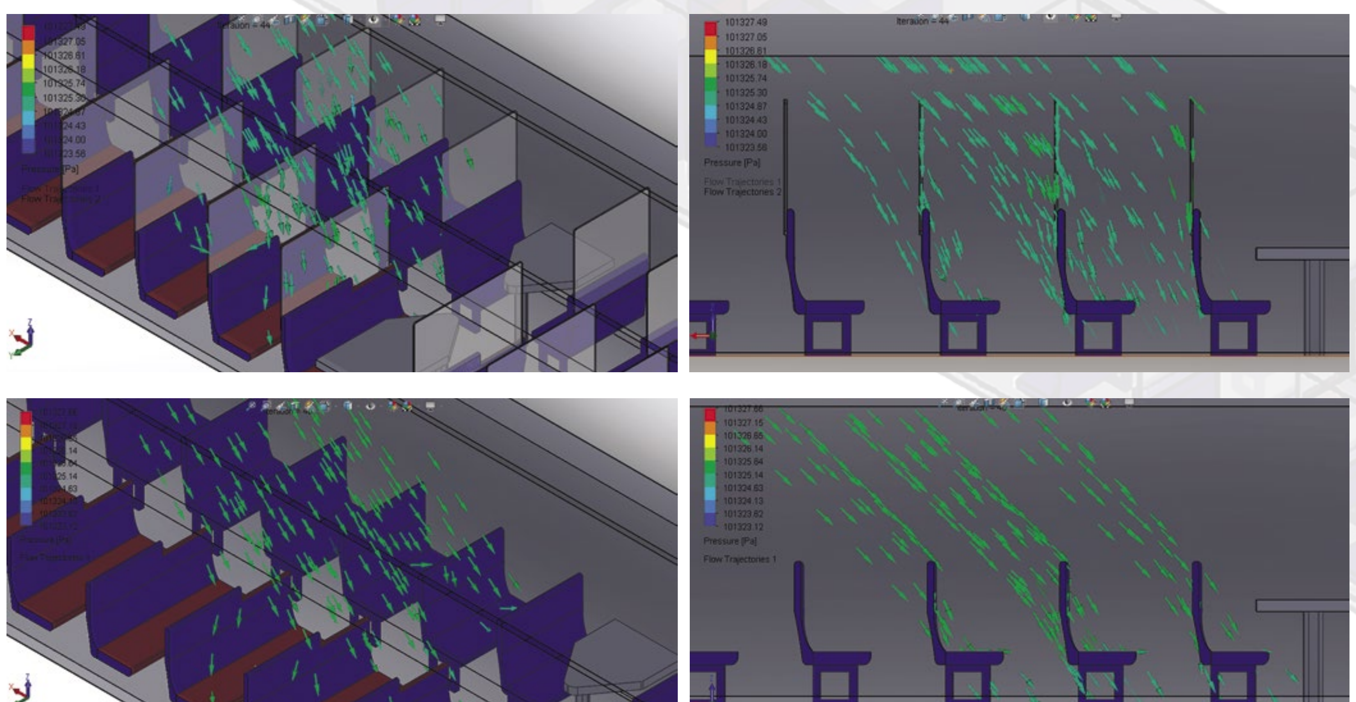
"There were things where I thought, 'Oh, this will be easy — slap on a HEPA filter and call it a day!'" said Macarewich, a chemical engineering major. "Then, after looking at all the diagrams and talking with experts around the world, we realized it's not as simple as that."

One complication is that the particular trains aren't designed for the filters they had in mind. "We really had to question how we thought about air flow," she said.

After eight weeks, Pharr and Macarewich wrote a highly detailed 40-page report that they submitted to the DOT. Miller said their work "represents the best of Yale Engineers."

"They approached this critically important project with optimism, determination, and an inspiring spirit of collaboration," she said. "Their hard work and fortitude resulted in extremely helpful guidance that will keep Connecticut and all its rail riders safer."

Richard Andreski, the DOT's bureau chief for public transportation, also praised the work and said it "provided invaluable research on ways to reduce the potential transmission of COVID-19 on passenger trains."



Top: *Close-up of model demonstrating airflow after the implementation of plexiglass shields in Connecticut railcars.* Bottom: *Approximate airflow without implementation of shields.*

"Connecticut DOT is grateful for its partnership with Yale's School of Engineering & Applied Science," he said. "They dove into the problem as a true partner, listening to their client and taking the time to understand our operational challenges. Their efforts yielded practical, straightforward solutions to improve public safety that will be implemented across the state's passenger rail system."

Overall, students in the program worked on more than a dozen projects. Some of these include:

- A team of students worked with the Smithsonian Institute on developing ways to design museum exhibits with equity and accessibility in mind. One exhibit, "World on the Move" has an interactive token-based system of representing global human migration and its motives. The team created a way to help blind and low-vision patrons participate in and experience this traditionally visual representation of data. With "Painting Sound," another team reimagined how patrons with hearing impairments could experience the emotion of music and sound that are often a critical part of museum exhibits.

"Think about a Civil Rights Movement exhibit with music; then think of it without," said the students' advisor, associate research scientist Katherine Schilling. "That powerful emotion is what the students wanted to make available to every visitor."

Continued →

Keeping the City's Frontline Workers Safe

Elsewhere in SEAS, computer science students Rachel Sterneck '21 and Varsha Raghavan '20, were instrumental in developing a program that keeps track of personal protective equipment supplies.

When the COVID-19 pandemic hit, personal protective equipment (PPE) such as gloves, masks and respirators was in high demand and managing inventories proved difficult. Nathaniel Raymond, a lecturer at the Jackson Institute for Global Affairs, wanted to create a user-friendly way for municipal and state agencies to manage their PPE.

Rachel Sterneck '21 and Varsha Raghavan '20 joined the project and led the coding work to get the open-source program up and running. The program, **PPETrackr,** gives both governments and healthcare facilities tools to help them understand their inventory changes. Users can log their daily inventory of PPE and see their data in various forms on the app's dashboard. It also allows government officials to oversee PPE inventory across healthcare facilities in their communities to help them make good decisions about acquiring and distributing PPE supplies.

"Our main priority was ease of use for the app because we knew that would be a big obstacle for us getting it adopted," said Sterneck, adding that they set a goal of "a few minutes or less."

The City of New Haven was the program's first adopter. That included police and firefighters, as well as personnel with little experience using PPE, such as city engineers, park officials, and mortuary workers.

Lt. Justin McCarthy of the New Haven Fire Department, who's in charge of tracking the city's PPE, called it "a huge help."

"When you're trying to manage something on this scale, it's extremely difficult because it's constantly changing," he said. "On top of that, you have requirements set forth by the federal government of what needs to be tracked and how."

With Face Shield Evaluations, Students Work Internationally

Other students stayed busy during the summer through the Yale Center for Engineering Innovation & Design's Summer Fellowship. The 2020 Fellowship, now in its eighth year, featured five teams working on projects that included stabilizing display cases holding invaluable sarcophagi, building a small satellite, an automated food-dispensing machine, and a multi-screen display system. The team of J.R. Stauff '23 and David Ewing '23 spent their eight weeks in the program helping the nation of Colombia develop guidelines for the use of face shields.

Earlier this year, the United Nations Development Program (UNDP) chose three face shield designs out of 300 that were submitted for a national contest in Colombia. To get more data on these three designs, UNDP member Alejandro Pacheco — a 2014 Maurice R. Greenberg Fellow at Yale — contacted his former advisor, a connection that led him to the Summer Fellows.

Stauff and Ewing were tasked with developing computer simulations to assess which of the three models best redirects airflow to prevent coronavirus infections for both wearers and those around them. The two students took the three physical face shields and designed 3D models for each. They combined those models with a mannequin head and built a test chamber in accordance with international test standards.

The assessments focused on facial coverage, effective curvature and air redirection, ventilation, and internal air flow. While each of the models had their strong points, Stauff and Ewing deemed the model called "re.co" as the best overall, adding that "sometimes, the simplest design is the most effective." They noted that it displayed excellent protection from airstreams from above and in front of the mask. For the benefit of future designs, they also listed the best qualities of each mask.

Juan David Martin Jimenez, one of the UNDP partners working on the project with Pacheco, noted that they've been meeting with representatives from the World Health Organization about the face shield designs. The feedback from the Yale students was very helpful, he said and confirmed many of their hypotheses. The nature of the situation, Pacheco added, required that their work gets done at a much faster rate than normal, and the Summer Fellows' contributions were a big part of that.

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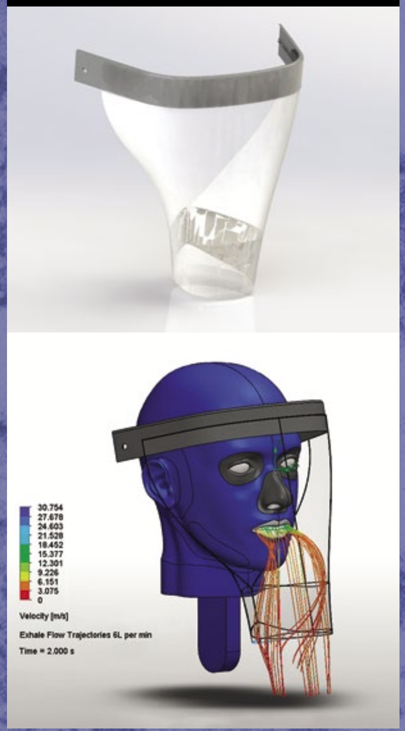

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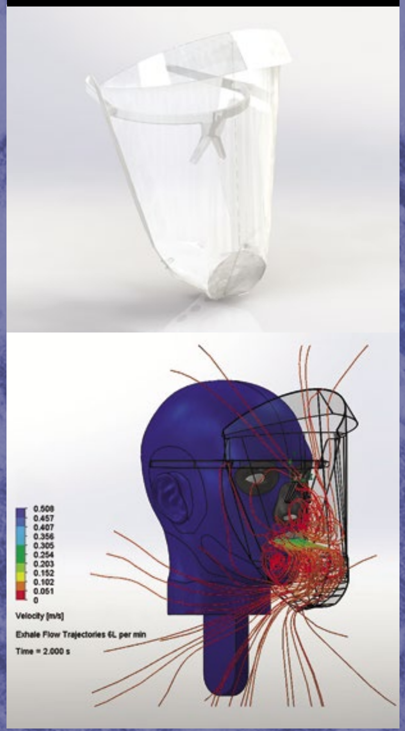
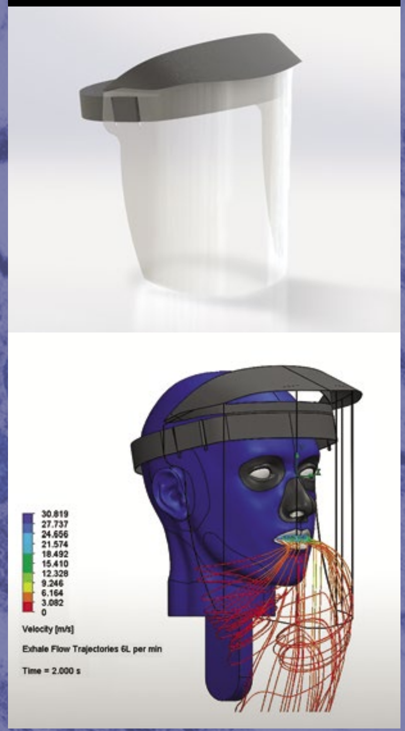
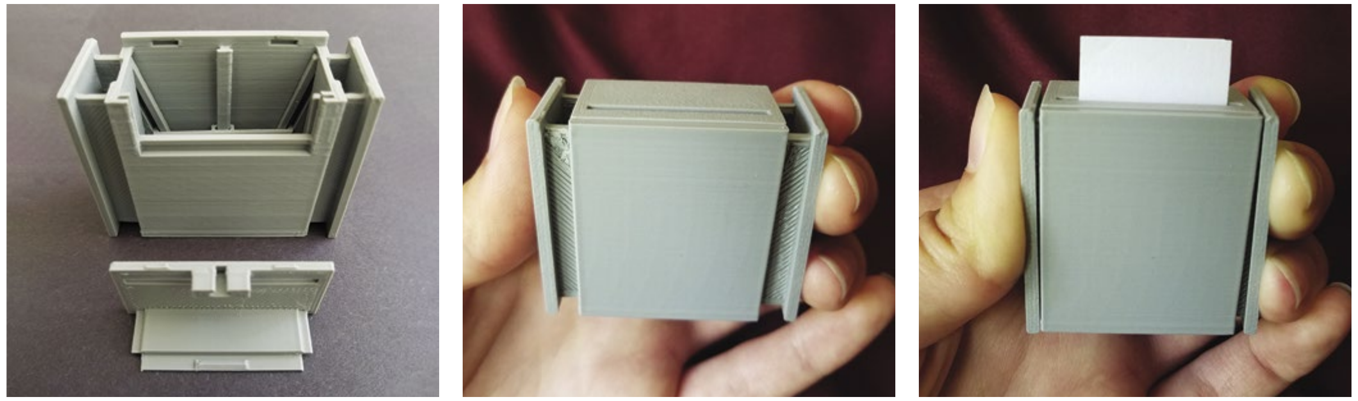


re.co





Above: *Students created a handheld device that provides prompts designed to break the user out of a negative thought cycle and cope with mental health challenges.*

- A group of students worked with Ron Adrezin, professor and chair of Mechanical Engineering at the U.S. Coast Guard Academy, to develop a system designed to help students cope with mental health issues, particularly during a difficult time like the pandemic. The system includes a device that gives prompts — "go for a walk" or "call a friend," for example — to break the user out of a negative thought cycle. Another component is a digital tool that helps students get away from their screens. Serena Riddle '21, who had started the project in the spring semester, said the student team expected to continue their work into the fall semester.

  "It's actually blossomed into a whole student-led mental health initiative," Riddle said. "Our mission is to become an extracurricular group at Yale, a group of students committed to raising awareness about mental health. We also want to bring people out of the shadows, because a lot of people struggle in silence, and also to equip people to take care of each other."

- Three students worked with Dr. Daniel Wiznia, assistant professor of orthopedics and rehabilitation and mechanical engineering & materials science, and Dr. Steven Tommasini, research scientist at the School of Medicine. The students focused on knee replacement research, innovating ways to prevent hip fractures, and how to treat geriatric patients with finger fractures. Wiznia said the program proved invaluable for both the students and their mentors. He and Tommasini were able to expand some of the projects, while the students were able to stay busy and get course credit.

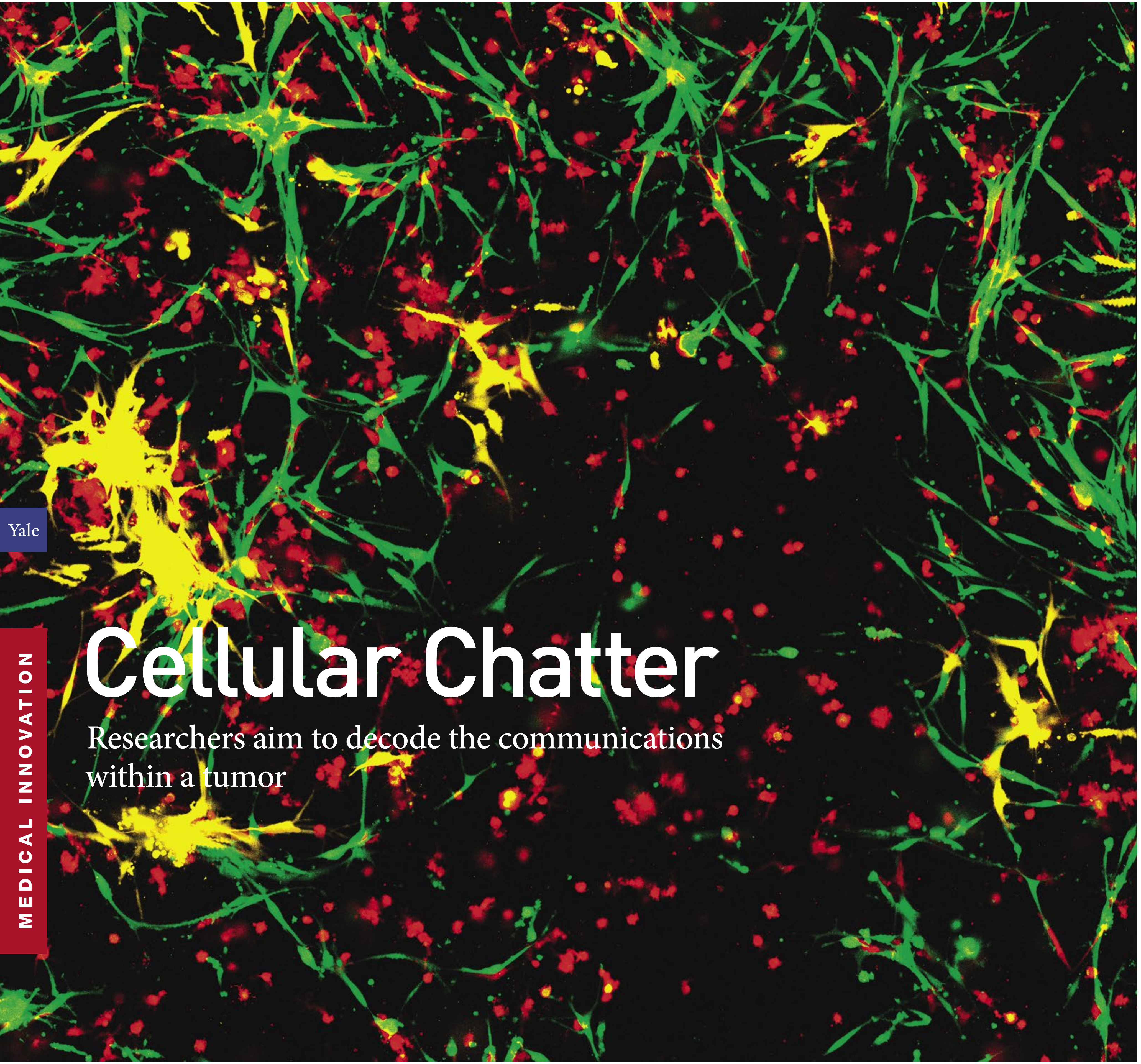
  "We felt really bad for those students, and this a really good opportunity to do some medical device design research," he said. "It's a display of the engineering faculty really stepping up for these students and making sure that they can make good use of their time and learn. We want them to succeed down the road."

- Yehia Khalil, a Yale-affiliated researcher, served as advisor to two students. Alexandra Saczawa '22 explored the topic of valorization of mixed plastic waste in the U.S. The project included parsing the different types of plastic waste management approaches and the pros and cons of each. JR Im '23, looked into the safety risks and economic viability of blending hydrogen into the natural gas grid by reviewing recent experimental and theoretical studies. Both students wrote term papers and created posters on their topics.

  For Im, the program came at just the right time. The abrupt changes brought on by the pandemic were concerning, but Im was able to find a bright spot in SEAS.

  "There was a constant effort in SEAS and the Chemical Engineering department to communicate with students, to listen to their situations and thoughts, and to provide an opportunity for us to do something productive and rewarding over the summer," Im said. "The SEAS fellowship not only gave me an opportunity to learn, but it also helped me take my mind off the worries about my future and focus on working on a project that I was passionate about."

Background: *Students dug into medical device design research and created an innovative way to treat fractures in the foot and ankle.*



Cellular Chatter

Researchers aim to decode the communications within a tumor

Inside a tumor, chatter abounds. Multiple cell types are constantly communicating with each other, exchanging various types of information. Some are working together against the tumor, while others help the tumor grow. Researchers have a good handle on who the main players are, but it can be difficult to tell the good ones from the bad ones, and who's communicating with whom. To make things even more complicated, sometimes good cells turn bad — and researchers don't know why.

A team of Yale scientists has set out on an ambitious goal of figuring out this tangled web of networks and getting a closer look at what kinds of cell-to-cell interactions lead to effective anti-tumor responses, and which ones cause tumors to grow. Ideally, this level of understanding could lead to a time when a patient's tumor could be analyzed and physicians would know how it might respond to certain treatments. The five-year project, led by Kathryn Miller-Jensen, associate professor of biomedical engineering and molecular, cellular and developmental biology, and Marcus Bosenberg, professor of dermatology, pathology, and immunobiology, recently received a $2.8 million grant from the National Cancer Institute.

"I think the question for the field — and the one we're trying to answer with this grant — is what are these immune cells doing and why is that important?" Miller-Jensen said.

Immune cells can recognize and destroy cancer cells, but immunosuppression in the tumor's microenvironment can thwart this built-in system. Immunotherapy, designed to restore anti-tumor immune activity, works for many cancer patients, but not all. By creating computational models of the networks, the researchers will try to identify potential targets for therapies with the aim of finding ways to reverse immunosuppression in non-responsive tumors.

The research is a form of "data-driven modeling," and it's a job that requires multiple cutting-edge technologies. The team will use single-cell RNA sequencing data from growing and regressing melanoma tumors to make computer models of the cellular networks. Single-cell sequencing is a relatively new technology that allows scientists to examine individual cells.

"You can take the cells from a tumor and sequence all of them individually," Miller-Jensen said. "When you do that, you can say 'I have T cells, fibroblasts, tumor cells...' You can identify many cell types."

Continued →

By itself, though, single-cell sequencing can tell researchers only so much. While it will give them clues about the receptors and ligands — parts of the cells that bind to each other — they also want to know if those ligands are actually being secreted by the cells they're testing. That's where another technology comes in — one that Miller-Jensen developed with Rong Fan, also a professor of biomedical engineering at Yale. Known as single-cell secretion assay, it measures the proteins known as cytokines, which are secreted by cells to signal to one another.

"With this, we can start to match cells up — 'This cancer cell has high levels of a receptor and that immune cell has a high level of its ligand' — so you can hypothesize that they would communicate."

In a typical study, single-cell sequencing might reveal 10 to 20 types of a cell in a particular tumor. The Yale team, though, wants to know exactly what those different types are up to. For instance, if they find that a cluster of these cells are suppressing T cells — cancer-fighting white blood cells — then they've got a potential target to aim for.

"Just knowing that there's 10 to 20 of these cells doesn't really help us," Miller-Jensen said. "We need to understand what they are doing."

The study's innovations also include mouse models that Bosenberg developed for testing melanoma therapies. Standard melanoma mouse models can't elicit an immune response from the host, so they don't accurately represent the human tumor microenvironment. Bosenberg designed the mouse models used in this study specifically for the evaluation of anti-tumor immune responses. As innovative as these mouse models are, the research team also needs to see how the therapies would work in humans, so they'll compare their results to samples from an ongoing clinical trial at Yale. The melanoma patients in the trial are among the half who don't respond well to the most common form of immunotherapy, known as checkpoint inhibitor therapy. They're being treated with the same alterative therapy targeting different cell types that will be given to the mouse models.

"We'll get some samples from those patients and do the same analysis on the human samples and see if there are things that look similar," Miller-Jensen said. "Then, we can focus on what the connections are between the mouse models we have and the human patient samples. That way, we won't go down some pathway that wouldn't be relevant to humans."

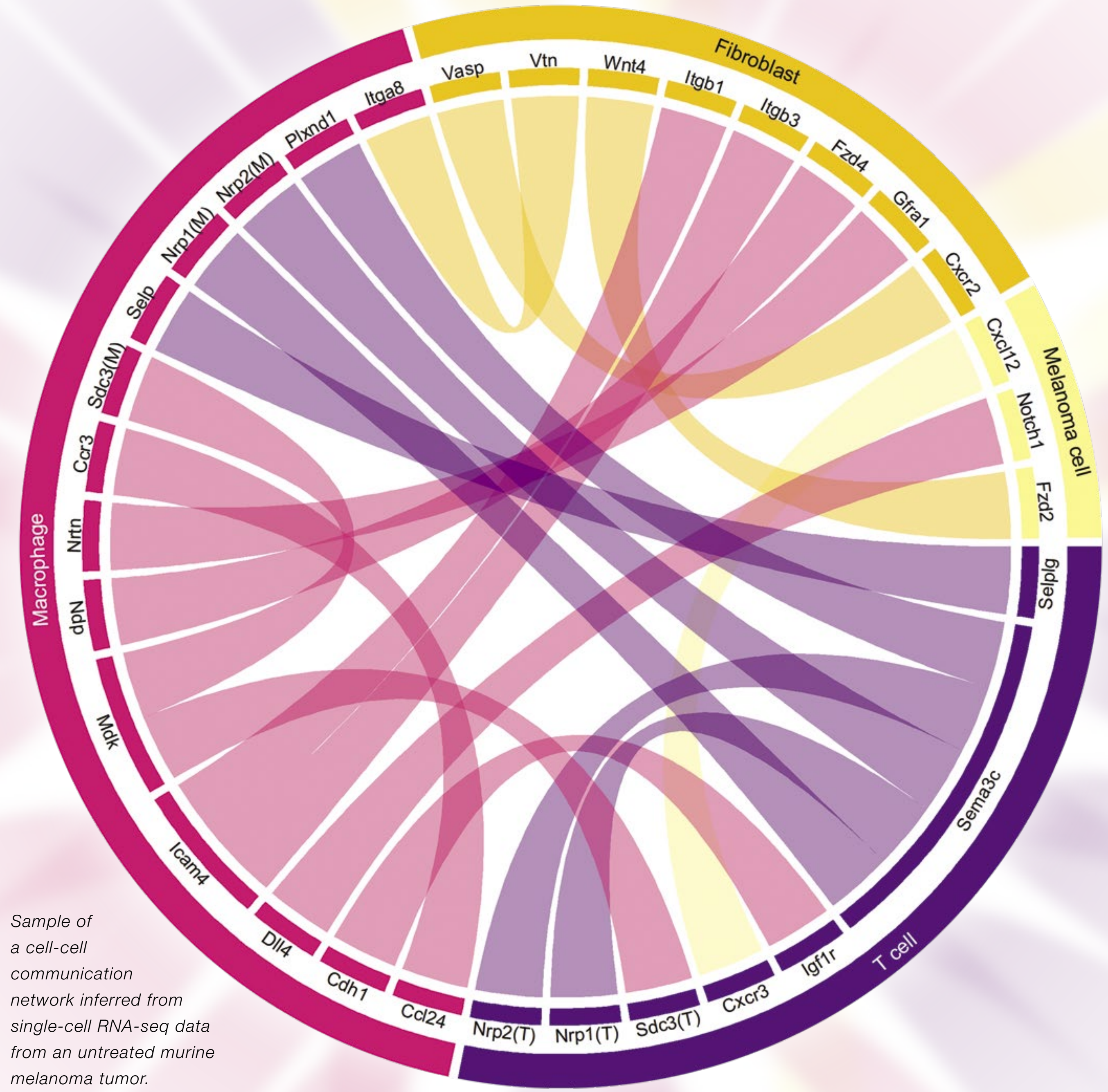
Harriet Kluger, professor of medicine, and co-director of Yale SPORE in Skin Cancer, is in charge of the clinical trials. She said the study is a good opportunity to use an in-house technology that could also be useful for other studies. She noted that the elaborate nature of the study is a good example of how complex the tumor's microenvironment is.

"That's why we need these fancy computational network models, so we can understand it," she said. "There's lots of different cells in there, and subsets of subsets that we weren't even aware of three years ago."

Another co-author of the study, Susan Kaech, was among the first to recognize the important, and often confusing, role of macrophages — a type of white blood cell found in tumors — in the immune system's fight against cancer. Formerly an immunologist at Yale, Kaech is now director of the Nomis Center for Immunobiology and Microbial Pathogenesis at the Salk Institute. Tumor-associated myeloid cells and macrophages (TAMs), are one of this study's focuses. TAMs have been shown to be a crucial element to an immune system's response to cancer, but exactly what they do isn't clear. They can both help and hurt when it comes to immunotherapy. In some cases, they can bolster a system's anti-tumor toxicity. Other times, they help tumors grow by suppressing T cells. And confoundingly, the same macrophage can actually turn from good to bad; what triggers this change is unclear.

"I think the question for the field — and the one we're trying to answer with this grant — is what are these immune cells doing and why is that important?"

› Kathyrn Miller-Jensen



Sample of a cell-cell communication network inferred from single-cell RNA-seq data from an untreated murine melanoma tumor.

Melanoma is one disease where TAMs prove to be particularly tricky. Of the half of melanoma patients who don't respond well to checkpoint inhibitor therapy, many have tumors with numerous macrophages. It's a clue that gives the researchers something to work with, but Bosenberg said there are still many more questions. Are the macrophages stimulated by cytokines, and if so, which ones? Are they activating or suppressing the cancer-fighting T cells?

"It's amazing how little we really know about how and why things respond, especially in humans, up to now," said Bosenberg, who is also co-director of Yale SPORE in Skin Cancer. "There's a number of elements that are probably in the conversation in the tumor microenvironment, and we just don't know who is saying what. Once we understand those things, we can then add new drugs to current therapies to try to make it a better response for patients who haven't responded."

Solutions in Sewage

How researchers are predicting COVID-19 outbreaks from wastewater

In early 2020, when COVID-19 was still just a vague threat to most in the U.S., a group of researchers at Yale were brainstorming about the virus that would shut down Yale and the state by mid-March.

"It was late February, so we were still meeting in person, and talking about different sorts of research projects," said Edward Kaplan, the William N. and Marie A. Beach Professor of Operations Research at the Yale School of Management. "I raised the question of environmental testing, and Saad Omer [director of the Yale Institute for Global Health] said 'This is a very interesting idea — we do that for polio and we should be able to do this.' So, the hunt starts: Who at Yale knows how to do any of this stuff? And all roads led to Jordan Peccia."

They contacted Peccia, the Thomas E. Golden, Jr. Professor of Chemical & Environmental Engineering, who immediately got on board with the project and already had some specific ideas of how to go about the testing. In addition to Peccia, Kaplan, and Omer, the multidisciplinary team included Albert Ko, department chair and professor of epidemiology at the Yale School of Public Health, Joshua Warren, associate professor of biostatistics, and Daniel Weinberger, associate professor of epidemiology.

By March 19, Peccia and a team of researchers were collecting samples from the wastewater treatment plant that serves New Haven, East Haven, Hamden, and parts of Woodbridge, as well as from the sewage systems of Yale New Haven Hospital and the railroad station in the city. Soon after, they learned not only that they could detect the presence of COVID-19 in the population, but that they could track its progression up to seven days before data from hospital admissions and other state health metrics. Since then, Yale has been working with the state on an expanded version of the project that tracks COVID-19

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Above: *Researchers collect wastewater samples from Yale-New Haven Hospital's sewage system.*

in the wastewater of Bridgeport, Stamford, New London, Hartford, and Norwich.

Specifically, they're looking for the RNA unique to SARS-CoV-2, the virus that causes COVID-19, and quantifying sequences of that RNA. Since the project began, the increases and decreases in the concentrations of the virus in their tests have correlated with the number of confirmed cases in the area — but these indicators show up days before.

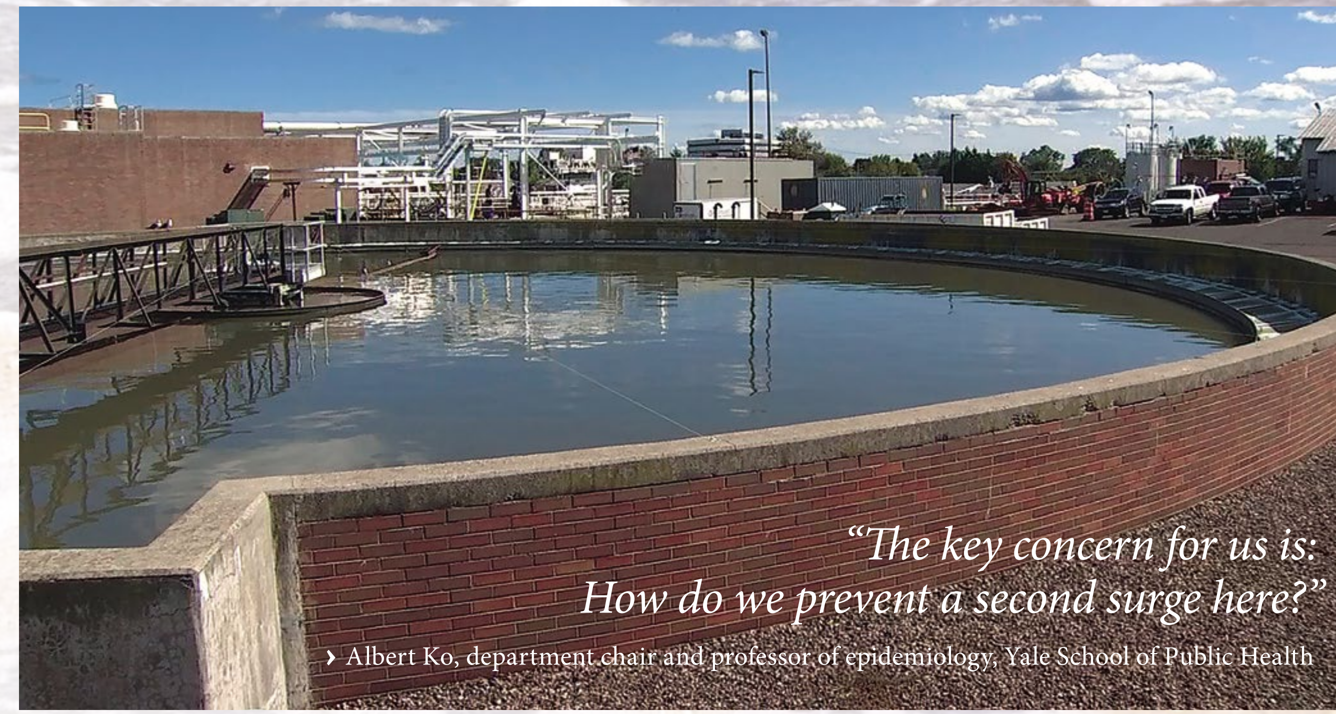
"If you take our smoothed curve for SARS-CoV-2 RNA in sewage sludge and overlay it on the smoothed curves from testing, the trends are very similar — but we're 5 to 7 days ahead of it," Peccia said. "So not only can we use the sewage sludge virus curve to do some forms of epidemiology, it's also a significantly leading indicator."

Ko noted that transmission in the community may occur "silently" before cases are identified by testing and are recognized, and that the number of hospitalizations — a commonly used indicator for COVID-19 — certainly doesn't give enough lead time.

"By the time you get hospitalizations, we know that community transmissions have been happening for at least two, three, four — if not six — weeks," said Ko, who is working with Gov. Ned Lamont's office on the state's handling of the coronavirus outbreak. "The key concern for us is: How do we prevent a second surge here? We want to make sure we're ahead of the curve, and not on the curve or behind the curve."

The samples they're analyzing are sewage sludge, the concentrated solids that settle to the bottom at a treatment plant. "It's the nasty part of a nasty process, but it's where all the stuff is — the pathogens, heavy metals, and contaminants are all right there," Peccia said.

Once the researchers set their sights on the project, a day-to-day routine quickly formed. Alessandro Zulli, was one of the graduate students who worked on the project after his original summer plans had fallen through due to COVID-19. In the morning, he and a student from the School of Medicine



Above: *Stamford is one of the many wastewater treatment plants across the state that supply samples to Peccia's lab for analysis.*
Below: *An assortment of sludge samples received from various Connecticut municipalities.*

who worked at the Yale-New Haven Hospital would scoop up samples from the hospital's sewage system using makeshift tools fashioned from tubes and other pieces of lab equipment. The next stop was the New Haven wastewater treatment plant, where a worker there would collect the samples and leave them for Zulli to pick up.

"Samples from the wastewater treatment plant became the main project once we got the analysis up and running because the samples from the hospital were a little more hit and miss," he said. "But the samples from the wastewater treatment plant are super homogenous. It's a well-mixed system, so you effectively get composite samples of anyone who's gone to the bathroom."

The samples then go to Peccia's lab on Hillhouse Avenue, where the RNA of the coronavirus is extracted — a messy process that takes five to six hours.

From there, the samples go to the Connecticut Agricultural Experiment Station (CAES) where the sludge samples are analyzed to quantify the SARS CoV-2 viral RNA. CAES Director Jason C. White praised the project as a great example of a university and the state teaming up to address a critical public health issue. The predictive nature of the result could prove crucial, he said.

"Detecting virus in sewage and wastewater has been done before, but showing that it has this 3- to 7-day leading indicator was really

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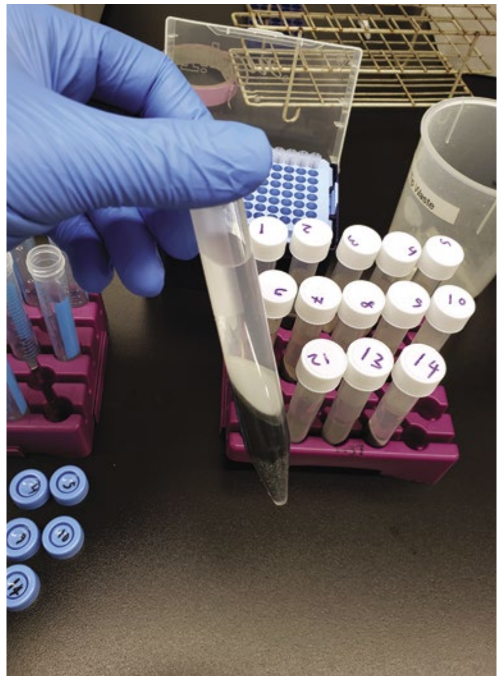
Yale

COVID-19



important, because it's going to give everyone a 3- to 7-day heads up on what to expect," he said.

The results of these analyses are the basis for the Yale COVID-19 Wastewater Tracker, a website that allows the public to check on the most up-to-date information from these regions of the state. In addition to the results of the lab testing, and the cases reported by health officials, the website also shows the data generated by a computer model that predicts COVID-19 levels several days in advance.

"Our intention is certainly for public health directors and people at the state to look at the website, but we also want teachers, principals, church leaders and parents looking at it," Peccia said. "We want everyone as aware and up-to-date with what's going on with COVID in their regions."

Omer notes that wastewater testing has important implications for low-income countries with significant gaps in testing, and can help inform decisions about matters such as whether to re-open parts of a particular city or area. It's an inexpensive method and very similar to one used in many low-income countries to test for polio in communities — that would make adopting the research team's method relatively easy.

The World Bank has expressed interest in piloting the program in a few cities very soon in south Asia to see how well it scales up to larger populations.

Above: *Peccia's lab extracts the RNA of the coronavirus daily from sludge samples provided daily by Connecticut wastewater treatment plants.*

"Once you have successfully piloted it, it can become a policy option for a lot of other places," Omer said.

Geographically, he said, New Haven is a good place to start with a project like this.

"It's the right size of a city to pilot this because we know where this sewage is coming from," he said. "We know the hospital data intimately, and we're not a city of 15 million — it will have to be scaled up to that level — but for now, we can do this in a more controlled but natural environment."

Omer describes the collaboration as a "perfect confluence of complementary skills, experience, and the vision to see that this could have pretty substantial implications."

"There are few institutions in the world where this story could happen, because it needs several ingredients," Omer said. "It needs the breadth of expertise, a culture of a willingness to work with each other, and the dedication to say 'This is important.'"

Research in academia tends to move very methodically. But the work on this project couldn't wait for the traditional peer-reviewing process, so the team of researchers were essentially executing their plans almost as quickly as they were developing them. The first few weeks were hectic, to say the least.

"It was a constant struggle to keep up because we had to develop these protocols from scratch — there wasn't a set protocol for doing this type of stuff," Zulli said. "After about two weeks after the stay-at-home orders, we started to figure out a protocol that actually worked, but now we had about a solid month of samples — a backlog to work through. There was a lot of catching up to get this data out and see if it could help us with the situation."

The decision to collect samples before they had all the methods perfectly in place proved invaluable to the end result, Kaplan said.

"Jordan had the foresight to start sampling right away — go out there, collect the stuff, store it — we can do the testing later from these samples," said Kaplan, who also has appointments in SEAS and the School of Public Health. "And lo and behold, we got the entire epidemiological curve — and I believe we are the first to have managed to do that. That, I think, is a great thing."

In his role in the project, Kaplan is using epidemic modeling to help understand the resulting data. He's using the data surfaced by this project as an epidemic monitoring measure to see if there is any sign of a resurgence in transmission. The way that the many researchers brought their skills to this project reminded Kaplan of an earlier public health emergency that he worked on. In the late 1980s, he had an idea for how to evaluate a needle exchange program and estimate the incidence of HIV among drug injectors in the area by tracking and testing used needles for the presence of HIV. That project also required expertise in multiple fields, and came together only because of a culture at Yale where researchers could mobilize quickly to work together.

Top Left: *SEAS research scientist Annabelle Pan preps samples at the Connecticut Agriculture Experiment Station (CAES).* Top Right: *Pan and CAES scientist Doug Brackney analyze and quantify the samples.*

"This is one of the things I've always loved about Yale — when we're working on problems, people find each other, and it's because of the interconnectedness," he said. "On some of these big picture crisis issues of immediacy, there really is a social network that almost swings to life. All this stuff happens when people come together — and they're coming together across different disciplines, and that's what makes it so great."

To access the Yale COVID-19 Wastewater Tracker website, go to https://yalecovidwastewater.com

Drawing from Nature's Design Lab

With botanical inspirations, innovation is flowering at SEAS

For years, engineers have borrowed from nature to spur new innovations. The skin of sharks has given us water repellent materials and the honeycomb structure of beehives has inspired numerous architectural designs. It makes sense — not only have these life forms survived thousands of years, natural selection has only perfected them over time.

At SEAS, researchers have also looked to nature's design lab. This includes a collaboration between Corey O'Hern and Yale's School of Environment in exploring the structural mysteries of flower petals, as well as work in the laboratory of Menachem Elimelech on a water-purifying device based on the mangrove.

Reverse-Engineering the Flower

Flowers are one of nature's architectural marvels. For instance, they're extremely strong for the amount of tissue that a plant uses to make them. They can also evolve rapidly and are the hallmarks of one of the most dominant and diverse plant groups on Earth. For all of the fascination that flowers have generated over the centuries, though, there haven't been many studies into how they're constructed. It's a question that labs at Yale's School of the Environment and School of Engineering & Applied Science have set out to answer.

It's an ambitious task that requires the use of a particle accelerator in California, discrete element method computer simulations, and sectioning of living flowers. The project, recently funded by the National Science Foundation's Program in Biomechanics and Mechanobiology, could lead to solutions of several long-standing mysteries about the evolution of flowers and the development of nature-inspired materials.

"Evolutionarily speaking, flowers are relatively new and we want to know how they came about — and why they're

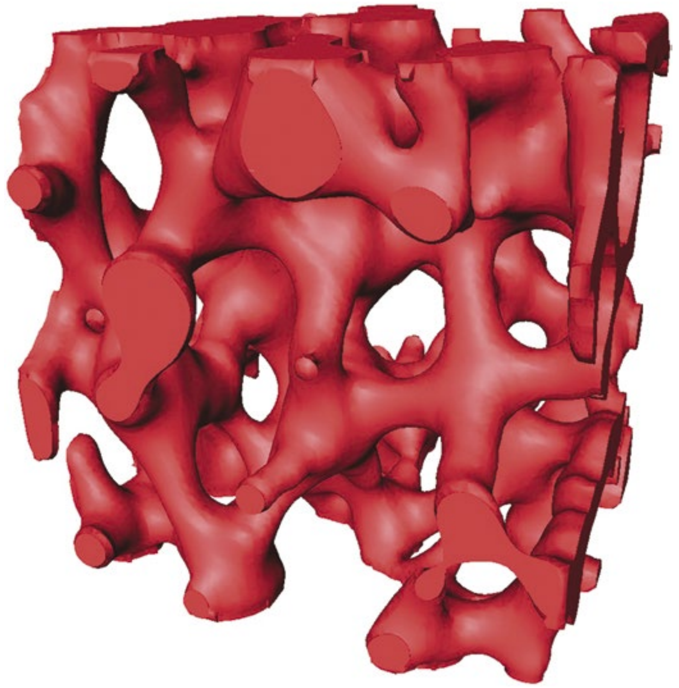
Continued →

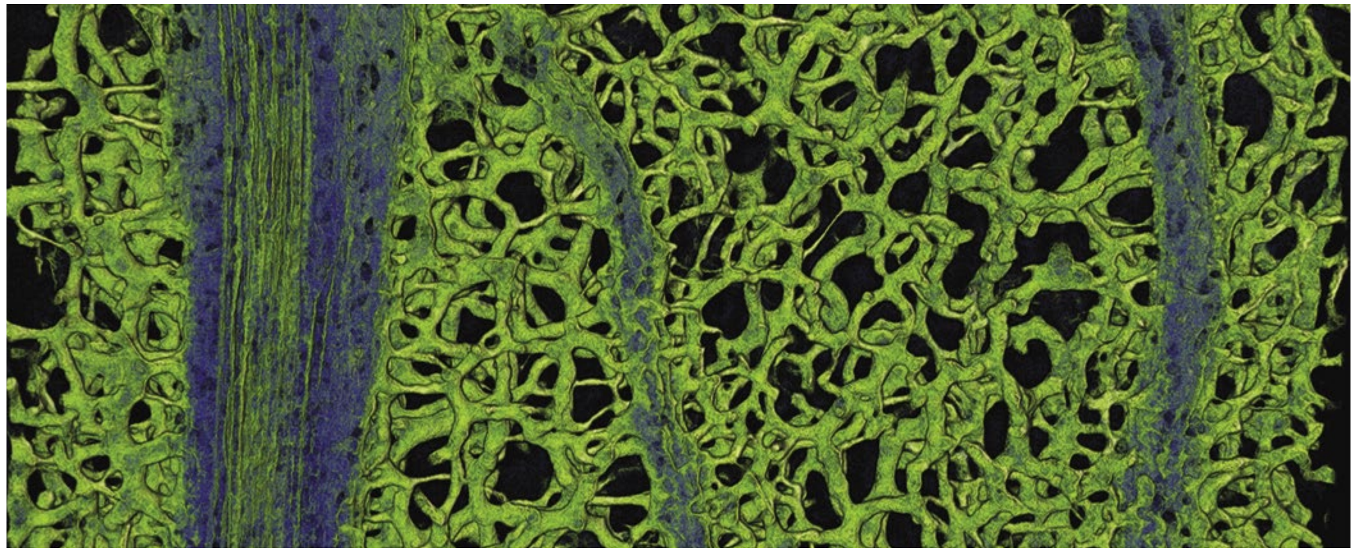
successful," said Corey O'Hern, professor of mechanical engineering & materials science, physics, and applied physics.

The green leaves of a plant are crucial to the plant's survival — they convert the sun's energy into sugar and food for the plants. So why would a plant divert any of its resources from leaves to build decorative flowers? For one thing, the flowers serve an important role in attracting pollinators. And, it turns out, they can create these flowers with only a small fraction of their resources while still making them solid enough to be a platform for pollinators.

The tissue inside flower petals is known as the mesophyll. The researchers' early data shows that this tissue spans a wide range of characteristics, from highly porous to very dense. That's because plants weren't always such efficient builders. Adam Roddy, an assistant professor at Florida International University and collaborator on the project, notes that the flowers of the oldest lineages — the ones that broke off the earliest from their evolutionary chains — boast flowers with denser tissue. In contrast, flowers from plants of newer evolutionary lineages have less dense tissues, making them substantially easier to build.

"So, you go from something like a bunch of people crammed into a room, and no one can move their arms, to something that looks like a truss bridge where there's very little material," Roddy said.



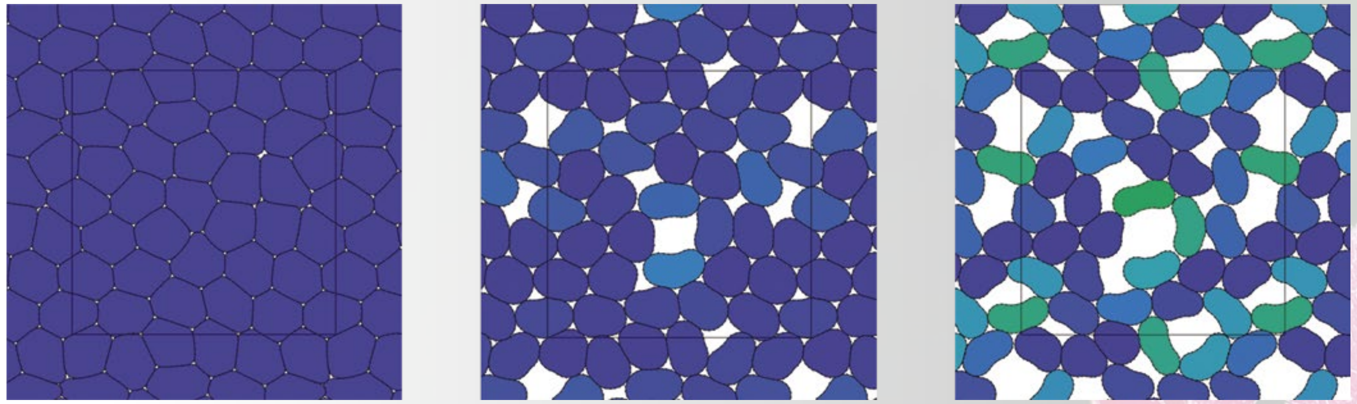


Above: *Mesophyll tissue volume of a Rhododendron cilipense petal digitally extracted from the epidermis.* Below: *Mesophyll tissue (green) and veins (blue) of a dogwood (cornus florida) flower.*

The researchers predict that there have been major evolutionary changes in the sizes, shapes, and physical interactions of the cells that have allowed flowers to be built so economically.

"We know that flowers can evolve rapidly in response to pollinator selection," Roddy said. "One way they may do this is by being so cheap."

Getting that answer, though, will take some work. To start the process, Roddy and Craig Brodersen, associate professor of plant physiological ecology at Yale's School of the Environment, will choose species that span the breadth of the evolutionary diversity of flowers. These samples will then be imaged at the Advanced Light Source at Lawrence Berkeley National Laboratory in California, a facility run by the U.S. Department of Energy. There, flower petals will be placed on a rotating stage, and an x-ray beam will pass through the sample. Just behind the sample is a camera with a device that converts the x-rays into visible wavelengths. It takes about a thousand images of a flower petal during a 180-degree rotation.



Above: *Progression of the proposed simulation: Starting from initially densely packed cells and going toward the more developed porous stages.*

Those images then go to O'Hern's lab. "What we want to do is develop a computer simulation that, with a few simple assumptions, can generate a structure that can recapitulate the flower mesophyll," O'Hern said. "When we generate a structure, we'll compare it to the real structure and see how they're similar and how they're different."

Creating the computer simulations requires some initial assumptions about how the cells behave, and then a lot of trial and error in matching the structural and mechanical properties of the simulations and flower petals on the tissue scale. Cell properties that can be tuned include the deformability and adhesive interactions between cells.

That is, with an accurate model, the researchers can try to make their own "flowers" in the laboratory. If they do, it would be — as far as the researchers know — the first time anyone has done so. These studies could also lead to the creation of new biomimetic materials. One thing that's particularly appealing about a flower-inspired material is that flowers seem to be *tunable* — with material properties that can adapt for various functions — thanks to their rapid evolution.

If this research helps reveal the self-assembly process that creates these porous yet strong tissues, then it opens the possibility for numerous applications. O'Hern speculates that somewhere down the road, new catalytic materials for batteries could be made from material based on flower tissues. In the medical field, this research could inspire new ways to make artificial tissue or tissue scaffolds.

Roddy has been studying flowers for about 12 years, starting with a professor's offhand suggestion that "someone should look into flowers." For O'Hern, this is his first time working with flowers. But his lab focuses on soft and particulate materials and has applied that knowledge to everything from solving protein structures to figuring out how birds build their nests.

"What I like about this project is that it's really interdisciplinary," Roddy said, but he added that it's the kind of collaboration that takes some work. "In a lot of the early meetings we had, I think we just didn't understand each other. I would say something, and I don't think the rest of the group understood what I was saying, and I certainly didn't understand what they were saying."

But they were eventually able to find the common ground, and then the research took off.

"The value of putting in that time is that we're doing something really novel," he said. "We're blending what Corey does into a developmental biology context through a physiology framework and an evolutionary framework, and I think that's super powerful."

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An Artificial Mangrove

In the lab of Menachem Elimelech, it was the mangrove tree that inspired a new water-purifying device. Mangroves, of which there are at least 50 species and come in a wide range of sizes, are the only kind of the trees that can tolerate saltwater. They thrive in subtropical habitats by efficiently converting the salty water of its environment into fresh water — an engineering feat that has long baffled scientists.

By building a device that mimics the mangrove, Elimelech's lab offers us not just a better understanding of plants' plumbing systems, but potentially new technologies to remove salt from water. Results of their work appeared in *Science Advances* earlier this year.

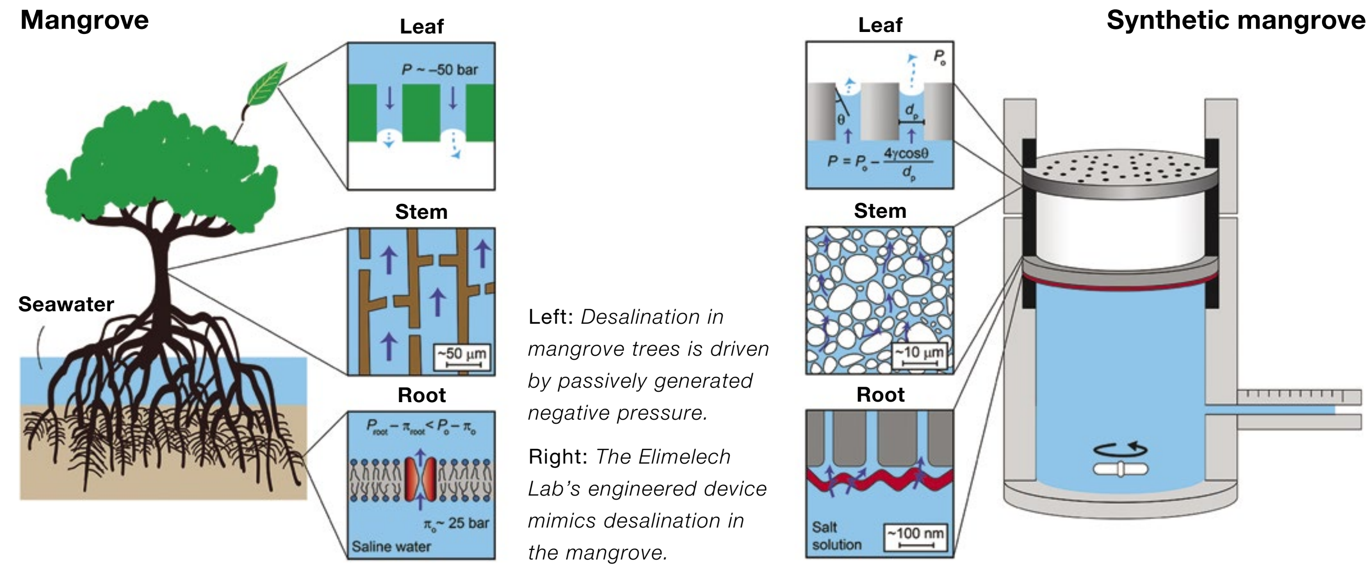
"We were just curious about how nature does some things, and it's such an amazing thing that we were able to describe it with physics," said Elimelech, the Roberto C. Goizueta Professor of Chemical & Environmental Engineering. "We showed that the tree follows physical principles, and that we can mimic them in a microfluidic device."

Plenty of biologists have looked at this problem. This time, though, the researchers brought an engineer's perspective.

"We're showing the mechanism that's been proposed for how mangroves work," said co-author Jay Werber, a former graduate student in chemical and environmental engineering in Elimelech's lab. The device, which the researchers call an artificial mangrove, combines the desalinating effects of the mangrove's root, the capillary pumping of the leaves, and the water-conducting capability of the stem. Key to its success is its ability to generate a high level of negative pressure — the same phenomenon that happens when you drink through a straw. In the synthetic mangrove, evaporation from specially designed membranes — acting as "leaves" — creates a large negative pressure, which drives desalination of salty water through a semi-permeable membrane "root."

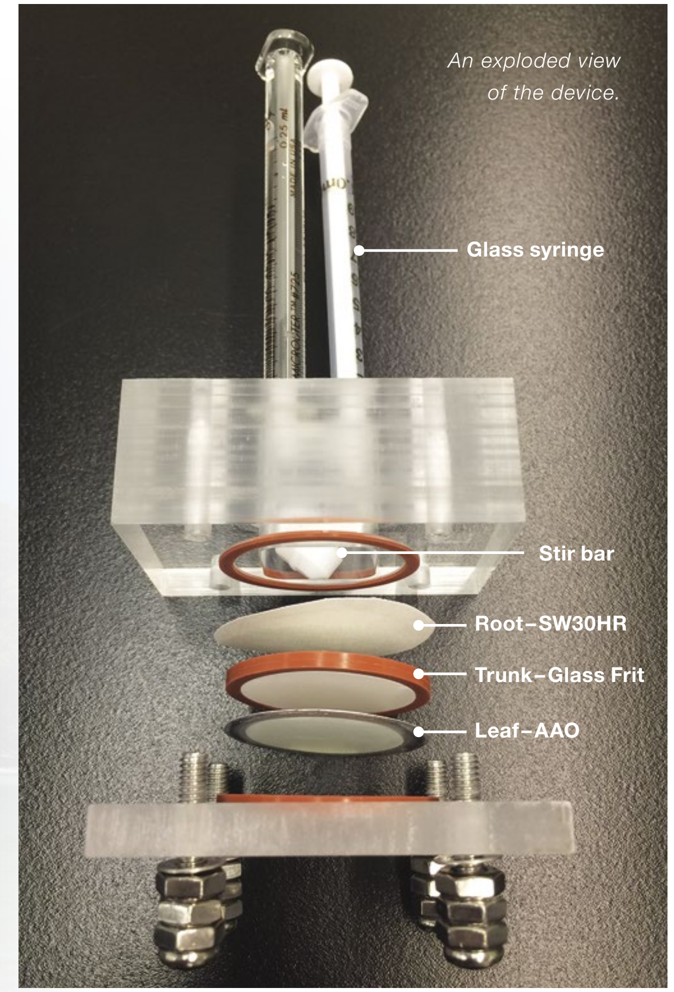
Trees need negative pressure, which is generated when water is evaporated through the leaves, to take in enough water. Mangroves, which can be found in Florida and are particularly abundant in such countries as Indonesia, Brazil, and Malaysia, perform a doubly impressive trick, researchers said: They need to produce greater negative pressure than the typical tree to drink up the salty water of their environment. Plus, they desalinate this water with their roots, in a process called reverse osmosis.

Particularly impressive is the way trees minimize the formation of air bubbles inside their system of water tubes, known as the xylem. Water tends to form bubbles under high negative pressures, which disrupts the flow of water in the plant's xylem.



Left: *Desalination in mangrove trees is driven by passively generated negative pressure.*
Right: *The Elimelech Lab's engineered device mimics desalination in the mangrove.*

Co-author Yunkun Wang, a postdoctoral researcher, said that the researchers' device manages a similar feat by minimizing the formation of air pockets, due in part to a porous silica structure known as a frit that's positioned in the middle of the device.



An exploded view of the device.

Not only did the researchers' device mimic the natural process, it generated much greater negative pressure than what the mangrove tree generates and could desalinate water with a salt concentration many times that of seawater. Elimelech said this means it could lead to ways of desalinating very salty water, such as the water produced through hydrofracking.

In addition to solving some long-standing mysteries about tree hydraulics, Werber said, the researchers' work could potentially lead to the creation of small-scale devices for separating solutions. "Typically, you have an expensive pump that creates really high pressure to separate those things," he said. "With the mangrove device, you can use the evaporation to drive that completely passively."

The researchers said the device would be particularly useful in situations where electricity isn't readily available. Jongho Lee, a postdoctoral researcher and also a co-author of the study, said the device also has the potential to be used for flood reduction by incorporating it into "sponge cities" — that is, urban areas designed to absorb and catch rainwater and quickly remove it.

"Buildings could be designed to work as mangrove trees: Their outside walls would work as leaves and the foundations would act as roots filtering out contaminants," he said.

Yale

SUSTAINABILITY

Yale

EDUCATION

Bridging Innovation and Entrepreneurship

SEAS professor to serve as Tsai CITY's new faculty director

On September 1, Anjelica Gonzalez, associate professor of biomedical engineering, took over as the new faculty director for Tsai Center for Innovative Thinking at Yale (Tsai CITY). Launched in 2017, Tsai CITY works to inspire students from diverse backgrounds and disciplines to seek innovative ways to solve real-world problems.

Much of Gonzalez's research has focused on how to build better engineered models of human tissue as a way to explore immunology, inflammation and fibrosis. Her work has led to the development of new technologies, such as PremieBreathe, a low-cost, mobile neonatal respiratory device that's being used in underserved and low-infrastructure environments across the world. Her long-running course, Biotechnology and the Developing World, looks at how life-improving technologies can be implemented in resource-limited environments. All of which makes Gonzalez a natural fit for Tsai CITY.

"I've come to realize that everything I do at the university, whether it's the research, the teaching or the service, has been human-centered," she said. "I think Tsai CITY is the same way. It really takes advantage of thinking about humans — in this case, that's the students — and what they need to use their innovative thought processes to produce something. The focus is on what the student is bringing and then giving them the resources to enact that in a meaningful and productive way."

As faculty director, what do you do?
When I was invited to do this, they told me that the faculty director is there to be the thought leader for the center and, specifically, advisor to the executive director. So I provide a hands-on link between Tsai CITY and the faculty and the students across the university.

I'm integrated at the university at a couple of levels — the administrative level, interacting with the provost and deans, but also as a faculty member interacting with students — so this gives me the opportunity to talk to the executive director and the staff at Tsai CITY about where we can really enhance resources for students and how to best engage with students to make sure they're taking advantage of every opportunity to further their entrepreneurial aspirations.

Tsai CITY is still in the third year of its operation, and they've done such a great job with it. But with something so young, there's always the opportunity to see where we haven't taken full advantage of the collaborations across Yale and the partnerships that Yale inherently brings from the outside.

What are some of your goals?
I see my role as contributing to some of the already recognized work that Tsai CITY has done in being a leader in the diversity, equity, inclusion — particularly around innovation and entrepreneurship for students. Last year, Venturewell, an organization that supports students' start-ups and global health entities, identified Tsai CITY as 9th out of 100 of the

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"For the students at Tsai CITY, the ability to engage with experts of many fields, including other students, provides the best opportunity for success."

› Anjelica Gonzalez

most innovative institutions promoting equity and diversity. I see my role and everything that I bring to it in regard to diversity and inclusion as taking advantage of where Tsai CITY already is, and taking that even further. We'll bring in mentors and advisors who are diverse in their skill sets, ethnicities, abilities, genders, sexualities — we'll bring all of that to Tsai CITY in a way that hasn't been done yet.

Another goal is specific to Engineering. Being one of the Engineering faculty, I want to make sure that faculty and students are well aware of everything Tsai CITY is doing and are taking advantage of those opportunities. Engineering students are innovative in their thought processes. They're entrepreneurial and they're willing to take the risks required to develop start-ups. With Tsai CITY they can build a skill set in business modeling or business development, which is key to developing a successful device, product, or business.

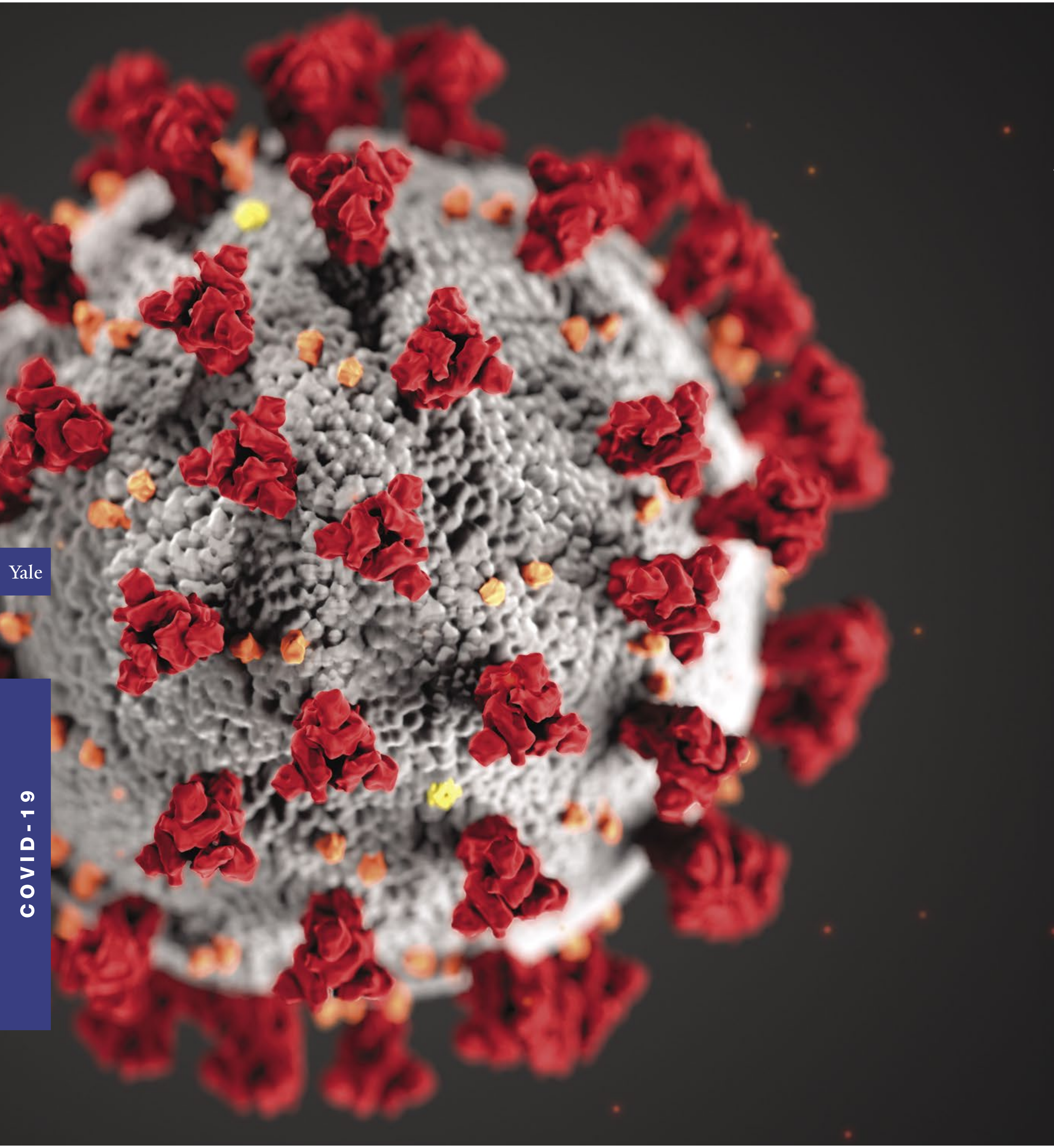
Tsai CITY's building neighbors the Center for Engineering Innovation & Design (CEID). How do you see the two working together?

I view the CEID as the place for students to come in and prototype and build out their models, build out their ideas and get them to fruition. Tsai CITY is really about getting students accelerated in the process of understanding what it takes to get those prototypes and ideas to the next level, to build the networks required to take something out of Yale and have it out in the world. So I think they are linked — they're part of the package that's required for getting something from the mental innovative state to getting it out into the real world.

As an engineer, how do you plan to work with those outside your field?

The people of Tsai CITY really push to make sure that all students feel welcome. That means it is inherently providing multidisciplinary expertise to students as a resource. However, the success of Tsai CITY is also dependent on the multidisciplinary nature of students who become engaged, giving breadth to the types of projects that are supported. I relate to this idea, because I'm an engineer, meaning that I can create things in the lab, but I also know what I don't know — and I don't know the clinic, I don't know patients. Success of my research requires that I look for that clinical expertise elsewhere. Success in almost any sector now requires a multidisciplinary effort, and it's the same thing with my own entrepreneurial efforts. With the PremieBreathe project, I can't be a CEO because I don't know anything about leading a business start-up, so I work with Yale's Office of Cooperative Research, and with the School of Public Health to find the expertise to lead a project like that. For the students at Tsai CITY, the ability to engage with experts of many fields, including other students, provides the best opportunity for success.

A multidisciplinary approach is also applied when we look outside of Yale, at partnerships with industry mentors who engage with students. We're looking at people who are CEOs of major companies who can lend some business savvy to these students, and some business resources to them. The goal is to acquire the resources and the knowledge that we can harness for the benefit of the students.



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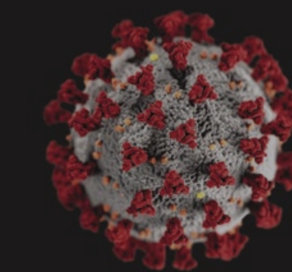
COVID-19



A Single Issue, Many Data Points

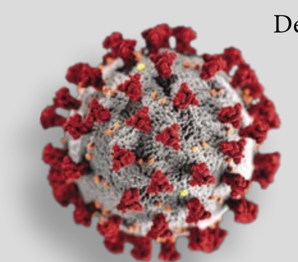
A workshop series sparks collaborations to fight COVID-19

A 19th-century map of a London neighborhood, immunized alpacas, and the burden of extended school closings on healthcare's labor force. These seemingly disparate topics all found their way in a series of workshops that demonstrated how quickly the wide-ranging researchers at Yale could repurpose their work, collaborate, and mobilize to address a public health crisis like COVID-19.

Organized by School of Engineering & Applied Science Dean Jeffrey Brock, the COVID HASTE (Hacking Across Science, Technology, and Engineering) Data Science Workshop series brought together researchers from across different fields to share work that could bring us closer to solutions to a very complex problem.

"With researchers having to work remotely, many approached me and said 'How can we help?'" Brock said. "This was a great opportunity to bring the community together to address COVID-19 and how basic science and engineering research can engage with this question."

The workshops, held over Zoom, began in March and continued into the summer. In addition to the featured presenters, the workshops included panel discussions and would often end with breakout rooms on Zoom. These breakout sessions led to further collaborations and new projects outside of the series.



Linda Niccolai, a professor in the department of epidemiology of microbial diseases, who spoke at the fifth workshop said "important work" has emerged from the numerous connections she made with people in computer science through the series.

"COVID-19 has been a dark and stormy cloud, but when I think of silver linings, the kind of partnerships that developed at the HASTE workshop come to mind," said Niccolai. "Together, we have worked to develop and pilot test technological approaches to enhancing contact tracing for the campus community. The complexity of the COVID-19 pandemic will require novel and interdisciplinary approaches to fight, and that is exactly what originated at COVID HASTE."

Participants in the series included School of Nursing Dean Ann Kurth; Saad Omer, director, Yale Institute for Global Health; Nicholas Christakis, Sterling Professor of Sociology; and Jordan Peccia, the Thomas C. Golden Jr., Professor of Chemical & Environmental Engineering.

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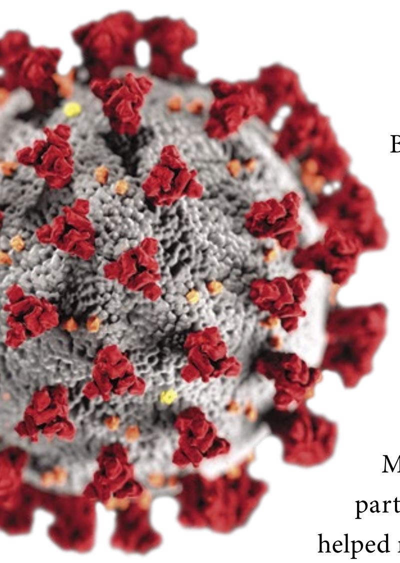


Because the workshops featured researchers from all different fields, Brock said he was pleased that everyone involved managed to get their ideas across in a very conversational way and keep things at an understandable level.

Many of the researchers who took part in the series said that HASTE helped make the most of a difficult time for research.

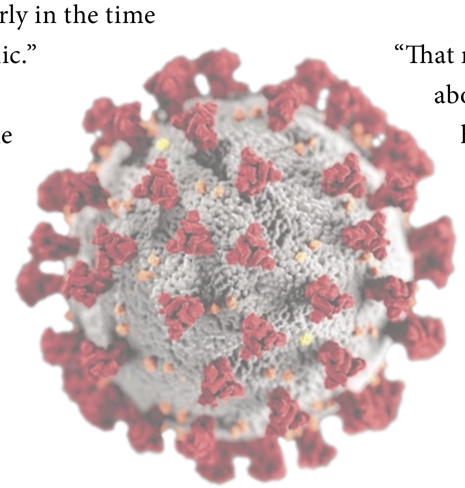
"Under the difficult circumstances, it is very encouraging to see researchers from different areas coming together to share ideas and work together towards a common goal of combatting COVID-19," said Robert Soule, assistant professor of computer science.

COVID-19 presents problems on multiple fronts — curbing its spread, stopping the virus itself, maintaining sufficient hospital supplies, to name a few — and requires a wide range of thinking and methods. To further complicate things, social distancing and the lockdown made it trickier than ever for researchers to form collaborations across fields. That's why Mark Gerstein, who gave a talk at the third workshop, said the series proved to be so crucial.

"Yale is a big place and it's often hard to make connections," said Gerstein, the Albert L. Williams Professor of Biomedical Informatics, Molecular Biophysics & Biochemistry, Computer Science and Statistics & Data Science. "The HASTE virtual workshops were a great vehicle for surmounting barriers, particularly in the time of isolation at the beginning of the pandemic."

One of the recurring themes throughout the series was repurposing existing research to address COVID-19-related issues.

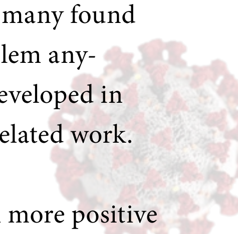
"We're not a virology lab and didn't immediately know what we could do that would be useful," Gerstein said at his presentation. But he was inspired by a fellow researcher's tweet that "it will be a molecule that will stop this virus."



"That motivated me and the lab to think about what we could do because we have a lot of experience with molecules," he said.

One potential area of research that his lab is exploring involves contact tracing, a means of identifying people who have been exposed to someone who's been infected. Michael Rutenberg Schoenberg, a postdoctoral associate in Gerstein's lab, noted that they had already been looking at ways to sanitize biomedical data from identifying information and developing blockchains for robust data storage and security. There's a possibility, he said, of creating a framework based on similar methods to protect privacy in contact tracing efforts.

Brock said that this kind of repurposing showed that many at Yale didn't see COVID-19 and the shutdown as a hazard to their research but as an opportunity to take it in a different direction. Typically, researchers focus on one very specific problem. When COVID-19 hit, many found that they couldn't work directly on that problem anymore — they instead used the tools they've developed in their work and applied them to COVID-19-related work.



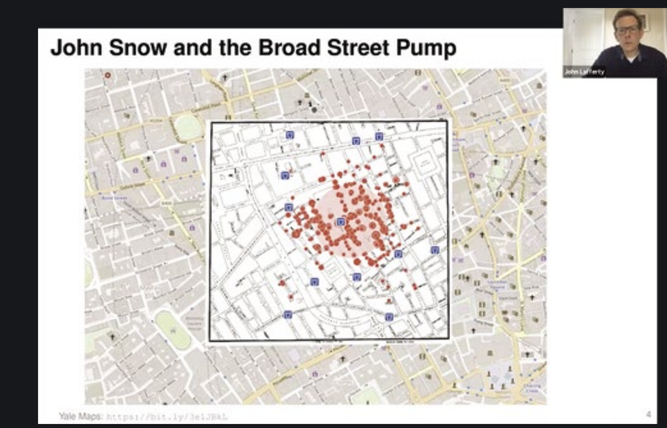
"I like that we're putting 'hacking' in a much more positive light: You have a problem to solve with a certain collection of tools available to solve it, and you just stitch things together to get from point A to point B," Brock said. "This has brought out the inner hacker in all of us in the scientific community."

DATA SCIENCE WORKSHOP

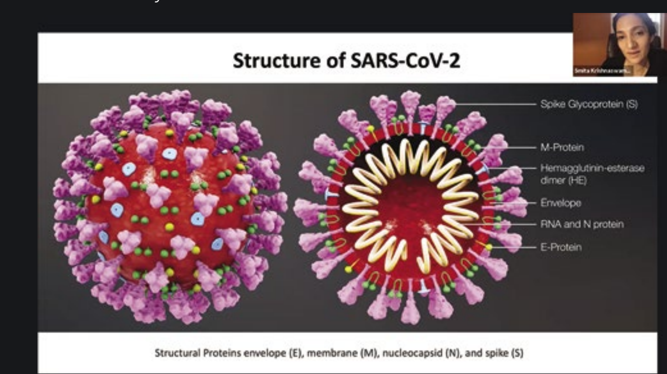
COVID HASTE
HACKING ACROSS SCIENCE, TECHNOLOGY & ENGINEERING

Featured speakers came from numerous research fields, as reflected by the diverse range of topics that they covered. These included:

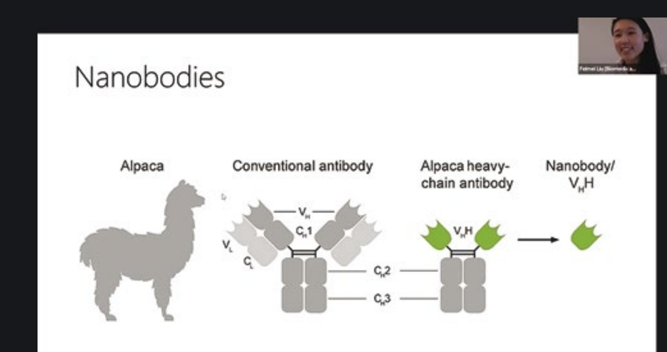
- **John Lafferty**, the John C. Malone Professor of Statistics & Data Science and Computer Science, discussed the importance of interactive visualizations during the COVID-19 crisis. As an early example, he presented John Snow's map of the Broad Street pump in the Soho section of London during the 1854 cholera outbreak. It was commonly believed that the disease was transmitted through the air, but Snow, a physician, posited that it spread through the water. His map helped him make that case to the public.
- **Forrest Crawford**, associate professor of biostatistics, ecology and evolutionary biology, management, and statistics and data science, discussed how he evaluates and predicts the effect of public health interventions to prevent the spread of COVID-19. This included his work in planning the ICU at Yale-New Haven Hospital and help in managing the influx of COVID-19 patients by estimating how quickly patients would come to the emergency department and the consequences of having too many patients for the hospital to handle.
- **Smita Krishnaswamy**, assistant professor of genetics and of computer science, talked about how certain types of datasets can help answer questions such as how mutations affect the ability of the coronavirus to infect, and what kinds of antibodies are good at neutralizing the virus. These include datasets related to viral genome sequencing, single-cell RNA sequencing, and protein-nanobody binding. Protein-nanobody binding also featured into the talk of **Feimei Liu**, a Ph.D. candidate in biomedical engineering, who noted that discovering nanobodies often involves the months-long process of immunizing alpacas. To streamline the process, she said, Yale researchers are helping design a synthetic nanobody library.
- **Eli Fenichel**, the Knobloch Family Chair of Natural Resource Economics at Yale's School of the Environment, has studied the benefits and tradeoffs associated with social distancing long before the COVID-19 outbreak. Data on the far-reaching effects of social distancing, he said, include how crime rates are affected by social distancing, the burden that extended school closings have on the healthcare labor force, and how that in turn affects the quality of healthcare.



John Lafferty



Smita Krishnaswamy



Feimei Liu

Arch Detective

An overlooked structure in the foot could be key to long-standing questions about evolution

When humans walk and run, the front of each foot repeatedly pushes on the ground with a force that exceeds the body's weight several times over. Despite this, our feet maintain their shape without severely bending. Humans are the only primates with this trait of stiff feet, and it has been critical to the evolution of walking on two feet.

But what gives human feet this unique property? A discovery, made by an international team of researchers and led by Yale's Madhusudhan Venkadesan shows that a long-overlooked part of the human foot is key.

The findings, published earlier this year, upend nearly a century of conventional thinking about the human foot. In addition to answering long-standing questions about how the foot works, how it evolved, and how we walk and run, the study could also open new avenues to explore in podiatry, as well as the fields of evolutionary biology and robotics. The study has also led Venkadesan to new research connections and sparked an increased interest in his work from the field of prosthetics.

Researchers in the field long believed that the longitudinal arch of the foot was the main cause of the foot's stiffness. This is the arch that runs from heel to forefoot, with elastic tissues underneath providing reinforcement. The arch and tissues create a bow-and-string structure, which for nearly a century, was considered the main source of the foot's stiffness. But there's a second arch that runs across the width of the midfoot, known as the transverse arch. Investigating this arch (which hadn't been studied previously), Venkadesan and his colleagues performed a series of experiments, using mechanical devices that mimic the foot, cadaveric human feet, and fossil samples from long-extinct human ancestors and relatives (hominins). It turns out, they found, that the transverse arch is responsible for much of the foot's stiffness.

The reason the transverse arch is so important can be found in your wallet. Take out a dollar bill, hold it at one end, and the dollar flops around. But press your thumb down to give the dollar some curvature, and it stands out straight.

"That effect also works in the foot," said Venkadesan, assistant professor of mechanical engineering and materials science. "It's not as simple as a sheet of paper because there are many other tissues and structures in the foot, but the principle turns out to be the same."

Continued →

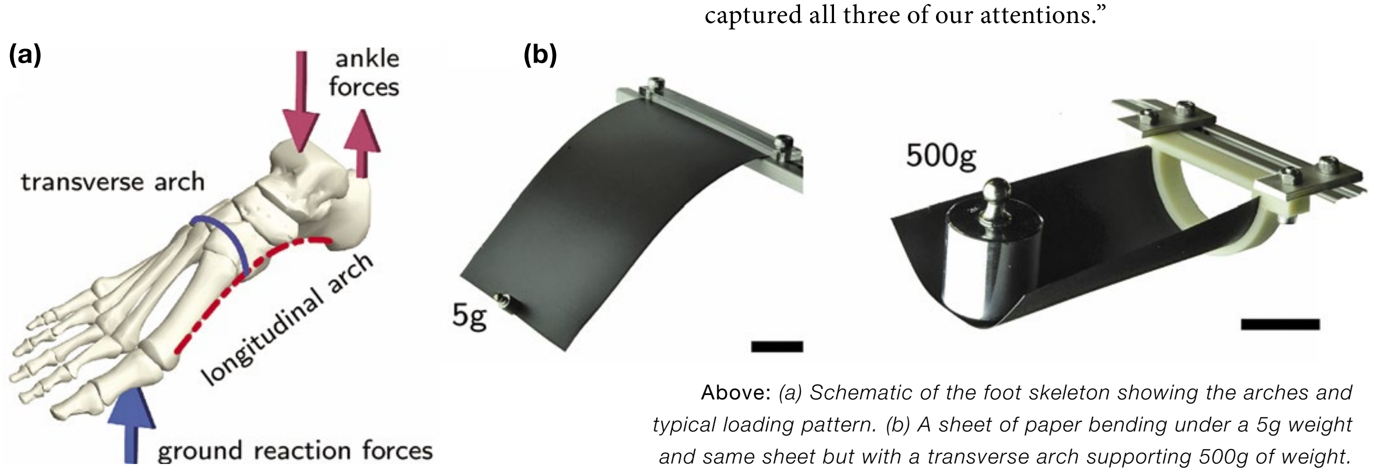
Left: *The three researchers (L-R): Yale's Madhusudhan Venkadesan, Mahesh Bandi, and Shreyas Mandre.*

Problems Long Pondered

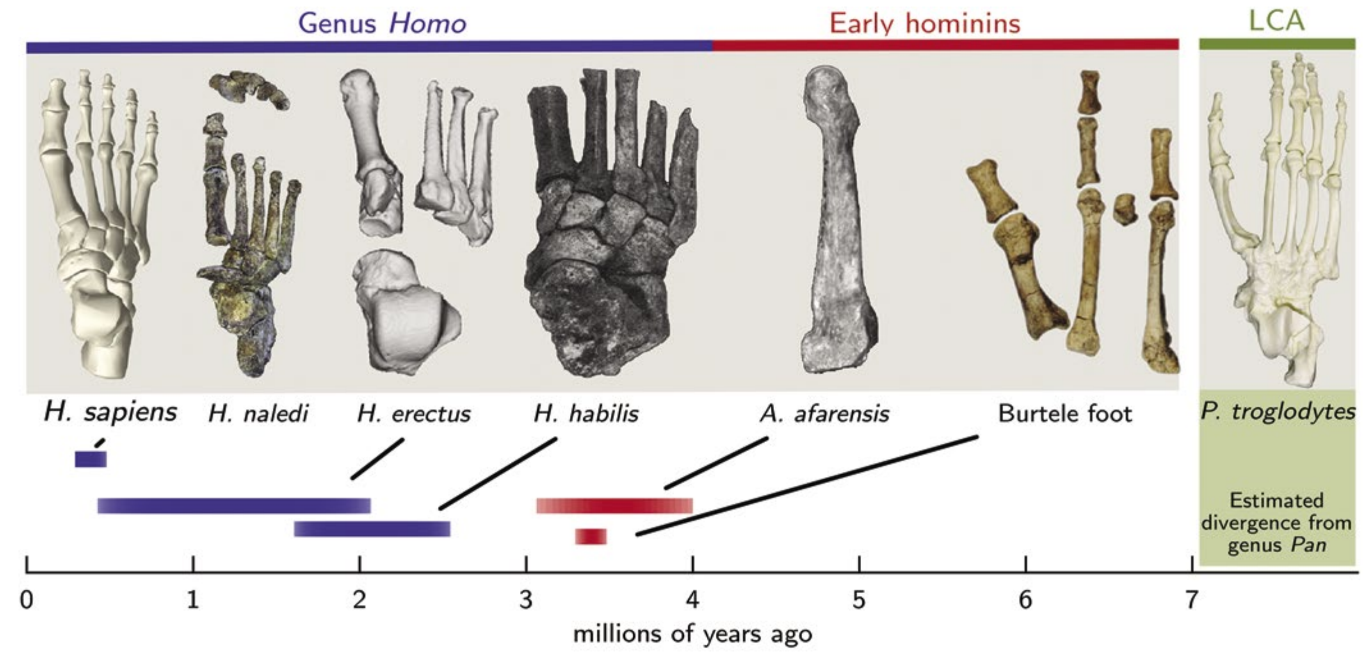
The dollar bill principle works beyond feet, albeit with some variations. In 2017, the same team of researchers — Venkadesan, Shreyas Mandre, and Mahesh Bandi — published a study on the rayed fin. It's a type of fin that's found in more than 99% of all living fish species, a testament to its versatility. Critical to the fin's function is its ability to curve and stiffen, again like a dollar bill. Unlike a piece of paper, though, it also has bony rays connected by a thin membrane. Because of this, even an externally flat-appearing fin can behave as if it is curved. The rays splay apart when water pushes against the fin, thereby engaging the interconnecting membrane and stiffening the fin.

These studies are all part of a larger set of questions that Venkadesan has pondered for some time about the biomechanics and evolution of limbs. As a doctoral student, Venkadesan touched on some of the broad principles of this field, but it was a lunch conversation he had as an assistant professor in India in 2012 with Bandi (an assistant professor in Japan at the time, now an associate professor at the Okinawa Institute of Science and Technology) that really set him down this path. They both decided they needed new problems to solve, and that they should work on them together. So the two, joined by Mandre (an assistant professor at Brown at the time, now associate professor at the University of Warwick), ended up at Mahesh's home in Japan to trade thoughts on a variety of problems. The three scientists first met at Harvard, where they all did their postdoc work, but didn't collaborate until after they each departed for different countries.

"He has a nice big glass door and we found a marker that can write on the glass and that door became the writing surface for a few days," Venkadesan said. "We talked about insects, and jellyfish, and feet, among other things. Thinking about the foot captivated all of our attentions. It had all the elements of a nice math problem, involving curvature and elasticity. It had all the elements of a physics problem, and it had elements of biomechanics which captured all three of our attentions."



Above: *(a) Schematic of the foot skeleton showing the arches and typical loading pattern. (b) A sheet of paper bending under a 5g weight and same sheet but with a transverse arch supporting 500g of weight.*



Above: *Timeline of species related to humans since the split from chimpanzees. The photographs show the fossils that were used in the analysis.* Below: *Identification of the various bones and ligaments of the foot.*

They collected their thoughts, and put together a proposal for the Human Frontier Science Program, based in France.

"We went to them and essentially said 'Hey, the foot's complicated, there's all this biology about it, but our idea is that it's a dollar bill. We think curvature is important, but it's not the curvature that everyone's been thinking about — it's the other curvature.'"

"And they funded it, to our pleasant surprise. That kind of launched this entire thing of thinking about feet, fins, and how people run on rough ground. All those pieces got propelled from that one grant."

It's influenced his life outside the lab as well. Today, Venkadesan is an amateur runner, but that wasn't always the case. Aside from a rather sedentary period during his graduate studies, he'd always been active — he played basketball, tennis, and cricket as a kid. But running was never a main activity of his.

"When I was a postdoc, my advisor asked me, 'So how come you don't run? You think about running very carefully, but

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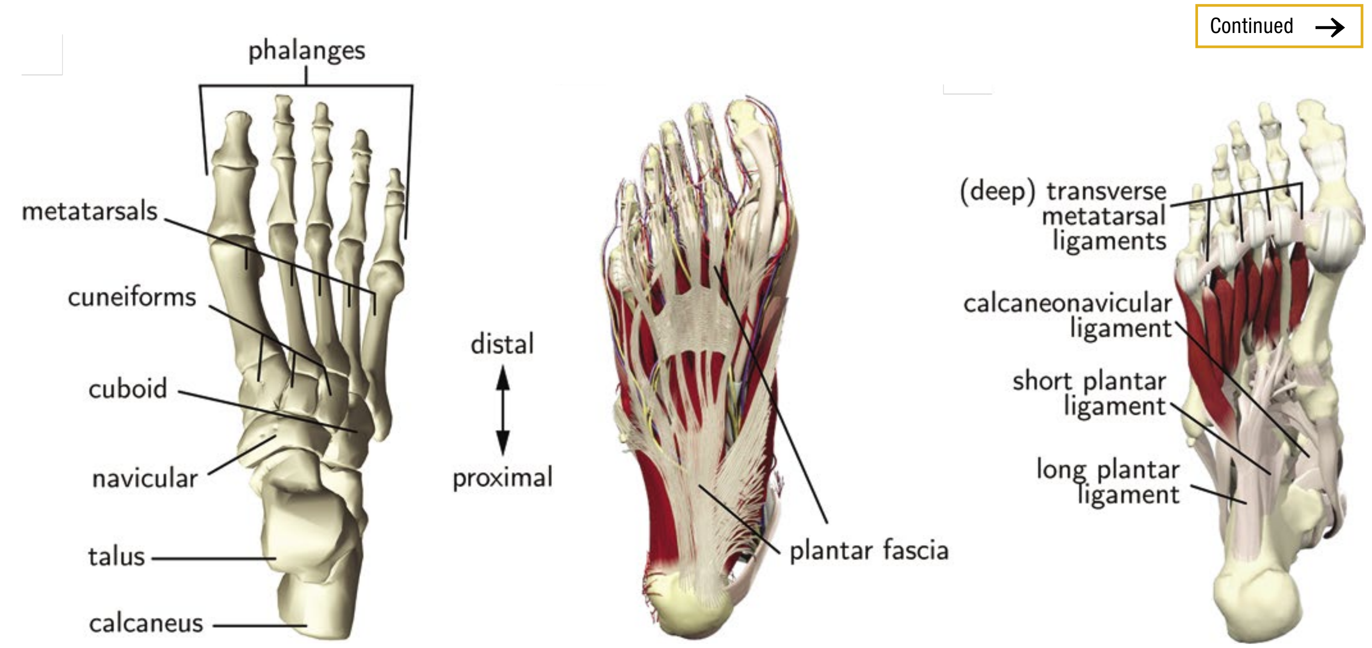
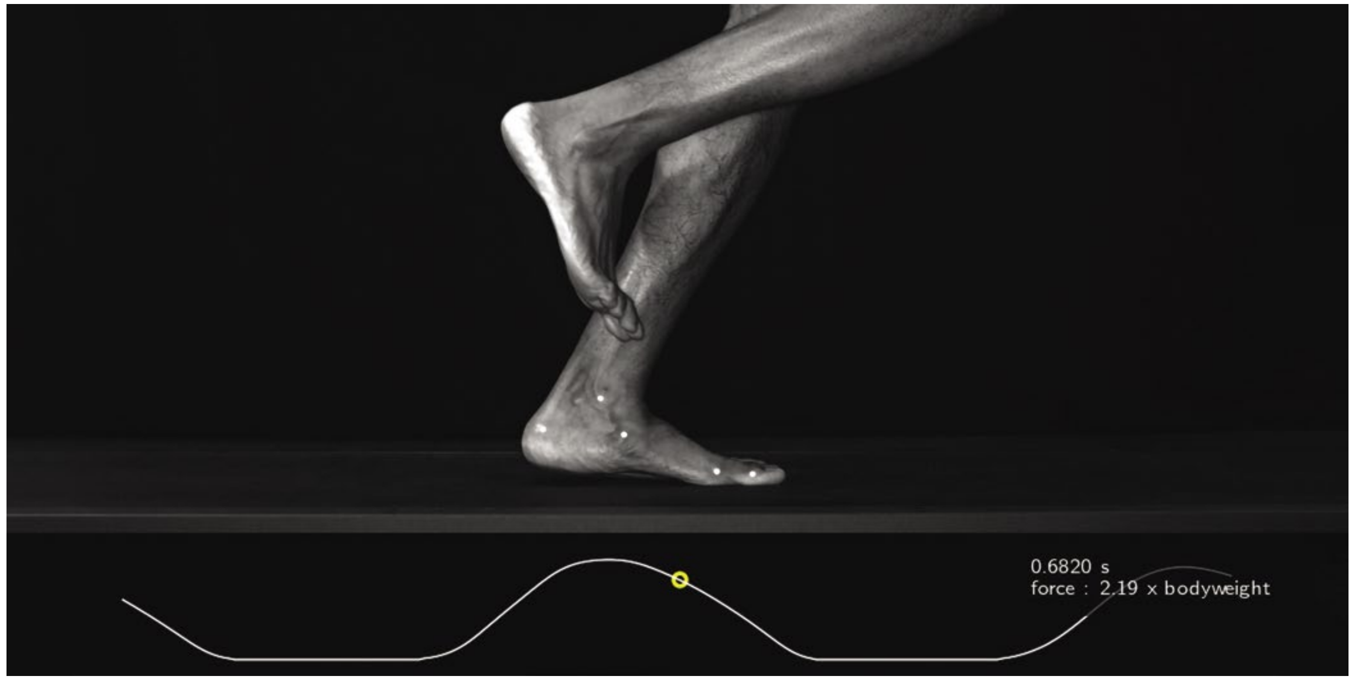




Above: *Illustrating the forces that cause slight bending of the foot during a run.*

you don't run,'" Venkadesan said. "My response, half in jest, was 'So that I'm a dispassionate scientist! So that I have no vested interest in the topic I'm working on.' That sort of prompted me to think again about running, and I started after we published a paper in 2010 on barefoot running."

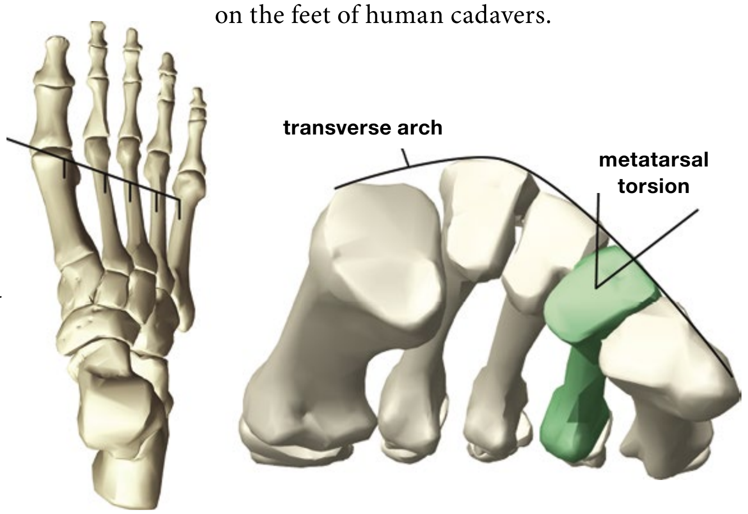
Answering Centuries-Old Questions, and Finding New Applications

The team's most recent discovery drew upon mathematical analyses and experiments to glean the mechanical principle for why curvature induces stiffness in feet — namely that bending a curved structure causes the material to also stretch. Even a thin sheet of paper is quite stiff if you try to stretch it. The transverse curvature engages this stretching stiffness to stiffen the whole structure.

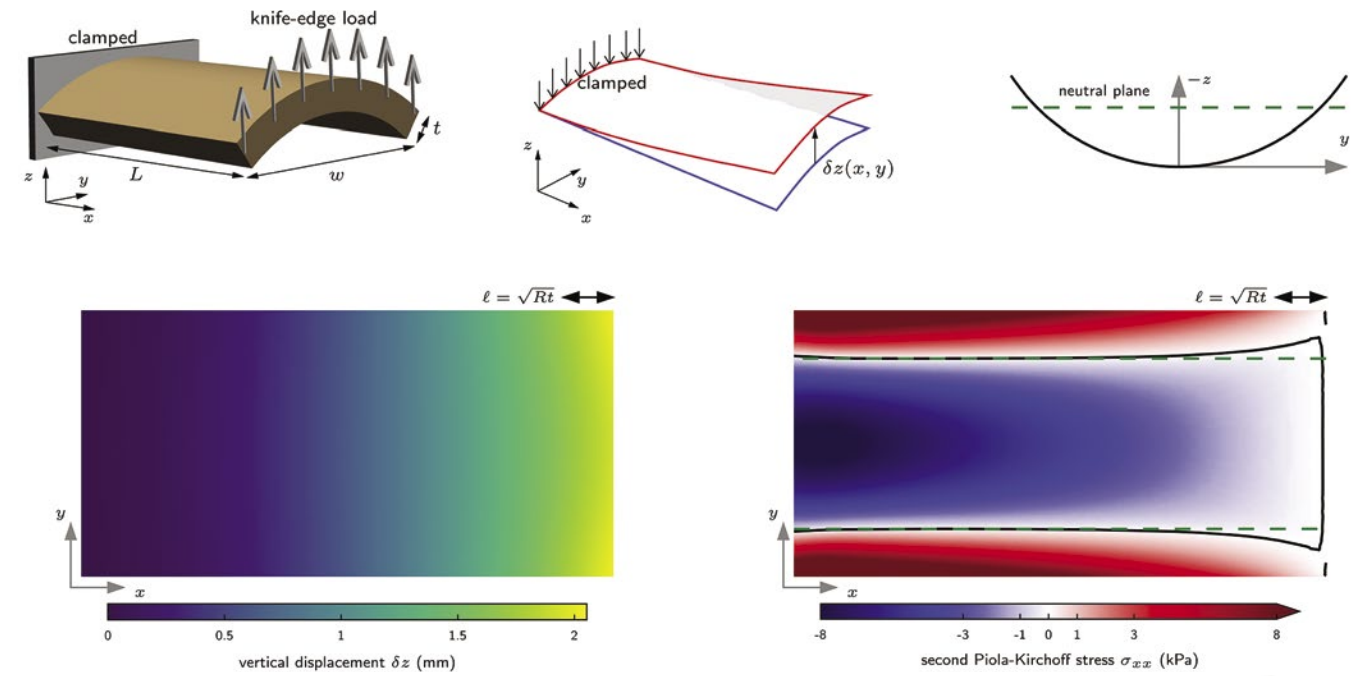
Because the foot is a complicated, multi-functional structure, it is not possible to modify just the transverse arch to test the theory without affecting other parts. So, using experiments on mechanical devices that mimics the foot, the researchers came up with a novel idea to see whether the transverse arch works the same way in human feet.

"We found that transverse springs, which mimic tissues spanning the width of your foot, are crucial for curvature-induced stiffness," said Ali Yawar, a Ph.D. student in Venkadesan's lab. "So we expected that stiffness would decrease in human feet if we were to remove the transverse tissues and leave everything else untouched."

Together with Steven Tommasini, a research scientist at the Yale School of Medicine, they conducted experiments on the feet of human cadavers.



Right: *Schematics showing the skeletal view of the transverse arch and the torsion of the fourth metatarsal.*



The researchers' findings draw upon mathematical analyses and experiments to glean the mechanical principle for why curvature induces stiffness in feet — namely that bending a curved structure causes the material to also stretch.

"We found that the transverse arch, acting through the transverse tissues, is responsible for nearly half of the foot's stiffness, considerably more than what the longitudinal arch contributes," said Carolyn Eng, an associate research scientist in Venkadesan's lab.

The researchers' insights about the transverse arch may also explain how the 3.66 million-year-old Australopithecus afarensis, the same species as the fossil Lucy, could have walked and left a human-like footprint, despite having no apparent longitudinal arch. Working with Andrew Haims, a professor at the Yale School of Medicine, the researchers developed a new technique to measure transverse curvature using partial skeletons of the foot. By applying this technique to fossil samples, including A. afarensis, they traced how the transverse arch evolved among early hominins.

"Our evidence suggests that a human-like transverse arch may have evolved over 3.5 million years ago, a whole 1.5 million years before the emergence of the genus Homo, and was a key step in the evolution of modern humans," Venkadesan said.

When the researchers published the study in February, it made a splash well beyond the field of biomechanics. Among others, it caught the attention of researchers at the University of Liverpool who are working with Jaipur Foot, a not-for-profit company based in India that supplies free-of-cost prosthetic feet to people who desperately need them. Many of these prosthetic feet go to low-income amputees.

"Several of these amputees are daily wage workers and their income is vital for their families. So losing their foot threatens the very survival of their family."

Despite its very low-cost, the Jaipur Foot is well-designed and gives people their mobility. Venkadesan is exploring how the new insights on the human foot could help improve these designs without increasing the cost to produce them.

The study has also helped Venkadesan make connections across Yale's campus. For example, the orthopedics group at the School of Medicine invited him to give a talk — an opportunity for Venkadesan to discuss his research on the foot and possibly get some of its ideas translated to a clinical setting.

"It has helped to have a visible paper in terms of drawing attention from different communities that perhaps would not normally be looking at the engineering or physics literature."

Taste and its Two Ways to the Brain

Taste and smell are "critical aspects to being human." So why don't we know more about them? Fahmeed Hyder is trying to change that.

There are a few ways we perceive food, and not all are particularly well-understood. We know that much of it happens in the olfactory bulb, a small lump of tissue between the eyes and behind the nose, but how the stimuli arrive at this part of the brain is still being worked out.

How these stimuli are processed in the brain plays a major role in our daily life. Fully understanding how our perceptions of food are formed is critical, Fahmeed Hyder said, but getting a clear picture of what our brains do when we smell has been tricky.

"Knowing which exact pathways are affected and teaching our brain to appreciate and acknowledge both modes of perception in understanding the flavor is a part of our culture that we haven't fully exploited yet," he said. A better understanding of how smells get to our brain would not only tell us a lot about our eating habits, he said, it could even potentially help patients of certain diseases.

Hyder, professor of biomedical engineering and radiology & biomedical imaging, has taken a detailed look at the function of the olfactory bulb. It may not be one of the most talked-about regions of the brain, but it helps us make sense of the outside world by taking in molecules from food — known as food volatiles — and then sending these signals further into the brain. It serves a pivotal role as the gateway for chemical stimuli to the rest of the brain — specifically the piriform cortex, amygdala, and hippocampus. To see exactly how it does that, Hyder and his team mapped the activity in the entire olfactory bulb. It's the first time that this has ever been done for the two independent routes of odor delivery — that is, the orthonasal and retronasal routes. The results were published earlier this year in *NeuroImage*.

The orthonasal route — one pathway odors take to the brain — is what we typically think of as smelling, when food volatiles or odor molecules enter the nasal cavity through inhalation. The other — the retronasal route — is more associated with eating, when food volatiles are released in the mouth while we chew and these odor molecules pass into the nasal cavity. Both of these routes, along with the flavors we pick up with the taste buds on our tongues, shape our perceptions of food. Professors Gordon Shepherd and Justus Verhagen, Yale collaborators in this study, have worked on comparing these routes of odor delivery before.

Among other discoveries in their recent work, Hyder and his team found that, regardless of the odor, responses to the stimuli traveling through the orthonasal route were much stronger than those that took the retronasal route. And while the

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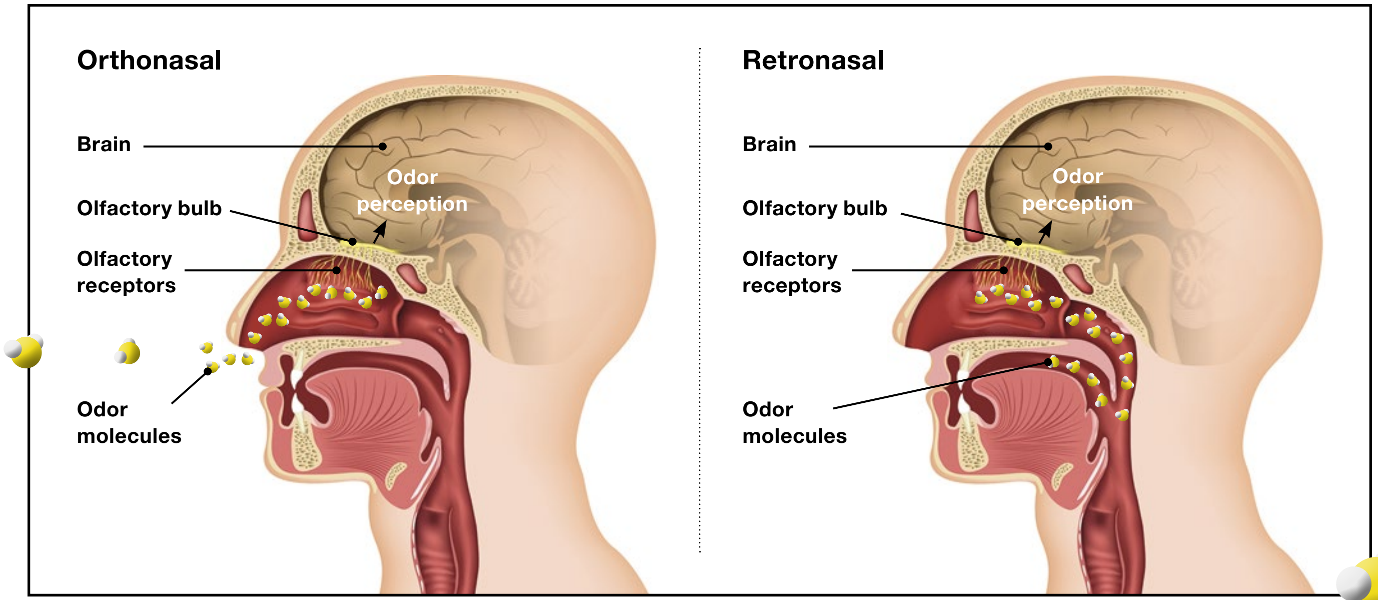


brain responses in the two routes were similar in many ways, the orthonasal maps were dominant in some parts of the bulb, while the retronasal maps were dominant in others. Scientists hadn't observed these differences before, mainly because of the limitations of the standard imaging tools for this kind of research.

Hyder has studied the olfactory bulb for years and worked with Yale researchers Gordon Shepherd and Robert Shulman on some of the first studies on this region of the brain. For the *NeuroImage* study, he and his team wanted to learn more about the different routes that smells take to the bulb. It's important, Hyder said, partly because our perception of food is key to living healthily and recuperating from disease. Certain diseases can affect taste and smell — the discovery that temporary loss of these senses is a symptom in COVID-19 is a recent example.

"It's been shown that a lot of diseases — especially among those with onset later in life — affect smell much more than taste," he said. "That fact hasn't been appreciated much in the treatment of disease, mainly because smell hadn't been considered an important sensation in practiced medicine. But much like how we see and hear, taste and smell are all critical aspects to being human."

Getting a highly detailed look at how these senses are processed could be crucial in helping certain patients. For instance, one common side effect of chemotherapy is that it diminishes the patient's sense of taste. By knowing exactly how the brain responds to food, health care professionals could help train patients to enjoy the flavor of food through the other routes. Conversely, dementia often takes away a patient's sense of smell.

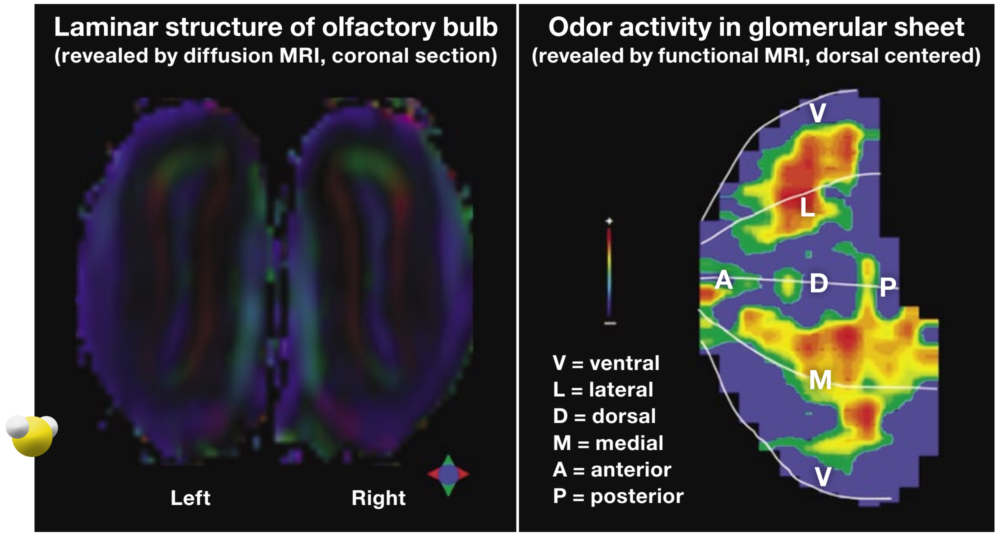
Above: *There are two pathways odors can take to the brain: Orthonasal (what we typically think of as smelling) and retronasal (what we associate with eating).*

"In those cases, people can be retaught how to enjoy a flavor with more concentrated doses that go through the retronasal path," he said.

"Taste" vs. "Flavor": What's the Difference?

"Taste" refers to the taste buds in the tongue to identify tastes like sweet, sour, bitter, salty and umami. "Flavor" is a sort of umbrella term that incorporates taste, but also the smell of the food and its texture as well. Culturally, Hyder said, taste has received the most attention between the two.

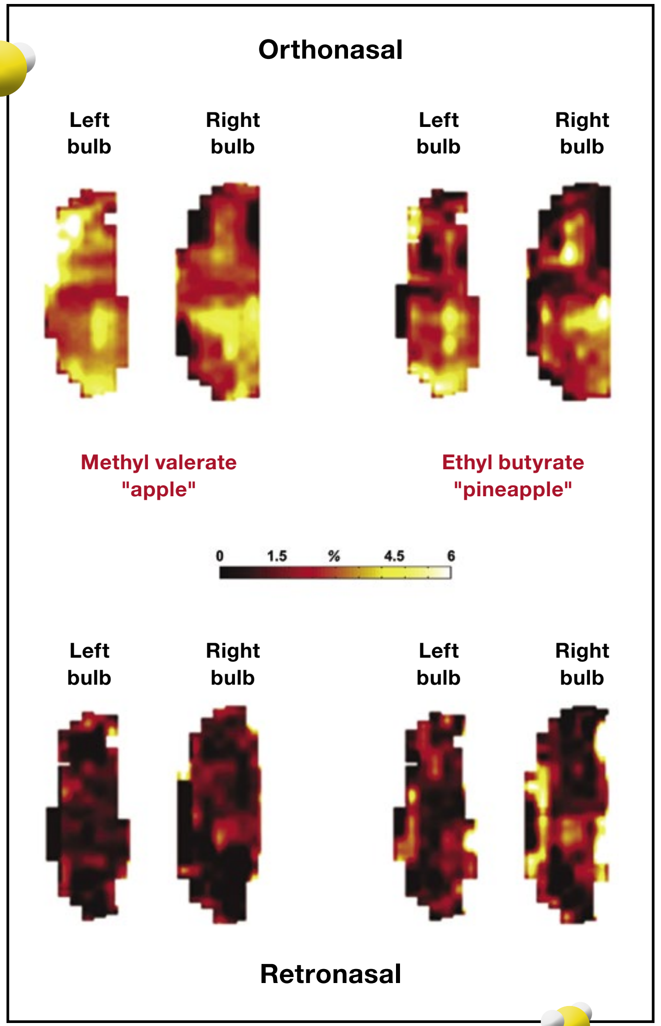
"If I ask what flavor is, most people will say 'taste' — the flavor of food and the pyramid of food that we've created in the Western world is very much based on taste, not the smell component," he said. "But a big part of flavor is actually the other part of the chemosensation — the smell components. Smell happens pretty much — not just in humans but also animals — as we chew our food. When we chew the food, molecules are released and become airborne."



Right: *Different magnetic resonance imaging methods reveal the unique structure and function of the olfactory bulb.*

Below: *Stronger bulb activity with orthonasal, compared to retronasal stimulation.*

One reason that the retronasal and the orthonasal routes aren't fully understood is due to the limitations of technology. Getting a full picture of the brain activity requires a technique that can map both routes simultaneously. Most studies of the olfactory bulb until now have relied on optical imaging, which can only map the bulb's dorsal and lateral regions, and only the superficial layers. Hyder is technical director of preclinical scanners at Yale's Magnetic Resonance Research Center. His team was able to map the entire olfactory bulb by charting these routes with functional magnetic resonance imaging (fMRI), which measures brain activity by detecting changes in oxygen inside red blood cells.



Hyder knows fMRI well. About 30 years ago, he helped pioneer its use in animal models for high-resolution neuroscience explorations. For this study, they created the maps by contrasting images of brain activity in rats — some with odors and some without odors. Between these sets of maps, they could determine how the amount of oxygen delivery was altered to support the activity of various synapses in the olfactory bulb.

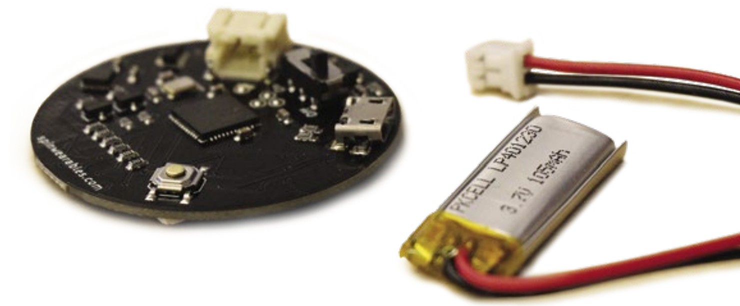
Hyder said the study is also a starting point to find new ways to study metabolism — another subject of interest in his lab. Typically, his metabolism research has focused on the cerebrum, but the work in the *NeuroImage* study has paved a way to explore it in the olfactory bulb. It's a promising avenue of study because the olfactory bulb is a well-organized region with layers that can be easily separated, like an onion. Because the anatomy in the olfactory has many layers, and each distinct neuroanatomical make-up can be readily detected, the localization of specific metabolic events can shed light on what happens when and where. "Because of the nature of these separate layers in the olfactory bulb, it's much more straightforward to study," he said. "So, we're combining optical techniques to look at specific types of cells, and we're using fMRI techniques to look at specific metabolic signals. By combining them, we can understand the physiology and chemistry of the neural code."

It's Stylish! It's Colorful! And it Makes Engineering Fun for Kids

The SpinWheel, created by GradSWE, gives families a way to take on STEM-related projects

Yale

EDUCATION



It looks like a keychain or earrings, but for kids with an interest in science and engineering, it's a gateway to the fields of physics, computer science, art, and more.

It's called the SpinWheel, a stylish device that kids can program any number of ways to create a unique, science-infused piece of wearable art. Created by the Yale Graduate Society of Women Engineers (GradSWE), it has motion sensors and LEDs that can be programmed to create different patterns. Thanks to some of its sensors, these patterns can even respond to the Earth's magnetic fields and the device can be programmed to act as an electronic compass. The group began selling them online earlier this year (and, yes, you can get one — see page 65 for ordering information). Proceeds go to funding GradSWE's future outreach efforts.

It was created to give families a way to take on various STEM-related projects at home. The idea for it arose from conversations with parents at outreach events for middle and high school students.

"They'd often ask 'Is there a take-home kit that we can get to work with our kids on engineering ideas at home?'" said GradSWE member Becky LaCroix, who completed her Ph.D. in biomedical engineering this year.

They based the device on the open-source Arduino platform, a popular choice among hobbyists and makers. They developed and tried out numerous designs, looking for something that was both wearable and looked good. Once they had their components and a rough sketch of the layout, they designed the circuit board with computer-aided design tools. They ordered a few test boards for hand-soldering to double-check the performance of each component and ensure that the final device would work reliably.

"It was important to test and make sure that the electronics worked like we wanted, and that took a few iterations — then we made the first board and assembled it," said Jenna Ditto, who completed her Ph.D. in environmental engineering this year. "The really expensive part is the manufacturing of the components and placing them onto the board itself. You don't do that until you have a big enough order."

While the prototyping and building of the board took a fair amount of work, coming up with the educational materials was the most time-consuming part of the project. They structured the lessons to be accessible to students who have never programmed, but also allow advanced users to create customized scripts. The SpinWheel comes with a "field guide" to give users a sense of all the things they can do with it, including multiple educational and artistic activities.

The device was directly inspired by one of the GradSWE's outreach lessons, in which they invited high schoolers to campus to use breadboards and LED strips to create a motion-sensing bracelet. The event went over really well, especially among the students who hadn't worked with electronic components before. That confirmed the SWE members' belief that building something beautiful can overcome initial fears about math and science.

"We very intentionally tried to bring together art and engineering, because often the people who don't see themselves as engineers are often artistic, but would be interested in the more technical side if they just saw it linked to something they're more comfortable with," said Bridget Hegarty, who recently completed her Ph.D. in environmental engineering. Hegarty is giving a talk in November at the Society of Women Engineers

Continued →

conference about how the SpinWheel can bring those two fields together and serve as a powerful outreach tool.

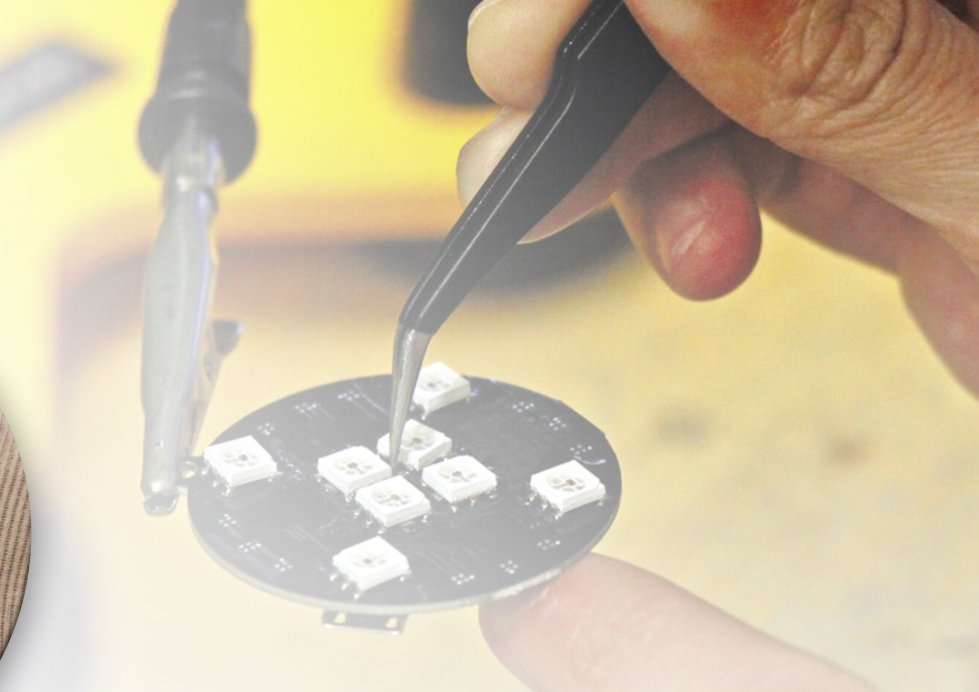
Then there was the matter of raising money for it, and then selling it. The group launched a Kickstarter campaign, an effort equal parts exhilarating and nerve-wracking. Long before the campaign officially kicked off, they went all out with the advertising to ensure that they'd have a big push for the first day.

"And for the rest of the campaign, we were reaching out to anyone possible," LaCroix said. "And then you see it tick up, and you're like 'Two devices bought today!' Or '10 bought today!'"

The efforts included a flurry of social media activity, plus appearing on podcasts around the world.

"That really surprised me, how much we had to spread our network and seek out all these different avenues," Ditto said. "I never expected we'd be on podcasts!"

Above left: *The SpinWheel has motion sensors and LEDs that can be programmed to create different patterns.* Above right: *Yale leadership represent the SpinWheel at the SWE National Conference.* Background: *SpinWheels coming off the manufacturing line at CircuitHub.*



Left: *GradSWE member Jenna Ditto solders an early SpinWheel prototype.*

Below: *The SpinWheel is built using Arduino software and can be programmed over USB from any computer.*

Timing of the Kickstarter campaign was a little awkward. It started officially on March 16, the first Monday when Yale began operating remotely to curb the spread of COVID-19. So certainly, many potential donors were otherwise distracted.

"We definitely weren't anticipating the challenge of competing with a pandemic," Hegarty said. On the other hand, it forced the group to think creatively in terms of promotion, including online events, which they were already well-versed in. Plus, after a few weeks of remote learning, a lot of parents were desperate for new things to occupy their kids at home.

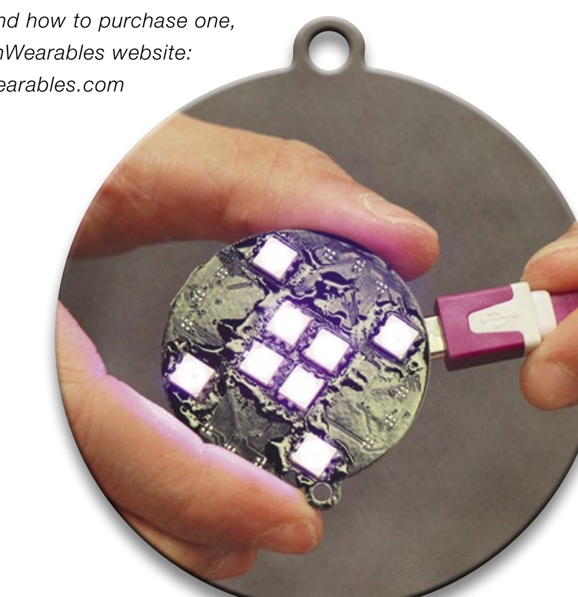
Since Hegarty and LaCroix founded GradSWE in 2014, outreach has been part of the group's core mission. Some of GradSWE's events are for elementary school students, but most are geared toward middle and high school students. For the most part, they try to keep the talking part of the lessons to a minimum, and introduce the students to real-world engineering tools and methods (like soldering).

"It's the kind of activities where they really get their hands dirty and get to experience engineering firsthand," Ditto said, adding that the motion-sensing bracelet is one example. "It lights up when you move around, and it's super cool and it's instantly gratifying when you program it to move, and it works."

The trick for a good outreach lesson is one that's just the right level of difficulty. Hegarty noted that the middle schoolers are particularly proud of being given the responsibility of a soldering iron. And at the end of the lesson, having something tangible that they built helps bring home that sense of accomplishment.

"At first, the kids have a sense of 'I wouldn't be able to do this,'" Hegarty said. "And by the end, because they're able to make something that works, they're like 'I did that,' and they have a better sense of what engineering is."

For more information about the ***SpinWheel*** *and how to purchase one, go to the SpinWearables website: https://spinwearables.com*



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