Engineering a Championship

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Solving Hard Problems with Soft Robotics

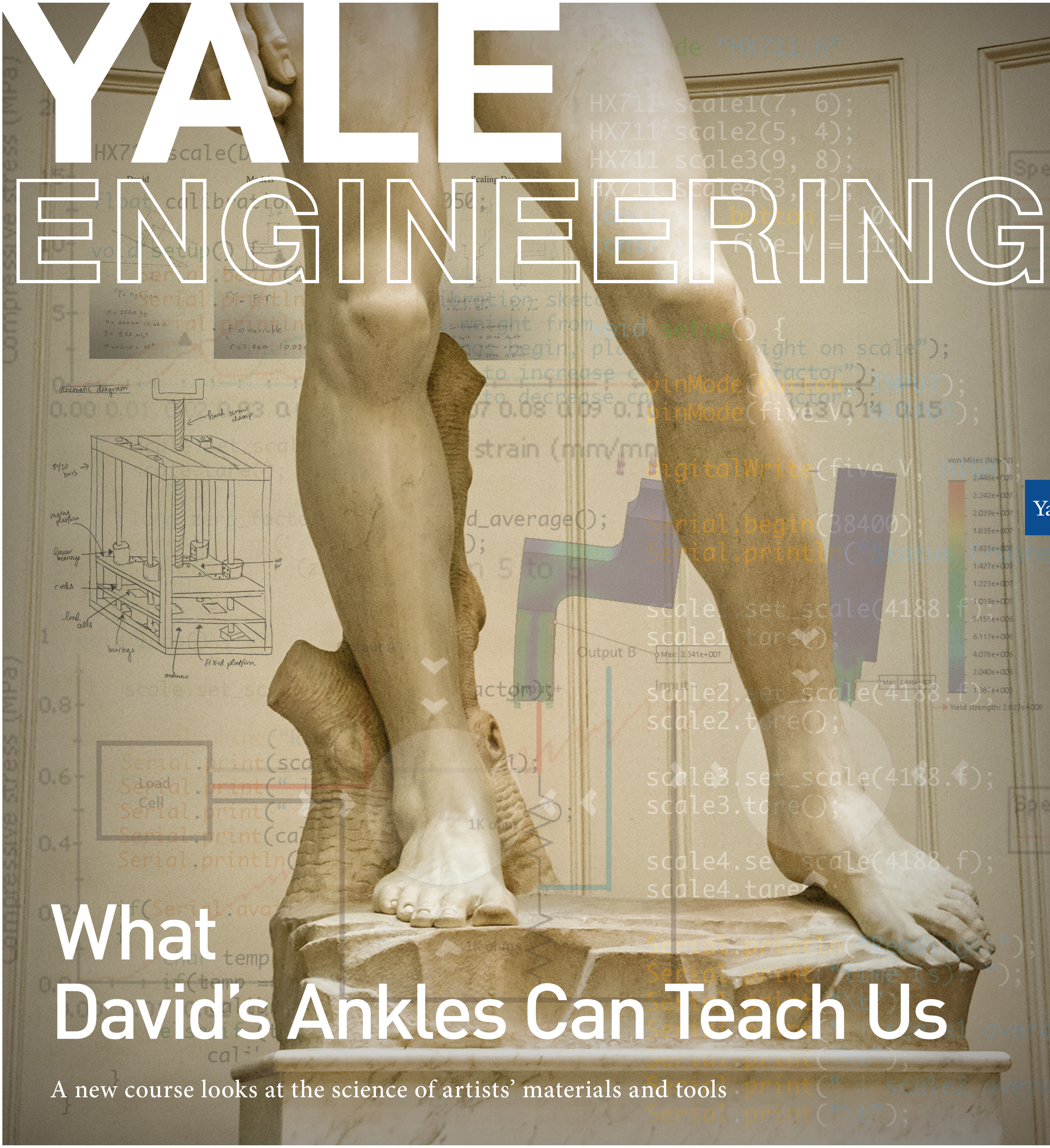
Shape-shifting devices herald the future of robotics

Building Safer, Healthier Athletes

Students at the CEID tackle the hazards of sports

2018-2019

YALE ENGINEERING



What David's Ankles Can Teach Us

A new course looks at the science of artists' materials and tools

Yale

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

CONTENTS

FEATURES

Front Cover: *SEAS students built an innovative "crushing" device to explore the science behind the failing ankles of David. Sensors, 3D printers, coding, mathematical models, strain maps, and stress simulations were also put to use in studying the centuries-old masterpiece.*

ALUMNI EDUCATION INTERDISCIPLINARY MEDICAL INNOVATION TECHNOLOGY

YALE ENGINEERING 2018-2019

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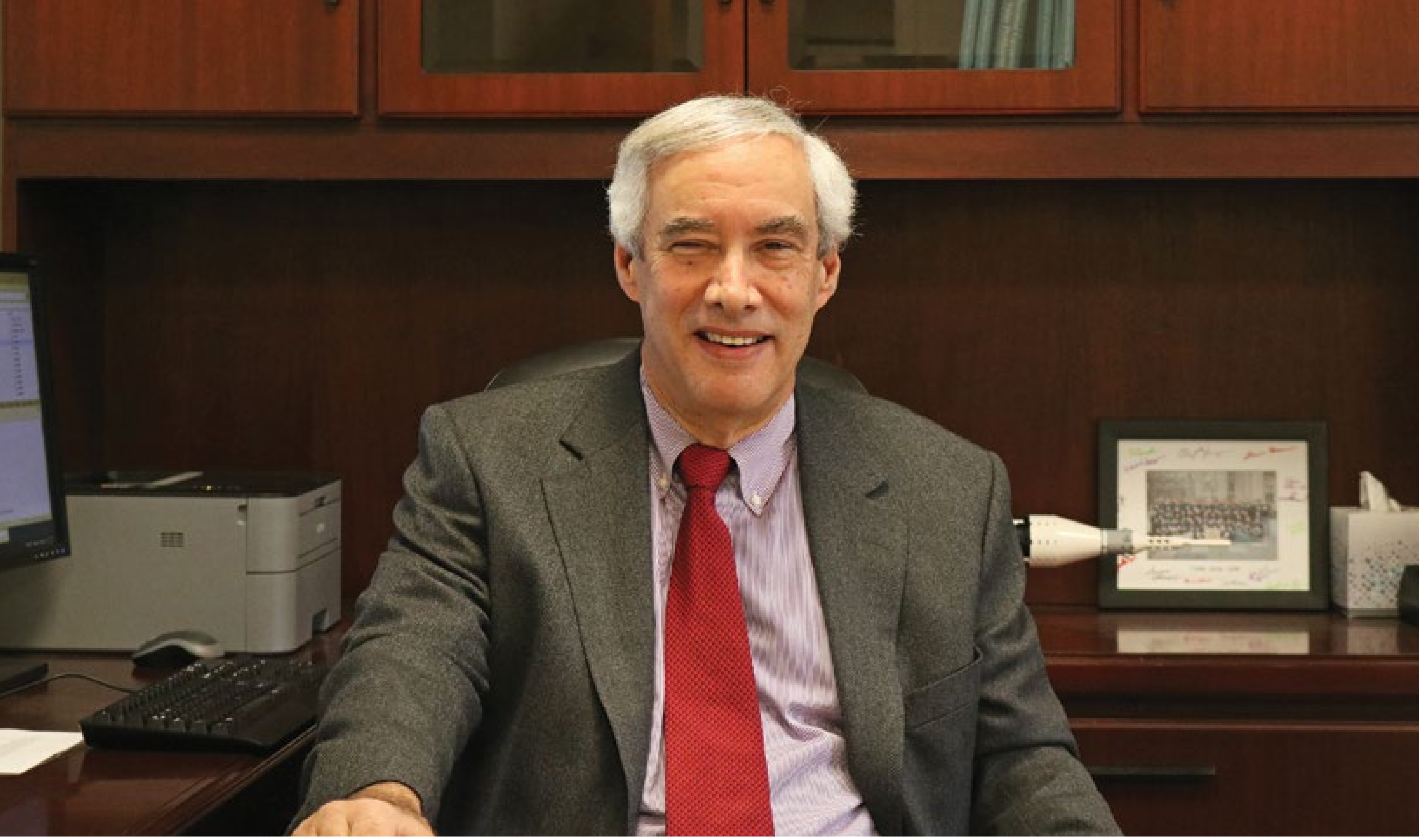


Message From the Dean

At the Yale School of Engineering & Applied Science we talk a lot about creating a "culture of engineering." But what does that actually mean? Growing our academic programs, developing creative partnerships across the university, or infiltrating the wider world with our own brand of engineering? Of course, we hope to be accomplishing all of that and more. And with this year's edition of *Yale Engineering*, I know you'll see examples of all the above.

On the home front, our five departments continue to grow as we now have more undergraduates declaring a SEAS major than in the last 60 years, with several of our majors ranking among the most popular in the entire university. The Center for Engineering Innovation & Design, now in its seventh year, celebrated its 5,000th member, and our newly-renovated Greenberg Engineering Teaching Concourse, space that includes eight adaptable teaching labs, opened to great success. We are also actively recruiting faculty on the forefront of new and innovative research.

Outside of the engineering bubble, we are seeing some unexpected, yet fruitful collaborations with our colleagues at the Institute for the Preservation of Cultural Heritage and Yale Athletics. As you'll read, these collaborations have spun out into the creation of new undergraduate course and an NCAA Championship. They've also created a drive among the entire Yale community to ask more questions and see what new and exciting solutions our students can engineer.

In the broader world, our alumni are making a big impact. Sharon Walker, one of the first graduate students in Environmental Engineering, was recently appointed Dean of Drexel University's College of Engineering. Current students are also having an effect with their participation in the FIRST Global Robotics competition. After serving remotely as mentors to several international teams, students traveled to Mexico City this summer to meet with their teams in-person and assist with on-the-fly fixes before the big competition.

Moving forward, we are in the process of developing unique joint Master's Degree programs with several of Yale's Professional Schools. Yale may be known for its liberal arts education, but our culture of engineering is a thriving one that works to complement all aspects of the university.

Mitchell Smooke
Interim Dean, School of Engineering & Applied Science

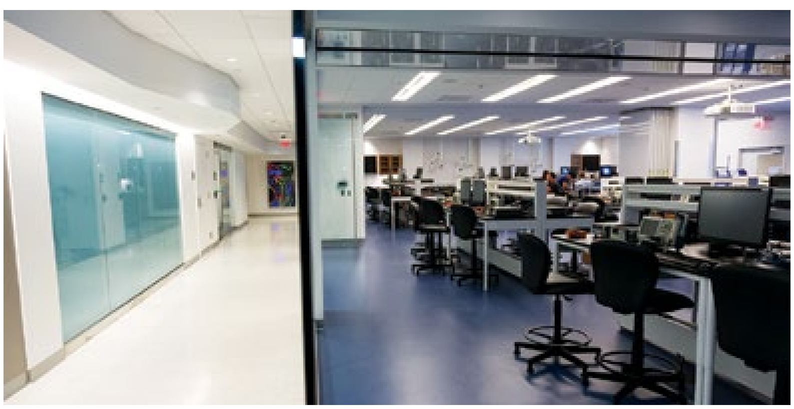
Year in Review

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

2017: September

Labs for Learning

The new semester brought SEAS a new teaching space, the Linda and Glenn H. Greenberg Engineering Teaching Concourse. Located beneath Becton Plaza in the center of Yale's engineering campus, the teaching space includes six new undergraduate teaching labs along with two wet labs with hoods. The labs have been outfitted with state-of-the-art equipment and computers. The project, funded with a $10 million donation from Glenn Greenberg '68, brings together labs from all disciplines in engineering — located over four buildings — into one space.



2017: October

Computing the Social Sciences

Yale's first Data Science Workshop on Computational Social Science covered a wide range of topics related to computational data analysis, from how languages spread to ways of improving the value of crowdsourcing. Event organizer Dragomir Radev, the A. Bartlett Giamatti Professor of Computer Science, said the event is a sign of the increasing importance of data in numerous fields, and something that likely would not have happened ten years ago. Future workshops will focus on how data science and computer science have influenced the digital humanities, medicine, and finance.

2017: November

Better Transplant Outcomes

To improve long-term outcomes for transplant recipients, Mark Saltzman, the Goizueta Foundation Professor of Biomedical Engineering, Chemical & Environmental Engineering and Physiology, and researchers at the School of Medicine combined drug-carrying nanoparticles with a device that keeps donor organs "alive" outside the body before implantation. The nanoparticles target cells of the organ that are the first point of contact with a recipient's immune system after the transplant and critical to the organ's acceptance. The system could provide new therapeutic strategies for transplants and new insights for systemic drug delivery.

2017: December

The Mysteries of Cornstarch

The lab of Eric Brown, assistant professor of mechanical engineering & materials science and physics, has gotten one step closer to figuring out the unusual properties of cornstarch-water mixtures. The material can solidify instantly upon impact and return to liquid in moments. They discovered that the way that the substance returns to liquid after solidifying is very different from conventional thinking in the field of rheology (the study of fluid properties). The discovery could help researchers use the material for protective gear and other practical applications.

2018: January

Innovation, One Cell at a Time

Technology created by Isoplexis, the company founded by Rong Fan, associate professor of biomedical engineering, was named the Top Innovation of 2017 by *The Scientist* magazine. The IsoCode chip and IsoLight platform is an all-in-one system that reads the individual cells of tumors created. This level of precision could be a key factor in what's known as CAR-T therapy, which re-engineers a patient's immune cells to better fight the patient's cancer. Although it's promising, the therapy can also elicit dangerously toxic reactions. The Isoplexis system could help in managing the toxicity of the therapy.

2018: February

Professor Earns Diversity Award

Anjelica Gonzalez, the Donna L. Dubinsky Associate Professor of Biomedical Engineering, was awarded the 2018 Diversity Award from the Biomedical Engineering Society (BMES). The BMES Diversity Award honors an individual, project, organization, or institution for outstanding contributions to improving gender and racial diversity in biomedical engineering. It is given for a broad range of activities, including research, education, and service that improve diversity in the biomedical engineering industry and/or academia. Gonzalez delivered the plenary lecture at the BMES 2018 annual meeting in Atlanta in October.

Continued →

Year in Review

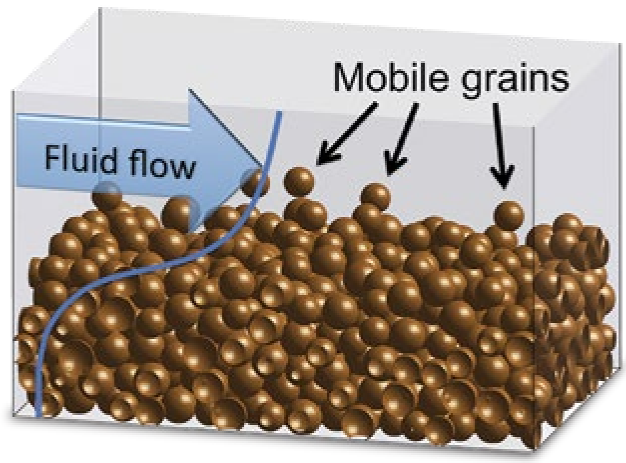
2018: March

Theatrical Engineering

Sydney Garick '18 combined her mechanical engineering major with her interest in theater by building an LED panel — a floor with programmable lights — for the first all-student production of "Fun Home," performed at the Off Broadway Theater. The stage, which was Garick's senior project, was built in the Klingenstein Lab of the Center for Engineering Innovation & Design. Sometimes the LED lights were used for effect — adding some flash to a disco number, for instance. Other times, they took the shape of furniture and other objects.

2018: April

A Granular Look at Sediment



Corey O'Hern, professor of mechanical engineering & materials science, physics, and applied physics, was awarded a Defense University Research Instrumentation Program grant from the US Department of Defense to study how sediment moves. Developing a clearer picture of how sediment beds evolve could allow for more ways to control those changes. Understanding the changes in fluid-driven granular beds could benefit the military and Army Corps of Engineers in a number of ways. For instance, it could help control the erosion near pilings of bridges and other large structures.

2018: May

A Windfall for a Firewall

Ruzica Piskac, assistant professor of computer science, received a Facebook Communications and Networking Research Award for her proposal "Automated Repair and Verification of Firewalls." Piskac's team of researchers developed FireMason, the first tool that can not only detect errors in firewall behaviors, but also automatically repair the firewall. Once computer administrators observe problems in a firewall, they can provide input/output examples that comply with what they want the firewall to do. Based on the examples given, FireMason automatically synthesizes new rules for the existing firewall.

Yale

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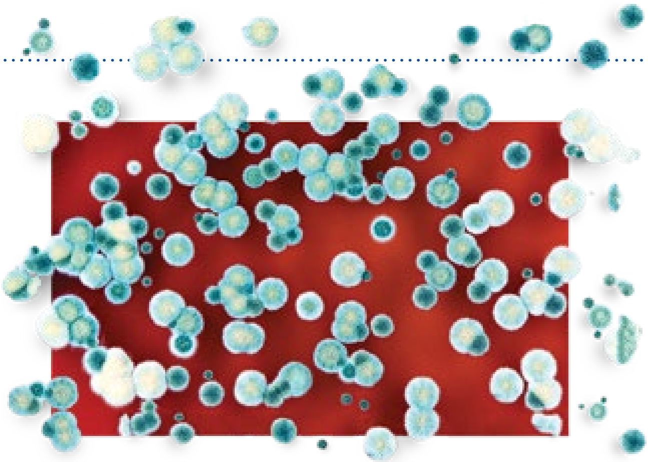


2018: June

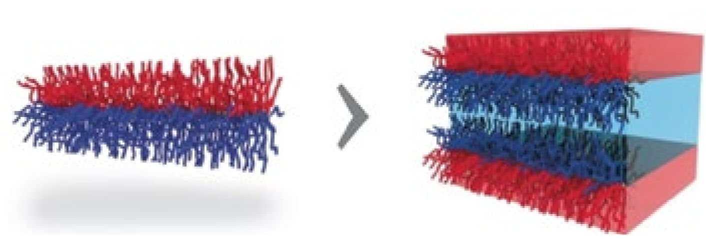
Germs and Desks

The lab of Jordan Peccia found that bacteria and fungi found on school desks overwhelmingly came from the children sitting at the desks. They also discovered that the germs were in full force within a few days after cleaning. The results, published in the *Journal of Applied Microbiology,* suggest that in times of outbreaks or for children sensitive to allergens, school officials should consider more rigorous desk-cleaning practices. The good news is that, under normal circumstances, parents shouldn't worry too much — exposure to microbes can even be beneficial.

2018: July

Improving a Promising Material

A nanostructured material known as block copolymers have been of great interest to researchers in recent years, as they could potentially be used for everything from cleaner water to the next generation of computing. Regulating their properties, though, has been tricky. But Mingjiang

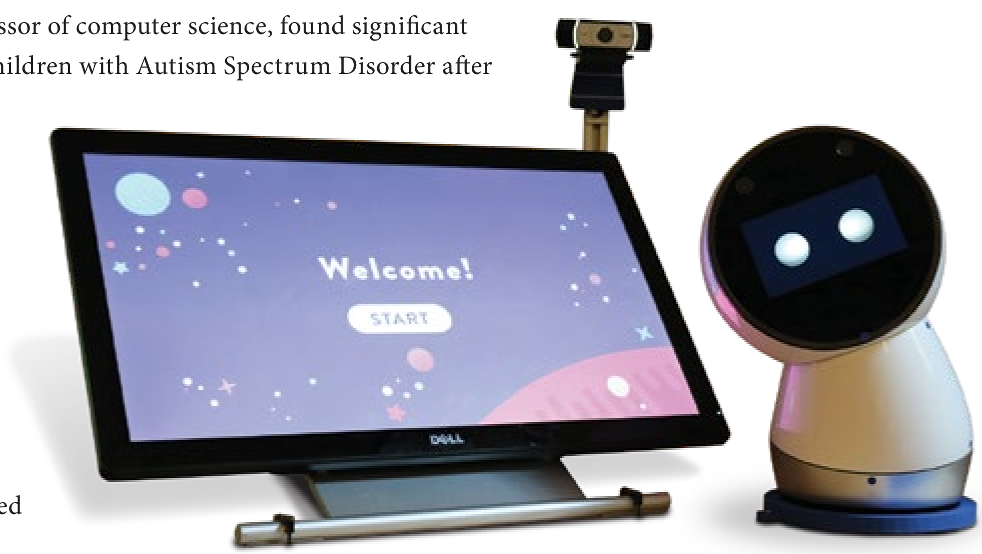


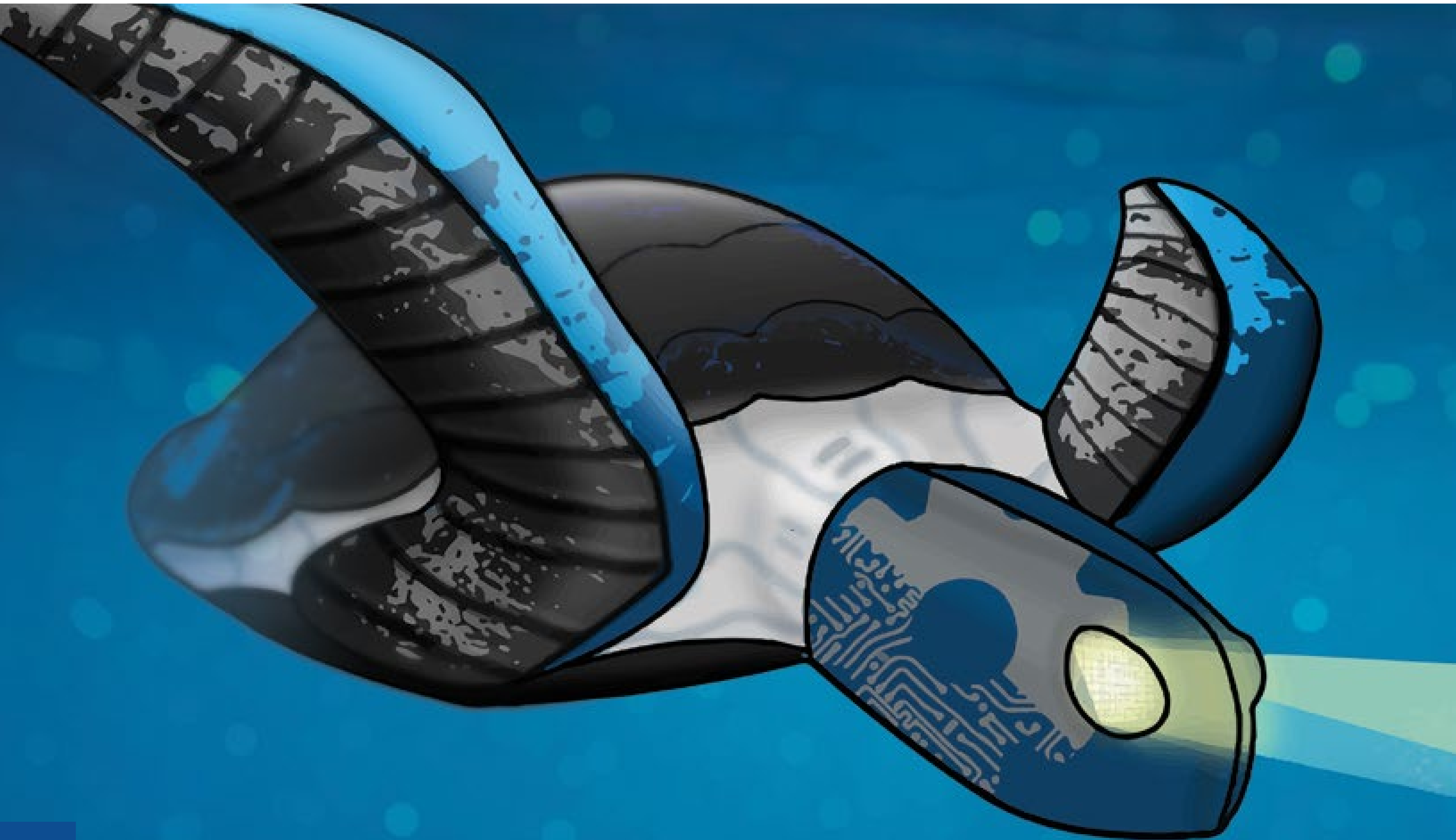
Zhong, assistant professor of chemical & environmental engineering, developed a method for designing these materials that allows researchers to control the thermomechanical properties. By doing so, these materials could mean a major advance in electronics and the development of higher-density chips.

2018: August

Robots Teach Social Skills

A study led by Brian Scassellati, professor of computer science, found significant improvements in the social skills of children with Autism Spectrum Disorder after a month of working with robots. Modeling eye contact and other social behaviors, the robots were placed in the homes of 12 participating families and guided the children through storytelling and interactive games for 30 days. The activities were designed to promote social skills such as emotional understanding, taking turns, and seeing things from others' perspectives. The results were published in *Science Robotics.*





Yale

TECHNOLOGY

Solving Hard Problems with Soft Robotics

Shape-shifting devices herald the future of robotics

Imagine a robot that could roll up to a door, flatten itself out, and slide under. Or one that could shape-shift as it encounters new terrains or environments. Traditional robots made from rigid materials can't accomplish such feats, but potentially new soft robots can. Made from soft, pliable materials, such devices could be invaluable for search-and-rescue or exploratory missions, safe collaborative robots, and a new generation of active wearable technology.

That's the thinking behind the work of Rebecca Kramer-Bottiglio, assistant professor of mechanical engineering & materials science. Since she arrived at Yale from Purdue in 2017, her Mason Laboratory workspace, The Faboratory, has increasingly filled with creations that push the boundaries of what robots can do. These include a soft robot that can lift its own power supply (more than 200 times its weight), and "robotic skins" that turn soft passive objects in active robots.

The mechanics of living creatures have inspired some of her projects, like a turtle- and tortoise-inspired robot with morphing limbs that shift between leg and flipper states, so the robot can move in both land and water environments. She's also made an octopus-like robot with eight tentacles, utilizing a new material to direct the motion of those tentacles upon inflation. When considering materials for next-generation robots, looking to nature is a good choice.

"Material clearly plays a role in our ability to interact with our environment," said Kramer-Bottiglio. "Given the prevalence of soft materials in animals, it makes sense to include soft materials in robots designed to perform animal-like tasks."

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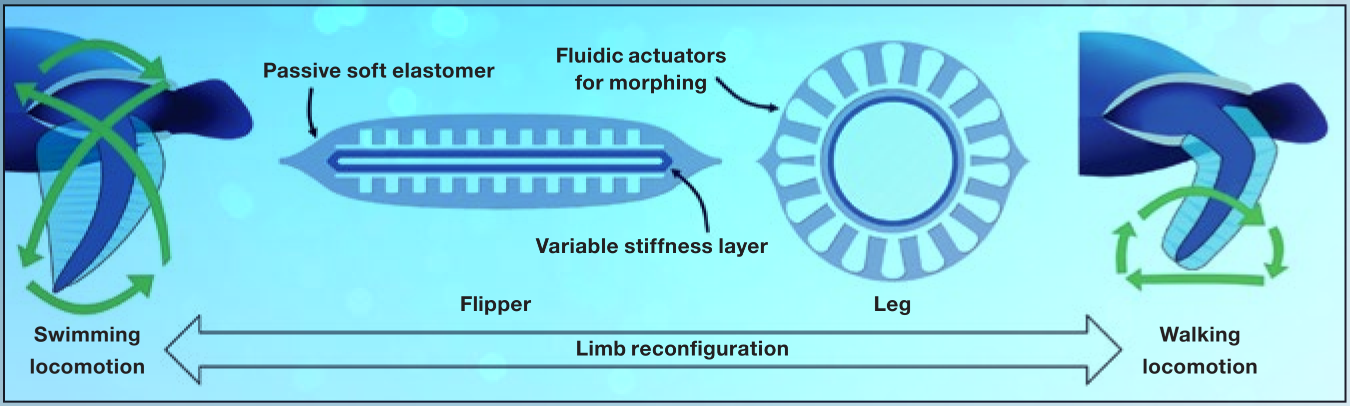
Biomimetic Unmanned Untethered Vehicle



But while nature inspires some of her work, she's not trying to copy it.

"We're not trying to reverse-engineer animals, but many of our robots are bio-inspired," she said. "We study animal morphology and movements to inspire design choices in synthetic systems."

Take the morphing limb project, for instance. Funded with a Young Investigator Research Program grant from the Office of Naval Research (ONR), Kramer-Bottiglio sought to create something that borrowed from the strengths of the sea turtle's flipper and the tortoise's leg. The two are anatomically similar, but the small differences between them make a big difference.


Rebecca Kramer-Bottiglio

"Sea turtles have flippers for swimming, stability control, and maneuvering, whereas tortoises have legs for support of the body and movement on land," she said. "Our limb design will allow movement in both environments while permitting functionality in the tidal zone.'"

Sea turtles move incredibly well in the water, thanks to their flippers. Tortoises, on the other hand, don't do nearly as well in the water but move fine on land. This works out well for both since they each tend to stick to their native terrain. Navy vehicles and devices, though, need to navigate between land and water often. The tricky landscapes of the three distinct environmental conditions of the shoreline — stable open water, turbulent surf zones, and dry land — highlight the limitations of the current generation of amphibious robots, most of which are built with rigid structures. Kramer-Bottiglio notes that the soft and reconfigurable robots that mimic systems in nature have the potential to operate in the kinds of environments that spell trouble for traditional robots.

Drawing from the differences and similarities of turtles and tortoises, Kramer-Bottiglio's lab is developing a Biomimetic Unmanned Untethered Vehicle with a reconfigurable actuation system that can change from a flipper optimized for water to a leg optimized for land. To make the transformation from the tortoise-like phase of the

Yale

TECHNOLOGY

Above: *Creating robotic skins in the lab. The skins contain embedded actuators and sensors that can impart controlled motions onto the objects they wrap around.*

robotic limb (nearly circular in cross-section to provide support for walking) to the flattened shape of the turtle's flipper, Kramer-Bottiglio will use materials that can change in stiffness to lock and unlock into the two configurations. Critical to this are the actuators — essentially, the "muscles" in robotics — that she's made in her lab.

"We have developed variable-stiffness fluidic bending actuators that can reconfigure between a thin, flat state and an inflated, bent state," she said. "Distributing these actuators along a limb will allow us to morph between the flipper and leg configurations."

Continued →

> *"Rebecca continues to be one of the most creative minds at this very rich intersection of materials science, novel manufacturing, and robotics."*
>
> › Robert Wood, professor of electrical engineering and former advisor, Harvard University

Above: *Kramer's robotic skins are a planar skin-like substrate with embedded robotic functions.*

When the three-year project is complete, Kramer-Bottiglio said the system should be at least as efficient in each mode as the tortoise and turtle limbs are in nature. Not only would the system have more control than traditional robots in the varying environments, they would also operate using less power. Potential applications would include payload delivery, mine-detection and disposal, surveillance, environmental monitoring, and diver support.

The Possibilities are Endless

Kramer-Bottiglio began her research in soft robotics at Harvard, where she was a Ph.D. student in the lab of roboticist Robert Wood, known for his work on robotic bees. Wood called Kramer-Bottiglio "a pioneer of the nascent field of soft robotics" and noted that, while in his lab, she was "fantastically successful" in finding various approaches for creating compliant skin-like sensors.

"This required a deep exploration of materials and manufacturing considerations for soft and multi-phase composites — something that was not typical for developing robots at the time," said Wood, a professor of electrical engineering. "Rebecca continues to be one of the most creative minds at this very rich intersection of materials science, novel manufacturing, and robotics."

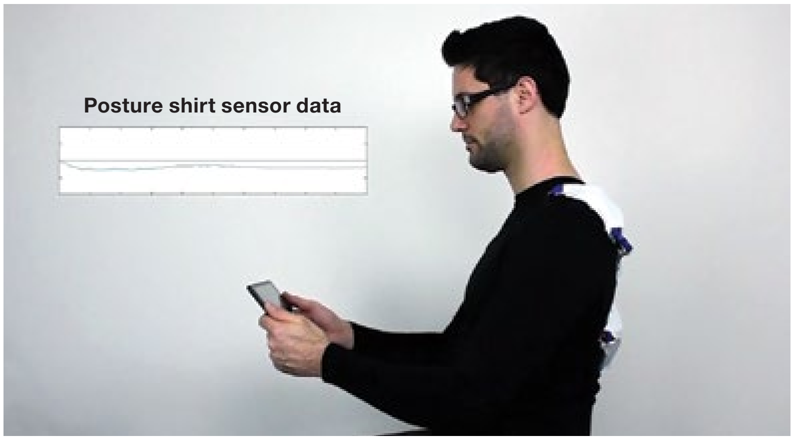
Among other honors, Kramer-Bottiglio has been named to the 2015 *Forbes* "30 under 30" list, received the Young Investigator Research Program grant from the U.S. Air Force Office of Scientific Research, and the National Science Foundation CAREER award.

For another project, supported by a NASA Early Career Faculty Award, Kramer-Bottiglio is focusing on the problem of task specificity in robotics. Most robots are designed with a specific purpose and environment in mind — assembling cars on a factory line, for instance. But the field of soft robotics might be uniquely suited to developing devices that do a lot of things. With this in mind, Kramer-Bottiglio has developed "robotic skins" — multipurpose robots that can be used to create different robots that perform different tasks. The devices, also known as OmniSkins, wrap around everyday, inert objects to convert them into robots. Take a stuffed animal or a foam tube, outfit them with the OmniSkins — elastic sheets embedded with sensors and actuators — and they become controllable robots. The skins animate these objects from their surfaces. The makeshift robots can perform different tasks depending on the properties of the soft objects and how the skins are applied.

"We can take the skins and wrap them around one object to perform a task — locomotion, for example — and then take them off and put them on a different object to perform a different task, such as grasping and moving an object," she said. "We can then take those same skins off that object and put them on a shirt to make an active wearable device."

Continued →

Left & Above: *Inanimate objects — like a plush horse — can come to life and walk when wrapped with a robotic skin.*



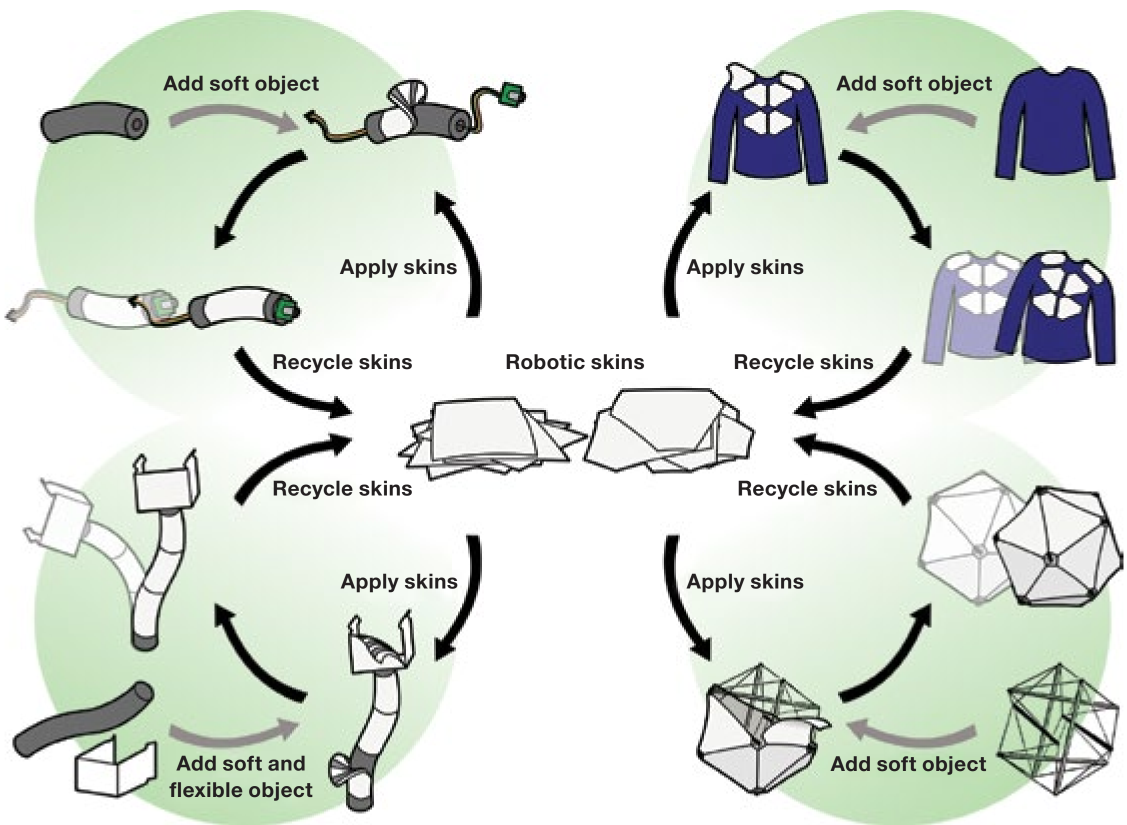
Above (l to r): *Robotic skins are not exclusive to inanimate objects. They can also be applied to an upper body garment using its sensors to track human posture. Actuators pulse to inform the wearer that they should sit upright.*

Kramer-Bottiglio said she came up with the idea for the devices a few years ago when NASA put out a call for soft robotic systems. With the robotic skins on board, she said, anything from balloons to pieces of cloth or paper could potentially be turned into a robot with a purpose.

"One of the main things I thought about was the importance of multi-functionality, especially for deep space exploration where the environment is unpredictable," she said. "The question is, how do you prepare for the unknown unknowns?"

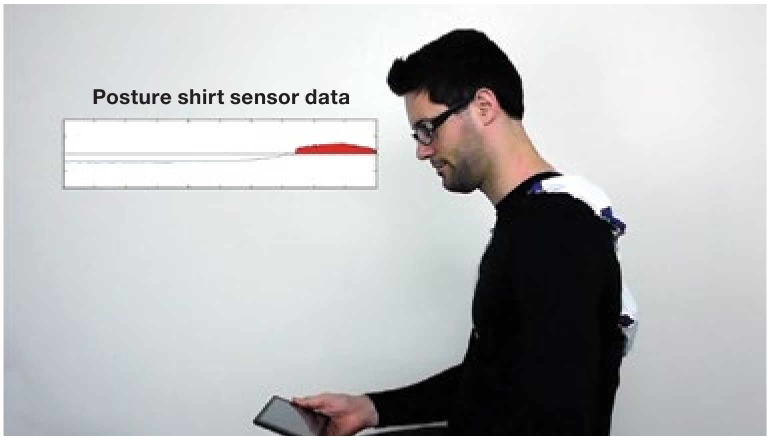
Sending multiple robots to perform numerous tasks is costly. But repurposing the same robotic hardware repeatedly and applying the technology to whatever objects are available means a huge boost in resources. With the

Illustrating the Versatility of Robotic Skins



Left: *Robotic skins can be recycled and repurposed to turn any soft object into a robot with a purpose.*

Right: *This 20-sided structure boasts multiple sensors and actuators that allow it to move in different directions.*



"I'm excited to see what people will do with this multi-purpose technology, the possibilities are endless."

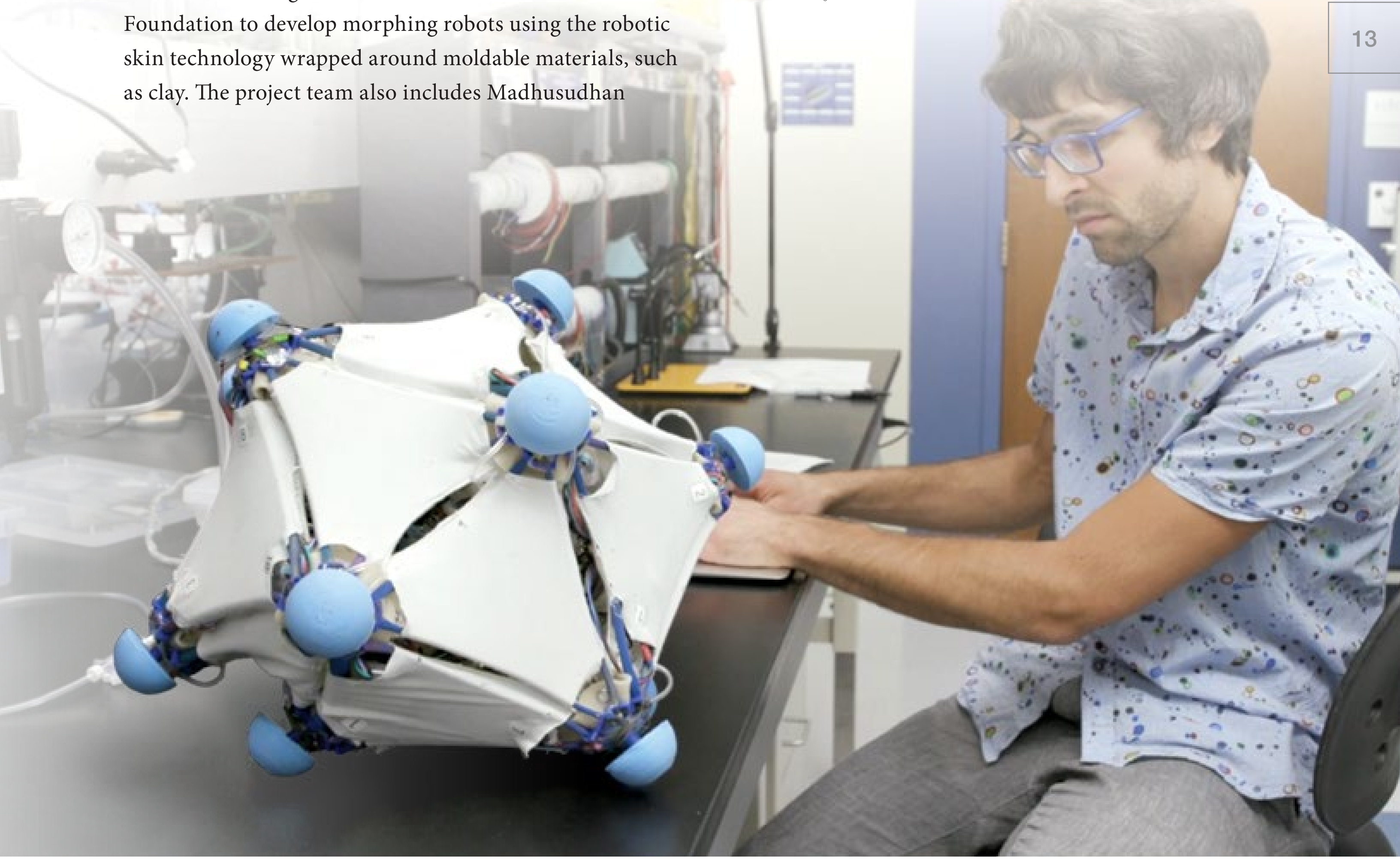
› Rebecca Kramer-Bottiglio, assistant professor of mechanical engineering & materials science

robotic skins, users can design robots within minutes for any number of different tasks.

Kramer-Bottiglio and her team have demonstrated the robotic skins in a handful of applications. These include foam cylinders that move like an inchworm, a shirt-like wearable device designed to correct poor posture, and a device with a gripper that can grasp and move objects.

For the same line of research, Kramer-Bottiglio recently won a $2 million grant from the National Science Foundation to develop morphing robots using the robotic skin technology wrapped around moldable materials, such as clay. The project team also includes Madhusudhan Venkadesan, assistant professor of mechanical engineering & materials science, who will focus on the mechanics of the morphing robot systems.

The technology is cutting-edge now, but Kramer-Bottiglio envisions a time when it could be a common part of people's lives. "In the future, I imagine kits of robotic skins and fabrics that people will use to design personalized robots on the fly," she said. "I'm excited to see what people will do with this multi-purpose technology — the possibilities are endless."



Yale

EDUCATION

Engineering a Championship

Yale's lacrosse team is now the best in the nation. The CEID has something to do with that.

Earlier this year, Yale Men's Lacrosse team won its first national championship since 1883. While no single factor is responsible for the team's success, it's certainly fair for SEAS to claim some of the credit.

It was at the Center for Engineering Innovation & Design (CEID) where students developed the Lightboard, a device designed to help goalies hone their reaction times. The students worked on it as part of the course, Introduction to Engineering Innovation & Design (ENAS 118), and it was in regular use by the lacrosse team, and later, the soccer and hockey teams.

Soon after he arrived at Yale in 2016, Thomas Newman, Yale's Director of Sports Performance and Innovation learned about the CEID and he didn't waste time paying a visit. "My mentors used to tell me, 'You can't have too many friends who are engineers.'"

SEAS Deputy Dean Vincent Wilczynski and senior research scientist Lawrence Wilen took Newman on as a client for ENAS 118, which they co-teach. For the course, student teams take on challenges from all areas at Yale and try to find a solution. Athletics was a natural fit, Newman said, since "there's never any shortage of problems in sports."

For their part, CEID and the class were happy to have Newman as a collaborator.

"He's a very good client for the 118 class," Wilen said. "He's really good with the student teams and understands what makes a good project."

Wilczynski said Newman works with everyone at the CEID along every step of the projects. As part of the process of developing new tools to help coaches and athletes, Newman challenges the staff and students to stretch in new directions.

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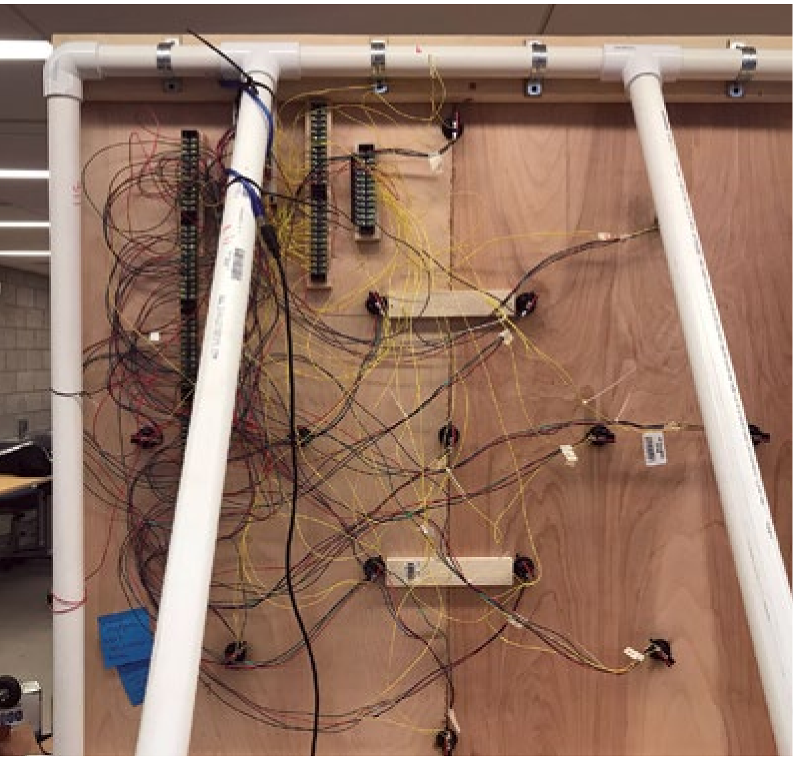
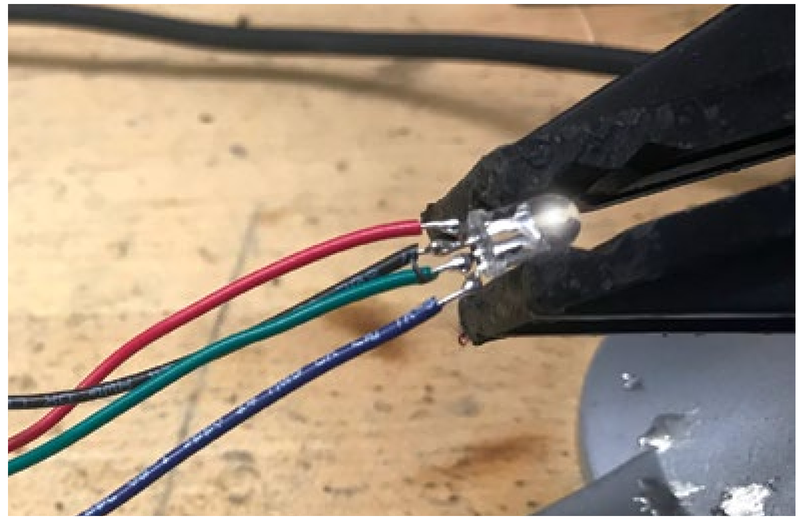
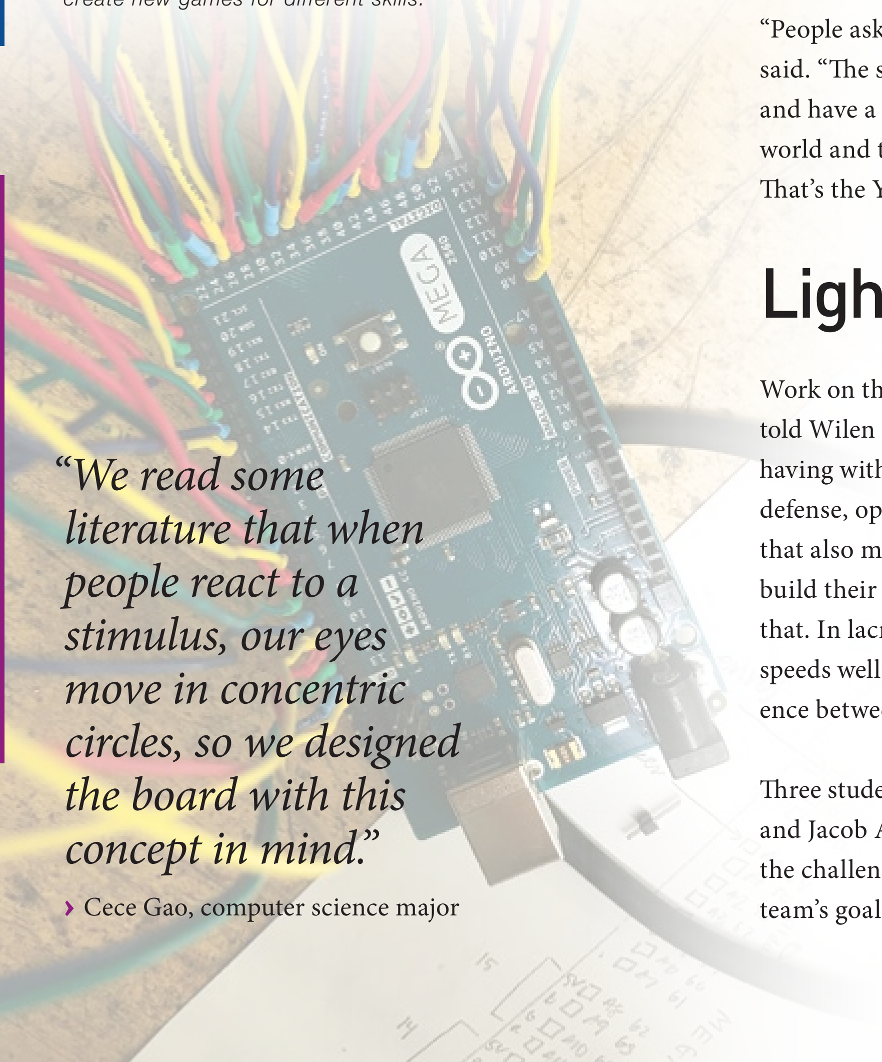




Top Left: *Wiring on the back of the Lightboard.*

Top Right: *The Lightboard is comprised of 15 LED lights, each capable of flashing different colors.*

Bottom: *Utilizing an Arduino, the Lightboard can be adjusted to create new games for different skills.*



"We read some literature that when people react to a stimulus, our eyes move in concentric circles, so we designed the board with this concept in mind."

› Cece Gao, computer science major

"Coach Newman brings the same intensity to the CEID that he brings to the sidelines of our sports fields," Wilczynski said. "He gives guidance and encouragement to get each project across the finish line. Working with him is akin to an intense intellectual workout that is immensely rewarding and extremely inspiring."

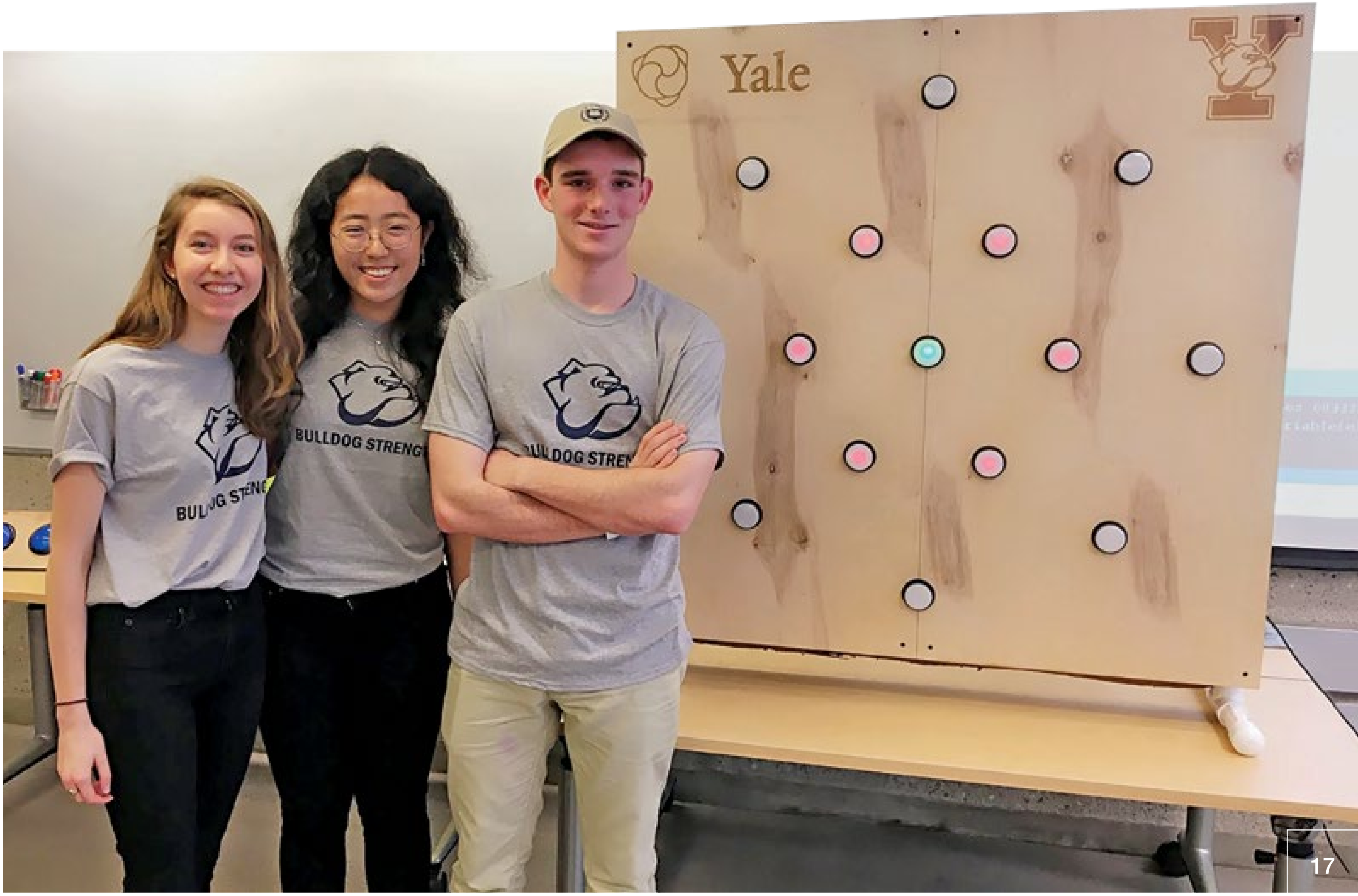
Newman said he sees his collaboration with the CEID as part of a larger culture at Yale.

"People ask me, 'What's the secret at Yale?'" Newman said. "The secret is we're Yale! I can walk down the street and have a coffee with some of the brightest minds in the world and they want to help us, and we help each other. That's the Yale community."

Lighting the Way

Work on the lightboard device came about after Newman told Wilen and Wilczynski about some issues they'd been having with the lacrosse team. Thanks to an unusually good defense, opposing teams don't get many shots on goal. But that also means Yale's goalies have fewer opportunities to build their skills. Improving reaction times is a big part of that. In lacrosse, the ball can come flying at the goalie at speeds well above 100 mph. A split second can be the difference between a win and a loss.

Three students — Cece Gao '21, Mary Clare McMahon '21, and Jacob Asher '21 — met with Newman and took up the challenge of engineering better reaction times for the team's goalies. The team brainstormed ideas. Inspiration



comes in all forms; for the ENAS 118 team, it was a psychology journal that sparked their best idea.

Above: *Mary Clare McMahon, Cece Gao, and Jacob Asher stand in front of the Lightboard, designed to improve better reaction times for the Yale Lacrosse goalies.*

“We read some literature that when people react to a stimulus, our eyes move in concentric circles, so we designed the board with this concept in mind,” said Gao, a computer science major.

Taking that as their focus, the team got to work, and soon, they had a prototype ready to present to Newman and the lacrosse team.

“It was really exciting to see how the team quickly got very competitive about it, which is what I think the lacrosse coaches were looking for,” Gao said.

The final product is a board with 15 circular lights, each capable of flashing different colors. The user hits lights flashing certain colors as fast as he or she can. The board can be adjusted to create new games that may be a better fit for different players with different goals.

It was soon adopted as a standard tool in practice, not just for lacrosse but also the soccer and hockey teams. Soon, Newman and the coaches had a body of data that gave a full picture of their players’ reaction times.

“We’re testing our goalies every day, so we know what their baseline is,” Newman said.

Now, if a player shows up to practice and there’s a significant dip in the Lightboard reaction times, he said, the coaches know there’s something wrong.

“Maybe they need more sleep or change in training style,” he said. “We have many tools to fix those issues, but we wouldn’t have found those problems in the first place if we didn’t have the

Continued →

board. So we're able to have complete clarity of what's going on in the nervous systems of our players and relaying it to their coaches."

The information proved particularly critical on game days. If the players' Lightboard scores are low on game day, it's a red flag. There are a lot of factors that go into how well a goalie performs, but Newman said one thing they learned was that a poor performance on the Lightboard almost always means a poor performance on the field that same day.

That attention to detail paid off. In May, the Yale team beat Duke 13-11 to take home the national championship. Despite a heavy workload that semester, Gao said she and her fellow ENAS 118 students got caught up in the excitement.

"When the news came out that Yale won the national championship, I went on all forms of social media," Gao said. "The fact that our device could have an impact on their successful season was really exciting."

"When you talk about what goes into making a champion it's a lot of different components. Did we measure things? Did we improve things? Absolutely."

› Thomas Newman,
Director of Sports Performance
and Innovation

Left: *Anthony Belanger, assistant strength and conditioning coach, and Thomas Newman hold the NCAA Championship Trophy shortly after the team's victory.*

Above: *With its ability to improve reaction times, the Lightboard was adopted as a standard tool in practice — not just for lacrosse, but also for the soccer and hockey teams.*

Newman said he's happy to share credit for the team's success with the CEID.

"I think it's a huge part," he said. "When you talk about what goes into making a champion it's a lot of different components. Did we measure things? Did we improve things? Absolutely."

Andy Shay, coach of the Yale Men's Lacrosse team said he saw a definite "correlation to our goalie play and the pattern of games they were playing on the board."

"I understand that a number of studies need to be done to see a true correlation," he said, "but we did win a National Championship with the help of some stellar goalie play… so I'll take that as a positive."

More important than the Lightboard or any one training device, Newman said, is the overall relationship that the athletics department has developed with SEAS, and other schools on campus. "It's the fact that our athletes know they have a resource that others don't have," he said. "That makes them more confident, and they play better. Whether it's the CEID or strength and conditioning, we all play a role in making the program the best it can be. And now we can say we're the best program in the country."

The CEID folks are also happy about their role in helping the team, but they're even happier about what the Lightboard indicates about the larger culture at Yale.

"For one thing, it's a great recruiting tool," Wilen said. "When students visit, they come with their parents, and this shows them that Yale is very progressive in using technology and building the kinds of collaborations that they don't see at other schools."

Shay said he hopes the partnership will continue for a long time.

"I think the CEID and Yale Athletics would be missing a huge opportunity if we stopped this collaboration," he said. "We have some of the brightest and most innovative minds working to solve real issues in the world of sports. From my perspective, it has been incredibly beneficial."

Continued →

A Large-Scale Collaboration

Newman had another question. He wasn't sure if there was an answer but figured that the CEID was the best place to ask it. He wanted a device that could not just record how much weight athletes were pushing and pulling, but a way to record the lifting and pulling processes at multiple points. Wilen and former CEID Design Fellow Max Emerson got to work on a crane scale, a device that measures the force pulling on it — the mechanics are similar to a grocery store produce scale.

Most weight measurement devices, Wilen noted, tell only part of the story. The scale Wilen and Emerson devised quantifies and plots out the forces at work every step along the way of a particular motion. Wilen and Emerson took apart a crane scale that Newman gave them, installed a radio and frequency chip that sends the information to a computer.

"Before, we could say 'Oh, you got up to 200 pounds' — but that doesn't tell you how fast they got there," Wilen said. "It doesn't allow you to figure out how long they can hold it there. All of these things are easily done if you can just read that number as a function of time into a computer. That's the power of this thing — to be able to measure anything they want."

Depending on how they rig up the scale, users can get all sorts of information about what's happening and when.

"Every two seconds, it gives us an impulse reading," Newman said. "So we see peak force, we see average force — it gives us a window, and we're able to track all of that."

For Newman and the other coaches, it answered many long-vexing questions. When two linemen lock up and push each other and nobody is moving, the outside observer might not realize the complexity of forces at work. As Newman notes, though, "there is actually a raging battle of physics underway." The crane scale sheds light on the dynamic changes in the mysterious forces of unmoving objects. "How much does a defensive lineman push?" Newman asks, and shrugs. "We didn't know either. Hook him up on the scale, and now we know."

Not only do they know that now, but they also now know how much weight they need to put on the training sled to simulate the force of a defensive lineman — and that they need to vary that weight depending on the surface of the practice. Before they relied on equations and general strategies — now they've got hard data.

"Now we're not arbitrarily picking a weight," he said. "Understanding those levels gives us an incredible clarity of understanding of what we need to do, how much we need to do it, and then measure the on-field change. That allows us to develop very powerful defensive linemen."

And its usefulness goes well beyond the line of scrimmage. The crane scale is also being used for the sailing team. One particular revelation that emerged was when members of the women's team used the scale. Newman said their ability to fine-tune their control of large pulls became clear once they looked at the results on the scale.

"Even though they aren't moving they must have tremendous, fine-tuned control — that's the very thing that makes them so elite," he said. "When you have scales, you have clarity and you can fine-tune your training. It's one of the most powerful tools we have in the weight room."

As Newman said, sports are full of problems, and he's planning to bring more to ENAS 118 for the next semester.

"The relationship with the Engineering School is going to be so critical to our future success," Newman said. "What everybody's most excited about is the collaboration and innovation — we're able to do things here that many athletic departments can't do. That's because we have some of the smartest minds in the field coming together for one cause, which is to make Yale the best it can be and our players the best they can be, on and off the field."

"How much does a defensive lineman push? We didn't know either. Hook him up on the scale, and now we know."

› Thomas Newman

By modifying a crane scale with a radio and frequency chip that sends data to a computer, Newman and other coaches now have answers to long-vexing questions.

From Student to Leader

From a pioneer of Yale's environmental engineering program to Drexel's new dean

Earlier this year, Sharon L. Walker, Ph.D. was named Drexel University's new dean of the College of Engineering. In 1999, she was one of five students to join Yale's then-brand-new environmental engineering program, and she received her Ph.D. in 2004. She has since spent much of her career at the University of California, Riverside (UC Riverside), first as an environmental engineering professor, and then as interim dean of UC Riverside's Bourns College of Engineering. She began as dean at Drexel Sept. 1.

We spoke with Dean Walker about what it was like being part of the first wave of a pioneering program, working with its founder Menachem Elimelech, becoming Drexel's first female dean of engineering, and why students can't be treated simply as "technical sponges."

You were among the first recruited for Yale's Environmental Engineering Program, which was part of the Chemical Engineering Department (since renamed Chemical & Environmental Engineering). What was that like?
I loved it so much — it was one of the happiest times of my life. I think most of us have some stage in life that you can pinpoint as your coming-of-age period, and I think my time at Yale was that.

There were three of us in the first class, plus two who had come the year before with Meny [Elimelech]. It was a very exciting time, although we had to prove ourselves because I think the chemical engineers hadn't quite got their heads around the fact that these environmental engineers were going to be joining them, and what that meant in intellectually and scholarly ways.

How was it working with Menachem Elimelech, the Roberto C. Goizueta Professor of Chemical & Environmental Engineering?
Meny would put the pressure on — he wanted us to prove that the environmental engineers were just as good and rigorous students. He's an amazing mentor — he expects an enormous amount of focus and hard work. You have to be a self-starter and motivated, but I always felt he was right there with me. He was devoted to his students and his lab — he would put in the

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hours with us. He was so quick to give feedback, you never got a break! You would send him a draft of the paper you had been working and laboring over for days and days, and hope you'd have a day to recover and breathe. He was such an early riser that the next day he would already have a draft, all marked up, and it would be sitting there on your desk waiting for you.

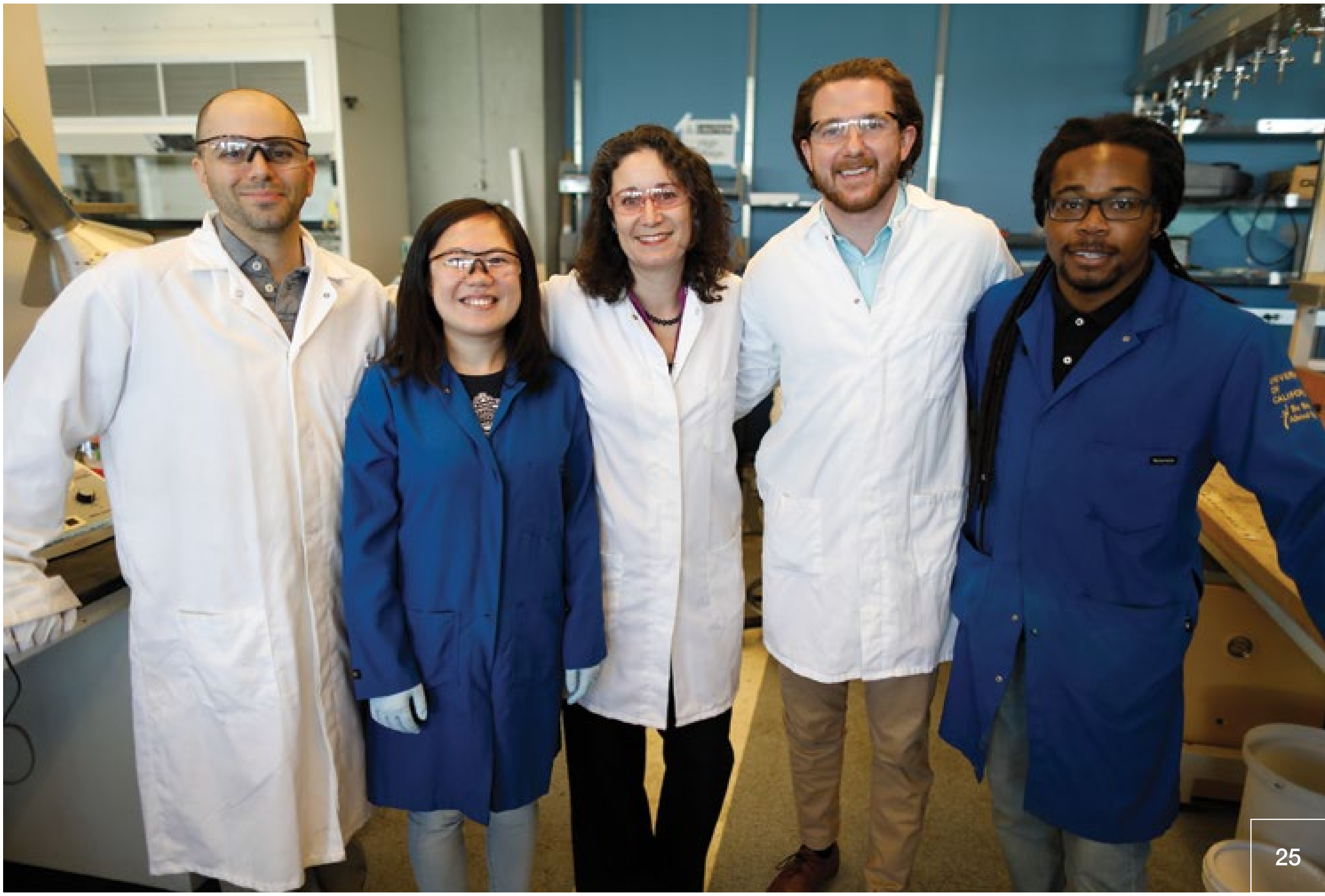
Do you still maintain a relationship with Yale?
One of the things that I have had such great pride in is not just being a graduate of the Yale program, but that I've continued to try to be an entry port and a recruiter for it. Over the years, I have sent four Ph.D. students to Yale, where a couple have recently finished, who have come out of my program at UC Riverside. I sent one Ph.D. student of mine to postdoc in the department at Yale, and there are currently two Ph.D. students at Yale in the environmental engineering program that were my undergraduates. I've actively mentored Yale students when they've reached out to me, both while they're students and while they've started their academic careers afterward. A rich, wonderful community of students have come through that program, and I love to be engaged with it. And I'm looking forward to building a pipeline, not just from UC Riverside, but back and forth from Drexel.

At Yale, your research focused on water quality. It has since shifted toward the use of nanoparticles for food safety. How did that happen?
I've been working in that area for at least six years, so I've been ahead of when it was in vogue. Meny taught us that you take your fundamental tools, your fundamental knowledge and apply it to the emerging problems, so I've been able to be nimble and adjust what I do. In some ways, one could say I've been able to reinvent myself a few times because of that. The reality is that it's all grounded in the fundamental tools that he taught us.

How has the transition been from teaching and research to administration?
One of the things I liked about teaching was working with the students and the transformation you see as they discover themselves intellectually. I think when you're a dean, it has that same sort of effect, but on a bigger scale and bigger impact. All of those things that I loved impacting as a faculty member, I could do on a scale that was unimaginable — everything from infrastructure to policy to curriculum.

There's always politics, but I enjoy people and I enjoy the fact that as dean that I can be an advocate for people and engage with people as a major part of my day. That's just fun — I love working with people.

Left: *Walker with her advisor, Menachem Elimelech, in 2001.*



You are the first female engineering dean at Drexel. How has the field changed for women and underrepresented minorities?

When I was hired, I was one of four or five women on the faculty, and by the time I left UC Riverside 14 years later, there will be 19 women. One can argue that's still low, but that's really a transformation. Women have gone from being 5 percent of faculty to now about 14 percent of the faculty. I think that's a very exciting trend, but there's a long way to go. While I was interim dean, I hired almost 40 percent women in the last two hiring cycles. I've also doubled the number of minorities on the faculty. This is what I was saying — the platform of being a dean can change people's lives. You can set a priority and steward these things. I'm not mandating certain opinions on the faculty, but there are ways that people in positions of leadership can set fundamental priorities and visions.

You've focused on helping students develop practical skills beyond academics. Why is that a priority?

One of the things I did at UC Riverside was teach a class called Professional Development for Chemical and Environmental Engineers. I loved teaching the class because it allowed me to work with students on their soft skills. At UC Riverside, there is a group of first-generation students, often from socioeconomically disadvantaged backgrounds. If no one in their family has ever had a white-collar job before, you can't necessarily take it for granted that they know what to wear for an interview or how to tie a tie and other important skills, so there are a lot of students who needed a little extra coaching.

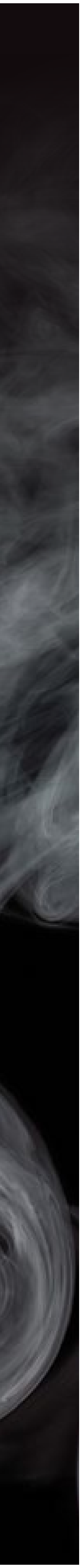
Teaching that class for a number of years allowed me to see how transformational the experience can be if we take the time to work with the students, not just as technical sponges, but to work on the whole person — a more holistic approach. Moving forward, I think that's how we as educators need to be. We need to make sure that the students have the technical competency, but they must also have these soft skills to be capable of transforming themselves as the world changes — and it's changing so fast.

Clearing the Fog

Vaping's popularity outpaces our understanding of its risks. A new machine can help.

Yale

TECHNOLOGY



The popularity of e-cigarettes — battery-powered simulations of actual cigarettes — has increased rapidly since their introduction just over 10 years ago.

Their rise has happened so quickly that science hasn't kept pace, and the health effects of "vaping" — inhaling vapor with nicotine, flavorings, and other chemicals — are still unclear. Advocates of e-cigarettes note that these devices don't use tobacco or produce smoke — both of which have been long known to promote cancer. However, very little is known about what happens when the chemicals that make up flavors that go into e-cigarettes' mixtures (known as e-liquids) are vaporized and inhaled.

To analyze these chemicals, the research team in the laboratory of Julie Zimmerman has developed a machine that mimics the mechanics of a person using an e-cigarette. The system, known as the E-Vaporator, is designed so the researchers can look at a commercially produced e-liquid or make their own and then put it into an e-cigarette device. The system sucks in the vapor, mimicking a human's inhalation, and then "exhales" the same vapor that a human would be exposed to when using an e-cigarette. The machine captures that vapor and collects it in liquid nitrogen so that it can be sampled and analyzed.

Getting a good read on these chemicals and how they change in the process of vaping is particularly important because e-cigarettes have proven popular among young people. The wide variety of available flavors is a big part of the appeal.

"They tend to be very sweet and have fruity flavors, or flavors like gummy bears and piña colada," said Zimmerman, professor of chemical & environmental engineering and forestry & environmental studies. "So, there's a concern about addiction to nicotine products and how people become addicted to nicotine through these flavor enhancements."

Just as science is working to keep pace with e-cigarettes' popularity, so are governing agencies. The chemicals that make up these flavors are currently unregulated, as the Food and Drug Administration has already approved most of them for candy and other food products.

"The flavor compounds that are added to candy and gum are not different to the ones added to e-cigarettes, necessarily," Zimmerman said. "It's the exposure route that's different. When you eat candy or gum, you ingest it, and now we're taking flavor compounds and inhaling them. The exposure route from a human health risk is quite different, and we don't have data on most of these compounds as an inhalation risk, as opposed to an ingestion risk."

Their research so far shows that the compounds in commercially produced e-liquids are unstable and reactive. When these products are sitting on the shelf, chemical reactions happen between the time they're manufactured to when they get used. More reactions happen when these liquids are vaporized and inhaled.

"We've learned that as these compounds are vaped — heated and oxidized — that there are chemical reactions happening and we have more toxic compounds that are forming," Zimmerman said, adding that these compounds are more irritating than the ones that were present at the time the e-liquid was produced.

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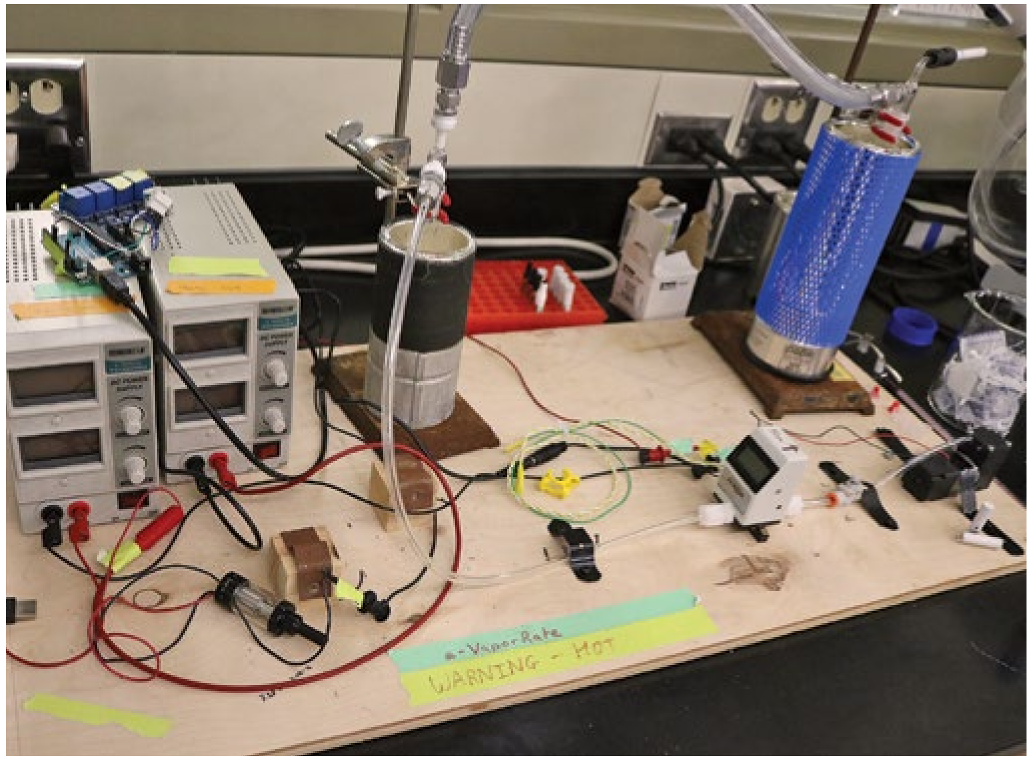


Now they want to know what that means as far as health risks.

"Whether it's storage of e-liquids or the heating and oxidation during vaping or biological reactions inside the body, we really want to understand the potential risk or toxicity of these compounds," she said. "We need to look at the dynamic systems in the vapor and what humans are actually being exposed to — not just the product they're buying on the shelf."

With the many questions that Zimmerman and her research team had, they needed a way to study these compounds and their effects. The task fell to Mark Falinski, a Ph.D. student in Zimmerman's Lab, who developed the world's first E-Vaporator.

"My advisor brought this project up to me and I thought it was great, because I have family members who use e-cigarettes all the time," Falinski said. They insist to him that it's healthier than smoking cigarettes, but Falinski tells them the jury is out. "There hasn't been any definitive proof yet, so I think it's a good project."

After a series of brainstorming sessions and some trial and error, Falinksi built a device that, when it's hooked up with an e-cigarette device, will pump the vapor through tubes, which is then collected in two vessels of liquid nitrogen.

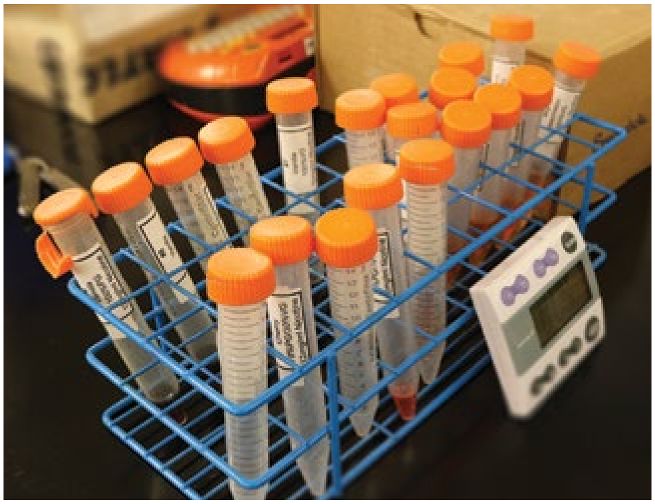
"As the vapor is pulled through the e-cigarette, it gets condensed inside these vessels with the liquid nitrogen, and then they're covered up and brought over for analysis," he said.

When he switches the device on, it emits a *rrrrrrrr* sound, which is essentially the sound of the machine's "lungs" breathing in the vapor.

There are two meters that evaluate the flow rates of the vapor. An arduino device that they programmed controls when the device turns on and off and how long it's on. It also helps control the flow rate. The design of the device gives the researchers the flexibility to use it on different e-cigarette devices. So far, much of their research has focused on new-fangled vaping technology. Recently, they've begun using the device to

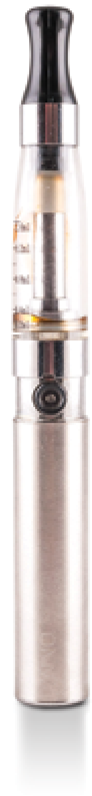
Top: *The E-Vaporator mimics the mechanics of a person using an e-cigarette.*

Left: *Two of the e-cigarette delivery systems that were tested.*



study the chemical processes that happen when using a hookah, a smoking device that goes back centuries and is having a resurgence of popularity.

The E-Vaporator has proven to be a valuable tool in the lab's collaborations with other researchers, including Barry Green at the John B. Pierce Laboratory and the Yale Tobacco Center of Regulatory Science (TCORS), led by Suchitra Krishnan-Sarin, a professor of psychiatry. In a recent study, the device was used to look at the effects of adding sucralose to the e-liquids. Hanno Erythropel, a Ph.D. student in Zimmerman's lab who worked on the study, noted that adding the artificial sweetener is a common practice among vapers as a way to enhance the flavors of e-liquids. Although results varied depending on what vaping system was used, they found that the sucralose (a stable, non-volatile compound) didn't have a huge effect on flavor or the users' preference. That's because most of the perceived taste came from the users' sense of smell, which was more effective at picking up the flavors from the unstable, volatile compounds of the e-liquids.



It's one more piece of information about vaping, but researchers still have a long way to go. As more flavors are concocted and new ways to inhale them are invented (Juul, a vaping device that looks like a USB drive, is one of the industry's more recent innovations), Zimmerman's research team will remain busy. As Erythropel notes, the field of research is wide open.

"No one had ever thought of this idea that you could heat something in a little device with a battery, and then you could inhale it," he said.

What David's Ankles Can Teach Us

A new course looks at the science of artists' materials and tools

There's no way Michelangelo could have known that David would be the most famous statue in the world 500 years after its completion. But what if he had? Would he still have chosen marble, or done anything else differently? Generally, artists want their works to last — how can they best choose the right materials for their art?

Those are the kinds of questions at the heart of The Materials Science of Art, a course that highlights the science that goes into the making of art, and how an artist's choice of materials affects the look and life expectancy of that work.

"The conceit of the class is that when artists are making works of art, they are engineering," said Paul Whitmore, director of the Aging Diagnostics Lab at the Institute for the Preservation of Cultural Heritage (IPCH). "They're using the materials that they've learned to use or experimenting with other materials to get a certain look or a certain form, which have to last to have their message persist."

The course was the idea of Kyle Vanderlick, former dean of the School of Engineering & Applied Science. She saw the course as an opportunity to bridge the West Campus, where the IPCH is based, with the main campus. Also, it would be a great showcase for the Greenberg Engineering Teaching Concourse — a new teaching space funded with a $10 million donation from Glenn Greenberg '68 with six state-of-the-art labs. It was completed just a few months before the course was offered.

Vanderlick is well-acquainted with the IPCH, having served on its faculty advisory committee. IPCH also assisted Vanderlick on a study in her lab on a gecko-inspired technology for cleaning dust from artwork. She figured the IPCH would be the perfect partner to highlight how engineering principles can guide the choices that artists make.

"I was really glad to be the catalyst for this collaboration — it's the perfect marriage," said Vanderlick, the Thomas E. Golden, Jr. Professor of

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Chemical & Environmental Engineering. "This is the kind of thing that Yale excels at. If Yale can't pull this off, then it's not happening."

Whitmore agreed that the course could be a great way to merge the two fields. They recruited Kate Schilling, a chemical engineer, to co-teach the course with Whitmore. Schilling saw the course as a way to show the many applications of engineering to students who might not otherwise get a chance to see its possibilities.

"We want to open up the world of materials science and engineering to students not typically engaged in STEM fields," she said.

The course's creators also relished the opportunity to take a deep dive into an aspect of the artistic process that's often overlooked. While the purely creative side of art may be what grabs the most attention, Whitmore notes that the practical decisions are what allow art to come to fruition — and hopefully, stay with us for a while.

"The class is an exploration of the nature of the materials," he said. "What materials and fabrication methods are artists choosing and why are they making those choices? How different would things have been if they had chosen different materials?"

For instance, Whitmore said, Michelangelo wasn't just carving stone randomly when he made David. He was carefully designing it so that the center of gravity would be just so, and the posture would be a reasonably stable one. He compares the process of making art to how a building is made. On one side is the architect, who has a specific vision for the building he's designing. Then there are the engineers and construction people who look at the designs and decide whether they're practical. The artist takes on both of these roles — "they have to be the thinkers and the doers."

Whitmore stresses that the course is not a research project to help future artists. Rather, he said, it's meant to pull back the curtain on what artists have already done and how they typically work. He wants the course to show the thinking and choices that were made that led to the creation of something that lasted 500 years and, hopefully, another 500.

"I'm not trying to advise artists on how to make art," he said. "If they want to make ice sculptures that last a day, that's perfectly fine. But it should be a conscious choice — it shouldn't be a surprise when the ice sculpture is gone the next day."

The Materials Science of Art course was broken into three sections: sculpture, photography, and paint. For the sculpture portion, Whitmore and Schilling wanted to focus on Michelangelo's David — specifically, its ankles. Completed in 1504, the statue was remarkably well-constructed, but it's been more than 500 years, and time takes a toll on everything. Hairline cracks have been showing up in David's ankles. It's a problem that had been known to some degree for many years, but only in 2014 did researchers pinpoint the problem: An imbalance of the statue's load when its pedestal shifted, applying new forces on the ankles — the weakest part of the statue.

Whitmore and Schilling figured these tiny cracks could serve as a window to the artistic process and how a work changes over time. One semester before the class was offered, Whitmore and Schilling sought help from Introduction to Engineering Innovation & Design (ENAS 118), a course that matches student teams with "clients" from across campus. Together, they identify specific problems and devise solutions. The IPCH-ENAS 118 collaboration focused on developing a lesson plan to explore the nature of materials in sculpture, keeping David's aging ankles in mind. The task fell to the student team of Ting Gao, Michelle Tong, Sinem Sinmaz, Julien Fernandez, and Zach Metcalf.

Working in the John Klingenstein '50 Design Lab at the Center for Engineering Innovation & Design (CEID), the five students brainstormed and came up with a "a lot of crazy ideas." Among the candidates were a mini-hydraulic press, a plate that

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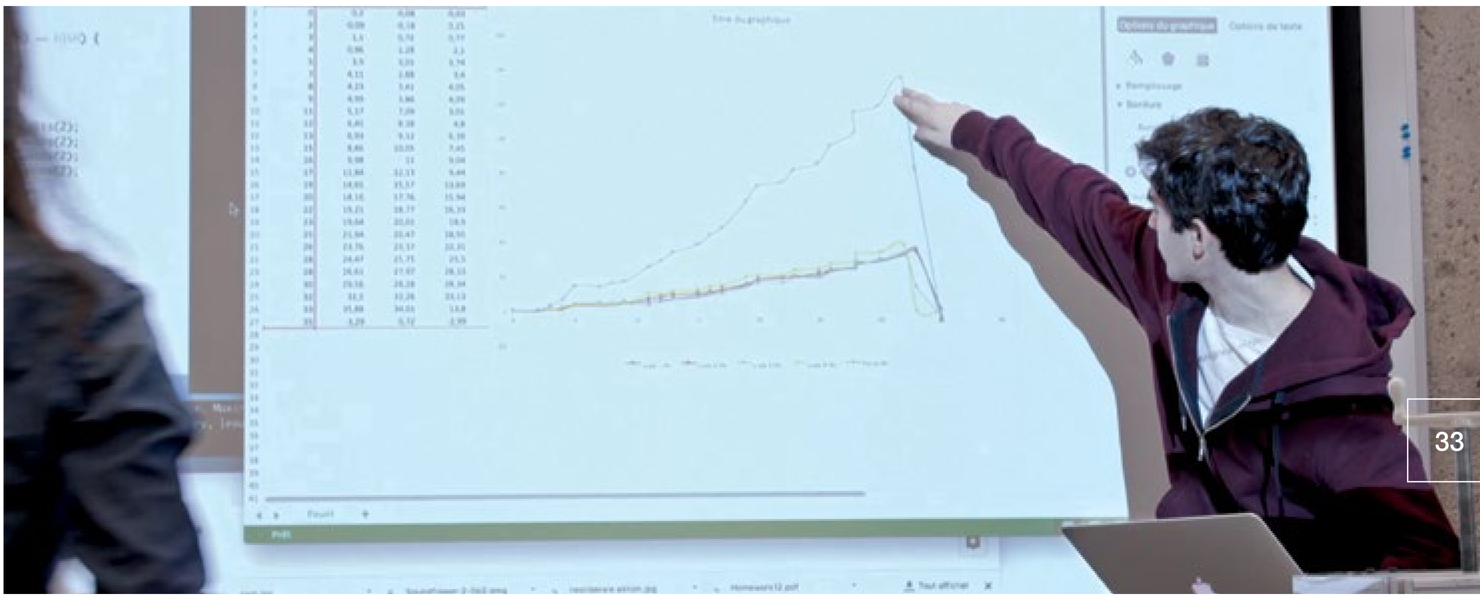
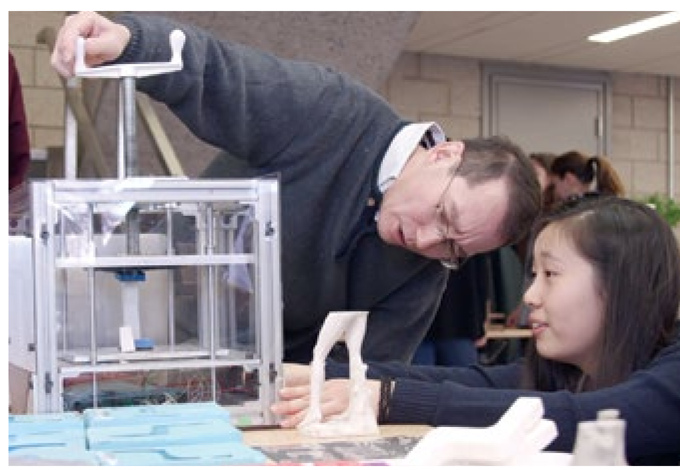




Top Left and Right: *The students created numerous molds of David's ankles in various mediums.* Middle: *Illustrating the time and force causing the model to crack under strain and compression.* Bottom Left: *The students discuss the load cell wiring of their device.* Bottom Right: *Whitmore and Gao test a prototype of the device.*

could move on all four corners, a replica of David sliced up with different amounts of pressure applied at different points.

"We talked to our mentors [Larry Wilen and Vince Wilczynski] and they said "Maybe take a few steps back,'" Sinem Sinmaz '21 said. "By 'a few' I think they meant 'a lot.'"

After consulting with Wilen and Wilczynski, they realized that the crux of the issue was neither the weight nor the posture of the statue by themselves, but how the two together created torque.

"Then we realized that recreating torque can most easily be done by having a lever arm and a weight without actually angling anything," said Ting Gao '21. "We basically looked at what David was actually experiencing and what are the physical problems and then broke that down to pure physics."

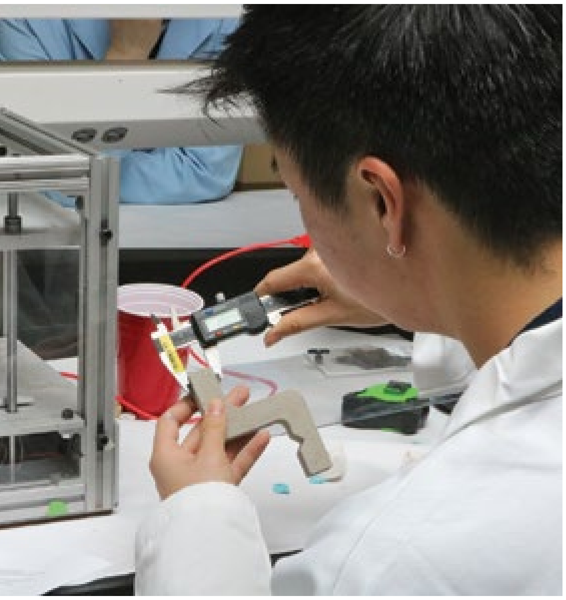
That came down to making numerous "Tetris blocks" — small s-shaped objects that could simulate the physics of the ankles on Michelangelo's masterpiece. They 3D-printed the molds and made the blocks from different materials.

To test the strengths of the blocks, they designed and built FRED (Force Relay Exertion Device). The device can hold the test block in place and has a mechanism that allows the user to apply pressure to the block by a hand crank. With this, they could see how much force and at what angles each model could withstand before breaking.

Wilczynski and Wilen were impressed with the student team's efforts. Wilczynski noted that they try to assign projects that can succeed based on the principles taught in the course's six labs. So it was gratifying when the students working on David's ankles developed FRED based on one of their labs.

"We have a lab in which we do dissection of a biomedical device," he said. "There are various medical tools, and they take them apart — and one is a digital scale with four sensors in it. The students working on the David challenge recognized that they could use that, and said 'Oh, four-sensor load cells, let's use that on David's ankles.'"

As if figuring out the physics of David's ankles wasn't tricky enough, the team also had to come up with a way to teach it to students who may not have the same science background.




"We had to create activities for people with very little physics experience to allow them to work with it and really understand it on a fundamental level," Michelle Tong '21 said.

Schilling said the student team's solution helped her students understand the science behind David's failing ankles.

"It's a conceptually accessible device, but also telling the engineering story of Michelangelo's David in a way their peers could connect to was an incredible help to us and our students," she said. "Peer-to-peer instruction is often crucial for helping students learn new and difficult concepts. Not only do the students see that it is possible for them to succeed, but they also benefit from having common perspectives and communication styles."

Wilen said the challenge was fairly open-ended, so the students could have gone in several different directions. Regardless of the outcome, he said, the main thing is what the students gain from the experience.

"We love to see successful projects, but if this hadn't been successful but they learned a ton and worked really hard, that would be great also," he said.

As it happened, though, the project succeeded on all levels. Whitmore and Schilling used FRED and the simplified ankle models in their course, allowing their students to explore for themselves the physics of an aging masterpiece.

"We can't destroy David, so we make crash test dummies that we can destroy and be able to explore something about that particular work of art," Whitmore said. "These help us look at such things as whether Michelangelo had made David out of rubber-reinforced plaster and how would that behave. Would it be vulnerable in the same way?"

So if they could go back to 16th century, what would the student team tell Michelangelo?

"Why don't you just 3D print it — and use polylactic acid?" Gao said, laughing.

In reality, the students said, it's not a matter of what Michelangelo could have done differently but understanding the choices that he made. Over five centuries, just about any material is going to show its age — it's just a matter of how.

"If Michelangelo used this other material there would have been other consequences," Sinmaz said. "Instead of cracking in this place, for instance, it might have crumbled."

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Courtesy of Harvard Art Museum

The paint section of the course was inspired by the work of Mark Rothko — specifically, a series of mid-century paintings commissioned by Harvard University that eventually suffered from faded colors. Using a kind of paint with a chemical makeup similar to the ink used in Sunday newspaper comics, the artwork originally boasted vivid hues. The paintings, however, were intended to be displayed in a room filled with sunlight, and those eye-popping reds quickly aged to a dull blue. At a 2014 exhibit at Harvard, the paintings were returned to their former glory, thanks to exhibition lighting designed to project particular colors onto the canvases, transforming the colors to closely match their original appearance.

The exhibit, Whitmore said, prompted numerous philosophical questions: Were viewers really seeing the work as Rothko's had intended it to look, or an illusion of it? Why do we generally accept the wear and tear of artwork created centuries ago, but are disturbed when that aging happens within our lifetime?

From a pure science standpoint, though, Whitmore called the paintings' transformation "a completely jaw dropping experience."

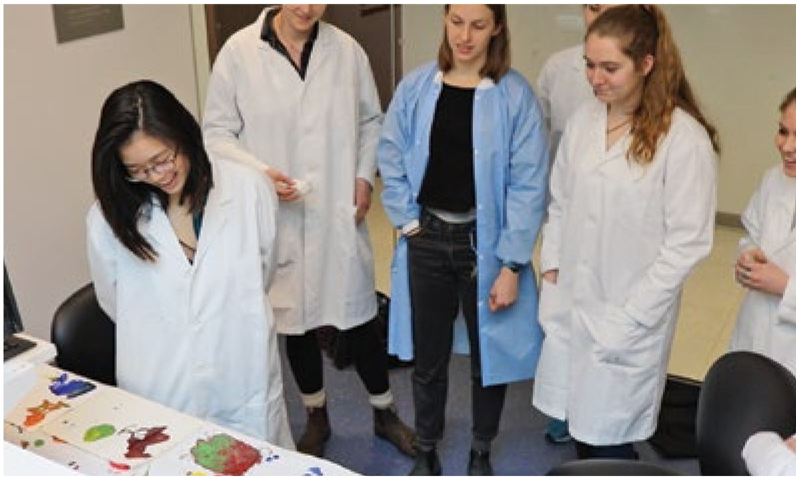
"It was so amazing and wonderful that you could do such a thing," he said. "When I did that, I said 'I want my students in my class to feel it like I feel now — because they will get hooked.'"

Top: *Mark Rothko; Untitled (Study for Harvard Murals), 1961.*

Left and Background: *Whitmore replicating the recovery of faded paint color experienced by Rothko's paintings with custom colored light projections.*

Yale

EDUCATION



Left: *Students experiment with altering paint viscosity, surface tension, paint droplet size, and velocity to understand Jackson Pollock's signature style of painting.* Right: *Students examine the fluid dynamics in the artwork of David Alfaro Siqueiros.*

When preparing a lesson based on the exhibit in his lab, he replicated the recovery of faded paint color with tailored colored light projections. Working with the same fundamental science, the students experienced the same breath-taking success.

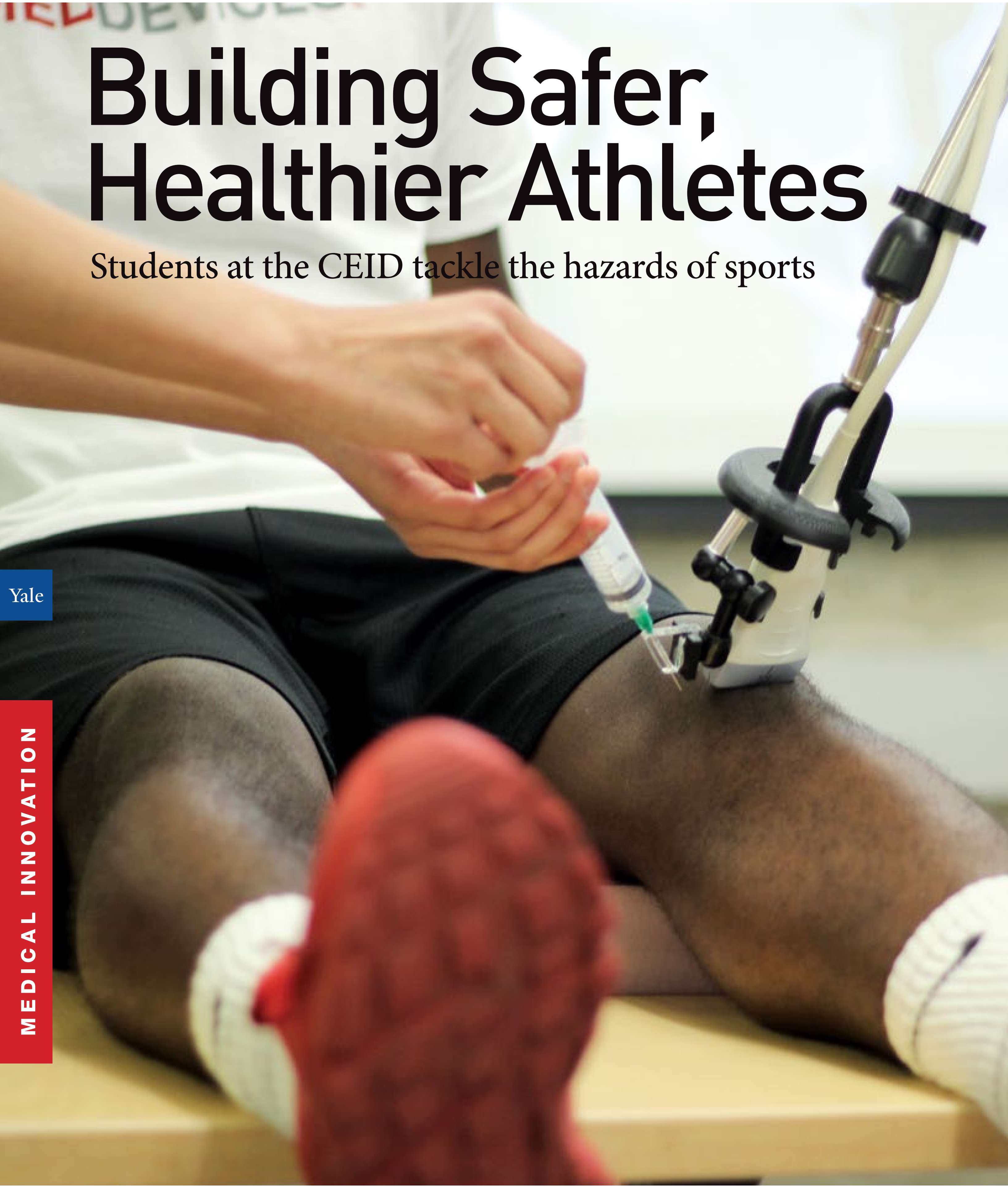
Another section was also inspired by fading colors, this time in photography. The students looked at why photos in "The Pencil of Nature," a series of booklets of photographs by 19th-century photographic pioneer William Henry Fox Talbot, had faded to ghostly remnants of the original images. Essentially, the work was designed as a promotion for the potential of photography — then, in its very early stages. Over a very short time, though, the images had faded significantly. Whitmore's previous experiments showed that light exposure wasn't the culprit, and that certain chemical processes were more likely to blame.

"For the lab in this class, we made some salt prints just like the ones that Talbot had made and exposed them to peroxide to see if that could have been what happened to those images in 'The Pencil of Nature,'" he said.

Below: *Student-made salted paper print that recreates Talbot's work. The lab was designed to provide insight into how the earliest paper photographs were made.*

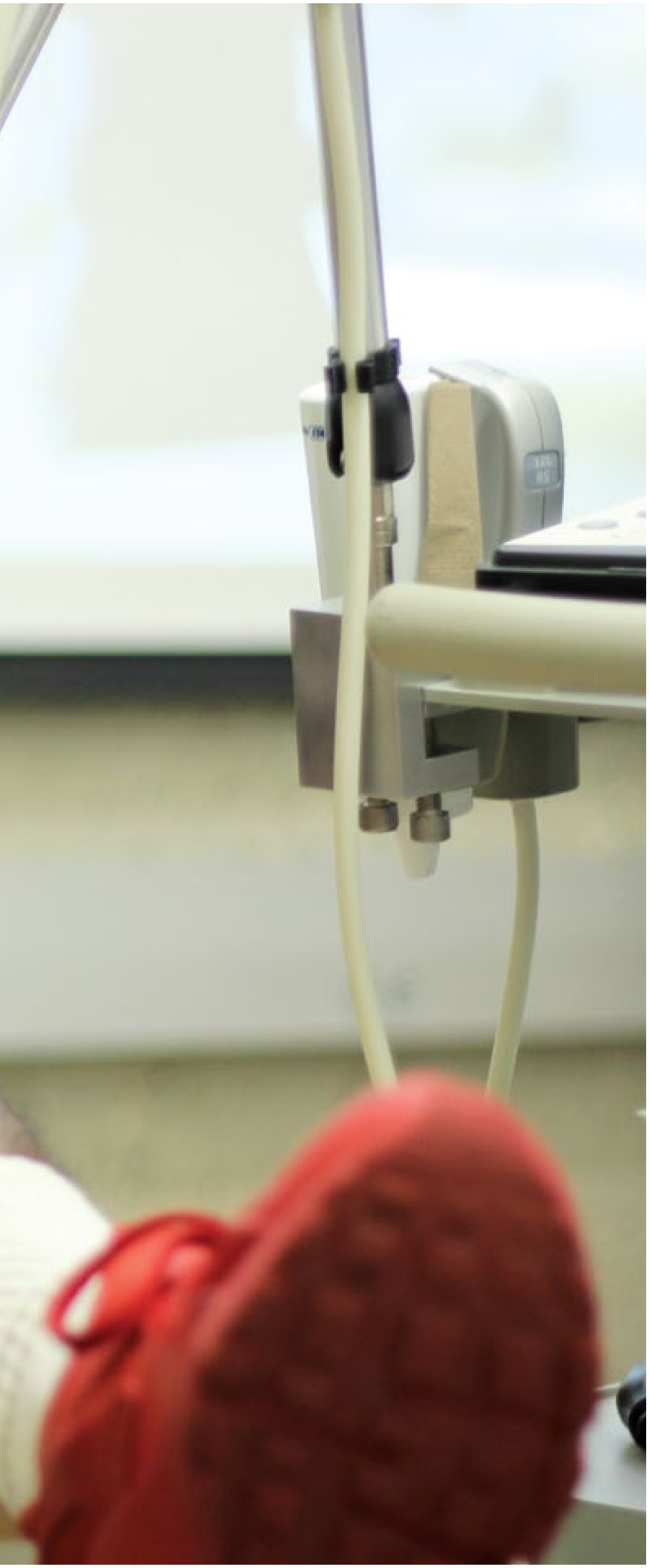
Ultimately, he said, these three labs are the kinds of explorations that conservators and scientists engage in to learn how to best preserve art without fundamentally changing it. For instance, conservators might try to use titanium pins to repair a broken sculpture, but those pins may end up causing their own problems down the line. With more options available to them, they can avoid those issues. Those additional options will be invented more and more as the art world collaborates with engineering.

"Art preservation has become more sophisticated as more conservators become engaged with the technical expertise they need," Whitmore said. "The conservator can't become an engineer easily, but they're no longer bench practitioners in isolation at the museum either. They are connected with the academics and the industrial experts they need to answer some of these questions and add to the toolkit that they use for their work."



Building Safer, Healthier Athletes

Students at the CEID tackle the hazards of sports



Since it was first offered, the course Medical Device Design and Innovation (MENG/BENG 404) has worked with numerous partners, including the Yale School of Medicine, Yale-New Haven Hospital, the VA Connecticut Healthcare System, and the Yale School of Nursing.

This year, for the first time, it's collaborating with the Yale Athletic Medicine department. Joseph Zinter, who started the class at the Center for Engineering Innovation & Design (CEID) five years ago, said the field of sports medicine sounded like a great fit.

"With all of the clinicians we work with, I try to identify specific challenges that are well-scoped for the course," said Zinter, assistant director of the CEID. That means projects that can feasibly be completed by the students — juniors and seniors of varying disciplines — in one semester. It also means choosing projects that jibe with the resources and space of the CEID. It's a formula that has produced patented devices, awards, and student-authored journal publications.

The partnership with sports medicine was sparked by a conversation between Thomas Newman, director of sports performance and innovation for Yale, and Dr. Eliot Hu, Yale's director of athletic medicine. Newman told Hu about the very productive collaboration he had with Introduction to Engineering Innovation & Design (ENAS 118), also at the CEID (see story on page 14).

Hu figured it was worth a shot and met up with Zinter. In their conversations, Zinter and Hu homed in on two issues that have long been a concern in sports medicine: concussions and inflamed joints. Awareness about both has increased significantly in recent years, but the medical field is still looking for ways to improve how it addresses each one.

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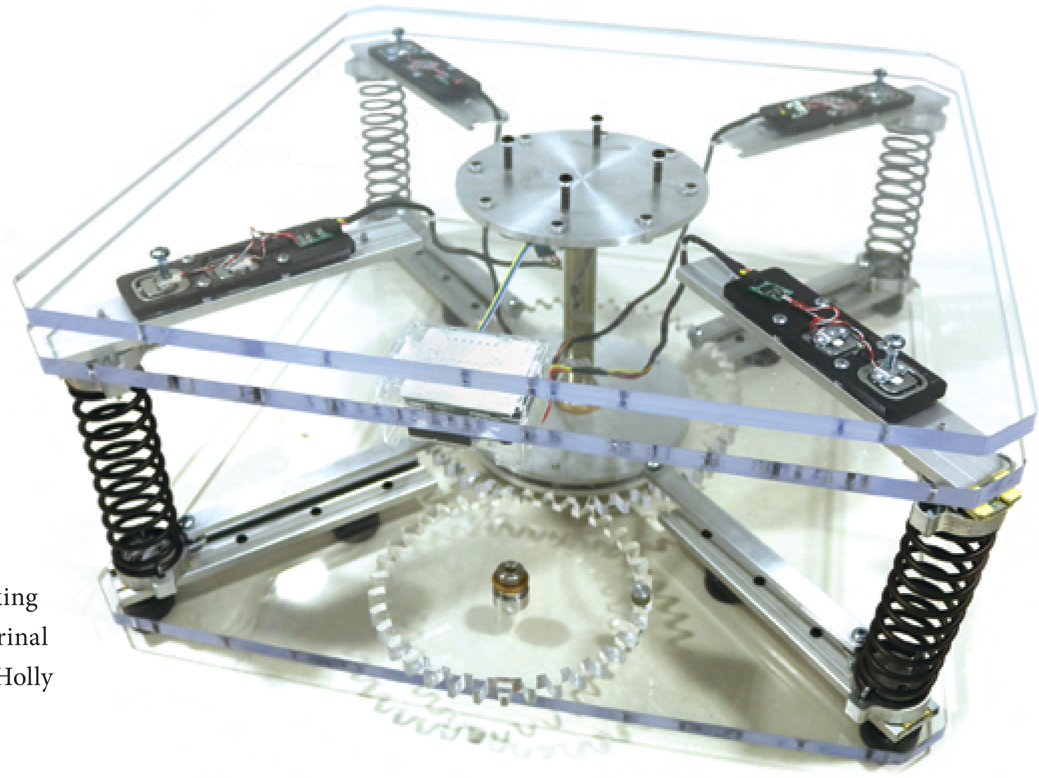
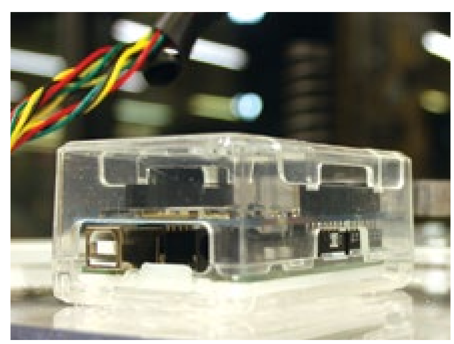
A Better Concussion Recovery

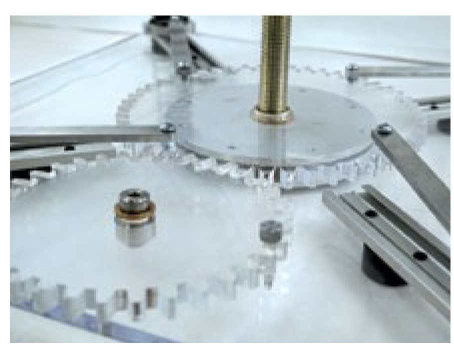


In both the sports and medical worlds, concussions have been given a great deal of attention in recent years. However, diagnosing them and overseeing recovery has remained an inexact science. Working with Hu, students Brian Beitler, Mrinal Kumar, Pong Trairatvorakul, and Holly Zhou teamed up to address that.

The four students developed Ontrack, a system that combines virtual reality with a balance board. How it works: a patient recovering from a concussion balances on the platform of the device wearing a virtual reality (VR) headset. The balance board is equipped with load cells and an accelerometer to measure the patient's center of gravity. While balancing on the board, the patient wears a virtual reality headset and interacts with a virtual environment. Data collected by the balance board and the VR system is combined with the patient's subjective observations (such as dizziness or headache) to evaluate the progress of their recovery.

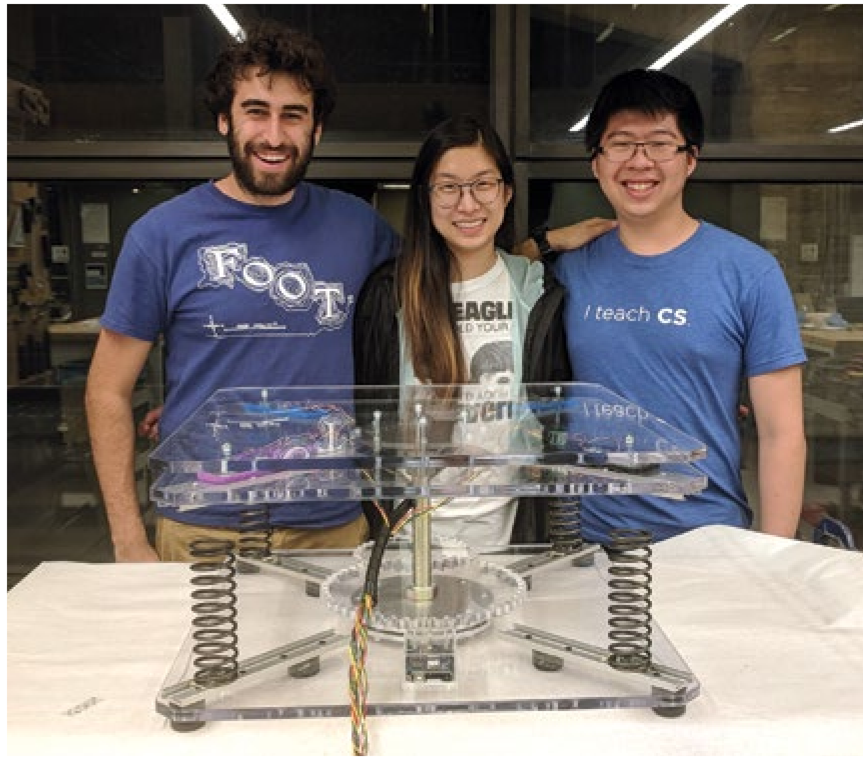
Health experts have long sought a more accurate way to diagnose and treat concussions — and with good reason. Each year, between 1.6 million to 3.8 million sports and recreation-related traumatic brain injuries occur in the U.S., according to the Center for Disease Control and Prevention. Many of these cases go untreated. Symptoms





Left: *Brian Beitler constructs the Ontrack device.* Top Right: *Microprocessors collect and send specific measurements about the patient.* Bottom Right: *Gears allow the balance board to be adjusted for individual users.*

Right: *Beitler, Zhou, and Trairatvorakul proudly display Ontrack.*



"I gave them an incredibly and increasingly difficult project… And they came up with something that encompasses everything — and it's something we've never seen before."

› Dr. Eliot Hu, Yale's director of athletic medicine

range from mild to severe, including depression and chronic dizziness, nausea, and seizures. Repeated concussions can be even more serious, including permanent cognitive and emotional problems. Concrete data to assess the trajectory of the condition is hard to come by. Measurements of cerebral blood flow can be conducted by fMRI, but it's costly. Instead, doctors tend to rely on symptoms to monitor recovery.

Hu suggested to the team that they focus on two areas: Ocular (eye movements) and vestibular (balance). "There's some research that shows that combining the ocular and vestibular aspects will help patients speed up their recovery," team member Pong Trairatvorakul explained.

"Right now, there's nothing that really quantifies the symptoms for the balance aspect, so we created an unstable platform that's able to measure balance," Trairatvorakul said. "We expect that for a concussed patient, we might see fluctuations in the center of mass."

With sensors built into the board, users can see the center of mass of the person standing on it, and how well they're able to maintain their balance.

As for the ocular half of their project, the team created a virtual reality component composed of exercises that track eye movements and measure coordination. In one exercise, the patient tries to catch a virtual ball. It's based on a real-world exercise that Hu conducts with his own patients.

"Eventually, we want users to play this game on the VR headset, while on the balance board, and then we can combine the two," Trairatvorakul said.

Hu said the system is where he believes concussion treatment is heading.

"I gave them an incredibly and increasingly difficult project," he said. "And they came up with something that encompasses everything — and it's something we've never seen before."

Continued →

A Joint Effort

Joint inflammation is a common ailment among athletes, caused by the wear and tear of physical activity. Specifically, synovial fluid builds up in the joints, causing pain. One treatment is to remove the fluid by needle, or aspiration. It's a common, low risk procedure, but not without some difficulty. For one thing, it's unwieldy: One of the doctor's hands must be in contact with an ultrasound probe the whole time, while the other hand endures significant strain performing the injection. The combination of motions makes it difficult to keep a steady hand, which is required for imaging accuracy and keeping the needle stable throughout.

"Often, because of the setup, physicians feel there's not enough hands," Hu said. "A lot of people use assistants as their extra set of hands."

Below: *The completed UltraStable product. The device gives physicians a free hand to stabilize the needle and probe without taking up too much space.* Top Left: *Dr. Hu teaches the students how to use the ultrasound probe.* Top Middle: *Testing angles of injection for the device.* Top Right: *Dr. Hu displays the current system used by physicians and the need for the UltraStable device.*

In their report, the students note that there are systems currently available that are designed to correct these issues. However, they tend to be too large to be conducted easily, or in an office setting.

After speaking with Hu, the team of Alyssa Chen, Michael Johnson, Sienna Li, and Allison Skinner set out to develop a system that gives the physician a free hand to stabilize the needle and probe — and does so without taking up too much space. The result was UltraStable, a system that features a large, locking articulating arm with a probe holder connected to its end. It also has a 320-degree needle track above the probe holder that allows for another locking arm to slide around the track and serve as a flexible needle guide system.

As captain of Yale's women's softball team, team member Allison Skinner said the project had personal significance for her.

"As athletes, the sheer amount of stress we're putting on our bodies means we're often getting injuries, and most of the time these happen to our joints," she said. Sometimes they can take an inflammatory agent to ease the build-

"The system they created cuts down on the time that's needed to do the procedure and gives the ability to lock it in place."

› Dr. Eliot Hu

up of fluid in the joint, but sometimes it means having it aspirated with a needle.

Hu thought the student team's efforts were a significant improvement over the current standard.

"The system they created cuts down on the time that's needed to do the procedure and gives the ability to lock it in place," he said. "It's a big help to the physicians out there who may not have the manpower to help with this procedure. You basically have another hand free to put on a Band-Aid or clean up the area before you inject or aspirate."

Overall, Zinter said that Hu was a great client for both teams. "One aspect of the class is learning how to interact with a client and communicate across disciplinary lines," he said. "The students were working very closely with Dr. Hu. It's a lot of work — visiting the clinic, observing procedures — and he was there at every step."

For his part, Hu said the collaboration worked for both sides.

"The students are amazing, and they definitely exceeded my expectations," Hu said. "I'm glad I had this opportunity to work with them — it was a great experience. I think we learned a lot from each other."

Below: *Students in the course celebrate their success with fellow classmates and physicians.*

TECHNOLOGY

Better Living Through Algorithms

From faster rides to better health outcomes, Amin Karbasi makes data work for you

Whether you're figuring out the best place to catch an Uber ride or mapping the human brain, there's a better, faster way to do it. Amin Karbasi, assistant professor of electrical engineering and computer science, is working on it.

Working at the intersection of learning theory, optimization, and information processing, Karbasi's research focuses on developing ways to better navigate our increasingly data-filled world. There's a greater need than ever for this kind of research. Thanks to the Internet and social media in particular, a tremendous amount of data is generated every second by millions of users. Every minute Instagram users post nearly 220,000 new photos, YouTube users upload 72 hours of video, and Facebook users share nearly 2.5 million pieces of content.

"It's no secret that data's getting bigger and bigger, and one way or another, we need to deal with that," said Karbasi, who is also a faculty member at the Yale Institute for Network Science.

How we organize and make sense of all this information is an ongoing challenge in computing. In many cases, he said, we just discard the data. It's easy, but not the best way to deal with it. Using data-driven algorithms and other techniques, such as summarization methods that find the right representative subset to get a clear picture of the whole set, Karbasi wants to find a better way. One approach is sampling.

"You have a huge amount of data and you want to sample the most important points," said Karbasi, who was listed this year by the prestigious International Conference on Machine Learning as one the most prolific researchers in the field. "If you sample and find the most important points, you're going to have a much smaller data set, but hopefully the quality is going to be similar."

Speed vs. Accuracy

Much of Karbasi's work involves finding the sweet spot between accuracy and speed in data searches. In each case, they need to figure out how comprehensive the list needs to be.

"Do you want to be exact or do you want to be fast? You can't have both," Karbasi said. "That's the trade-off. In medical applications, you want to be really accurate, but in mundane mission-learning applications, deciding if this image is a cat or a dog — the stakes are lower — I can make mistakes once in a while. But if it's a doctor trying to tell whether it's a tumor or not, you have to be very, very careful."

Once they assess the proper speed/accuracy ratio, Karbasi and his research team can develop the right methods for extracting the data. "Tell me how much wiggle room I have and I can tell you how fast I can compute," he said.

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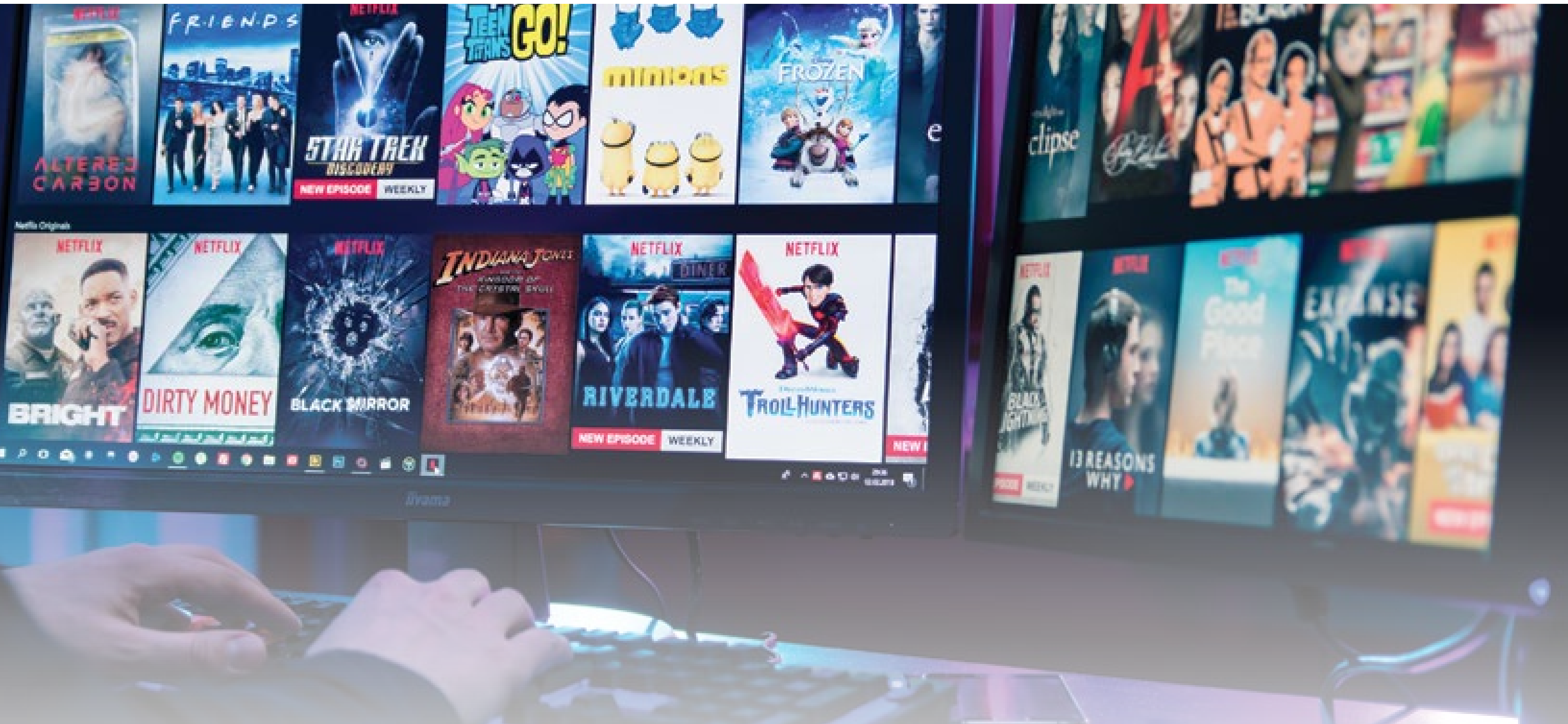


Karbasi's work is filled with high-level mathematics, seemingly endless equations and many abstract concepts. But the results play out in some of the most everyday ways — a better online system for making movie recommendations, for instance, or finding the best place to catch a ride. A recent study of his aimed to create the most efficient system for finding waiting locations for an Uber.

"If you're in Manhattan, every centimeter, ever corner can be a pickup location," he said. "The question is which corner should I pick?"

For this, a mathematical strategy known as discrete optimization, comes into play.

"You have 10 million data points in front of you but you want to choose only 100 of those," he said. "If you want to find the representative points or intelligently summarize the data, you have to maximize these discrete functions. Our group has focused a lot on the discrete optimization problems — how fast and accurate we can compute them."

A fully comprehensive algorithm that factors in every street corner would take a prohibitively long time to compute. But an algorithm that takes only a few seconds to provide results would likely be welcomed by consumers, even if it required them to to walk a block to catch their rides. Throughout the year, the best spots change — areas near ice rinks are popular in winter, for instance. A way to update the best locations each day would be invaluable to the company.

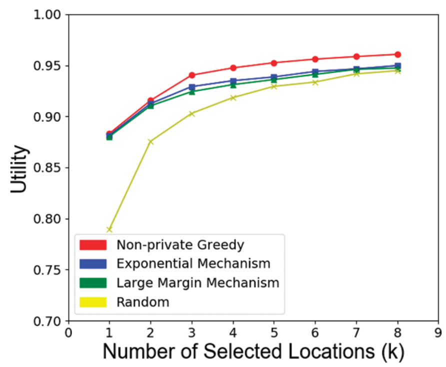
To find the optimum waiting spots for Uber drivers, Karbasi and his fellow researchers analyzed a dataset of 100,000 Uber pickups in Manhattan from April 2014 (just a fraction of potential pickup locations in Manhattan). They developed an algorithm that reduces the set of 100,000 to 30 spots representative of the larger set, and then chooses three different waiting locations within each region.

And if you get antsy waiting for a ride, try completely mapping the neural connections in the human brain — an endeavor estimated to take some 14 billion years. That is (obviously) a long time, but identifying the topology of the brain's network could tell us a lot about the physiological basis for how we process information. Fortunately, Karbasi is working on other less time-consuming methods to do so.

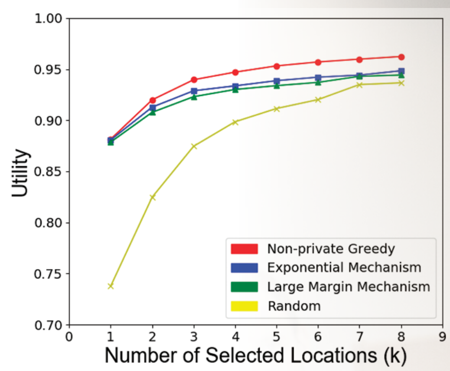
Working with researchers from the Ecole Polytechnique Federale de Lausanne in Switzerland, Karbasi helped develop an algorithm that scales to large datasets of recorded neural activities. By mathematically analyzing this mapping, the researchers could tell the conditions under which the algorithm successfully identified the type of synaptic connections within the available data.

Differentially Private Submodular Maximization

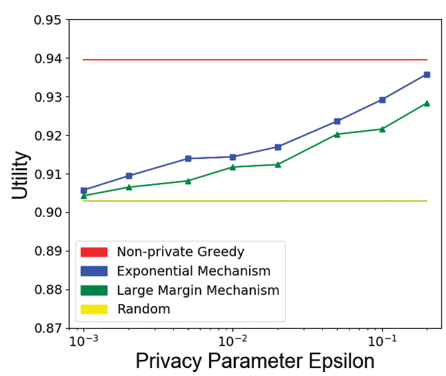
(a) $L_{Popular}$



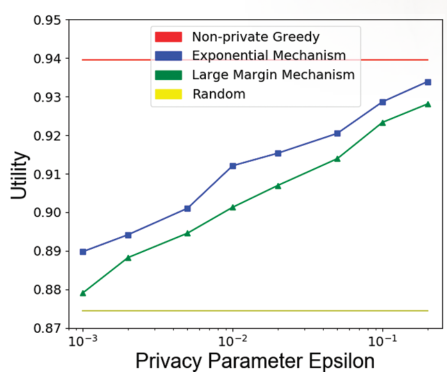
(b) L_{Grid}



(c) $L_{Popular}$



(d) L_{Grid}



Above. *Amin Karbasi, assistant professor of electrical engineering & computer science*

Left and Below: (a) *and* (b) *compare the mathematical utility of the privacy-preserving algorithms (blue and green) vs. the non-private approach (red).*

(c) *and* (d) *demonstrate how the new algorithms can trade off privacy vs. utility.*

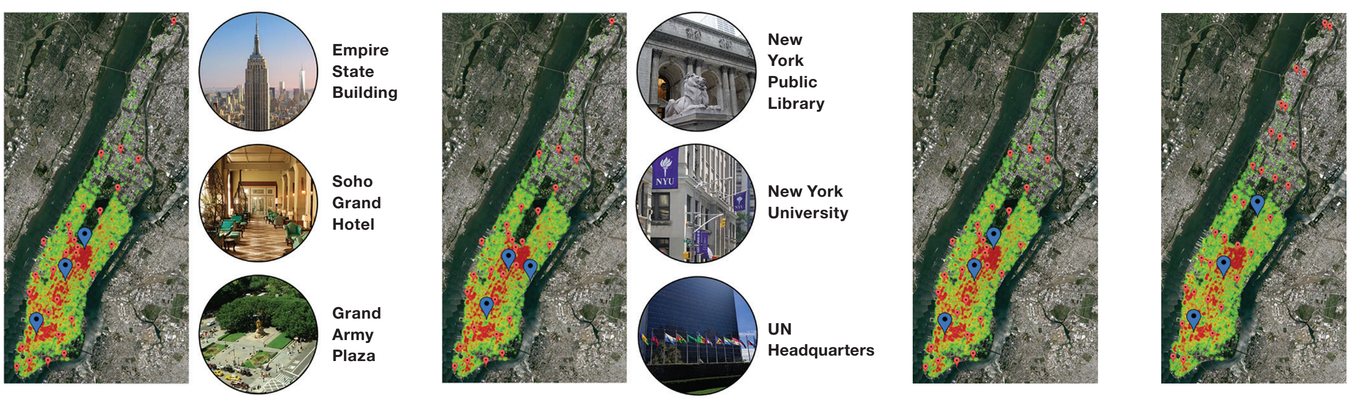
(e) - (h) *visualizes how the privately-derived results can be just as good as those found by the non-private baseline.*

(e) $L_{Popular}$ *Non-private greedy*

(f) $L_{Popular}$ *EM-based greedy*

(g) L_{Grid} *Nonprivate greedy*

(h) L_{Grid} *EMbased greedy*



Another brain-related study brought Karbasi in collaboration with two other researchers at Yale, Todd Constable and Dustin Scheinost in the departments of neurosurgery and radiology and biomedical imaging. The researchers analyzed the fMRI scans of more than 100 subjects from the Human Connectome Project, a five-year effort to create a network map of the human brain. Doing so allowed them to develop a method of analyzing the neuronal connections of individual brains that allow them to successfully predict the subjects' IQs, their sex, and even tasks they were performing at the time of the brain scan.

The researchers focused on what's known as voxels. Analogous to a pixel, a voxel is the lowest resolution achievable in the scans, and each can represent up to millions of neurons. Researchers cluster voxels into different areas called nodes or parcels, a process known as parcellating. A universal

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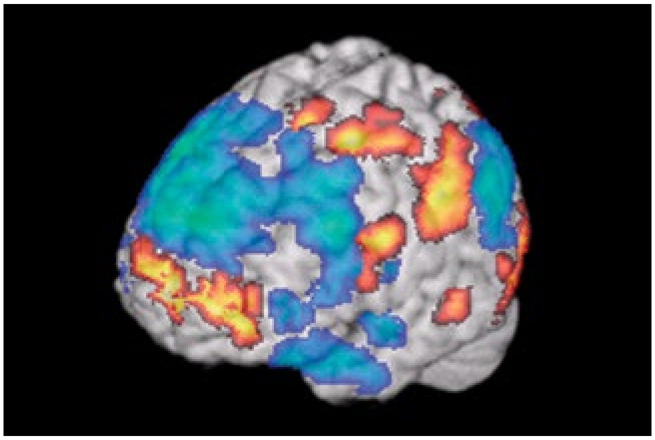


Above: *Collaborating with researchers at Yale's Medical School, Karbasi is working to create a network map of the human brain.*

atlas of the brain has been developed through traditional methods of parcellating the brain, but these methods don't factor the many inter-individual variations and the unique nature of the neural connections. Because a single functional atlas may not apply to all individuals or conditions, these variations are particularly important for patient and developmental studies.

"Traditional approaches to human brain parcellation collapse data from all the subjects in the group and then they cluster the average," said Mehraveh Salehi, a Ph.D. candidate in the the labs of both Constable and Karbasi. "But we've shown that if you do this at the individual level, each individual has a different parcellation."

To individualize the existing parcellations, the team used a method of summarizing large amounts of data known as exemplar-based clustering, which seeks the most representative elements of the data.

"If we account for those variations, we can build up better models from the functional connectivity analysis, and those models are better at predicting behaviors, such as IQ," she said.

Karbasi said it was remarkable how much information they could get from the network of voxels.

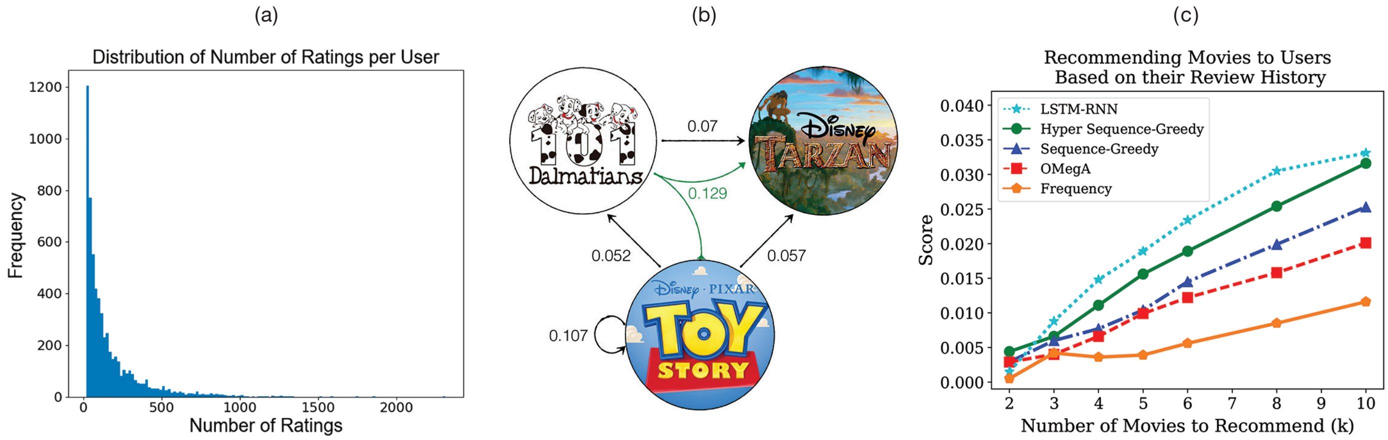
"What was very fascinating was that the shape of the network tells a lot of stories," Karbasi said. "For example, we can say whether this person in the scanner is a male or a female. It also tells us that these people are performing different types of tasks. It's like reading the brain."

He added that they're just "scratching the surface" of the technology's potential.

"Just imagine what we might do in 20 years if we can really read the brain, and understand what people are thinking," Karbasi said. For example, he said, it could potentially lead to a better understanding of how the brain makes the transition from one emotional state to another and new treatments for depression.

In focusing on these problems, Karbasi's group needs to factor in which platforms they're designing their solutions. For instance, a typical home computer has a much more limited capacity than a company such as Google, which has massive computing power. So it makes sense that the Internet search giant has sought Karbasi's expertise. His upcoming sabbatical will be spent doing research for the company, which recently awarded him with with funding to help turn the tens of millions of data points into something manageable. One method Karbasi is looking at involves choosing elements from a particular dataset that fall into a category, but aren't overly similar.

Submodularity On Hypergraphs



Above: (a) *shows how the majority of users in the MovieLens dataset have reviewed a small number of movies.* (b) *shows a snapshot of the hypergraph that can be learned from the MovieLens dataset. The arrows represent the conditional probability of a user reviewing the corresponding movies.* (c) *compares the prediction accuracy of Karbasi's algorithm (in green) against other baselines. The algorithm is competitive even with a state-of-the-art deep learning approach (in teal), while offering numerous other advantages.*

"We are trying to come up with algorithms that can do this kind of thing fast," he said. "What we do is we represent every image by a data point, or a vector, and then we can define distances between the vectors." He compares the data points to molecules of a gas — they're far from each other, but fill the entire space.

To do this, Karbasi's research team applied their method on a publicly available dataset, called "tiny images," which contains 80 million images crawled from the web. "What we wanted to do was summarize this data — if you want to pick 100 images, which ones? We came up with algorithms that can do this very fast."

They developed a distributed algorithm that chops the data into small pieces so that each piece can be performed on a single computer. "And then we merge the results, and do something intelligent with them," he said.

Using classical algorithms would take an extremely long time to essentially perform the same task. Using his algorithms, the computers in his lab finished in only a few hours. Google — with all of its resources — might take only a few seconds.

Karbasi's work has made him a sought-after expert. In addition to Google, the U.S. Air Force and Microsoft are among those to have also funded his research. He recently completed an online training program for the Defense Advanced Research Projects Agency (DARPA) that aims to create a better data-driven online education system that interacts with humans. Recruiting subjects from Amazon's Mechanical Turk platform, the test trains users to distinguish between three types of woodpeckers.

As part of the test, users try to identify a specific bird and then receive another example based on that answer. The system monitors the responses and adjusts its teaching approach to the test taker's learning style. While computer training programs often take a "one size fits all" approach, Karbasi's program personalizes massive online courses. The general idea behind the test has applications well beyond wildlife.

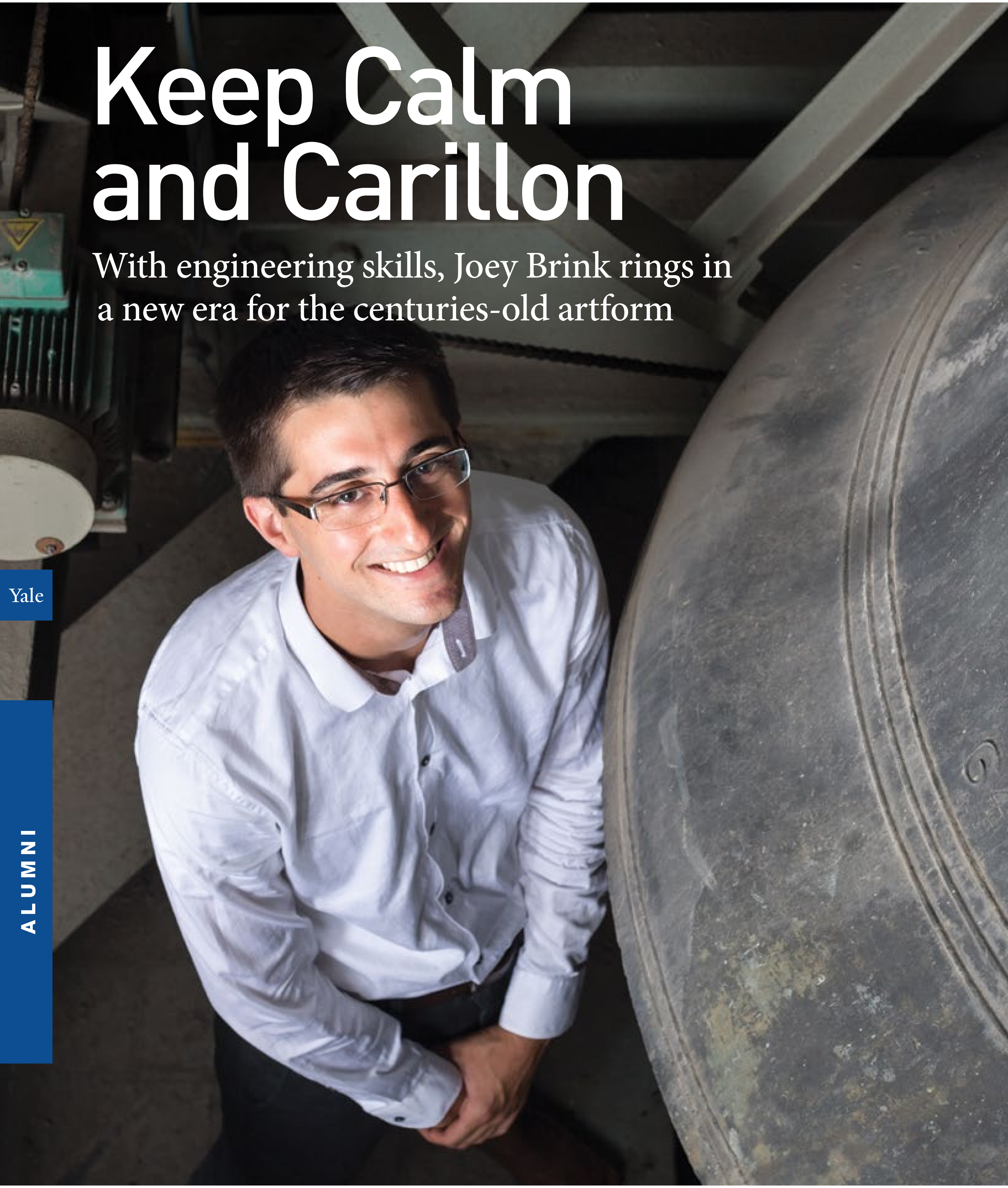
"At DARPA, they need to know 'Is this person OK, is this person not OK?'" Karbasi said. "It's very hard for people to read and understand the cues, so they want an automated machine learning system that learns about humans."

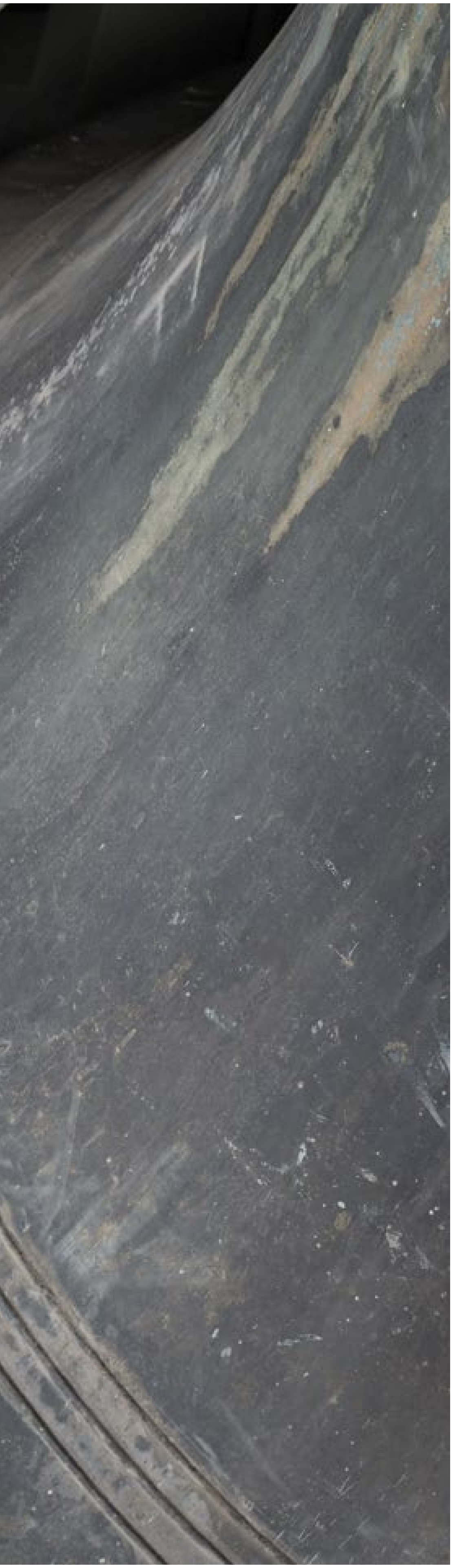
From our mundane tasks to critical medical procedures, data is becoming ever more present in our lives and serves as a common thread through seemingly disparate problems. Karbasi is among the researchers making the daunting amount of information a little more manageable.

"These are all very different applications, but at end of day, these are the same problems — and we can solve them," he said.

Keep Calm and Carillon

With engineering skills, Joey Brink rings in a new era for the centuries-old artform





Does the name Joey Brink ring a bell? While an undergraduate student majoring in mechanical engineering, Brink was not only a star carillonneur on campus, his senior project focused on modernizing the centuries-old art of bell-ringing.

Today, he ranks among the top carillonneurs in the world (in 2014, he won the International Queen Fabiola Carillon Competition, considered the most prestigious honor in the field). And he continues to apply his engineering skills to the craft, expanding what carillon music can be and who can play it. He has toured the world playing the carillon, and released the CD, "Letters from the Sky," featuring his own compositions for the carillon.

When he was a student at Yale, Brink quickly became entranced by the music coming from the Harkness Memorial Carillon and joined the Yale University Guild of Carillonneurs. By the time he was a senior, his musical and engineering lives merged neatly into a senior project where he created a miniature practice carillon that could be adjusted to mimic the feel of a real instrument. He took advantage of the laser cutters and 3D printers, newly available at SEAS at the time to create a practice carillon that was "haptically accurate" — that is, the larger bells have more weight resistance than the treble bells which are much lighter.

The goal, he said, was to make the process of learning and practicing the carillon more accessible to someone on a student budget. In the carillon world, accessibility is something of an issue. The carillon — a set of chromatically tuned bells usually housed in the tower of a church or institutional building — is arguably the least accessible musical instrument. Its sounds may be ubiquitous, but to actually play a carillon is to enter a rather exclusive club. For one thing, there's only about 185 of them in North America. And even if you are among the few who gets to play one of these, how do you practice? In many cases, you have to practice on the carillon itself, which means that everyone within a few blocks can hear your rehearsal, flubs and all. There are practice carillons, but they go for $15,000 to $100,000. "No student is going to be able to afford one of these," Brink said.

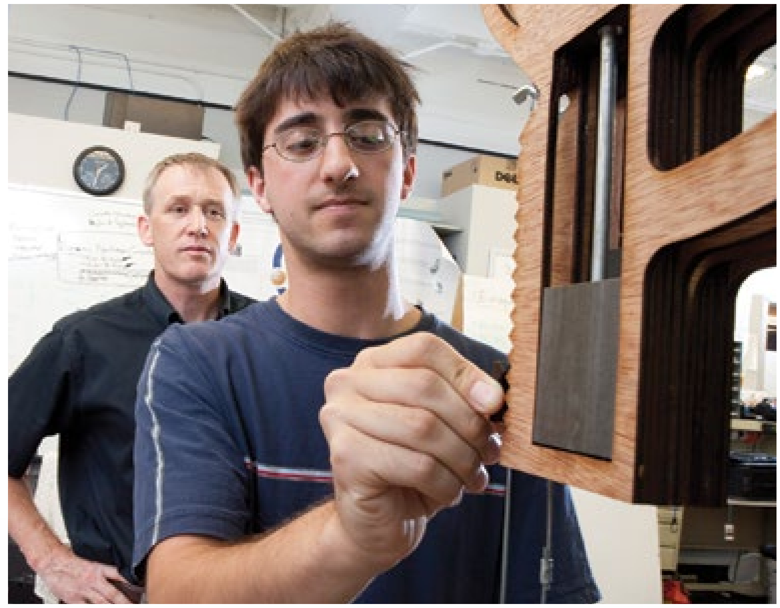
Not only are most practice carillons extremely expensive, using one often doesn't feel much like playing an actual carillon. That's largely because of the difference in the weight of the bells. For instance, Yale's carillon has 54 bells. The lightest is 23 pounds, and the heaviest is seven tons. To strike each note, the carillonneur depresses a baton connected to a clapper for each bell. For the higher notes (the lighter bells), the batons are depressed without much force, but the lower notes require considerably more. Most practice

Continued

carillons don't take these differences in force into account. Complicating things further, each carillon is unique in its number of bells and their respective weights.

For his senior project, Brink traveled throughout Connecticut and Massachusetts to better understand the wide range of bell weights and how that affects the feel of playing different carillons. Doing so allowed him to build a 15-key device that could be adjusted to mimic different carillons.

After graduating, Brink received his diploma from the Royal Carillon School in Belgium, and then a master's degree in mechanical engineering from the University of Utah. He continued his research on practice carillons and how to make them more accessible and received a grant from Guild of Carillonneurs of North America (GCNA) to advance his research.



Above: *Joey Brink working on his senior project in 2011. Brink created a 15-key device that could be adjusted to mimic various carillons.*

"I made some prototypes — I had learned a lot from my time at Yale about fabrication and materials that lend themselves to efficiency and portability," he said. To inform practice carillon designers and manufacturers about how to better make affordable practice keyboards, he conducted extensive surveys of those in the carillon community about what carillonneurs are looking for in a practice instrument. Using his prototype, subjects would offer feedback about their preferences on such things as materials, spring tension, and whether digital or analog generated better sounds.

A year ago, he presented his research at a conference of the GCNA. He also caught the attention of Benjamin Sunderlin, a carillon manufacturer, who has long wanted to sell an affordable practice instrument.

"I was really interested in Joey's research," said Sunderlin. "I think one of the things that's a big concern is the price — trying to find something affordable enough to call it 'affordable,' but robust enough to stand up to regular playing."

Taking Brink's research, Sunderlin started building models, and finished the first ones that were ready for sale this past summer. A four-octave instrument goes for $4,000, and a five-octave one sells for $5,000. It's still

pricey, Sunderlin said, but much more in the range of something many carillonneurs can afford. He's already heard from more than a dozen musicians, asking about the instruments.

Ellen Dickinson, advisor and teacher for the Yale University Guild of Carillonneurs, said her former student's unique mix of expertise gives him a valuable perspective.

"Joey understands the whole picture, which is one of the things that makes him a really important person in the carillon world," she said. "He really understands the engineering, understands the business side of things and — first and foremost — he's one of the finest players out there."

And Brink is using his engineering skills for other carillon innovations. This year, he set a goal to install a new speaker system in the bell tower at his new home, the University of Chicago. Besides honing his audio engineering skills, it helps broaden the possibilities of the carillon. As an instrument, the carillon isn't the easiest fit for a collaboration with other musicians. It's not exactly the kind of instrument that you can pick up and bring to a nearby jam. Other musicians pretty much have to come to you.

Brink and another musician recently took advantage of the new sound system with a piece for trombone and carillon.

"Normally, of course, no one would hear the trombone outside, so he played it through a microphone hooked up to these huge speakers in the tower blasting the trombone at the same volume as the bells," he said. "So you're hearing at the same time the trombone and the bells, which is a strange experience."

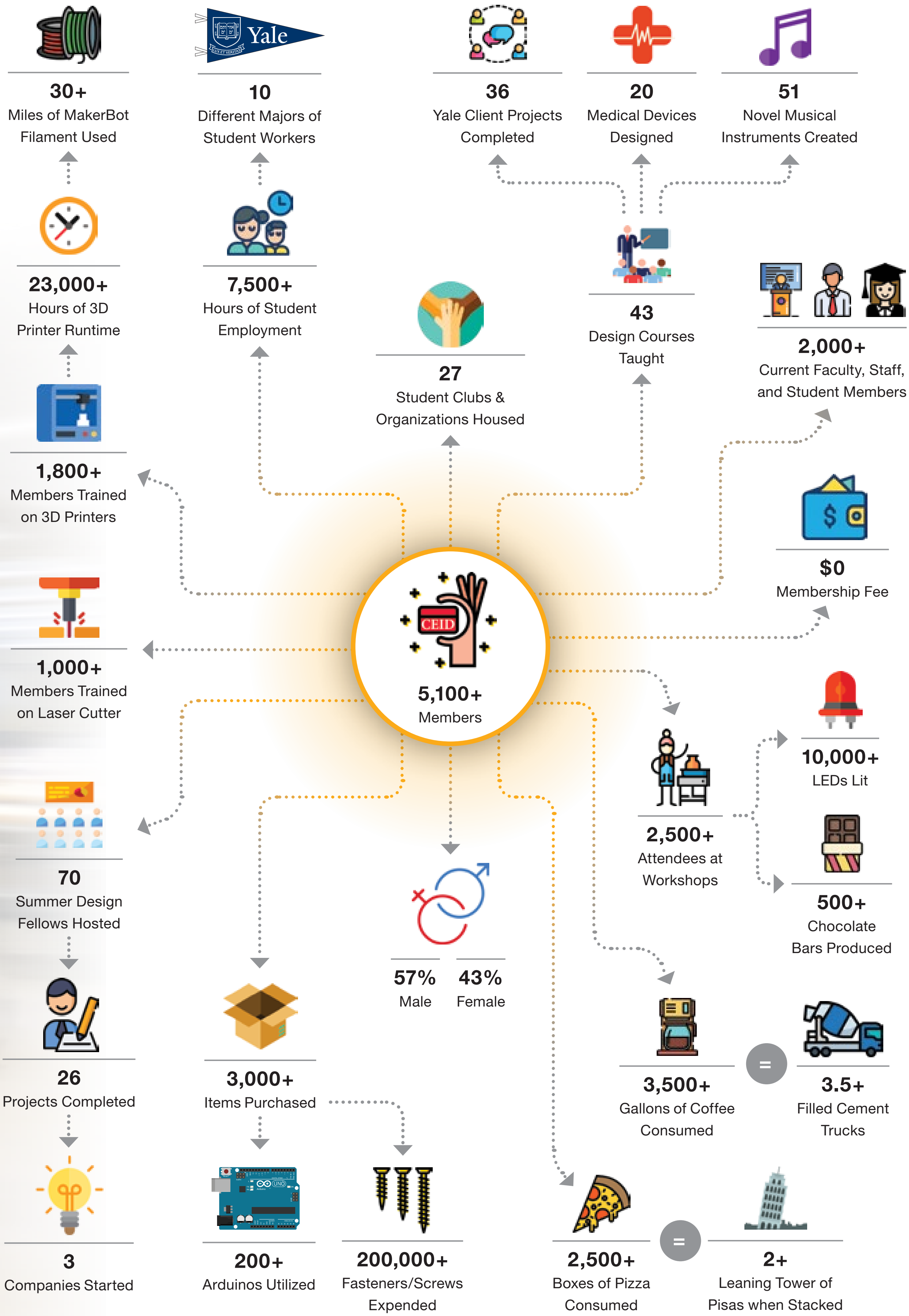
Another recital also expanded on the possibilities of the instrument when Brink performed "The Curve is Exponential" at the University of Chicago's request. The piece, a 28-minute commission for carillon and electronics written by Ted Moore, commemorated the 75th anniversary of the world's first self-sustaining nuclear reaction, which occurred under the bleachers of the university's football field.

The world of the carillon may be steeped in tradition, but it's a growing one. New carillons are being built at a faster rate than ever and Brink says interest from students has increased since he started teaching. And with his efforts to expand the carillon's repertoire and how people can practice help ensure that the artform will continue to evolve.

CEID by the Numbers

When Alessandra Cervera, a lab manager at the Yale Department of Psychology, signed up to be a member of the Center for Engineering Innovation & Design (CEID) in April this year, applause and cheers suddenly erupted around her. The surprised Cervera soon learned that she was the CEID's 5,000th member — just the latest milestone for Yale's makerspace. When the CEID opened its doors on August 27, 2012, who knew how many student clubs would make it their home, or how many workshops would be held there? Or how many chocolate bars would get made there? Curious, we rounded up the numbers:

Below: *The CEID staff present Alessandra Cervera with a bulldog plaque in honor of her being the 5,000th CEID member.*


30+
Miles of MakerBot Filament Used
Yale
10
Different Majors of Student Workers
36
Yale Client Projects Completed
20
Medical Devices Designed
51
Novel Musical Instruments Created
23,000+
Hours of 3D Printer Runtime
7,500+
Hours of Student Employment
43
Design Courses Taught
27
Student Clubs & Organizations Housed
2,000+
Current Faculty, Staff, and Student Members
1,800+
Members Trained on 3D Printers
$0
Membership Fee
CEID
5,100+
Members
1,000+
Members Trained on Laser Cutter
10,000+
LEDs Lit
2,500+
Attendees at Workshops
500+
Chocolate Bars Produced
70
Summer Design Fellows Hosted
57%
Male
43%
Female
26
Projects Completed
3,000+
Items Purchased
3,500+
Gallons of Coffee Consumed
=
3.5+
Filled Cement Trucks
3
Companies Started
200+
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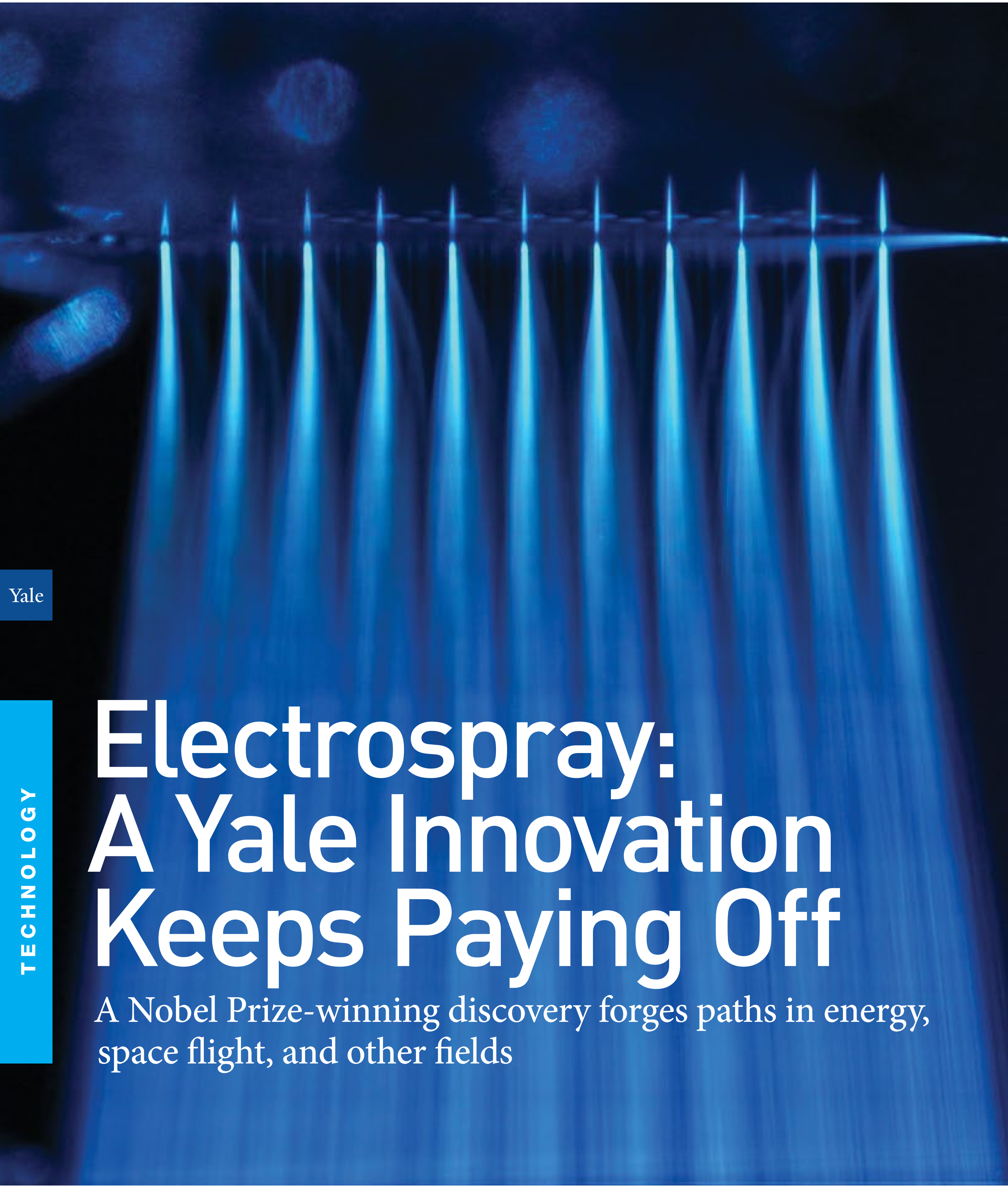
2+
Leaning Tower of Pisas when Stacked



Yale

TECHNOLOGY

Electrospray: A Yale Innovation Keeps Paying Off

A Nobel Prize-winning discovery forges paths in energy, space flight, and other fields

In the early part of the 20th century, Yale physicist John Zeleny was the lone pioneer in electrospray studies, which he pursued in connection with his interest in electrical discharges in gases. Work on the technology, though, was pretty quiet for a several decades until John Fenn began work on electrospray ionization — also at Yale — in 1968. That research didn't get much attention until the late 1980s when he applied the technology to mass spectrometry, an innovation that led to his winning the 2002 Nobel Prize in Chemistry. Fenn was key in the founding of Yale's Chemical Engineering Department, and spent most of his career here.

Today, work on electrospray technology continues in the labs of Juan de la Mora and Alessandro Gomez, both professors of mechanical engineering & materials science. Together, they're finding new ways to use electrospray and they're applying it to advance innovations in space flight, drug delivery, energy, and other fields.

So, What is Electrospray?

Electrospray involves combining a sample with a highly conductive fluid, which is pushed through a small electrically charged needle, causing the sample to exit in the shape of a cone (known as the Taylor Cone). The tip of the cone forms a tiny jet that breaks into a fine mist of uniform-sized charged droplets at low flow rates. The size of the droplets it produces can be controlled from several nanometers to hundreds of microns.

Applications for it were fairly limited until Fenn began working with it, and applied it to mass spectrometry. Mass spectrometry, which accurately determines the mass of ionized molecules, previously couldn't be used to study large biological molecules because they couldn't be ionized. Fenn's electrospray ionization method changed this, and the field of biology benefitted from the precision and speed of mass spectrometry.

"The jet would form tiny drops, and then the drops would themselves explode multiple times," de la Mora said. "Each one of these drops now explodes because the charge is concentrated as the liquid evaporates. So, you have these multiple stages of atomization and, at the end, you have such tiny drops that they only contain one molecule."

Observing what electrospray could do inspired de la Mora's line of research.

"When I saw the beauty of the thing in Fenn's work, my students and I contributed a few articles clarifying some of the physics of the phenomenon," he said. "In collaborating with Fenn, I was sucked into researching some of these applications."

One of the lines of research that de la Mora took up was applying electrospray to developing an "electronic nose."

"We built a mass spectrometer system to smell volatile things of very, very low vapor pressure, and it's 10,000 times more sensitive than a dog's nose," he said. Fenn first proposed the idea, but never got much

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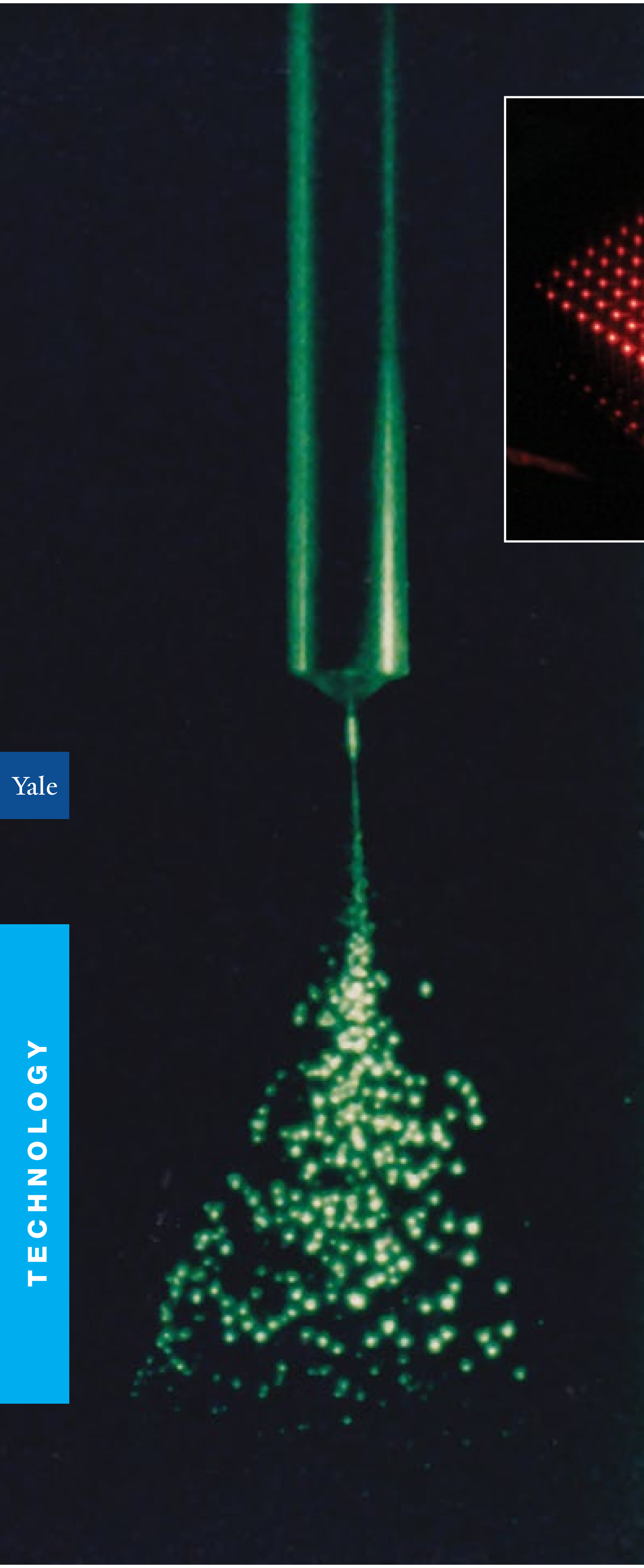
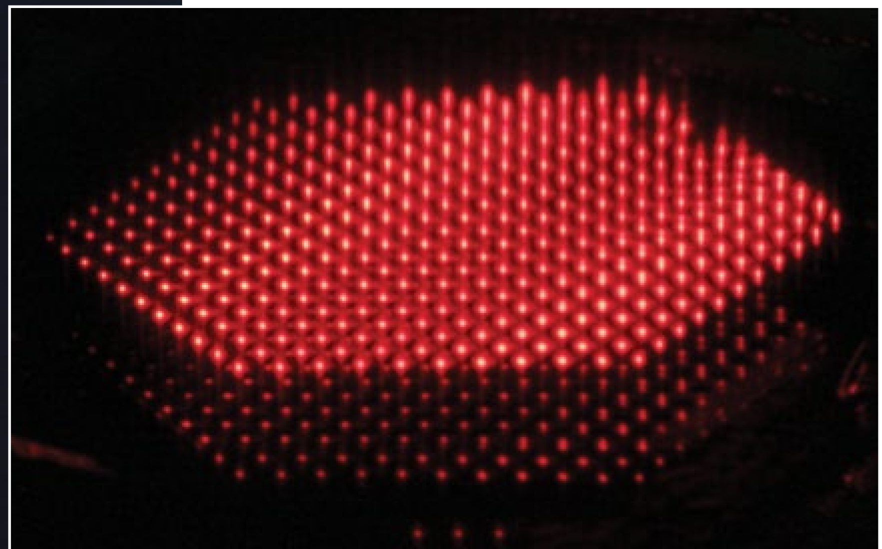




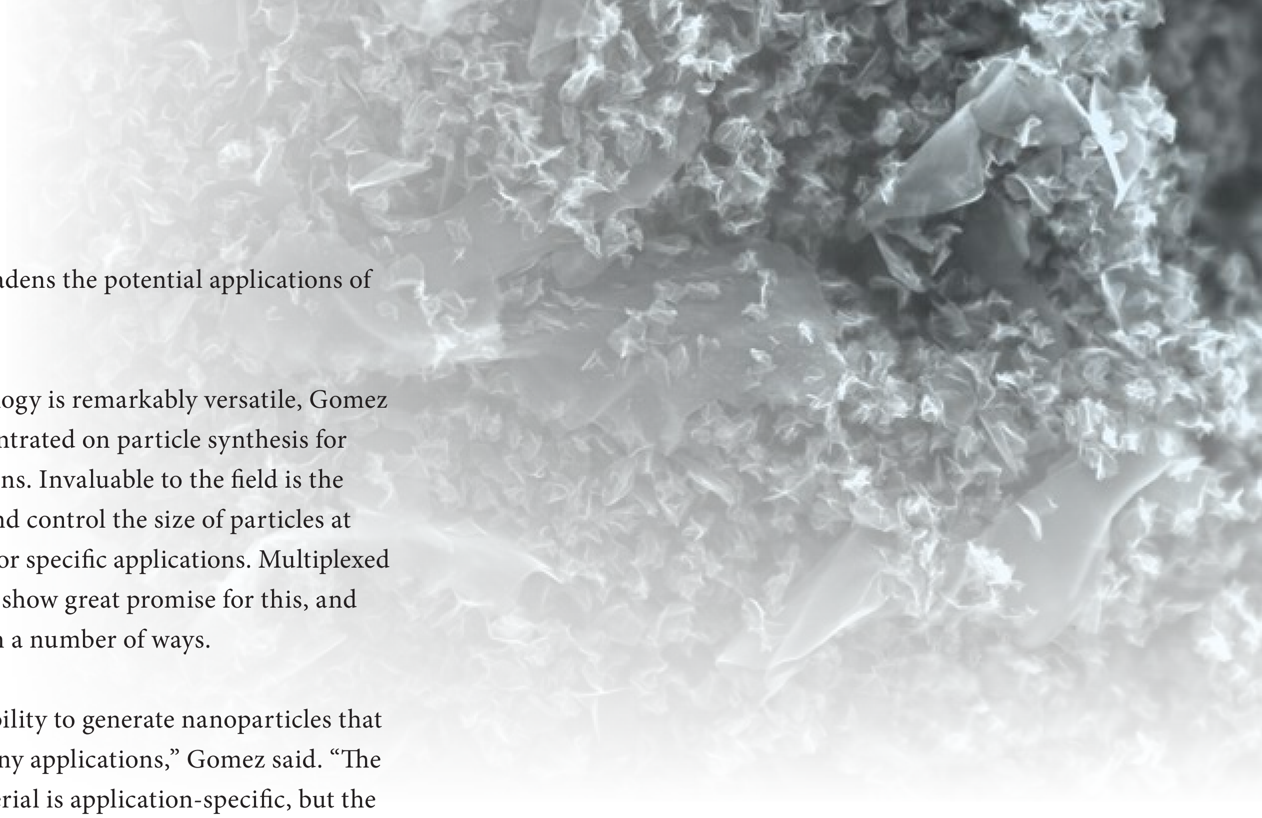
Above: *Multiplexed electrosprays illuminated by a laser sheet "cutting" through the source of the sprays.*

Left: *A single electrospray under pulsed laser illumination.*

of a chance to develop it. Following his lead, de la Mora and his brother Gonzalo Fernández de la Mora in Madrid, Spain have further developed this technology for detecting explosives and vapors emitted from human skin and from hidden explosives.

Alessandro Gomez, who started as a Yale faculty member in 1989 after serving as postdoctoral researcher in chemical engineering, also found himself drawn into the field of electrospray. "Fenn was a dynamo of ideas and his enthusiasm for his research on the electrospray was contagious," Gomez said. "So, when the time came for me to spread my wings, I figured out a different angle to work on the electrospray and chart my own path out of Fenn's shadow." Gomez recalled the pride he felt when Fenn used in his Nobel lecture an image that Gomez's lab captured of a charged droplet fission, which is at the root of the mechanism of electrospray ionization.

Gomez' research involves his development of "multiplexing," a technique that he has honed over the years in which multiple electrospray devices work in coordination with each other. Because a single electrospray device doesn't produce a powerful force, its use had for years mostly been limited to mass spectrometry. Multiplexing increases the



throughput and broadens the potential applications of electrospray.

Electrospray technology is remarkably versatile, Gomez noted. He has concentrated on particle synthesis for numerous applications. Invaluable to the field is the ability to generate and control the size of particles at adequate flow rates for specific applications. Multiplexed electrospray devices show great promise for this, and Gomez has used it in a number of ways.

"It has the unique ability to generate nanoparticles that you can tailor to many applications," Gomez said. "The selection of the material is application-specific, but the fundamentals of the technique are always the same."

The versatility of the technique means that he has had a wide range of collaborators.

"When people come to me with a need for certain things that I think electrospray is well-suited for, that's when I intervene and scratch my head and try to figure out how to produce or synthesize the particles they need," he said.

Batteries and Drugs

Gomez recently worked with chemistry professor Hailiang Wang to develop more efficient batteries. He used an array of electrospray devices to synthesize very small particles of metal-oxide nanomaterial for one of the electrodes of a lithium-ion battery. "This is very important because a lot of electrochemistry is surface-related, so the smaller the particles that make up the electrodes, the more surface is exposed to whatever treatment you apply."

Publishing in *Advanced Materials,* Gomez and Wang were able to verify the battery's improved performance and its potential to streamline the technique to reduce the cost of large-scale fabrication.

Working with the lab of Tarek Fahmy, associate professor of biomedical engineering and immunobiology, Gomez and his team took on the task of synthesizing nanoparticles for the delivery of cancer drugs. Electrospray was critical to ensuring that the particles were of uniform size.

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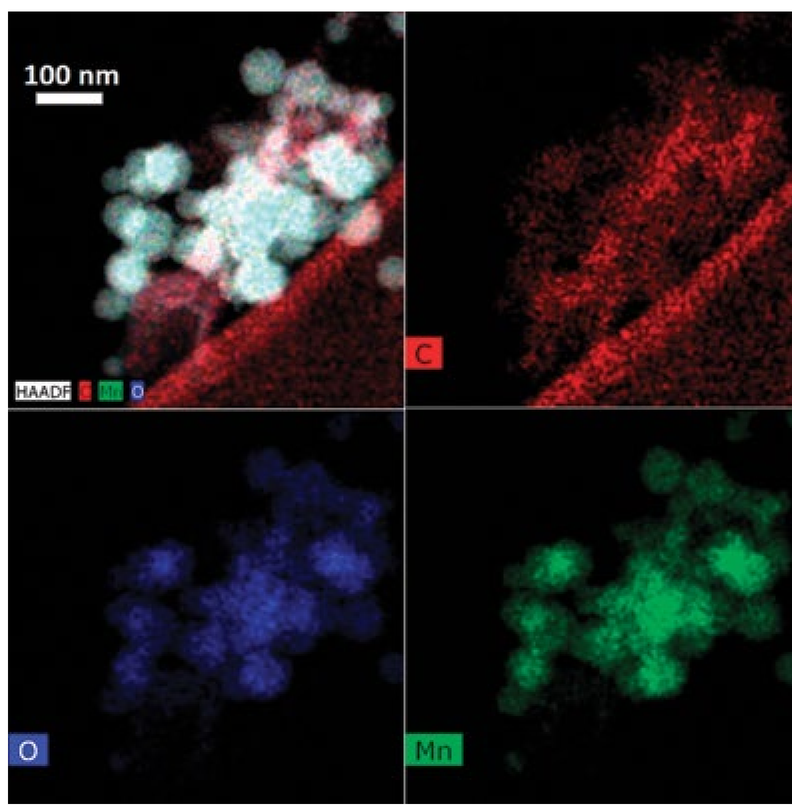
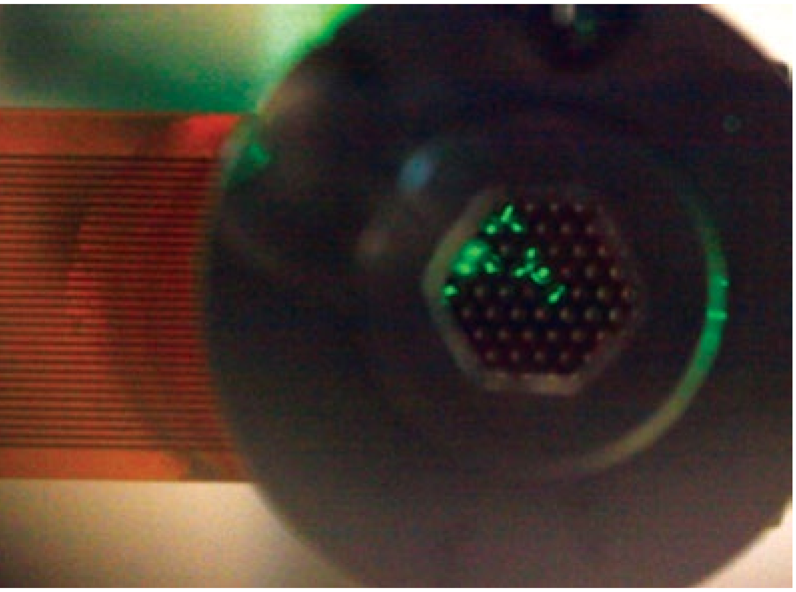
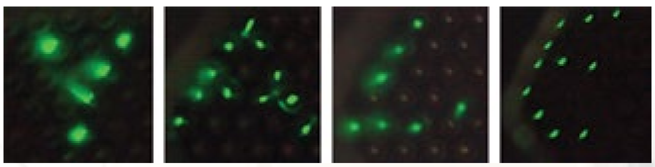


Right: *Energy dispersive x-ray elemental of a composite consisting of electrospray-synthesized manganese oxide nanoparticles and electrospray-dispersed graphene oxide nanosheets.*





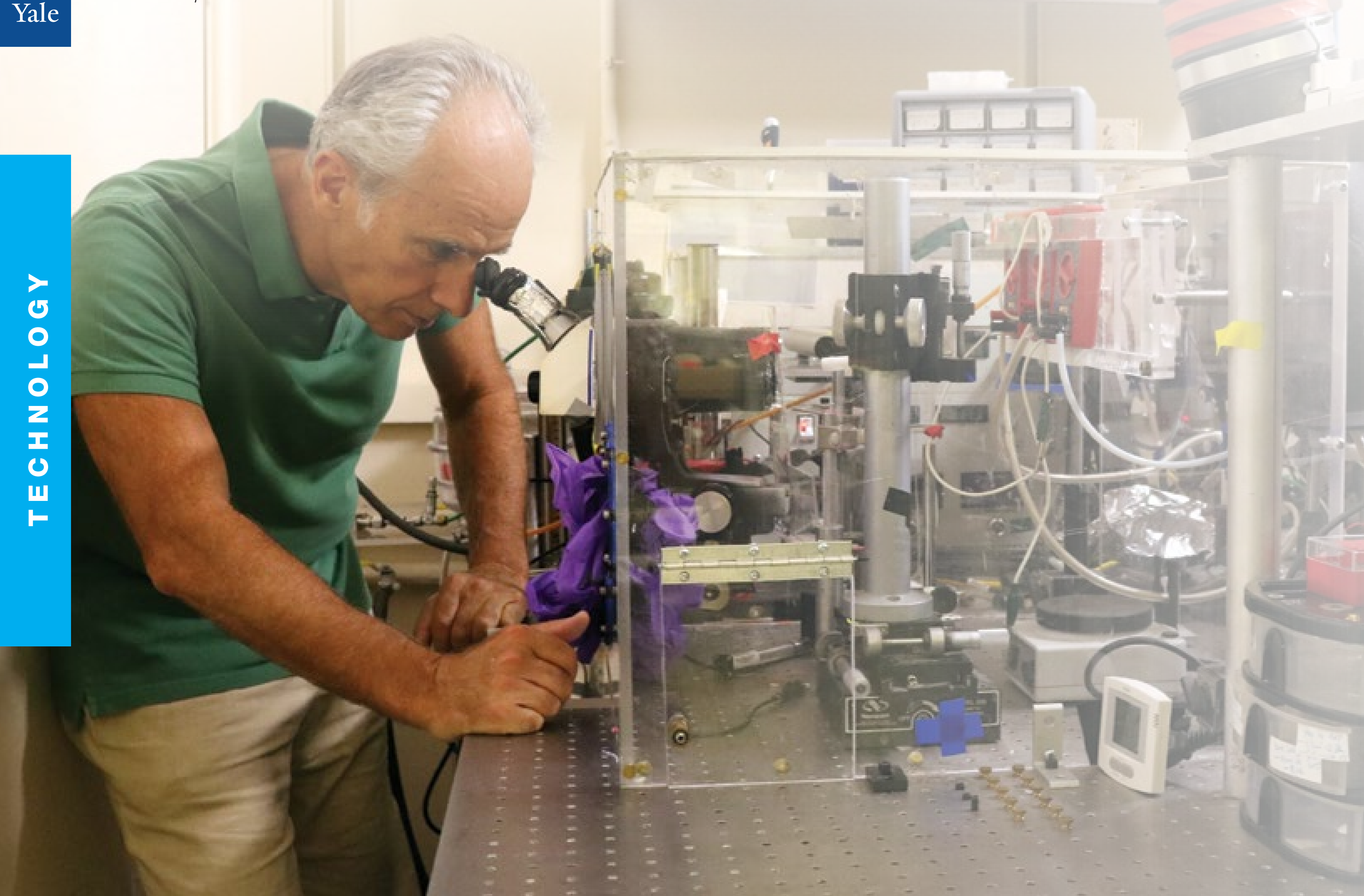
Above: *Digital electrosprays with computer-controlled activation of individual sprays in the multiplexed system.*

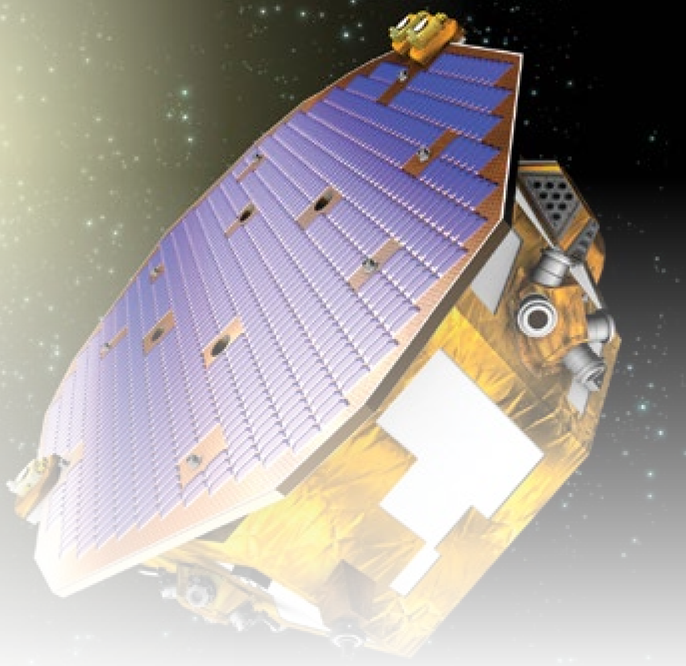
Below: *Gomez and his electrospray system with observation of the cone-jet at the base of the electrospray by a long-distance microscope.*

“These polymer particles are important because they lead to a controlled drug delivery,” Gomez said. “Instead of going through spikes in the delivery of the drug, they can deliver it steadily and in a better controlled way. We spent a fair amount of time preparing the witches brew — that is, achieving the right properties that lead to those particles.”

The particular biomedical applications for this synthesis technique required very high particle production rates — far more than what could be generated from a single source. To do so, Gomez again applied the multiplexing technique. It’s a tricky process because it requires getting all the devices to work together. The results, though, proved worth the effort.

“Looking at its delivery rate and time, it turns out the technique is a significant advance over the standard industry method, which is a solvent evaporation technique that is much less controlled.”





Left: *Former SEAS graduate student, Giovanni Lenguito, at work on the electrospray application for space propulsion.*

Right: *Missions, such as CubeSat and the LISA Pathfinder, could incorporate electrospray systems as a means for propulsion.*

Taking Electrospray to Space

Recent years have seen an increased interest in small satellites, such as CubeSat, for research and education applications. That means there's also an increased interest in tailored propulsion systems for these devices. Electrospray technology has shown to be a promising tool for developing dual propulsion for these satellites.

"Suppose you wanted to go on a space mission in which you first go to Mars," de la Mora said. "Initially, you may take your time to get there by launching very little propellant at very high speeds."

But once at Mars, you have to maneuver to change your orbit and use the gravitation there to be launched to the next planet. This maneuver, however, normally requires considerably higher thrust. Unless you have two motors or are infinitely precise, you are lost. Fortunately, a thruster with electrospray technology would be able to span a broad range of thrust forces with modest changes in power. That's because it would be able to adjust the size of the droplets emitted, which changes the amount of force.

Funded by the U.S. Air Force, de la Mora and Gomez worked on the concept. With multiplexing, they were able to achieve the amount of power and versatility they needed.

"There's too little thrust from a single electrospray, so you would need a few hundred of these electrosprays for the type of missions that NASA has in mind," Gomez said.

And because the nozzles for the electrospray devices need to be created with great precision, the researchers employed microfabrication similar to what's used for creating microchips.

"We can have small nozzles carved with great precision into a silicon wafer of the dimension," Gomez said. "To make sure each nozzle behaves as the next one, you want to have precise sizing of the nozzles."

Creating a prototype this way is pricey, Gomez noted, but once you have the formula down — the right spaces and correct dimensions, for instance — it can be mass-produced at a reasonable cost.

A Global Effort

Yale students mentor high school robotics teams for international event

Left: *Team Afghanistan meets with their SEAS mentors in the CEID in May.*

Right: *(L-R) FIRST Global founder and prolific inventor Dean Kamen, host Ricardo Salinas, Mexico's President-Elect Andrés Manuel López Obrador, and Mexico's Secretary-Elect of Public Education Esteban Moctezuma.*

There are plenty of challenges involved with designing and building robots — even more so when you're working from several different points on Earth.

This past summer, 17 Yale students worked with teams of high school students from eight countries for the 2018 FIRST Global Challenge, an annual international robotics competition held for four days in August in Mexico City. FIRST Global, a non-profit organization that focuses on STEM-related initiatives, held its first international competition last year in Washington D.C.

As part of the organization's Higher Education Network — designed to increase access to STEM education — Yale was among several universities with students serving as mentors to teams around the world. Two to three Yale mentors worked with each of the teams, from Bangladesh, Georgia, Japan, Afghanistan, Madagascar, Syria, Germany, and Liberia.

In the weeks leading up to the competition, the teams and Yale students strategized and conferred on robot designs remotely, connecting via Skype, WhatsApp, and other technologies. At the Center for Engineering Innovation & Design (CEID), the Yale students worked on the same robot kits supplied to the teams in their home countries.

Robert Graf, coach for Germany's team, said he and the students were grateful for the assistance from the team's mentors, Evelyn Huang '20 and Sebastian Rivero '19.

Above: *SEAS undergraduates with Brian McCormack, Chief of Staff for Secretary Perry.*

Above: *SEAS undergraduates with Dean Kamen and U.S. Secretary of Energy Rick Perry.*

"During the prototyping and building, we kept the two of them updated on our progress," he said. "They were most supportive and encouraging, commenting on our designs and going the extra mile of keeping tabs on our social media accounts."

And while the German team is a long-time veteran of the robotics competition, he said it was good to get some fresh insights from Huang and Rivero. At the same time, he said they ensured that the new ideas were also feasible.

"From time to time, we do get very crazy ideas like building a rope line and a gondola to deliver the cubes into the goal," he said. "Fortunately, everyone talked us out of it. Our mentors nudged us to think unconventionally, but on the other hand, they also tethered us to reality when our creativity got ahead of us."

Huang, though, was reluctant to take too much credit, adding that the German students were self-starters. "We helped them in the very beginning with design stuff, but honestly, most of it was them," she said.

Razeen Ali, student team member for Bangladesh, praised mentors Ian Denzer '21 and Michelle Tong '21 for their work with the team. Denzer's work at the event itself also proved critical.

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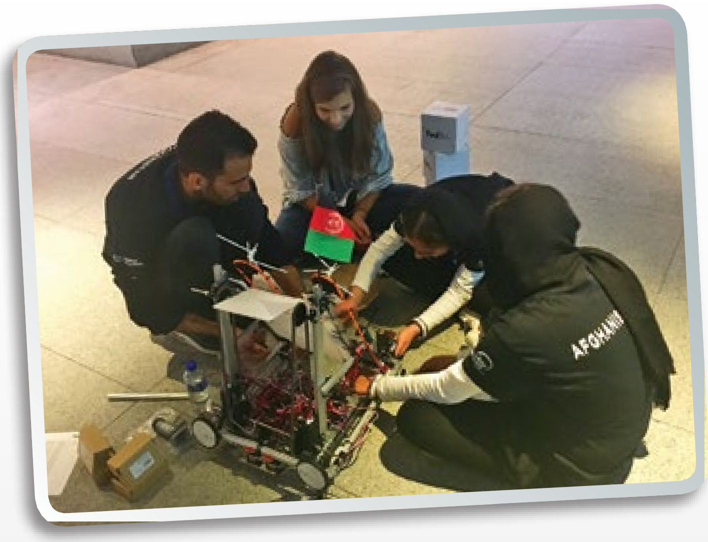


Left: *Laura Wayland '21 advises Team Afghanistan minutes before the competition.*

Right: *Team Yale with Yale Honorary Ph.D. recipient Dean Kamen.*

"He had provided very interesting solutions to our robot design, which made it more functional," he said. "If it wasn't for his time and design ideas and helping us rebuild/redesign our robot moments before our matches, we wouldn't have done as well as we did."

Yale students Rowan Palmer '21, Laura Wayland '21, and Emily Chu '19 worked with one of the competition's best-known teams, from Afghanistan, which made headlines the previous year when they were initially denied visas for the competition in the U.S. They met briefly with the Yale students at the beginning of the summer before corresponding with them remotely. Team leader Roya Mahboob said working with the mentors was an "absolutely great experience," even with some technical complications leading up to the event, which meant some serious scrambling at the actual competition.

"The students were working very hard with Yale University's students on building a new robot while the competition was going on," Mahboob said. "But I loved their not-giving-up attitude, positive behavior and persistence in working on the project. And the students from Yale were there all the time to help and support our students, and we were very appreciative of their patience and hard work."

As is often the case with ambitious projects, not everything went smoothly for all the teams. For one thing, there were time differences.

"I was working with Sebastian and he was on the East Coast and I was on the West Coast, so we had a three-hour time difference and Germany had a six-hour time difference," Huang said. Luckily, the German team regularly posted on their blog about their work. "They would update their progress there, and even if we weren't in direct communication with them all the time, we could just check out their blog and see what they were up to."

Time zones also plagued communication between the Yale students and the Bangladesh team, as did faulty Wi-Fi connections. But eventually things worked out. Denzer noted that WhatsApp allowed for individual calls between mentors and team members, and that probably worked out better.

From August 15th to 18th, more than 1,000 high school students from 193 countries came to Mexico City's Arena Ciudad de México to take part in the competition. Besides the teams and their coaches and mentors, the event also drew thousands of spectators. Those in attendance also included Mexico President Enrique Peña Nieto and inventor and entrepreneur Dean Kamen, who founded FIRST Global.

Graf, Germany's coach, said the competition was where the Yale mentors' work really paid off.

"They made sure to drop by often, ask about our scores, our robot and our games — and their positive attitude was really infectious," he said. He did add, however, that "our snacks were diminishing suspiciously fast when they were around."

Top Left: *Adam Wolnikowski '21 and Tongan Olympian Pita Taufatofua on stage with the Yale CEID-built random team generator to create national competition alliances.*

Bottom Left: *Team Yale with astronaut and X Prize CEO Anousheh Ansari and the Intel Drone Team engineers.*

Right: *Ian Denzer '21 assists Team Bangladesh with their competitive robot.*

Besides the competition itself, many said the real thrill of the event was the chance for young people from nearly every country in the world to gather in one building and cheer each other on. The teams were arranged in alphabetical order, so there were kids from Uruguay hanging out with competitors from Uzbekistan, while not far away, the Azerbaijan team was comparing notes with the team from the Bahamas.

"Watching all the kids run around going crazy and saying hi to everyone else was probably the coolest part of the program," Rivero said. "It's impressive to have an event where there's kids from almost every country on the planet all there. You'll see kids from five different countries who have probably never interacted otherwise, and they're all having a conversation about, you know, a robot."

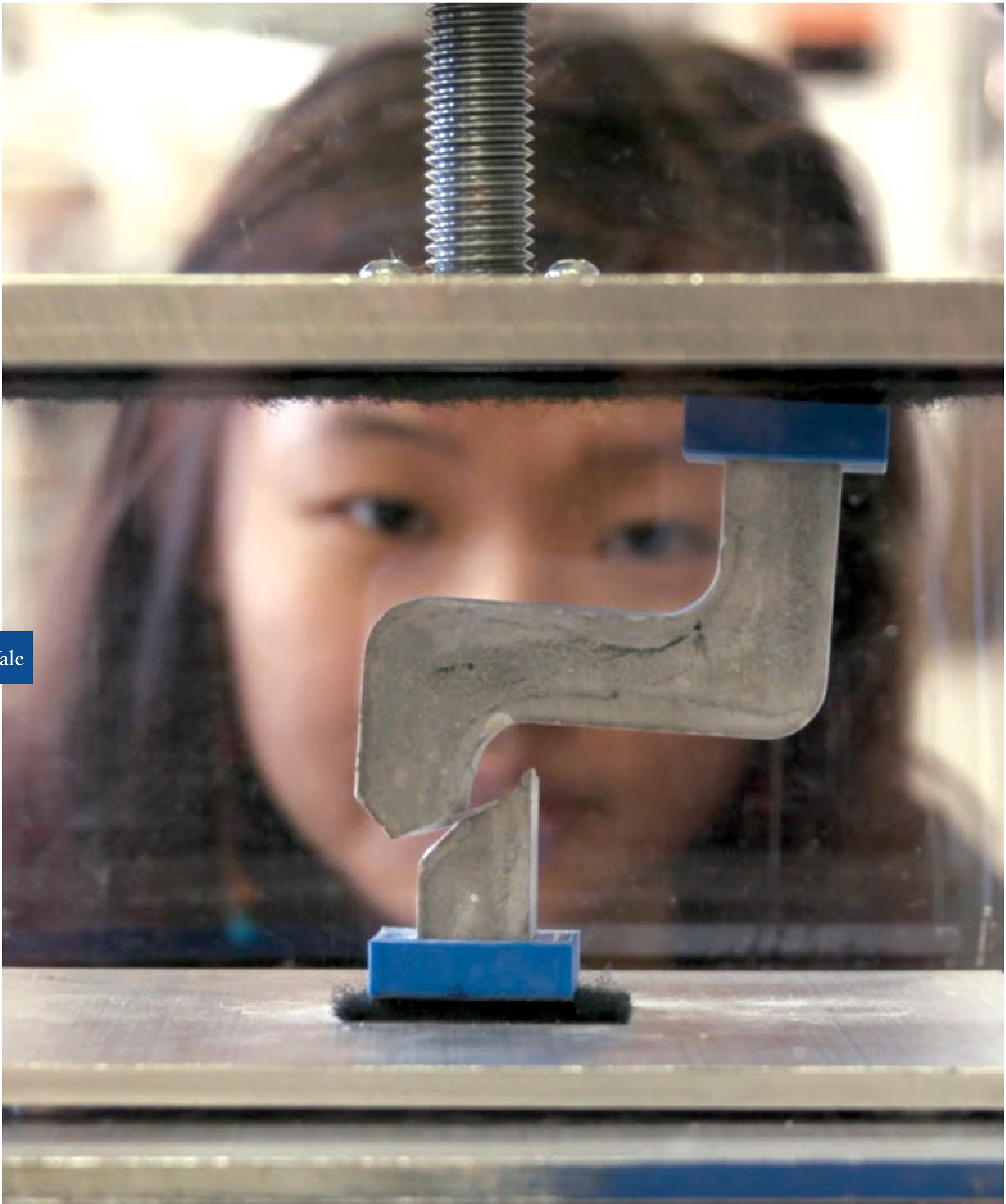
The nature of the competition also fostered teamwork and cooperation. Each year, the competition focuses on one of the 14 Grand Challenges of Engineering identified by the National Academy of Engineering. This year's theme was the impact of energy. The teams were split into three-nation partnerships, which would compete against other alliances to see whose robots could pick up and carry the most power cubes and solar panels to the goals on the field. While some robots might be good at picking up cubes, other robots were better at picking up solar panels. That meant that the teams had to learn quickly how to work together and strategize.

Razeen Ali of the Bangladesh team said that being part of a group that was representing his country was an "irreplaceable feeling." And seeing the robot they had been working on for months finally on the field and competing against others was remarkable.

"We knew that our two months' worth of hard effort and the large amount of time we spent preparing for this event had finally paid off," he said. "We didn't let our losses in the first few matches bother us. Instead, it motivated us to make last moment changes and finally make it work."

He added that the international spirit of the event may have been the most exciting part of the trip.

"It was really astounding to see people from all around the world in one venue," he said. "It gave us a great opportunity to make international friends and meet people we'll never forget due to the memories we made together. This is something we would definitely do again and again."



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