Developing Tomorrow's Energy

The Energy Sciences Institute is fostering collaborations, finding power solutions

Big Data

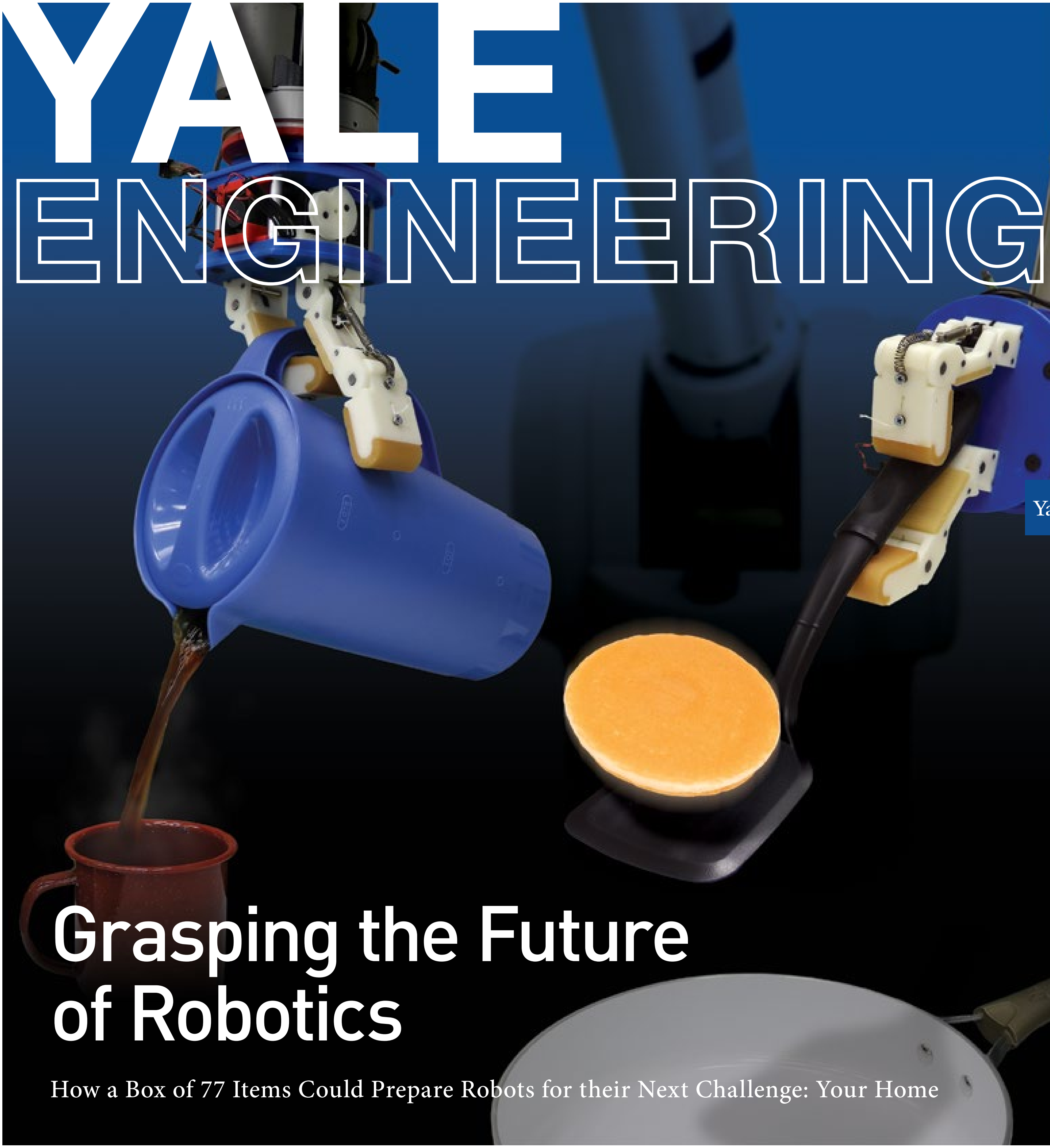
SEAS researchers are tapping into an unprecedented amount of data and making sense of it

Inside/Outside

Environmental engineers are finding new ways to study the air we breathe — both indoors and out

2016-2017

YALE ENGINEERING



Yale

Grasping the Future of Robotics

How a Box of 77 Items Could Prepare Robots for their Next Challenge: Your Home

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

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FEATURES

Front & Back Covers:

Whole arm manipulator designed to grasp objects in unstructured environments. Researchers at Yale have curated numerous household items to be used as a new standardization for robots.

EDUCATION SUSTAINABILITY INTERDISCIPLINARY MEDICAL INNOVATION TECHNOLOGY

YALE ENGINEERING 2016-2017

YALE UNIVERSITY
School of Engineering & Applied Science

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Message From the Dean

As they say, hindsight is 20/20. That was certainly the case when Yale created a Department of Biomedical Engineering in 2003. Today, this engineering major is one of the most popular of all STEM offerings at Yale and attracts many of Yale's brightest students. It was also a brilliant move in 1998 to launch the Environmental Engineering program, built upon chemical engineering synergies as opposed to civil engineering practices. This was a forward-looking idea that captured the molecular nature of the discipline as it seeks to address global needs for clean water, renewable energy, and long-term sustainability. And perhaps our best recent example of a perfect play was the creation of the Center for Engineering Innovation & Design (CEID), launched in 2012, which now boasts more than 2,200 members from all corners of campus, including students, staff, and faculty. Arguably one of the best views on the Yale campus is that through the street-side CEID windows where passersby can see innovation happening in real time.

Vision, generally speaking, was on my mind this fall when I welcomed the Class of "2020" students who are thinking about majoring in engineering. If they are like me, those who do choose to major in engineering will look back on this decision as one of the best they made in their lives. Engineering taught me, and will teach them, how to think quantitatively, how to both analyze and design, and how to wrap one's mind around complex systems. I think all aspiring engineering students have good vision, but I think Yale engineering students also have what I call great "peripheral vision." They understand that while engineering is a central focus for their study, they also crave to learn other things as well, with all these pixels of study melded together to form a more cogent representation of the world around them.

I hope you will like what you see in this year's edition of *Yale Engineering*. I trust you won't have to squint to see the many examples of student "peripheral vision" clearly displayed in many of the stories in this issue.

T. Kyle Vanderlick
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

2015: September

Twice The Trash

A study from the lab of Julie Zimmerman, professor of chemical & environmental engineering and forestry & environmental studies, found that we are disposing of twice as much solid waste as previous estimates suggested. Led by Jon Powell, a Ph.D. student, the study revealed that 262 million tons of municipal solid waste were disposed of in the United States in 2012 — a 115% increase over the U.S. Environmental Protection Agency's estimate of 122 million tons for the same year.

2015: October

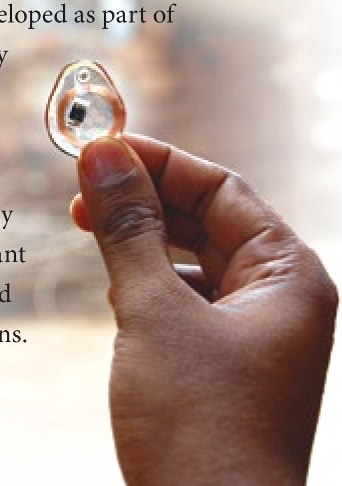
Presidential Shout-Out

The Yale Undergraduate Aerospace Association received a White House salute for its work on developing an automated optical telescope. With software written by a team of students, the large telescope is motorized and computer-controlled. For better data collection, it will have the ability to see deep-space objects and track celestial objects as they progress across the sky. It will also be equipped to take long-exposure photographs of deep field objects. The presidential recognition was part of the annual White House Astronomy Night.

2015: November

A Life-Saving Necklace

The Yale-founded social enterprise Khushi Baby won the Wearables for Good Challenge co-sponsored by UNICEF. The device, developed at the Yale Center for Engineering Innovation & Design (CEID), is a small, high-tech necklace that could save countless lives by storing an infant's complete medical history and vaccination records, and made accessible to physicians. It was developed as part of "Appropriate Technology in the Developing World," a course designed to tackle ongoing global issues co-taught by Dr. Joseph Zinter, assistant director of the CEID, and SEAS lecturer Bo Hopkins.



2015: December

Shedding Light On An Artist's Work

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

2016: January

Keeping The Bugs Out

Zhong Shao, a professor of computer science, was selected for a National Science Foundation project known as Expeditions in Computing: The Science of Deep Specification (DeepSpec), which aims to exterminate the kinds of software bugs that create security vulnerabilities and computing errors. Funded by a $10 million, five-year grant, Shao and other researchers from Yale, Princeton, MIT, and the University of Pennsylvania will develop tools to eliminate uncertainty from the complex task of software development and enable engineers to build bug-free programs and verify that their programs perform as designed.

2016: February

Hacking The Brain

Having hosted a number of medical hackathons, the Center for Engineering Innovation & Design served as the venue for the university's first mental health hackathon. Organized by the student group BulldogHacks, "Hack the Brain: Rethinking Our Approach to Mental Health" challenged teams to identify a problem in the field of mental health, devise a solution, and build a prototype. In less than 24 hours, teams produced such innovative ideas as devices to assist people who can't speak and an app to improve patient-doctor communications.

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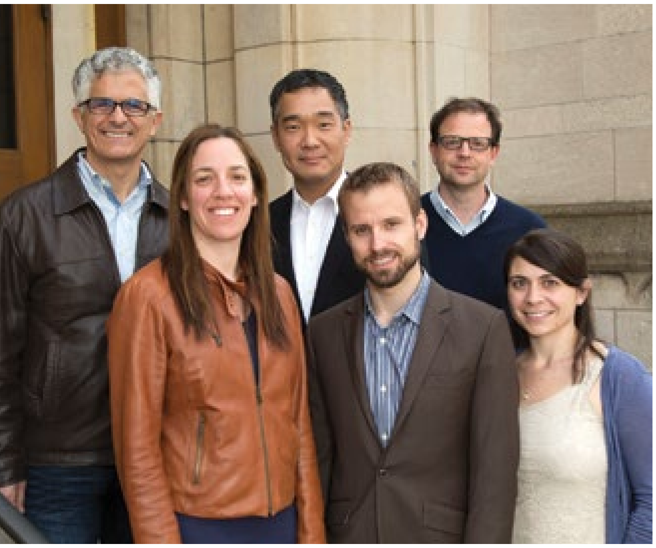
Year in Review



2016: March

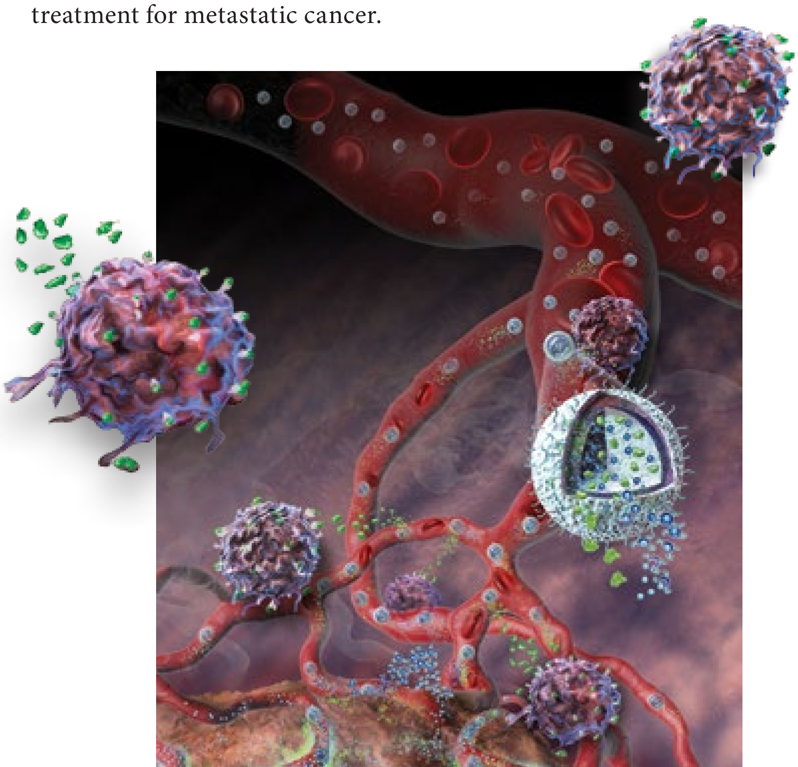
Breaking Into The Top 10

In just a few years, Yale's Environmental Engineering program has established itself as an international powerhouse. One reflection of this is found in the 2017 *U.S. News & World Report's* Graduate Engineering Rankings, which lists the program at No. 9 in the category of "environmental engineering." Yale's program tied with those from MIT and Johns Hopkins University. Menachem Elimelech, the Roberto C. Goizueta Professor of Chemical and Environmental Engineering and founder of the environmental engineering program, attributed the program's success to the dedication of the faculty as well as the many outstanding graduate students and postdocs who have gone through the program.

2016: April

Nano-sized Drug Delivery

An immunotherapy drug delivery system developed by Tarek Fahmy, associate professor of biomedical engineering and immunobiology, heads to its first phase of clinical trials as a possible new treatment for cancer. The delivery system is a nanogel designed to deliver multiple drugs with different chemical properties. A single particle can carry hundreds of drug molecules that concentrate in the tumor, increasing the efficacy of the drug combination while decreasing its toxicity. The first use of this delivery system will be a multi-pronged treatment for metastatic cancer.



2016: May

The Environmental Cost Of Oil Sands

Working with scientists from Canada, chemical & environmental engineering professors Drew Gentner and Desiree Plata found that oil sands operations — a major source of oil production in the last several years — emit very high levels of a critical class of air pollutants known as secondary organic aerosols and pose risks to health and climate. The researchers, who studied oil sands operations in Alberta, Canada, noted that this could have a major impact on climate, since highly oxidized organic aerosols reflect incoming solar radiation.

Yale

INTERDISCIPLINARY

2016: June

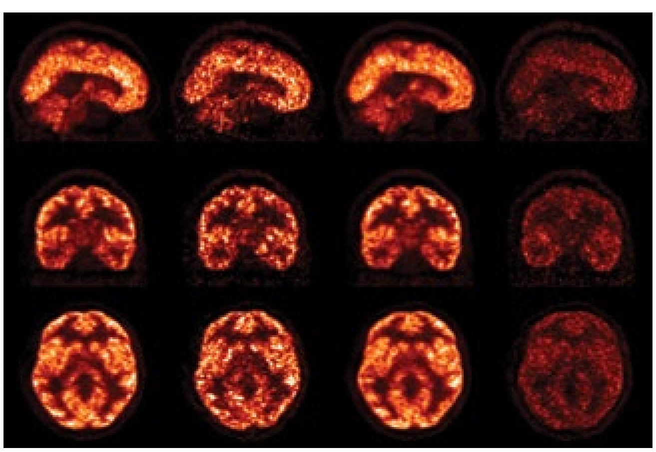
Clues From Individual Cells

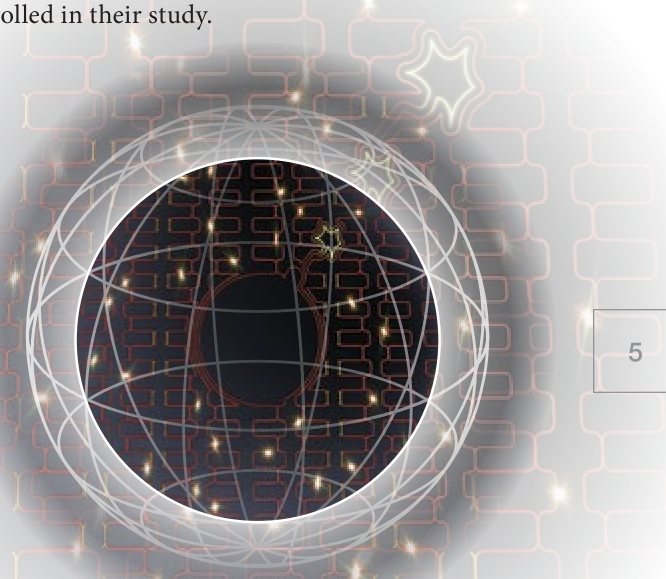
Andre Levchenko, the John C. Malone Professor of Biomedical Engineering and director of Yale's Systems Biology Institute, developed a new nano-fabricated platform for observing brain cancer cells. The platform provides a more detailed look at how cells migrate and a more accurate post-surgery prognosis for brain cancer (glioblastoma) patients. Levchenko and his research team created an environment similar to the one that glioblastoma cells naturally navigate. This allowed the researchers to observe cells individually, isolate a subset of particularly aggressive cells, and accurately predict the clinical outcomes of the 14 brain cancer patients enrolled in their study.

2016: July

Observing The Living Brain

Led by Richard Carson, professor of biomedical engineering & radiology and biomedical imaging, a team of researchers developed a new approach to scanning the brain for changes in synapses associated with common brain disorders, and may provide insights into epilepsy, Alzheimer's and other disorders. Traditionally, researchers can only observe synaptic changes through autopsies, but the Yale team's method can measure synaptic density in the living brain. They achieved this in part by developing a new radioactive tracer that binds with a key protein that is present in all synapses.





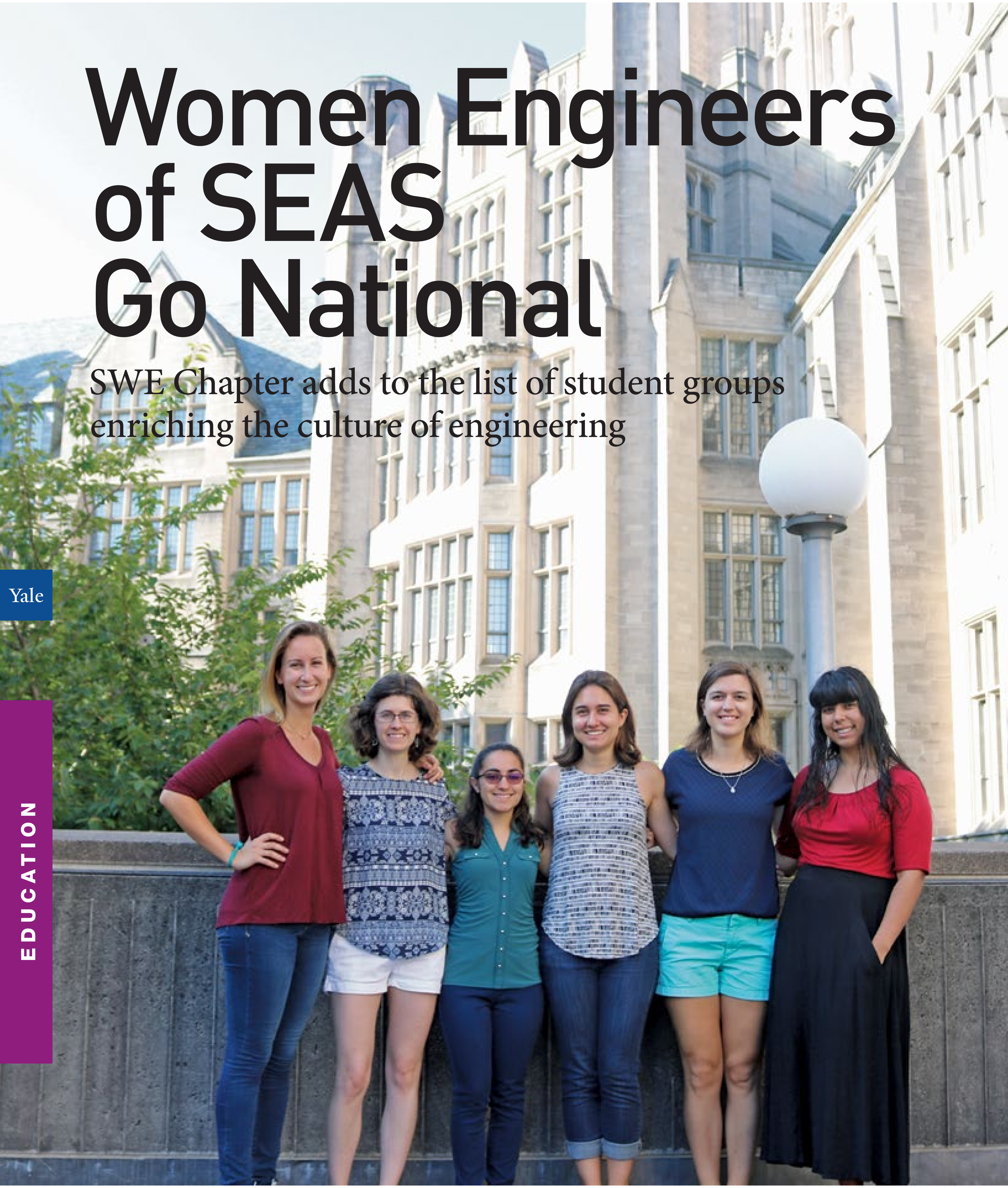
2016: August

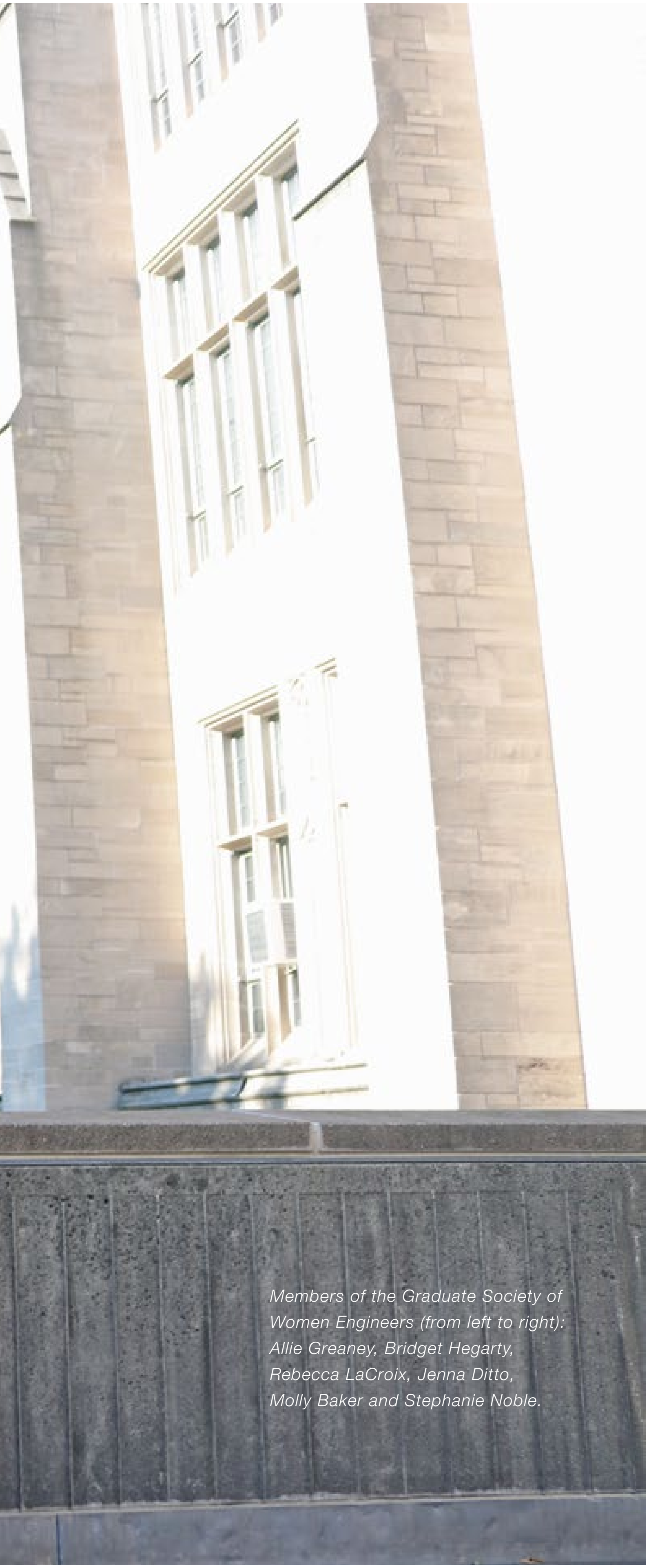
Securing Communications

Hong Tang, the Llewellyn West Jones, Jr. Professor of Electrical Engineering & Physics, was named leader of a team of researchers for a National Science Foundation (NSF) initiative to advance technology for secure communication over long distances. It is the first engineering-led research cohort of its kind. The team, which also includes researchers from Princeton University and BBN Technologies, will develop technology that enables secure quantum communications on a global scale. NSF officials said the cohort was organized "as the demand for cyber-security increases."

Women Engineers of SEAS Go National

SWE Chapter adds to the list of student groups enriching the culture of engineering





Members of the Graduate Society of Women Engineers (from left to right): Allie Greaney, Bridget Hegarty, Rebecca LaCroix, Jenna Ditto, Molly Baker and Stephanie Noble.

“They founded it to develop a strong, well-organized community of women engineers and to reach out to prospective women engineers and to enrich students’ academic and professional experiences as women engineers.”

› Dr. Beth Anne Bennett, lecturer of mechanical engineering & materials science and SWE advisor

By bolstering the formal curricula and enriching the social environment, student groups have long helped to shape the culture of School of Engineering & Applied Science. Although they have faculty advisors, the groups are largely self-starting and self-sustaining. They allow students to further immerse themselves into particular interests while continuing the SEAS tradition of commitment to teamwork. Together, they’ve proven that when students work together, they can help impoverished communities thousands of miles away, launch satellites into space and develop countless innovations.

The newest addition to the many students groups of SEAS is Yale’s national chapter for the Society of Women Engineers (SWE). A local chapter of SWE (commonly pronounced “swee”) has had a campus presence since 2011, when undergraduate Brigid Blakeslee and graduate student Monika Weber first saw the need for the group.

Continued →

Members of the Undergraduate Society of Women Engineering (from left to right): Julia Zhang, Saisneha Koppaka, Alexa Caruso and Chaihyun Kim.

"They founded it to develop a strong, well-organized community of women engineers and to reach out to prospective women engineers and to enrich students' academic and professional experiences as women engineers," said Dr. Beth Anne Bennett, a lecturer of mechanical engineering & materials science, who has been SWE's advisor since the start.

In February this year, it officially became part of the national SWE organization.

"That means there's more funding opportunities at the national level," said Bridget Hegarty, who is the co-leader of the graduate student section of SWE with Rebecca LaCroix. "That means we get to go to more conferences and have more of a voice in SWE nationals. There are also opportunities for scholarships and outreach funding."

Bennett said the group serves multiple functions. For freshmen women who are interested in engineering, but haven't committed to it yet, SWE is a welcoming introduction to SEAS. It's also a structured space for upperclass and graduate students who want to share their experiences with younger students. And for everyone involved with the organization, Bennett said, it's "a lively community of women engineering students engaged in activities to advance the engineering experience at Yale."

The group's overall purpose is to support female engineers at Yale. Significant progress has been made in bringing more women into engineering, but it's still an underrepresented group. During the 2015-16 year, the group held a gender bias workshop. Led by a faculty member from the psychology department, the workshop went over a number of scenarios designed to illustrate biases people often have without knowing it.

"The scenarios were really good conversation starters," said Hegarty, who's working toward a Ph.D. in environmental engineering. "They make you think 'Oh! I never thought about the fact that I do this,' and they've led to some really excellent conversations about implicit biases — the things we don't think about."

All of the SWE events are open to both men and women and have also included mentoring workshops, faculty-student dinners, resume tutorials and an etiquette dinner that instructed attendees in the art of job interviews and working the room. In addition to the SWE national conference, members also attended HerStory, an evening of 5-minute "flash" presentations by student volunteers about pioneering women in engineering over the past 200 years.

Outreach is another important part of the group's mission. SWE members frequently visit local middle and high schools to conduct engineering workshops. For 2016, the outreach theme was "From Oil Spills to Heart Failures: Engineering Solutions for the Future." Through activities

"We're definitely focused toward women and women's issues in engineering, but also in working with everyone and creating a more friendly community for everyone."

› Rebecca LaCroix, SWE graduate co-leader

and demonstrations, the students learned about the role engineering plays in solving big problems. The outreach events also let younger female students meet and talk with women engineers. Hegarty and LaCroix noted that those kinds of interactions can go a long way toward encouraging girls to think about a future in engineering.

"I think it's something that's really started in the last 10 years," Hegarty said. "My sister, who's four years younger than me, has had many more of these opportunities to see women in the roles of engineers. It just seems like they're doing more hands-on activities, where they see role models who are women in engineering. Growing up, I didn't."

Hegarty remembers that, as a senior in high school, she would mention to others her interest in engineering. "They'd say 'Oh, not

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many girls do that — are you sure you'll be comfortable in a class with all guys?'" That didn't change her mind, but Hegarty said she could see how those kinds of comments might discourage some girls. "So if we can help some girls get through those questions and decide to persist in engineering, that would be great."

LaCroix, a biomedical engineering graduate student, said increasing diversity within the Engineering school is another big issue for SWE.

"We're definitely focused toward women and women's issues in engineering, but also in working with everyone and creating a more friendly community for everyone," she said. The Yale chapter is unusual in that it encompasses both undergraduate and graduate sections. Both are vital to accomplishing SWE's goals, Hegarty and LaCroix said. "I know that Yale at the undergraduate level is making a real push to accept more women, and we hope to support them throughout their time here," Hegarty said. "I think we're beginning to see the fruits of those efforts, but there's still more that needs to be done."

Among those who found support from SWE was Saisneha Koppaka '18, who joined the organization as a sophomore.

"I was nervously beginning my mechanical engineering major at the time, so the advice I received during that event was incredibly valuable," said Koppaka, who is serving this year as president of SWE's undergrad section. "Undergrad SWE was filled with extremely friendly and supportive people!"

The lack of women represented nationally in engineering "is definitely a concern," Koppaka said, and it can discourage other female students who might otherwise consider studying engineering.

"One of the purposes of SWE outreach is to show kids at local schools the achievements women have in engineering and related fields," she said. "The hope is that by presenting role models, some of the inherent biases towards women and engineering fall apart."

Student Groups at SEAS: A Primer

From rockets and electric cars to bringing clean water to communities in need, the student groups of SEAS offer a broad range of interests. Join one, and you're guaranteed to learn new things, help others and have a lot fun!

Yale Undergraduate Aerospace Association

Working with the enterprising YUAA means developing skills from computer programming to fundraising. Their many projects — all student-run from conception to completion — include building and flying rockets, planes, quadcopters, and unmanned aerial vehicles.

The 2015-16 year was a big one for YUAA, which has been on a rocketing ascent since its start in 2009. The group's work on an optical telescope and its first CubeSat — a small satellite that will go into lower orbit — won recognition for YUAA at the 2nd annual White House Astronomy Night.

At the most recent Intercollegiate Rocket Engineering Competition (IREC), YUAA competed against 80 other teams and took second place in the payload category with its first biology-related project — a rocket that collects air samples during its flight.

For the 2016-17 year, YUAA continues its ambitious path to the skies. Besides finishing the CubeSat and "exploring the universe," the new YUAA agenda has a couple of firsts on its to-do list: build

Below: *Engineers Without Borders work with natives in Roh, Cameroon to bring clean water to the village.*

Left: *YUAA members pose with their rockets at the CEID.*
Above: *YUAA members prepare their rocket for flight at the Intercollegiate Rocket Engineering Competition.*

its first liquid-fuel rocket and build its first jet engine. The YUAA has also set out to build a hot air balloon. This project is a reprise of sorts, since one of the club's earliest projects involved a hot air balloon. The new one, though, will be a lot more advanced and is expected to go up 35 kilometers in the air to the edge of the atmosphere.

Engineers Without Borders

They've traveled to Central America and Africa, and led outreach projects in local schools. The members of the Yale chapter of Engineers Without Borders (EWB) work together to use their skills to improve the environment and health in numerous communities.

Made up of students, staff, and off-campus mentors, EWB has made frequent trips to

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Student Groups at SEAS: continued

Cameroon in central Africa since 2006. Most recently, they've been helping provide clean water for the residents of the Cameroonian village Roh. In January this year, EWB members brought additional water to the village by accessing a new spring source. When they returned in May, members worked with villagers to build a catchment for the spring water, and placed 20 taps around the village to increase access to the water.

Jordan Peccia, faculty advisor for the group, said that EWB emphasizes teamwork when they're working with the Cameroonian village.

"We design it and they build it, so the work is done when we're not there," he said. "So it's us working together with them."

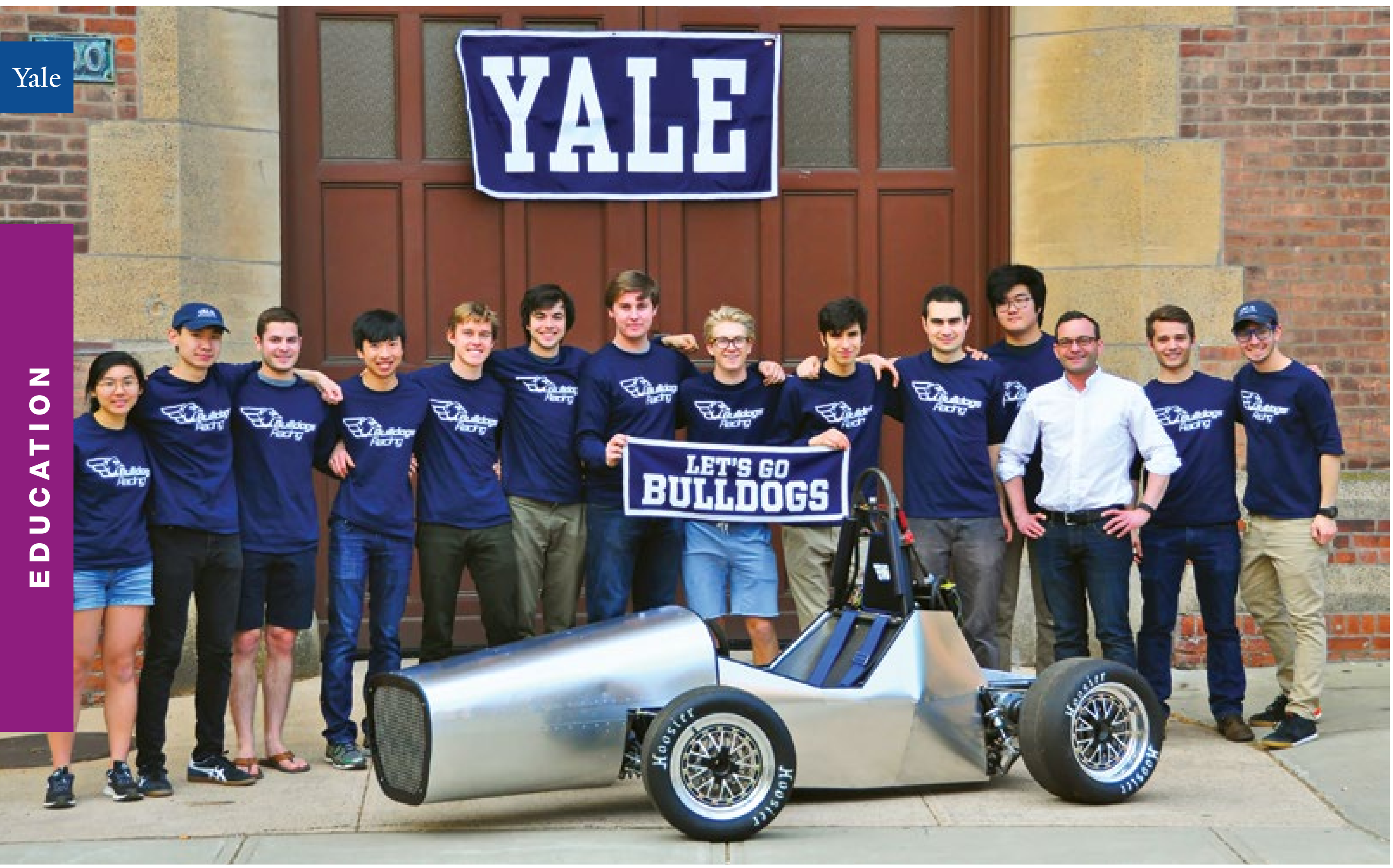
For the next year, the residents of Roh will continue work on the structure, including building a dam. When EWB returns next year for its final trip to Roh, members will check the work and then head off to help other communities.

Bulldogs Racing

Founded in 2006 as the Yale Formula Hybrid Team, Bulldogs Racing has racked up some impressive achievements in recent years.

The Yale chapter of the Society of Automotive Engineers (SAE), Bulldogs Racing is dedicated to designing and building innovative — and fast — cars. The club was runner-up for the GM Best Engineered Hybrid Systems Award and was a finalist in the design category at the Formula SAE Hybrid Competition in 2010. The team then spent the next three years working on its car BR13 — which

Bulldogs Racing team members pose with their advisor, Dr. Joseph Zinter, at their garage in Mason Laboratory.



Bulldogs Racing members put the finishing touches on their competition vehicle.

proved to be time well spent. At the 2013 Formula SAE Hybrid Competition, BR13 turned the Bulldogs Racing team into international champions. The club posted the fastest times in all dynamic events and took first place for both the Ford Most Efficient Hybrid Award and the Chrysler Innovation Award. It also took second place for the GM Best Engineered Hybrid System Award.

Fast cars are fun, but building them does more than give the team members bragging rights. The scope of the work is broad enough that it prepares members for a wide array of careers and gives them skills ranging from computer-aided engineering software and machine shop tools to proper safety practices and business administration.

After a solid showing in the 2014 race, the Bulldogs Racing team decided to forge new ground by building the first all-electric vehicle at Yale. Some battery box complications that the team experienced did nothing to derail the Bulldogs Racing team. Bulldogs Racing former President Taha Z. Ramazanoglu promises for 2016-17 “a strong comeback to compete in this year’s races.”

Design For America

Combining know-how with a commitment to social change, the Yale chapter of Design for America (DFA) seeks to make a positive impact through innovation. Students from different disciplines team up and work with local community partners to tackle real-world challenges. A number of impressive projects have come out of DFA. One is the Illumiloon, an inflatable signaling device designed to be used by people stranded by floods and other natural disasters when other communication systems fail. Users inflate the device and then place LED bands on it. Each band has a color designating a specific need — food or water, for instance. The device is then attached it to their homes.

During the 2015-16 year, a team of DFA members worked on a new tennis ball design with TennisServes, a non-profit organization that teaches tennis to the blind. Another team worked with a non-profit organization in Haiti to develop sustainable technology, such as vertical farming along building sides.

This year, DFA president Jessica Alzamora said the group plans to increase its outreach to New Haven high schools. “Our projects will focus on creating social impact in areas such as elderly health and maker spaces for children,” she said.

Tau Beta Pi

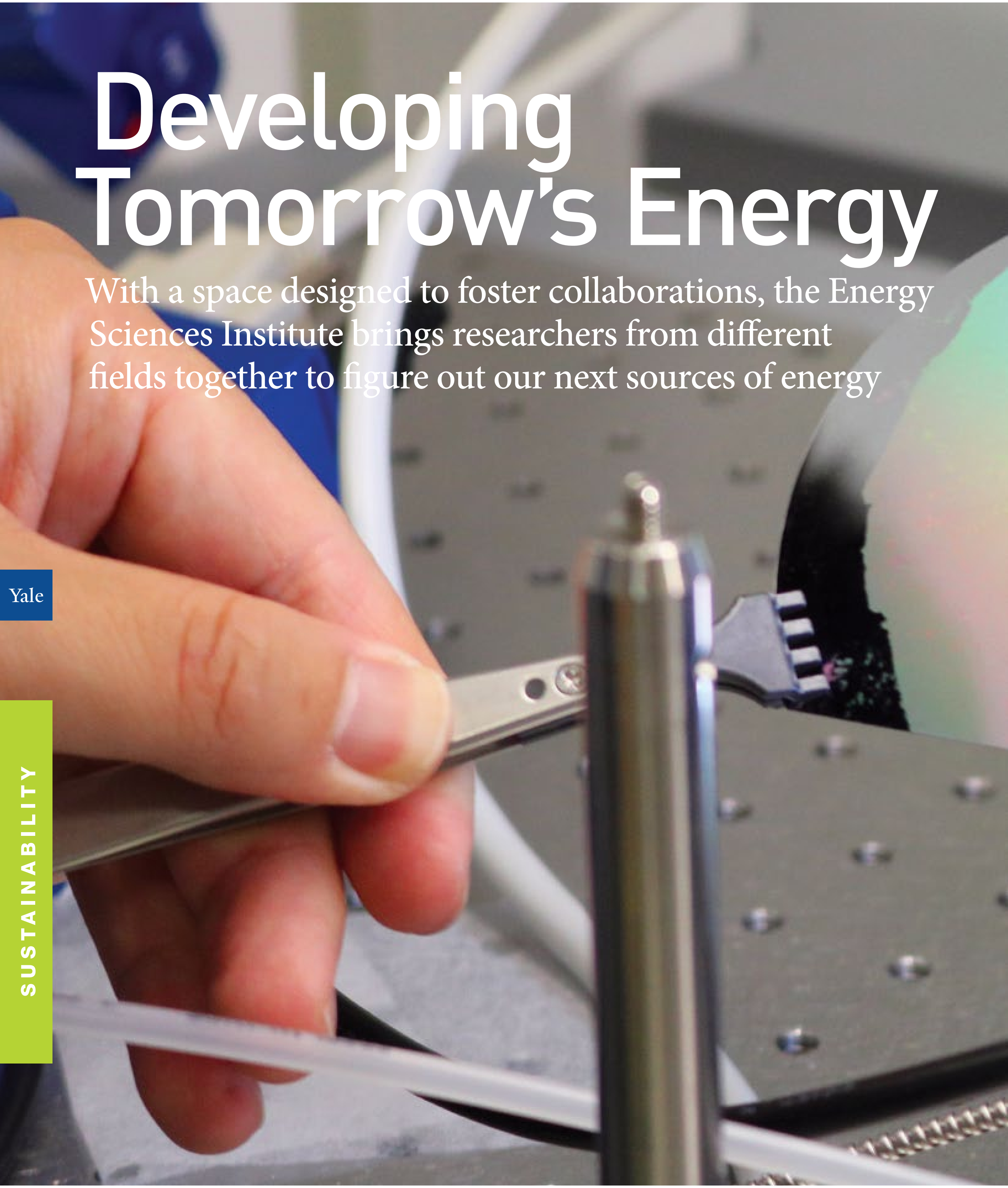
The only national engineering honor society representing the entire engineering profession, Tau Beta Pi, Connecticut chapter — known as Connecticut Alpha — was established at Yale in 1923. The chapter admits junior students in the top one-eighth of their class and seniors in the top one-fifth of their class. In recent years, Connecticut Alpha has organized “Hoodie Night” and other events to promote engineering culture at Yale and in the greater New Haven community.

President Joseph Kohrman-Glaser said the chapter will continue the tradition of outreach and cooperation for the new school year.

“We are going to connect Yale engineering students with tutoring programs in New Haven, to share our knowledge and passion with young students from underfunded local schools,” he said. “On campus, we are going to help SEAS design engineering student-spaces. We want to use these spaces to foster a greater sense of community and collaboration for SEAS students.”

Developing Tomorrow's Energy

With a space designed to foster collaborations, the Energy Sciences Institute brings researchers from different fields together to figure out our next sources of energy



In his office at the Energy Sciences Institute (ESI), Shu Hu holds a small box in his hand. Five years in the making, Hu hopes it will be a breakthrough that could one day lead to making solar power storable at a large scale — something that would be a game-changer in the field, but has so far proven elusive.

“This is one of the very first all-in-one devices that does all the things that you need to split water into hydrogen and oxygen,” said Hu, assistant professor of chemical & environmental engineering. “You just put water in, and sunlight will do the rest.”

It’s known as the “artificial leaf,” and as a handheld device, it works great. But Hu’s real challenge is making it work on a much bigger scale. That’s one of the projects that he set out for himself when he was hired at the ESI. It fits right in with the very ambitious aims of the Institute, just a few years into its existence.

The formation of the ESI was announced five years ago this September, with the vision of bringing together physicists, chemists, geologists, biologists, and engineers to develop solutions to the world’s energy challenges. With four full-time faculty members and more hires planned over the next few years, the Institute now occupies two spaces on West Campus. The second, known as ESI 2, opened this year, bringing the total space to about 38,000 square feet.

Continued →

Top: *Aerial view of the West campus.*
Left: *Gary Brudvig, Benjamin Silliman Professor of Chemistry and Energy Sciences Institute Director*

The idea for the ESI emerged shortly after Yale purchased the West Campus property from Bayer Pharmaceuticals nine years ago. Several Yale researchers and officials convened to brainstorm how the space could be used.

"The question was: If we had the opportunity to tackle the challenges of the 21st century, what should those topics be?" said Gary Brudvig, the Benjamin Silliman Professor of Chemistry and director of the ESI. "We had little breakout groups, and every group put energy at the top of the list as one of the grand challenges. We knew that this was something we needed to be pushing — we needed to have something on energy at the West Campus."

When Yale received a $25 million gift from Tom Steyer and Catherine Taylor to create the ESI, Yale's scientists and officials were able to fine-tune their vision for energy research.

"We decided that we need to come up with a sustainable renewable energy basis to power our planet and focus on renewable energies — particularly, solar and storage of solar energy and wind energy," Brudvig said. "A big problem with solar and wind is that they're intermittent; you need to store them to use them on a large scale."

Left: *Hu's "artificial leaf" is an all-in-one device that splits water into hydrogen and oxygen.*

Using hydrogen as a sustainable source of energy has long intrigued researchers. One of the challenges, though, is finding an efficient way to split the molecules of water into oxygen and hydrogen. That's where Hu's artificial leaf comes in.

It's a photoelectrochemical (PEC) device that mimics the photosynthesis of plants. Two electrodes split the water molecules to produce protons and electrons and oxygen. When the second electrode recombines the electrons and protons, hydrogen gas is produced. Mixing hydrogen and oxygen can cause an explosion, so a polymer membrane is there to keep the two separate.

Hu and his fellow researchers knew they were on to something when the technology could convert 10% of the sunlight's energy into stored energy. His lab is now working on one with 15% efficiency.

The device is small, but it provides a big window into how we can mimic nature at the nanoscale, where photosynthesis takes place. And that could lead to designs that go beyond the conventional solar energy technologies to achieve high-efficiency and long-term stability at a low cost.

Stability of materials in solar fuel devices has long been the biggest obstacle for turning handheld demonstrations into real-word applications. The oxidation process for the kind of device that Hu is working on requires a light-absorbing material. However, these materials corrode quickly when exposed to water. Finding a good protective layer has been tricky, since it needs to be conductive enough to allow charges to transport through and reach the device's catalyst, and thick enough to prevent the water to penetrate the coating.

Continued →

Another big step toward that goal is Hu's rediscovery of a material often found in toothpaste and commercial sunblocks. Using what's known as the atomic layer deposition (ALD) technique, typically performed in the field of microelectronics, he and his fellow researchers created a protective coating of titanium dioxide over the device's semiconductor crystals. Acting as the catalyst that oxidizes the water are nanoscale dots of nickel oxide, an inexpensive and accessible material. The discovery has dramatically increased the materials' stability for up to thousands of hours, or about one year of sunlight cycles.

"This is promising," Hu said. "Now we need to find ways to show the stability of tens of thousands hours, which means they can work for 10 to 15 years."

Hu, who came to Yale from CalTech earlier this year, is the third faculty hire at ESI. He joined ESI's first affiliate, Judy Cha, the Melamed Professor of Mechanical Engineering & Materials Science, who came to Yale in 2013. In 2014, Yale hired ESI's second full-time faculty member, Hailiang Wang, assistant professor of chemistry. The fourth ESI faculty member, Owen Miller, assistant professor of applied physics arrived at Yale in July 2016.

One branch of Cha's research is a class of materials known as chalcogenides, which include sulfides, tellurides and selenides. Like Hu, Cha is trying to find better ways to split water to produce hydrogen. She thinks chalcogenides are a good bet.

"Some of these materials have recently been found to be a reasonable catalyst to split water into hydrogen and oxygen," she said, "so people are looking at the chalcogenides to see if they can improve their catalytic performance, and perhaps replace some of the more expensive catalysts."

To that end, her lab has studied molybdenum disulfide (MoS2), playing with its atomic structure to boost the hydrogen evolution reaction — that is, how well the material produces hydrogen by way of water electrolysis. More recently, her lab has been making a semimetallic chemical compound known as tungsten telluride (WTe2). "So far, it appears that no one has studied the catalytic activity of tungsten telluride to see if it's better than the molybdenum disulfide," she said. Her hope is that it can be used for fuel cell type applications and anything that requires hydrogen production.

Cha, who splits her time between the main campus and West Campus, said the ESI space has been a boon to her research. The resources there allow her lab to take on experiments that she otherwise couldn't. She's particularly excited about the Materials Characterization Core, a new facility that houses state-of-the-art instruments for materials analysis. Capabilities include the investigation of crystal structure, surface topography, materials microstructure and chemical microanalysis. The instruments first arrived at the beginning of the year. Although primarily used by the ESI researchers, the facility is shared with researchers throughout Yale.

"The type of experiments we can do expands because we have some capabilities that we didn't have until now," Cha said. "That's going to benefit us by accelerating the pace of our research, and being able to look at properties that we couldn't previously because we didn't have the right instruments. That could lead to answers to research questions that we couldn't address before."

Christopher Incarvito, Director of Research Operations & Technology at West Campus, said the purchase and installation of the instrumentation is a well-considered process.

"Research instrumentation is ridiculously expensive, so we make sure that we put it in an environment where we get the return on investment. We want to make sure that it's getting used to its full capacity and that it's very accessible so that groups that might have a need for it know it's there and have access to the people who know how to use it."

But perhaps an even greater contribution to the research is a much lower-tech innovation. Approaching the lab spaces of the four full-time faculty members, Incarvito notes the lack of walls, and general flow of foot traffic.

"The beauty of this space is that Judy's group is here, Hailiang's group is here, Shu's group is here, and Owen's group is here." he said. "You have four different departments represented in one open space, so you don't have to seek out collaborators who are focused on the same type of research. From a support perspective, you don't have to replicate all of those resources from each of the individual labs."

For example, he said, Cha's group has thermal deposition equipment with a lot of experience making finely tuned materials. Now, the labs of her three fellow ESI faculty members can leverage that expertise.

The famous layout at Bell Labs — designed to promote chance encounters, or "collisions," among researchers — served as inspiration for the ESI workspace, as well as the six other Institutes on West Campus. From the hallways to the offices and labs, everything is designed to foster collaborations and

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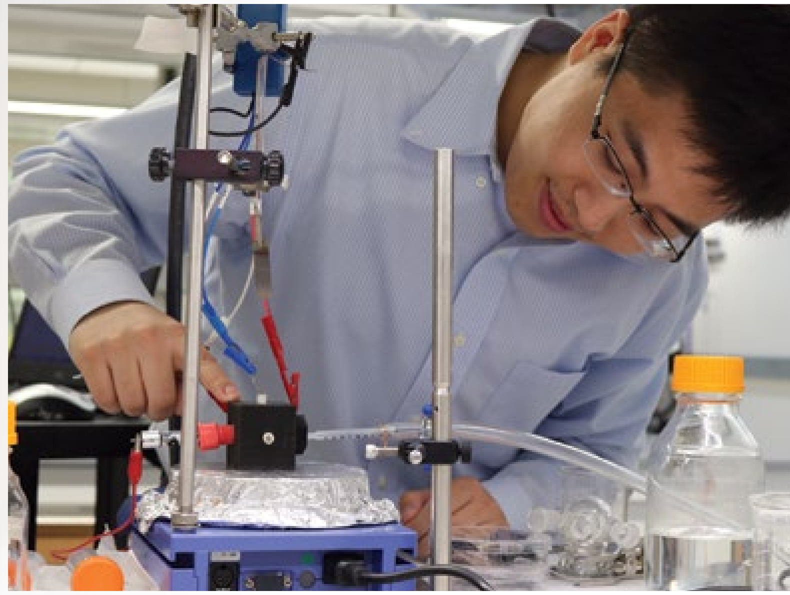
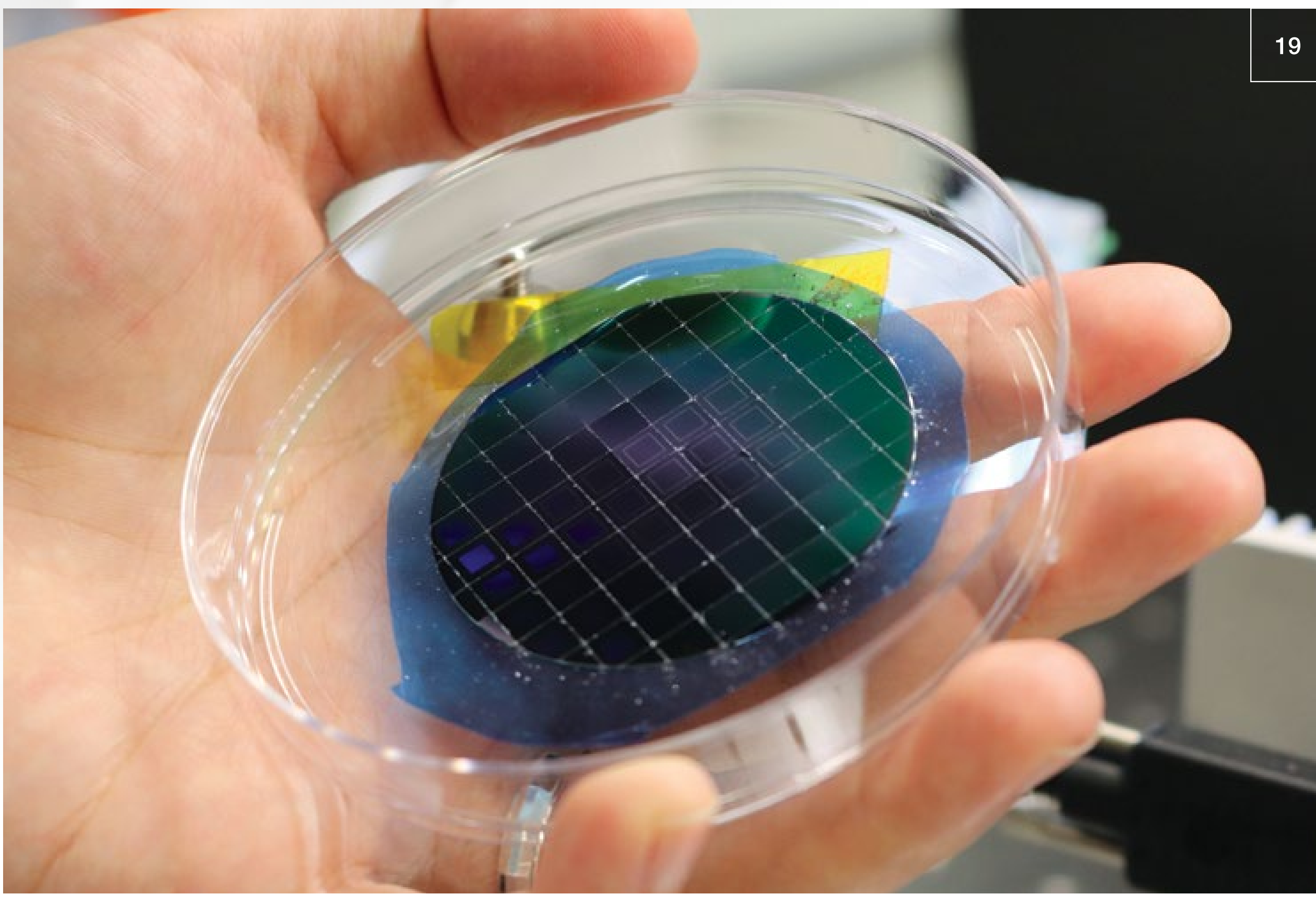


Top: *Hu, in his lab at the Energy Sciences Institute, prepares his "artificial leaf" for testing.* Bottom: *Hu's engineered semiconductor's stability is equivalent to one year of sunlight.*



Taylor FRETs about Solar Energy (and that's a good thing)

Shu Hu's artificial leaf device isn't the only technology that draws from nature for better solar power. For the last several years, scientists have been looking at the potential of biomimicry to improve solar power. Researchers, for instance, are looking at ways to harness the sunflower's ability to track the sun for solar panels. Elsewhere, the microstructures of rose petals are being studied as a means to boost sunlight conversion.

In Andre Taylor's Transformative Materials & Devices Lab, researchers there have also taken their cues from how plants use photosynthesis. The most recent result is a solar cell that has surpassed the 10% efficiency rate — a milestone within photovoltaics circles. Much of that has to do with creating a solar cell with an active layer consisting of multiple materials, although it's an approach that brings some formidable obstacles.

"Adding more materials to create a blend is the easiest strategy," said Taylor, associate professor of chemical & environmental engineering. "But this typically has a negative impact on the active layer as the different materials are typically disparate and incompatible for blending."

To get around this, Taylor and his group looked to the process of Förster resonance energy transfer (FRET). That's when energy is transferred between closely spaced molecules, and it's critical to how plant cells convert energy.

Organic polymer solar cells are a promising new alternative to the inorganic devices that have long dominated the field. Traditionally, silicon is the material used for most solar cells on the market today. But Taylor notes that we're starting to hit the ceiling when it comes to improving on conventional silicon solar cells. So researchers are intrigued by the promise of polymer cells, which cost and weigh less. But their lack of efficiency — that is, how much electricity is needed compared to the input of sunlight — is a problem. Polymer cells generally fail to convert nearly half their absorbed light energy to electrical power. One reason for this is that the polymers used in these cells don't line up well enough to allow energy to exit the cell easily. On the other hand, polymers have a mechanical flexibility that silicon cells don't, so Taylor's lab didn't give up hope on them.

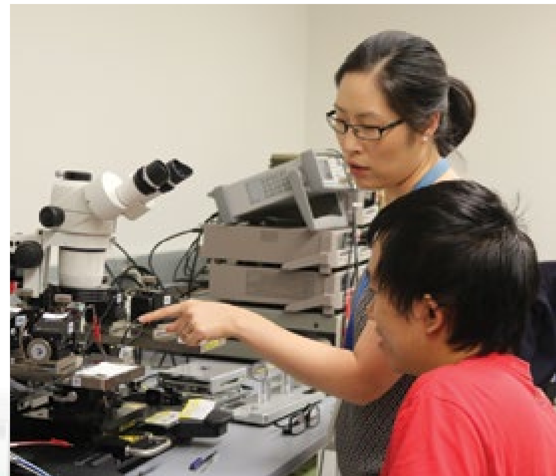
To that end, his lab was the first to show that FRET can occur between small molecules and a polymer known as P3HT. It then moved on to demonstrate some of those same benefits in blends of two polymers or more. Specifically, they developed a cell that incorporated the polymer PTB7 in addition to P3HT. Both are light-sensitive molecules known as chromophores, and together, they can absorb a very large part of the visible-light spectrum. The blue cell PTB7 absorbs primarily at the yellow-red spectrum, while the red cell P3HT absorbs the blue-green side of the light spectrum. Rather than working independently, the proximity of the two polymers also facilitates the FRET process. It was first time that FRET was shown to work among the components of a multi-blend organic polymer solar cell.

Getting these cells to configure correctly, though, took some work. Tenghooi Goh, a graduate student in Taylor's lab who took the lead on the project, describes the alignment: "P3HT stands like a wall and PTB7 is positioned more like a stack of pancakes."

The strange alignment was perfect for light absorption, but bad for electron transport. As a corrective, the researchers used a technique known as solvent vapor annealing — specifically, they made the polymers better align by chemically modifying them. The more commonly used method is thermal annealing — strengthening the material by heating and then slowly cooling it — but they found this method would diminish the performance of the polymers.

What they ended up with was a solar cell with the promising energy conversion rate of 8.7%. This ternary structure (that is, containing three major components) led to a 38% increase in efficiency compared to devices containing only P3HT. Not satisfied with the result, Taylor's lab continued to tinker.

Most recently, they've developed a quaternary device (four components) with even better results. They accomplished this by adding two types of a fluorescent organic dye. Known as squaraines, these dyes boost light absorption and recycle electrons. In addition to these squaraines, the active layer consists of the two polymers PTB7 and PTB7-Th. The final product is a cell that performs at an impressive 10.7% conversion rate — a sign that nature might be onto something after all.



creativity and encourage people to meet and talk with each other. Just by leaving the lab area, Incarvito said, "you have to walk by three or four interesting things."

For her part, Cha said the emphasis on collaborations and chance encounters has been great for her work.

"One thing that helps is that my colleagues are occupying the same space, because that can determine what kind of research you do together," she said. "Hailiang joined the ESI in my second year here, so now he and I work together, especially on the hydrogen evolution reactions and chalcogenides. My research direction has changed a little bit because we've started working together."

Wang's office is two doors down from Cha's, and their students and postdocs share the same space. "With the open design concept in the lab, I think there's a lot of fluidity," she said. "The students will initiate measuring something together and if the results are interesting, then they tell us. Now that Shu Hu has joined, I can see similar collaborations happening with him."

In fact, Wang said, it's usually the postdocs and students who spark the collaborations. "They often have lunches or dinners together in the kitchen, they bring food and share it," he said. "They meet each other often and they have fantastic interactions between them."

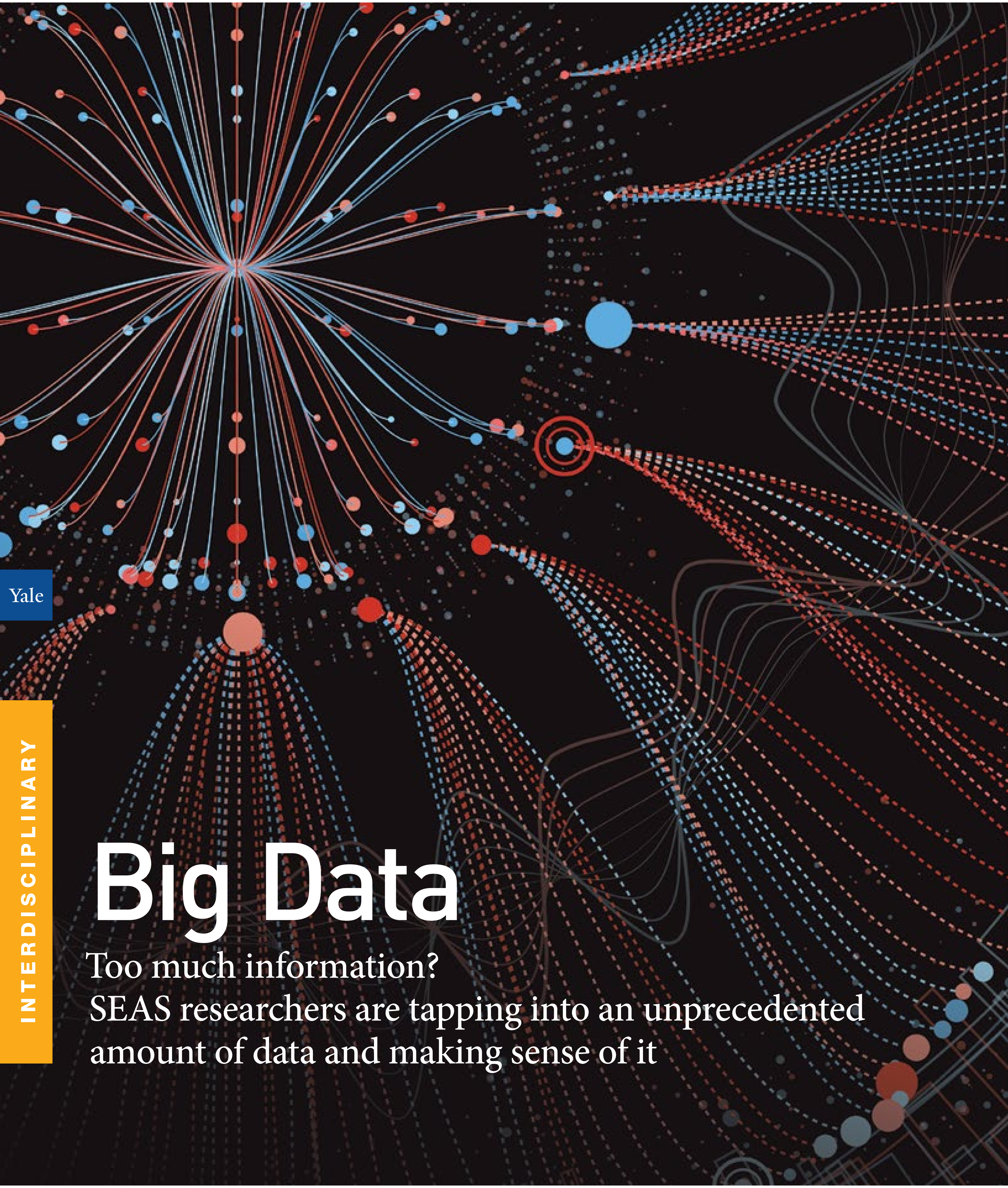
That's how the research on the electrocatalysis of chalcogenides between Cha and Wang got started. "That has been going really well and we've published one paper in *ACS Nanomaterials*, and we have another paper in preparation now," Cha said.

Judy Cha, who specializes in materials known as chalcogenides, in her lab at the Energy Sciences Institute.

Cha said she's excited to work with ESI's fourth hire Owen Miller, a theoretician in applied physics, who came to the ESI from MIT. That adds one more discipline to the equation. "That'll be a nice balance," she said, "and it will truly be interdisciplinary in nature."

Brudvig said the goal currently is to have 10 full-time faculty members, averaging one new hire per year.

"They'll bring their different expertise together and collaborate and develop new initiatives that wouldn't have been possible from someone working only within their own department," he said. "They'll tackle problems that they wouldn't have been able to by themselves."

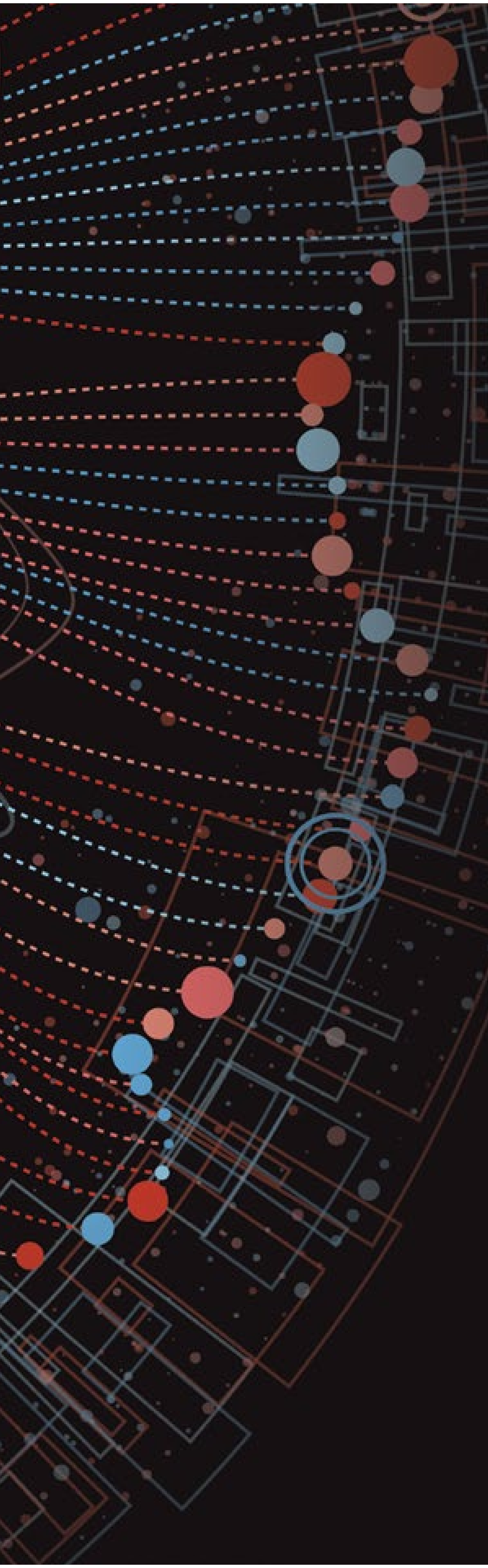


Yale

INTERDISCIPLINARY

Big Data

Too much information?
SEAS researchers are tapping into an unprecedented amount of data and making sense of it



You can't have everything. After all, where would you put it?

That joke, from comedian Steven Wright, now seems a little dated. When it comes to information today, we actually are pretty close to having everything, thanks to the internet and modern computational power. But the question persists: Where *do* you put it? And, then, what do you do with it?

That's where big data comes in. It's a burgeoning and far-reaching field that affects everything from the categorization of Instagram cat photos to predicting medical outcomes. On YouTube, 300 minutes of footage are uploaded every minute. Instagram users post 220,000 photos per minute, and Facebook generates 2.5 million pieces of content per minute. So sorting this all out is a big task.

The field of big data is interdisciplinary by nature, drawing from fields that include electric engineering, biomedical engineering, and computer science. That makes it a natural fit for Yale, where such collaborations are common.

"In some sense, big data is a lot of different techniques, and we're sort of at the beginning of a new field in that there aren't clear obvious methodologies," said Sekhar Tatikonda, associate professor of electrical engineering and statistics and a faculty member of the Yale Institute for Network Science (YINS). "It's subsets of different departments — computer science, electrical engineering, statistics, some of the social sciences. We just found each other and started talking. We've been doing that for multiple years and the opportunity came for us to be a little more organized."

The reason for the seemingly sudden interest in big data is simple, he said. "We have lots of data and people want to predict the heck out of everything," he said, laughing. "It's so much easier to collect data, and memory's super cheap. You can buy a terabyte of hard drive for like $40."

The awareness of big data has been increasing for a while, but there's been a major uptick of interest in the last five years or so.

"There's a huge amount of new problems that traditionally one hasn't thought about — that's fun as an academic," Tatikonda said. And there's plenty of interest outside academia. Facebook, Google and LinkedIn are a few obvious examples of companies that are analyzing massive amounts of data. But big data now plays a critical factor in operations at countless other companies. The demand in the business sector has led to a great deal of interest within the undergraduate population at Yale.

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The interest goes both ways. Google recently awarded Amin Karbasi with a Google Research Award. Karbasi, who has been with Yale since 2014, frequently meets with Google officials to talk about his research.

One of Karbasi's projects involves figuring out ways to categorize visual data. For personal collections of photos, even for the most prolific of shutterbugs, this shouldn't be too arduous of a task. But how do you do that with photos uploaded from around the world?

"Even the simplest machine learning methods that people use aren't going to work efficiently when you gather tens of millions of data points," said Karbasi, assistant professor of electrical engineering and computer science. "My research is focused on how you can turn this bigger data into smaller, but representative, data."

One method Karbasi is looking at involves choosing elements from a particular dataset that fall into a category, but aren't overly similar. "We are trying to come up with algorithms that can do this kind of thing fast," he said.

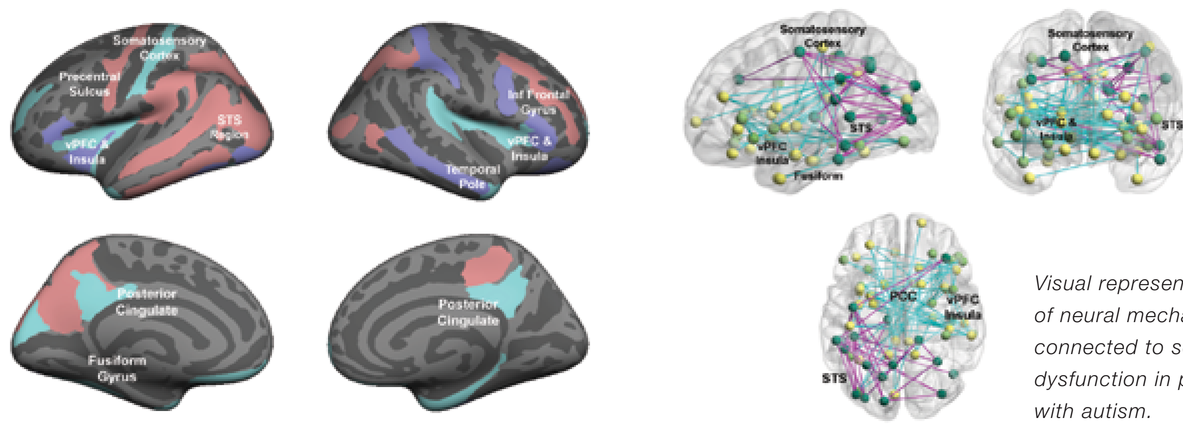
"What we do is we represent every image by a data point, or a vector, and then we can define distances between the vectors." He compares the data points to molecules of a gas — they're far from each other, but fill the entire space.

To do this, Karbasi's research team applied their method on a publicly available dataset called "tiny images" that 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 to perform the same task, he said, would take a very long time. With his lab's computer resources, it took only a few hours. With the kind of resources Google has, Karbasi said, it could take only a few seconds.

Top: *Student interest in big data has increased dramatically in recent years, says Sekhar Tatikonda.* Bottom: *A visual dictionary of 53,464 English nouns arranged by meaning. Karbasi applies algorithms to datasets for quick and accurate categorization.*



Visual representation of neural mechanisms connected to social dysfunction in people with autism.

Finding ways to process information faster is also a priority in the medical world. Coupling modern computing power with a centuries-old statistical approach, big data is being used in the lab of James Duncan to unlock information about a number of medical conditions, from heart disease to the brain operations of autism.

"What our lab does is basically try to derive information from multi-dimensional image data sets and analyze it so that we can then describe some biomedical situation," said Duncan, Ebenezer K. Hunt Professor of Biomedical Engineering, Electrical Engineering and Radiology & Biomedical Imaging. "For example, 'how big is a tumor, is it shrinking? How's the heart beating — did it change?'"

Duncan said the goal is to get not just qualitative interpretations, but quantitative information to compare things and measure them over many datasets and populations. To do that, he said, they need a "mathematical decision maker in the middle, like some kind of optimization or estimation technique."

For a recent study, Duncan's medical image processing and analysis lab drew from Bayesian analysis — a set of statistical rules that can be used to predict outcomes. The researchers (spearheaded by postdoctoral associate Archana Venkataraman and including Kevin Pelphrey from Yale's Child Study Center and Lawrence Staib, professor of biomedical engineering and radiology & biomedical imaging) developed a mathematical framework that provides valuable insights into the neural mechanisms connected to social dysfunction in people with autism.

The researchers examined the brain images of 115 people — 72 with autism, and 43 controls — to look at the blood flow between different regions of the brain to see how the groups compared when shown images of objects and people while undergoing functional magnetic resonance imaging (fMRI). That required examination of the functional interactions or connections (roughly based on blood flow) between the nearly 200 brain regions known from functional atlases.

"You look at the signal in response to these different biological tasks and you're trying to see whether it 'lights up,'" Duncan said. "Is there a strong signal, how similar is it to signals around the same region?"

It turned out that the results jibed with previous work in the field, yet yielded new insight about how different brain regions work together, in communities, to process the presented stimuli. "For kids with autism, there is a sort of hyper-acute ability to see patterns, but they're not very good at social/emotional processing," Duncan said.

Analyzing all the data they had by more traditional means, he said, could take an expert several hours — and may not yield consistent results. "Now, you're talking about processing time in the range of milliseconds with stable, reproducible findings."

"Now we can deal with 4-dimensional datasets — three spatial dimensions over time — so we can learn 4D trends and build it into a model. This is not only useful for analyzing the brain, but the heart as well. Now, reliable quantitative analysis of hundreds of datasets can be performed in days, as opposed to months or years."

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Top and Bottom: *Szefer and Balakrishnan's prototype of a hardware device that acts as a kind of software.* Facing Page Background: *Sardex network within the city of Cagliari, the capital of Sardinia.*

Tapping the Potential of Big Data Through Collaborations

About 10 years ago, computer technology allowed for the storage of a massive amount of data, said Mahesh Balakrishnan, associate professor of computer science. "But what would you do with it? Now you can actually process all of this data."

"It's like a feedback cycle — now that it's more useful, people will collect more and then hopefully it becomes more useful," said Jakub Szefer, assistant professor of electrical engineering and computer science.

Innovations in big data have mostly focused on software, due to the ease and speed of prototyping. Most existing big data systems — such as Apache Spark and Google's venerable MapReduce — are software-only implementations that are used with commodity hardware. While such systems allow for fast and easy development and deployment, they fail to make use of the full power of the hardware.

In an effort to accelerate big data processing, Balakrishnan and Szefer are combining their talents to create hardware that acts as a kind of software in how it stores and retrieves data.

"You either have to have new applications or new hardware — that's the only way to have innovation," Szefer said. "So we're trying to combine them both. The idea is that there will be a new type of storage device. And we'll prototype the hardware and the software for the storage device, and that could actually be used as part of a data center."

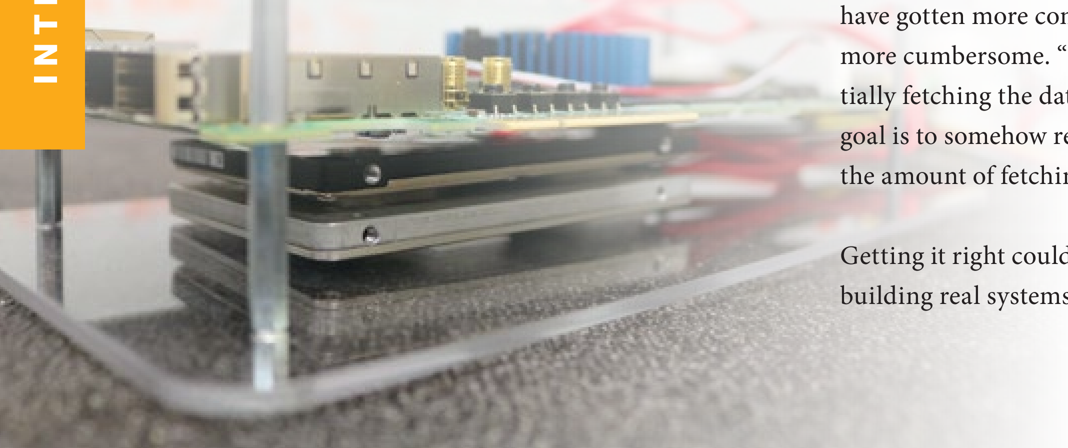
Balakrishnan said this kind of collaboration occurred to him shortly before he came to Yale in 2015. "I was working with some folks at Cornell on a transaction disc, which is basically a disc that behaves like a database," he said. "We were emulating all of this in software and I was thinking 'I wish we had an architect who could actually build this hardware.' So when I came to Yale, I started talking to Jakub, and we realized this was one of the dozen things we could do if we had this platform."

"It's pretty exciting to have the hardware and software working together for some new innovation," Szefer said. Balakrishnan agreed.

"Collaboration is fun — I think that if nothing else, that's a reason to do it," he said. "But also, I think when you put together teams of people with diverse skill sets and a common goal, you end up achieving more than the sum of your parts."

For a number of reasons, software developers haven't worked closely with the hardware industry. As systems have gotten more complex, processing data has become more cumbersome. "The big problem is that you're essentially fetching the data back and forth," Szefer said. "So the goal is to somehow redesign the network storage to reduce the amount of fetching."

Getting it right could take years, the researchers say. "We're building real systems and trying to do so with academic



rigor, so we have to take our time," Balakrishnan said. "But the good things about these products is that once you build the platform, you can then explore many interesting ideas based on the same platform."

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The kinds of things that big data can promise today would have seemed like pie-in-the-sky a couple decades ago, said Nicholas Christakis, co-director of YINS.

"If you asked scientists then about what powers they dreamed of having, they would say 'It would be unbelievable if we could have little tiny black helicopters flying over everyone so we could know where people are, who they are talking to, what they are saying and thinking and buying,'" said Christakis, a social scientist and physician. "'That would be unbelievable,' the scientists would have said. But of course, that's what we now have."

Not black helicopters, specifically, but mobile phones in the pockets of billions of users that record their purchases, communications and travels. The data that the technology generates is so abundant that making any sense of it was the next challenge.

"How do you drink from a firehose?" Christakis said. "We need to develop nozzles."

That's where big data techniques come in. Researchers have to develop algorithms to remove the irrelevant information without sacrificing the useful data. It's a breakthrough that's allowed Christakis to study topics that range from the way that emotions spread through Facebook to how social networks can warn us about outbreaks of contagious diseases.

Recently, he teamed up with Leandros Tassiulas, the John C. Malone Professor of Electrical Engineering, to study the structure of Sardex, a novel digital currency used in the Italian province of Sardinia. A fully decentralized economic scheme, Sardex both leverages and reinforces trust among local community members, business owners and employees.

The researchers used a two-year transaction data set and employed tools from network science to create and analyze the Sardex trading network. The study shed light on the currency flow across time and different towns, and described exactly how the community members collaborate using Sardex. They found that transactions are facilitated by the geographic proximity of the involved members, and also that this economic network has small-world properties — that is, even distantly located members can be reached within a few hops of trading relationships.

"Instead of using typical economic metrics, however, we employed tools and concepts from network science," said Georgios Iosifidis, co-author of the study and a postdoctoral student in Tassiulas' lab at the time.

The idea of "community currencies" is something that dates back to the early 19th century, but it's only the last decade that digitization has let communities self-organize and efficiently create such collaborative platforms. "That makes it possible for us to create and analyze all the data of these digital economic activity traces, and to monitor and improve the health of such systems," said Iosifidis, now at Trinity College Dublin, School of Computer Science and Statistics.

Christakis said the project appealed to him because it was an opportunity to apply some old ideas from network science to a challenging topic: Why do some novel currencies succeed and others fail? Working with Tassiulas' lab (nearby in YINS) the research drew from many disciplines — electrical engineering, statistics, sociology, and economics among them. The project is another example of how big data research can take what might have once seemed a jumble of numbers and figure out who we are as individuals and as communities.

"The big data revolution has allowed for new insights regarding social systems," said Christakis. "The kind of data we have tells us about how societies are organized and shed light on some of the most deep and fundamental questions about human behavior: how the whole becomes greater than the sum of its parts and how groups of people come to acquire properties that aren't present in individuals themselves."

Yale

MEDICAL INNOVATION

Secret Life of the House Sparrow

The brain of a long-maligned bird as revealed by 3D printing

CEID Fellow Max Emerson and radiology & biomedical imaging postdoctoral fellow Christine Lattin.

Since it was introduced to North America in the late 19th century, the house sparrow has received little love. “Nothing can be urged in its favor,” declared an 1891 editorial in the *New York Times.* A few years later, the same newspaper deemed the birds “rats in the air.” Adding insult to injury, the International Union for Conservation of Nature has long kept the house sparrow on its unceremonious list of species of “least concern.”

Not all are so dismissive, though. With the help of technology and know-how at the Center for Engineering Innovation and Design (CEID), a postdoctoral fellow at the Yale University PET Center is gaining insights into the inner lives of these long-maligned birds. In many ways, it turns out, we are not so different from the house sparrow.

“There are some interesting things you can learn about birds that you can apply to humans,” said Christine Lattin, a researcher in the lab of Richard Carson, professor of biomedical engineering and radiology & biomedical imaging. Working with the CEID, Lattin is currently focusing on the physiological stress response of the house sparrow.

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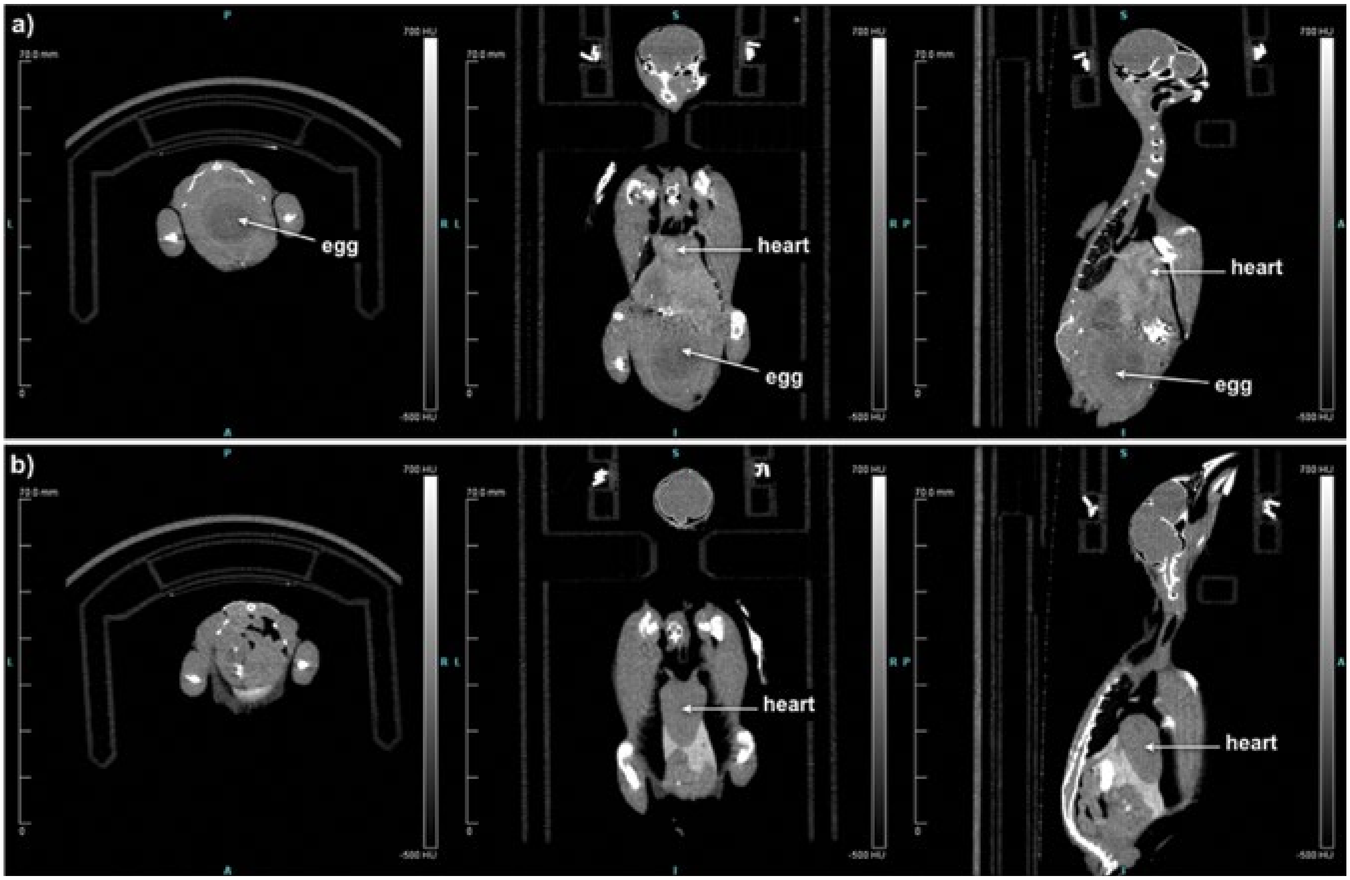
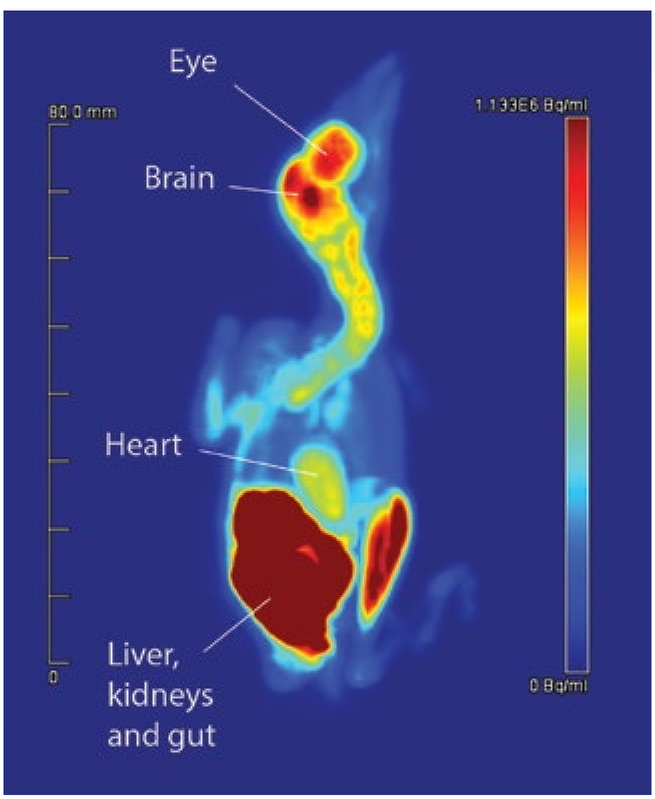


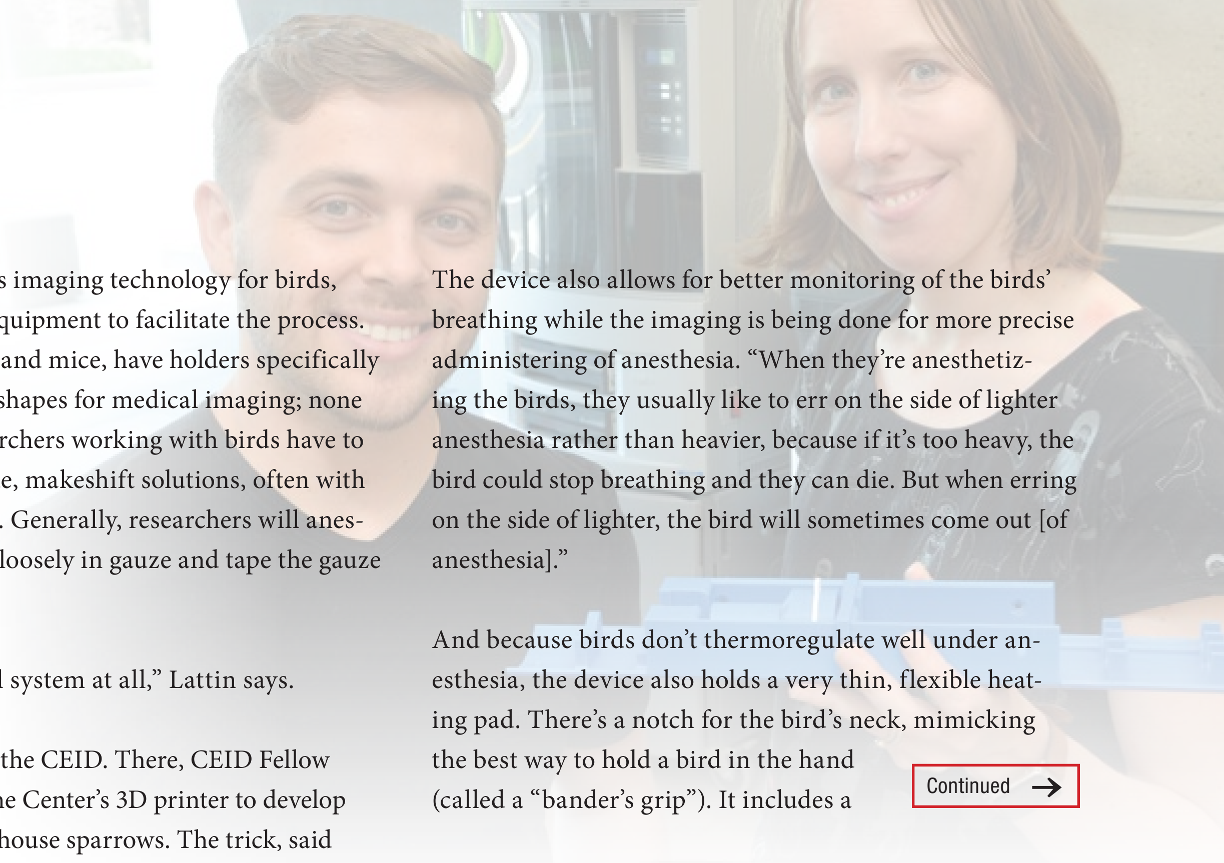
Top: *Computed tomography image from three different scans of the same female house sparrow. An egg and large masses of reproductive tissue are visible in the body cavity.* Bottom: *Positron emission tomography image of a house sparrow.*



Unlike rats or mice, house sparrows are not conditioned to captivity (Lattin finds the birds in the wild, catching them herself), which is important if you want to measure their stress response to captivity. "I think captivity is potentially a really powerful kind of model for chronic stress," Lattin says. "A bird brought into captivity is in some ways not that different from a person who's suddenly thrown into a totally alien and stressful environment, like a soldier in combat or a child taken to a foster family. It's an alien environment, and it's highly stressful. That's one reason I'm interested in using the birds."

Medical imaging suits Lattin's work well because it allows for multiple scans of the same animals, which give researchers a better way to study variation in an individual subject, including before- and after-treatment results. Without it, Lattin said, most brain studies on animals require euthanizing the animals involved and slicing the brains.

Positron emission tomography (PET), which uses a special scanner and a radioactive drug known as a tracer to identify different types of activity in the body and brain, is the type of imaging most useful for Lattin's research. But making a PET scan of a bird isn't easy. Only a few other



labs in the world use this imaging technology for birds, so there's no universal equipment to facilitate the process. Other animals, like rats and mice, have holders specifically designed for their body shapes for medical imaging; none exists for birds. So researchers working with birds have to make do with homemade, makeshift solutions, often with less-than-perfect results. Generally, researchers will anesthetize the bird, wrap it loosely in gauze and tape the gauze to the scanner.

"I mean, it's not an ideal system at all," Lattin says.

So Lattin reached out to the CEID. There, CEID Fellow Max Emerson is using the Center's 3D printer to develop a holder customized for house sparrows. The trick, said Emerson, is designing it in such a way that the birds stay in a uniform position. Because the birds' brains are so small, even the slightest twitches can significantly diminish the quality of PET images.

"The goal was to make a standardized position for the bird," Emerson said. "Then, the researchers can look at a lot of studies without having to do too much post-processing of the data. It minimizes head movement without restricting their abdomen, so they can breathe while they're under anesthesia."

The device also allows for better monitoring of the birds' breathing while the imaging is being done for more precise administering of anesthesia. "When they're anesthetizing the birds, they usually like to err on the side of lighter anesthesia rather than heavier, because if it's too heavy, the bird could stop breathing and they can die. But when erring on the side of lighter, the bird will sometimes come out [of anesthesia]."

And because birds don't thermoregulate well under anesthesia, the device also holds a very thin, flexible heating pad. There's a notch for the bird's neck, mimicking the best way to hold a bird in the hand (called a "bander's grip"). It includes a

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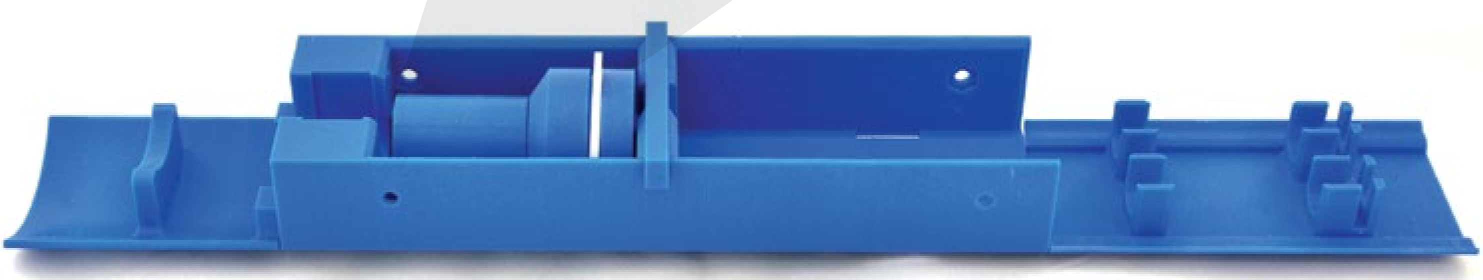


Recent iteration of the 3D-printed bird holder.

The Mystery of Monkey Bones

What A 3D Printer Could Reveal About Evolution

A bird-holding device may be a one-of-a-kind product, but one-of-a-kind creations are not uncommon for the 3D printer at the Center for Engineering Innovation & Design (CEID). Replicas of everything from ancient sculptures to skulls, neurons and greatly magnified molecules are just a few of the products to have come from it.

However wide-ranging or esoteric the subject, CEID Assistant Dr. Joseph Zinter said, it makes sense for researchers to want a permanent object that they can pick up and study. It's one thing, he said, to see images of an object on the page or computer screen. But being able to hold it or turn it around and feel the texture of the object is its own distinctive learning experience.

So it's no great surprise then, that the laboratory of Dr. Robert Wyman, professor of molecular, cellular and developmental biology, recently took advantage of the CEID printer to make replicas of monkey bones. Specifically, Wyman's lab is getting 3D prints of the bones of extant specimens of the cercopithecoid primates — also known as the Old World monkeys — which include baboons and macaques. The bone replicas will be used for comparisons to fossils and apply what are known as morphometric techniques to study the degree of variations between the bones.

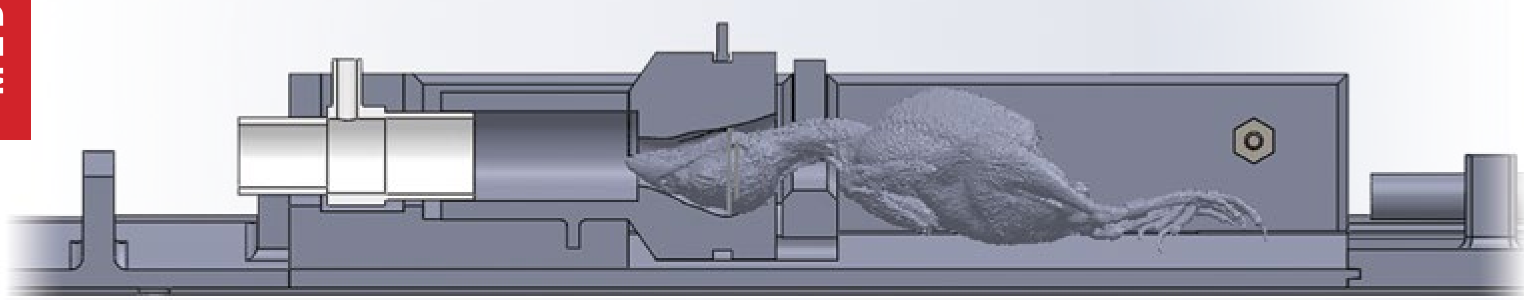
"The 3D scanning allows us to quantify joint surfaces in a manner that we were previously unable to measure," Wyman said.

Dr. Paul Whitehead, an associate in Wyman's laboratory, said the bone replicas could shed some light on a mystery that has intrigued researchers for years. Among Whitehead's discoveries is that palm walkers make one extra motion to lower the body to be supported by the palm rather than just the fingers. That

cone designed to fit the contours of the bird's head, which is connected to a tube that pumps the anesthesia. Emerson based it on very detailed computed tomography (CT) images of the birds' skulls, which were created in collaboration with Elliott Brown, assistant professor of radiology & biomedical imaging at the Yale School of Medicine.

Emerson also created special anchors that attach the holder to the scanner bed, and a spacer to make sure it is always placed in the same location on different days they

Lattin and Emerson's device is designed to hold the bird's head firmly in place.



means they raise and lower their body more per step than their finger-walking counterparts. It's only a few inches difference per step, but add those up over millions of steps, and a lot of energy is at stake. In connection to this, the researchers want to know what the joints between the wrist bones and palm bones have to do with the maintenance of the two different hand postures and how these differences in anatomy can be related to muscle activity.

The research could even shed light on the matter of nature vs. nurture.

"How much is inborn due to genetics, how much is learned from parents, how much is the result of repetitive behavior during early development, and how much is pure randomness?" Wyman asks. "These questions have been approached many times to answer big questions like the inheritance of IQ. But that is not the way biology works. Biology works via very small tweaks to a basic program."

By focusing on the differences in walking styles, Wyman said Whitehead found a seemingly small but very compelling difference.

"Monkeys, close to our line of evolution, are extremely agile and spend a lot of time running about and climbing trees," Wyman said. "Speed is essential to escape predators, like leopards, and a high percentage of their total energy expenditure may be used up by locomotion."

Printing out the bones, Whitehead said, provides a number of benefits.

"First it's material that belongs to another institution, so we want to be able to return it," he said. "But beyond that, by scanning it and printing it out, rather than examining it solely through a microscope or magnifier, you have something that you can see more easily and something we can compare and discuss more easily. And 3D scanning allows quantification of characteristics that are more difficult to study with traditional morphometric techniques."

So if you have to be one or the other, which is better: Finger walker or palm walker?

"It depends on your circumstances," Whitehead said. "If you spend more time on the ground, it's better to be a finger walker because you're lengthening your stride every time you take a step. If you spend more time living in trees, then palm walking is advantageous because then you're lowering your center of gravity."

perform scanning. Other notches hold the syringes that deliver drugs and the radioactive tracer. Best of all, the entire device is made of lightweight, low-density plastic, which is important because very dense materials, such as metal, can cause errors and distortion in PET-CT imaging.

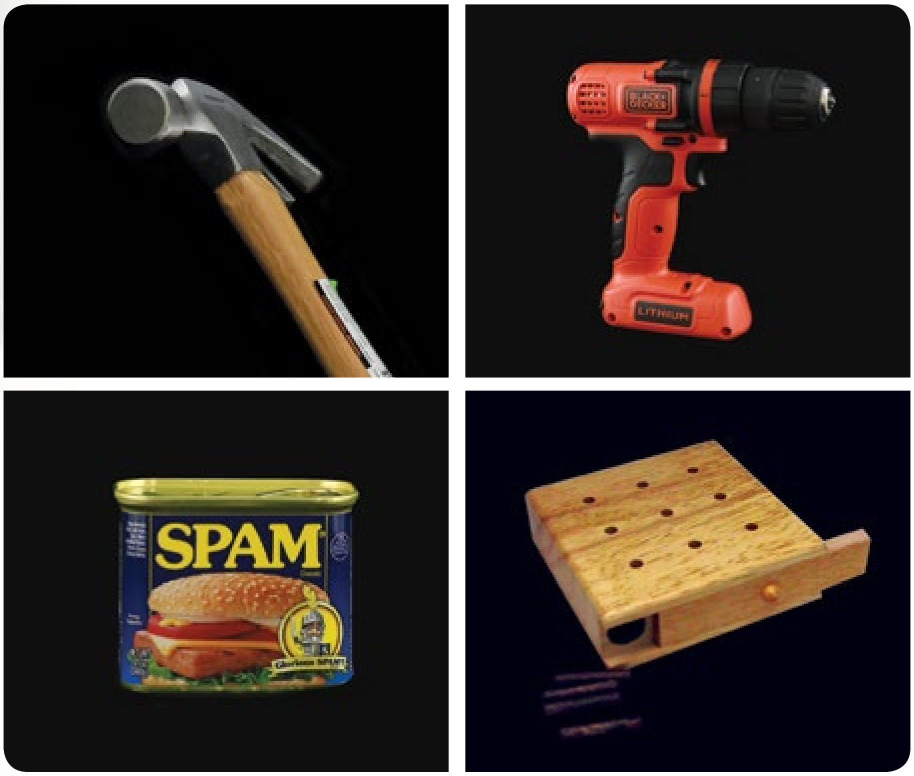
Previous methods for keeping the bird in place made it difficult to observe the bird during imaging. Lattin recalls one session, scheduled for an hour, which had to be stopped after 10 minutes because she couldn't monitor the bird's breathing adequately.

The final designs are still being hashed out (Emerson has produced five iterations so far). Once they get the current prototype finalized, they plan to design a two-bird holder, something that would save a lot of time and money. So far, Lattin says she's very impressed with what she's seen.

"Before, when the bird was wrapped up in gauze, I would be trying to look at their tail sticking out at the bottom, and be like 'Uh, I just saw it move, so I think it's OK,'" she says. "I haven't had to do that at all with the new bird holder because you can see their breathing so well. You can turn the anesthesia down when their breathing gets pretty slow, or you can turn it up if the breathing is faster. It's just so much better."

A New Standard in Robotics

How a box of 77 items could prepare robots for their next challenge: Your home



On the wall of Aaron Dollar's office is a poster for *R.U.R. (Rossum's Universal Robots),* the 1920 Czech play that gave us the word "robot." The story ends with the nominal robots seizing control of the factory of their origin and then wiping out nearly all of humanity. Dollar, fortunately, has something more cheerful in mind for the future of human-robot relations.

He sees them as helpers in our daily lives — performing tasks like setting the table or assisting with the assembly of your new bookcase. But getting to the point where robots can work in the unstructured environment of our homes (as opposed to industrial settings) would take a major technological leap and a massive coordination of efforts from roboticists around the globe. The living room has been called the last frontier for robots — but first, the robotics community needs some standards that everyone can agree on.

Enter a suitcase-sized box containing 77 objects. It contains things like hammers, a cordless drill, a can of Spam and a nine-hole peg test. As ordinary as they may seem, these carefully curated household items could be the future of a new kind of standardization for robotics. Known as the Yale-CMU-Berkeley (YCB) Object and Model Set, the intent is to provide universal benchmarks for labs specializing in robotic manipulation and prosthetics around the world.

Dollar, an associate professor of mechanical engineering & materials science, came up with the idea about two years ago. He wants to bring a level of specificity and universality to manipulation tasks in robotics research. For instance, a research paper today might describe a particular task as "robotic hand grasps hammer." Are we talking about a big hammer or a little one? We don't know,

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and that's a problem if you work in a robotics lab looking to replicate the research. With the YCB Set, everyone's on the same page — in this hypothetical case, by working with the same 23.45-ounce Stanley hammer included in the set.

"People in the robotics community today are thinking about robots that can work in daily environments, and in the home."

› Aaron Dollar, associate professor of mechanical engineering & materials science

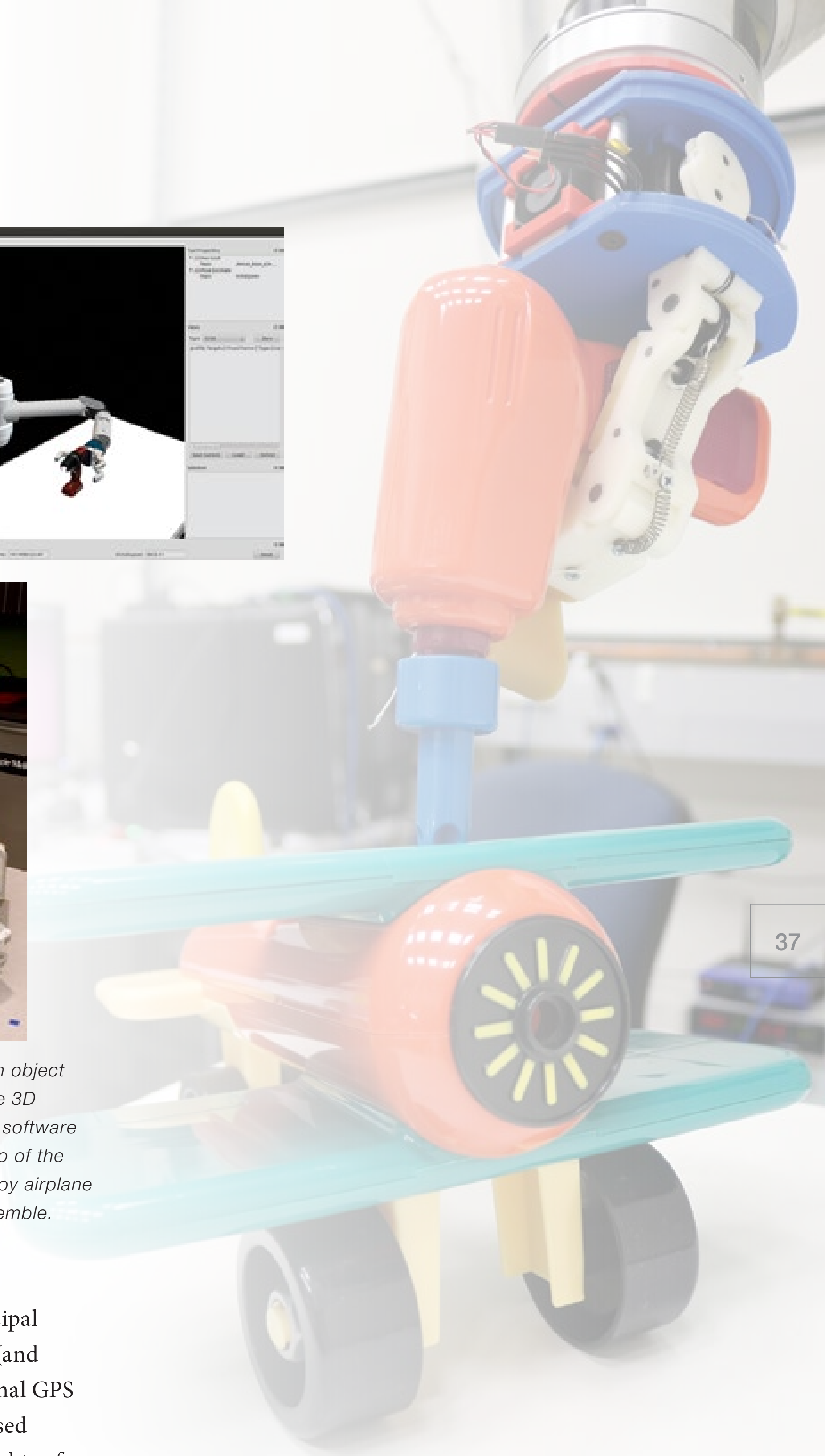
In addition to the objects, the project also provides five examples of manipulation tasks (such as pouring water from a pitcher to a mug, or setting the table) and benchmarks for each. A website for the project also allows other laboratories to expand on these tasks by contributing their own protocols and benchmarks. When laboratories work solely by their own standards and protocols, Dollar said, there's often an unconscious bias toward that lab's particular strengths. Universal standards would provide a more impartial way to evaluate results.

The YCB Set arrives at a time when the robotics field has reached a critical point. Robots currently do well in structured environments, such as factory settings, where they perform and repeat a very limited number of tasks. "In a structured environment, a robot sees exactly the same object in exactly the same place," Dollar said. "It's a relatively straightforward thing to get robots to operate in those environments because you just have to program it to do one thing. And you can always program something to do one thing well."

But Dollar and other roboticists have something more challenging in mind for their creations.

"People in the robotics community today are thinking about robots that can work in daily environments, and in the home," he said. "That's sort of the flip side of assembly lines."

Standards have long been a crucial part in the advancement of science. Until the 19th century, the schedules



There are numerous steps a robot must take to identify an object (clockwise): The object-scanning rig was used to generate 3D models; texture-mapped 3D mesh model of a power drill; software simulation of a robot grasping the power drill; actual grasp of the power drill being executed by the robot. Background: *A toy airplane is just one of the objects the robot is programmed to assemble.*

of individual communities were governed by municipal clocks. Today, thanks to globally coordinated time (and increasingly accurate atomic clocks), we have personal GPS systems and driverless cars. For centuries, people used their hands and feet to measure the lengths and heights of things. When things got standardized around the world, the International Committee for Weights and Measures stored metal rods in a climate-controlled vault in Paris, each serving as the standard bearer for a particular unit of measurement. In more recent years, those metal objects have been usurped by even more precise standards based on the speed of light (in which we come back again to atomic clocks and the standardization of time).

In a sense, the 77-item box is the robotics equivalent of the Paris vault or the atomic clocks, and may usher in an era when laboratories better communicate to advance the field at a faster pace. It's a critical step, since things get tricky as robots move away from the assembly line. Dollar specializes in robotic manipulation, or grasping. As humans, we often take for granted the complexity of something as seemingly simple as picking up

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a fork and using it. To build robots that can perform not just one of these tasks, but many, individual labs can no longer work as isolated villages operating on their own measurements. They need a universal standard.

"As robots move out of the lab and into the real world, it gets harder to understand their capabilities and limitations."

› Robert Howe, the Abbott and James Lawrence Professor of Engineering at Harvard

That's where the box of 77 items comes into play. The objects are the sort of things you find around the house. Certainly, it's easy enough for a robotics lab to find their own objects to manipulate. But for the research to move forward, the results of that lab's work has to be comparable to other labs.

"When we have a new idea for a new component or hand idea, we want to test it out and see how well it works," he said. "With quantitative evaluation, we can see how things

Left: *The 77 items, including a pan and spatula, were chosen for their diverse shapes and sizes to cover a broad scope of robotic capabilities.* Bottom: *3D models of various household items from the YCB Set.*

stack up compared to other ideas." There have been other attempts to standardize manipulation tests, but Dollar said they don't capture the high level functionality that the YCB Set demonstrates.

It's only recently, roboticists say, that such standards would have much purpose. The field simply wasn't sophisticated enough until recent years to benefit from such standardization. It's a different story now, though, as integrated systems require the work of multiple disciplines to create a robot that can do something like put away dishes.

"As robots move out of the lab and into the real world, it gets harder to understand their capabilities and limitations," said Robert Howe, the Abbott and James Lawrence Professor of Engineering at Harvard. "In a factory where everything is carefully arranged, you can rigorously test how they work, but in my kitchen I have 20 kinds of coffee mugs. So it's a big puzzle how to characterize and compare robots. The approach that Aaron is taking is a promising one."

Howe notes that even a seemingly simple grasping task requires very advanced engineering. You need to plan the hand and the arm so that it doesn't knock over other things, the contacts must be carefully controlled — and then you have to wrap up all these coordinated elements into a single system that works fast enough to be useful. His lab is concerned with tactile sensing, which is one piece of the puzzle, but the same task could also require the input of computer vision specialists.

"That's why the YCB Set is clever," he said. Now a lab can score how well they do on a certain task, and other labs can try to match or beat that score.

After Dollar had the idea for the standardized set, he brought on board two former colleagues in the robotics community, Dr. Siddhartha Srinivasa from Carnegie-Mellon University and Dr. Pieter Abbeel of UC Berkeley ("These are people I knew I could work well with and make something happen"). And he assigned Berk Calli, a postdoctoral associate in his lab, to take the lead on the project. Calli, who came to Yale in 2014, said the lack of reproducibility in robotics is a problem long recognized among researchers in the field. It's very rare, he said, for a paper to compare just two algorithms from other labs.

"If you can get five or 10 groups using one single protocol to compare their algorithms, that would be a huge step," he said. "It will be a huge thing in terms of quantification and comparison in robotics, because this has never been done before."

It's gotten to the point, Calli said, that the field doesn't have much choice but to take on the matter of standardization. "There's like a pool of algorithms and no one knows which performs the best.

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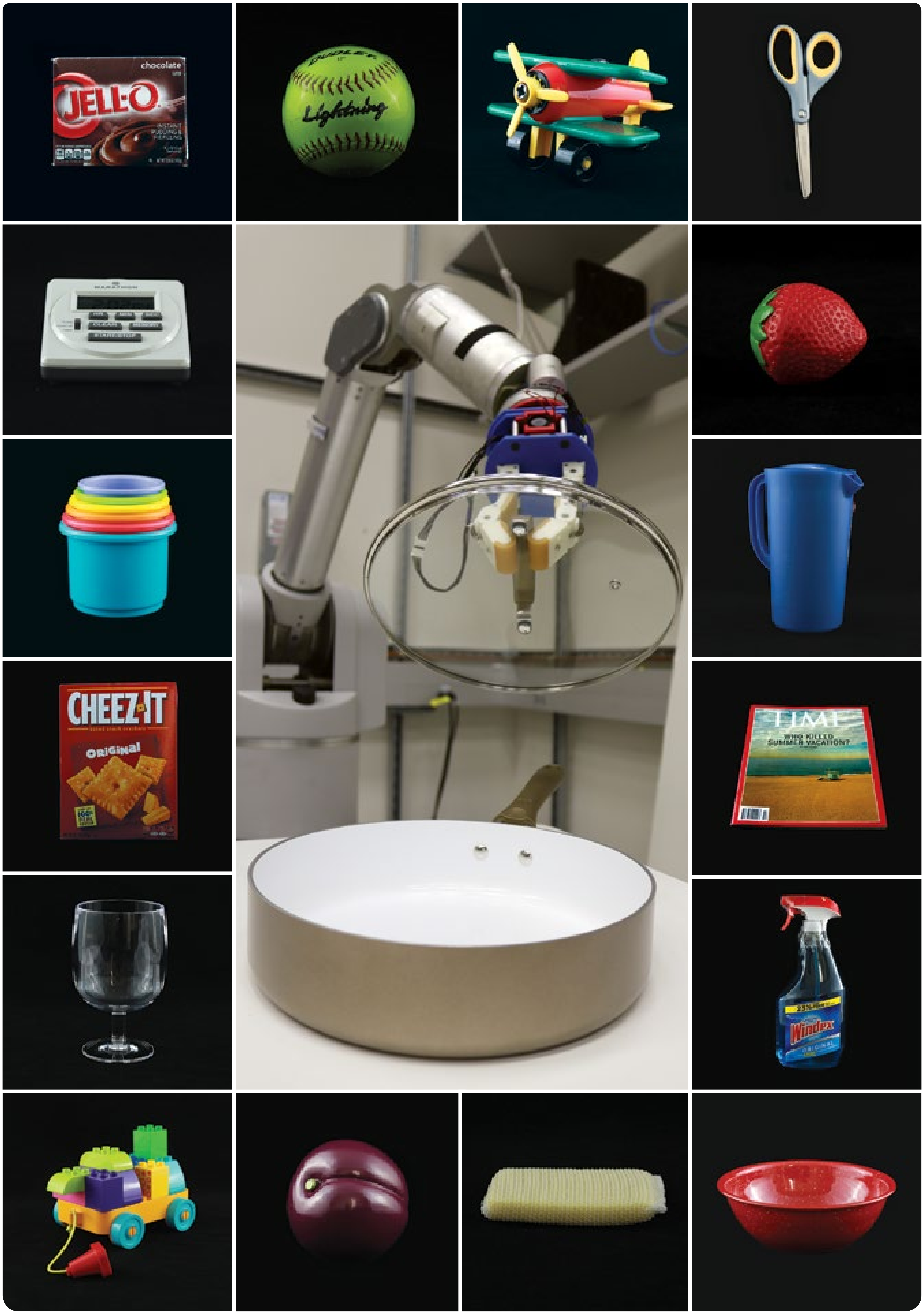
chocolate
JELL-O
Lightning
CHEEZ-IT
ORIGINAL
TIME
WHO KILLED SUMMER VACATION?
Windex

And we cannot proceed further without knowing what is working and what is not."

> *"Robotics deals with physical conditions, and if you can't replicate the physical environment, the data won't be useful."*
>
> › Yu Sun, associate professor in the Department of Computer Science and Engineering at the University of South Florida

Ideally, the YCB Set will take on a life of its own. The objects and example tasks provided are just a beginning. Manipulation research progresses quickly and covers a wide range of technical interests and research approaches, so the five manipulation tests Dollar and his team provide are only examples of protocols that labs can use with the objects. That's why on the YCB Object and Model Set website, the research team has also provided a framework for other labs to contribute their own manipulation tests and benchmarks. There, researchers can see protocols from other labs and have a forum for discussion.

"The main thing is just getting other researchers to propose their own protocols and get people to utilize them," Dollar said.

To pick the right objects, the researchers combed through numerous robotics papers to get a sense of what kinds of items were most commonly used in manipulation tests. They visited stores for additional ideas. "The nature of this project is to apply to and span a wide range of research interests," Dollar said.

Preference was also given to objects that are durable and likely to remain in circulation without much change in the future. Standard consumer objects were chosen to keep the costs down. Each set costs about $350.

The objects are divided into categories. The food group, for example, includes a cereal box, a cylinder of Pringles chips and a can of Spam. Tools range from small nails to wood blocks and a cordless drill. Dollar said he aimed for a wide variety of sizes (the smallest item is a washer, the largest a water pitcher). Some items have simple geometric shapes that are relatively easy to grasp, while the complex shapes of others pose a greater challenge for robotic hands.

The items also include various task-based objects: a "box-and-blocks test" in which wooden cubes are to be placed in a box; a toy airplane that can be assembled and disassembled; and a variety of Lego pieces for building structures. The set also comes with a digital timer to measure how quickly certain tasks are performed.

Finding all the right parts for the YCB Set is one thing, but for the project to succeed, Dollar needed to convince other labs to adopt it. He and his associates have been busy distributing the sets at international robotics conferences. The YCB Set debuted at the IEEE International Conference on Robotics and Automation (ICRA) in May of 2015. Dollar said the reaction was "very positive" and they received about 50 requests for the sets, which are packaged specifically for easy travel. Researchers can also order the sets and have them shipped to their labs. About 100 robotics labs around the world now have the YCB Set.

"We want to get this into as many hands as possible, because that's the only way it's really going to stick," Dollar said.

Yu Sun, an associate professor in the Department of Computer Science and Engineering at the University of South Florida, said his lab is "one of the lucky ones" to receive the set. He said the YCB Set was featured in a grasping competition that he organized for the International Conference on Intelligent Robots and Systems in South Korea this October. His own lab has already produced some manipulation data using the objects.

"The good thing about using Aaron Dollar's object set is that other people will be able to use our data sets because they have the same objects and they can apply them to their own algorithms," he said. "Robotics deals with physical conditions, and if you can't replicate the physical environment, the data won't be useful."

Inside/Outside

Environmental engineers Jordan Peccia and Drew Gentner are finding new ways to study the air we breathe — both indoors and out

Alexa Bakker, a doctoral student in Jordan Peccia's lab, takes samples from an air conditioning unit at Yale's West Campus.

Humans have long taken to the indoors in one fashion or another. Ice age humans lived in caves, or they made tents from the skins and bones of mammoths. By 8000 B.C. Mesopotamians were making houses from mud-brick, and our living situations became increasingly sophisticated from there. It makes sense. Outside can be cold or rainy, critters crawl all around, and you need a place to keep your stuff.

But there's a catch: the more your living quarters separate you from the outdoors, the more you're courting an unhealthy living situation.

"Humans evolved to live outside and not inside, and the organisms inside are very different from the organisms outside," said Jordan Peccia, professor of chemical & environmental engineering. "But with lots of ventilation, you can make your inside look like outside. That's seems counterintuitive to what buildings are for — they're supposed to protect us from the outside, but really, we need a lot more of what's outside."

Research shows that buildings with high ventilations correlate with better health than low-ventilation spaces, which are associated with higher incidences of dust mites and carbon monoxide. Ventilation is one of the focuses of an ongoing collaboration between Peccia's lab and researchers from the University of Tulsa, which is looking at about 100 homes and schools in Cherokee Nation, one of the largest Native American tribes in the United States.

"Cherokee Nation has a 19 percent asthma rate among children, compared to the U.S. population in general, which is 5 to 7 percent — so it's very high," Peccia said. "There are times of the year when there are so many respiratory diseases that they close schools because everyone has the flu. So it's pretty clear that there's exposure to microorganisms at the schools and at the homes."

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In the participating homes and schools, the researchers will look at air flow and how residents' cleaning methods affect the travel and settling of dust. After collecting samples from surfaces in different rooms and from the air inside and outside the homes, the researchers will also analyze the exchange rates of the ventilation in the homes. Once that part of the project is complete, they will take more measurements to determine whether better ventilation affects microbial communities — that is, whether it changes the concentrations of allergens, bacteria, and fungi.

Sarah Kwan, a doctoral student in Peccia's lab, is leading the study for Yale.

"We can't cure asthma or allergies in children who already have it," she said, "but we're looking at how we can change the indoor environments to lessen the number of bad episodes they have, decrease the absenteeism at their schools and have fewer days in the hospital due to their indoor environments."

Rates of asthma and severe allergies for the general population of Colorado are similar to those in the rest of the U.S. Poverty plays a big role in why the rates are so high among the Cherokee Nation population. The roofs, walls and windows in these homes are often compromised in a way that results in moisture damage and bad ventilation — all things that contribute to increased microbial exposures.

Compounding matters, indoor air quality resources are scarce in the Cherokee Nation. It's an unfortunate situation, but makes the Cherokee Nation volunteers an ideal group for the study. "If you can start with the most sensitive group and you can help them, then hopefully you can help anyone else suffering from it using the same changes," Kwan said.

The homeowners in the study will receive cleaning supplies and instructions on proper cleaning methods. After a few months, more samples will be collected, and the researchers will determine if the new cleaning equipment and methods had any impact.

"The idea is to understand what's going on in their homes," Peccia said. "We know a lot of these microorganisms are the ones that cause severity of asthma. We want to understand how some really modifiable parameters of a person's home can affect their exposure to these microorganisms."

Since the participants in the study are mostly families with low-incomes, the researchers need to come up with inexpensive remedies. Kwan said she expects their suggested solutions will buck current trends in architecture, which is to reduce the air exchange in buildings. This helps keep down energy costs, but Kwan and Peccia say it could also have health costs.

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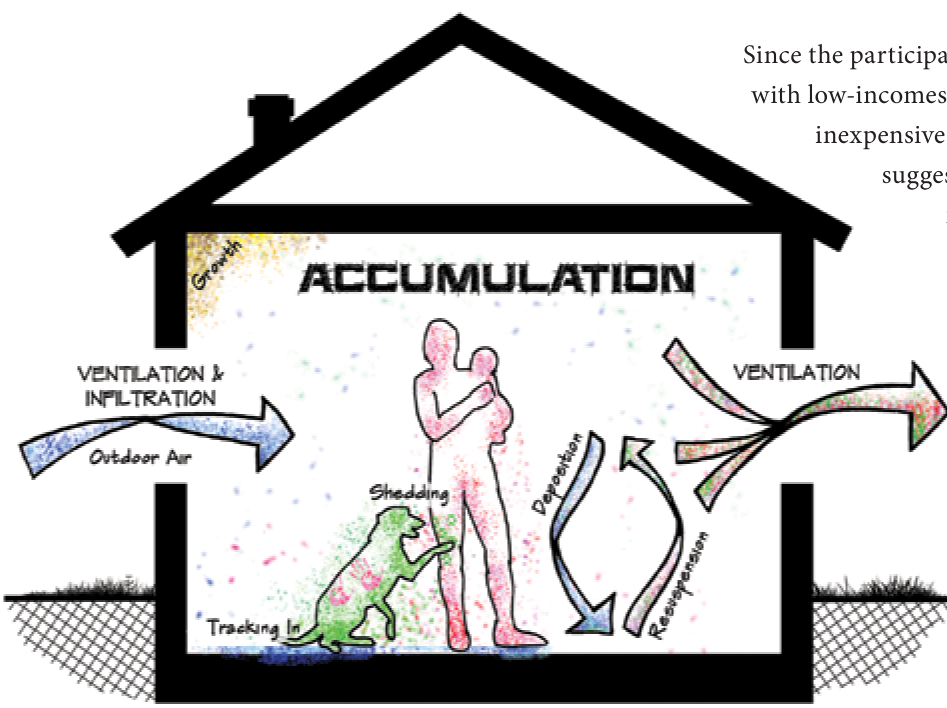
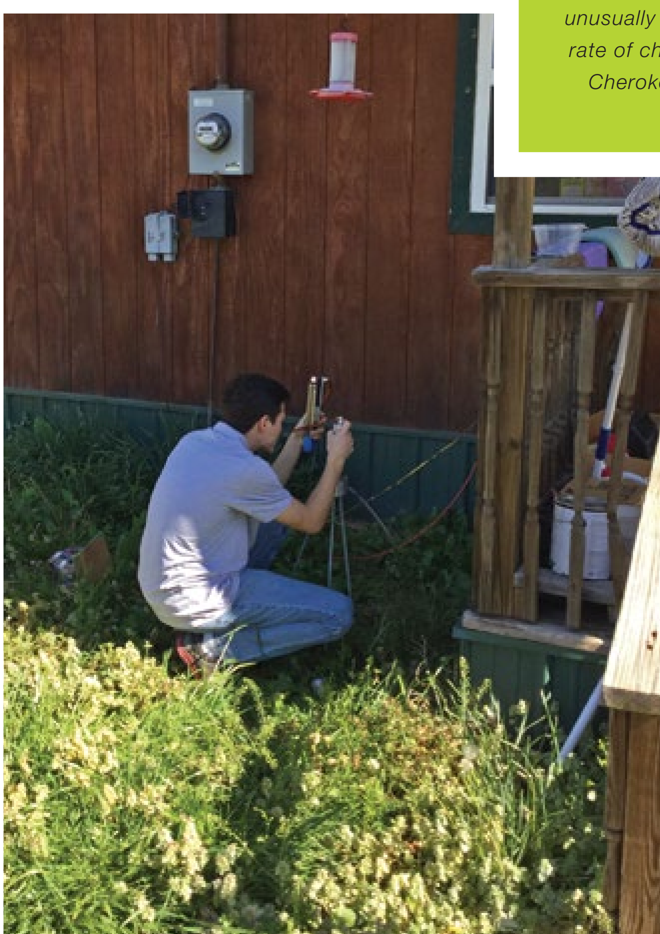


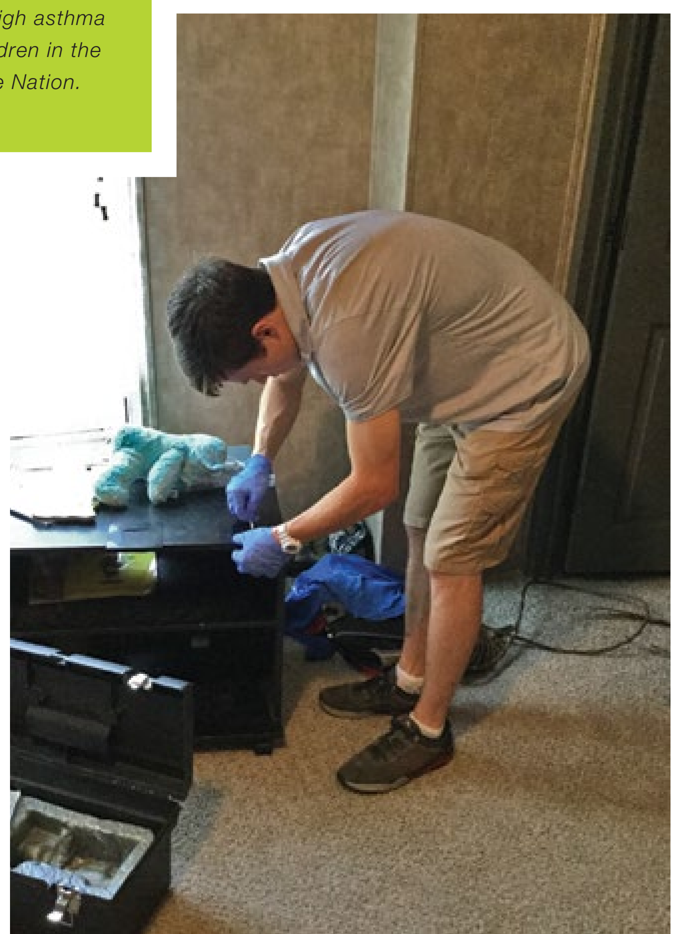
Sources and physical processes that govern the assembly of indoor microbial communities.

Yale

SUSTAINABILITY

Researchers take samples in an effort to shed light on the unusually high asthma rate of children in the Cherokee Nation.





Peccia suspects that the high proportion of illness of people who live and work in air conditioned buildings is directly related to microbes.

"The indoors can become concentrated environments and incubators for everything that you bring inside, and if they're closed up, there's no way for this stuff to get back out," she said. "We're trying to show that if you have a higher exchange rate, and let the outdoors flush out the indoors, then maybe we can reduce some of these health effects."

You don't have to travel far to happen upon the hazards of indoor living, as another project out of Peccia's lab shows. Although it has long made sweltering summer days bearable, air conditioning could also be making you sick. Studies have shown that there's a high proportion of illness among people who work and live in buildings with air conditioning. Not majorly sick, but some tightening of the chest, some dry coughs and other symptoms.

Researchers don't know why this is, but Peccia suspects it has something to do with microbes. "We don't know what or how, but it seems that when you take the microbes away from the air conditioning system, people feel better," Peccia said. His lab has received a grant from the Sloane Foundation to take a deeper look into the unseen world of the air conditioner, and what it might be doing to its users. He believes air conditioning units are creating unique environments conducive to only certain types of organisms.

"When you think about it, they're wet, kind of cold places but they go through cycles of wet and dry. There's stuff in there and that gets distributed throughout the building," he said. "We're going to dig through the coils of these big systems and we're going to try to see what grows there — what kind of fungi, what kind of bacteria are growing on these coils."

Using genetic methods, they'll take an inventory of all the microorganisms they find in the units. Then they'll measure the rate at which these microorganisms are distributed into the air.

For Peccia, it's one more project that keeps him inside, searching for new ways to improve our indoor life.

"This wasn't my idea of what I'd be doing when I went into environmental engineering," Peccia said. "I thought I'd be walking fields and testing water. But we spend 90 percent of our time in buildings. This is our environment, whether we like it or not."

Of course, the air outside isn't perfect either, and in some places, it's downright terrible. Getting a better handle on exactly what's in the air is an ongoing quest, and no easy task, considering that the atmosphere comprises a complex mixture of molecules with trace amounts of more than 10,000 organic compounds in the gas and particle phases. Drew Gentner, assistant professor of chemical & environmental engineering, is working to expand the range of measurement capabilities and couple them with new ways to analyze the data. By doing so, he hopes to get a clearer picture of what exactly is in the air to better get a sense of how to make it cleaner.

"In the past, the field has had several major instances where advancements in instrumentation have enabled research and a much more detailed understanding of the chemical composition and dynamics of air pollutants," Gentner said, while showing off some of the high-end instrumentation in his lab. Detecting the smallest of trace concentrations of chemicals in the atmosphere requires extremely sensitive instruments. Some of the machines operate at the level of femtograms (an order of magnitude below nanograms and micrograms — that is, very small).

Gentner said examining the air at this level of precision gives researchers in his field a new frontier to explore.

"It's almost the atmospheric equivalent of exploring the deep cosmos or the deep ocean because we're looking at a mix of compounds that are known, understudied and unknown," he said. As science has advanced in the last

Gentner displays an early prototype of his portable air sensor.

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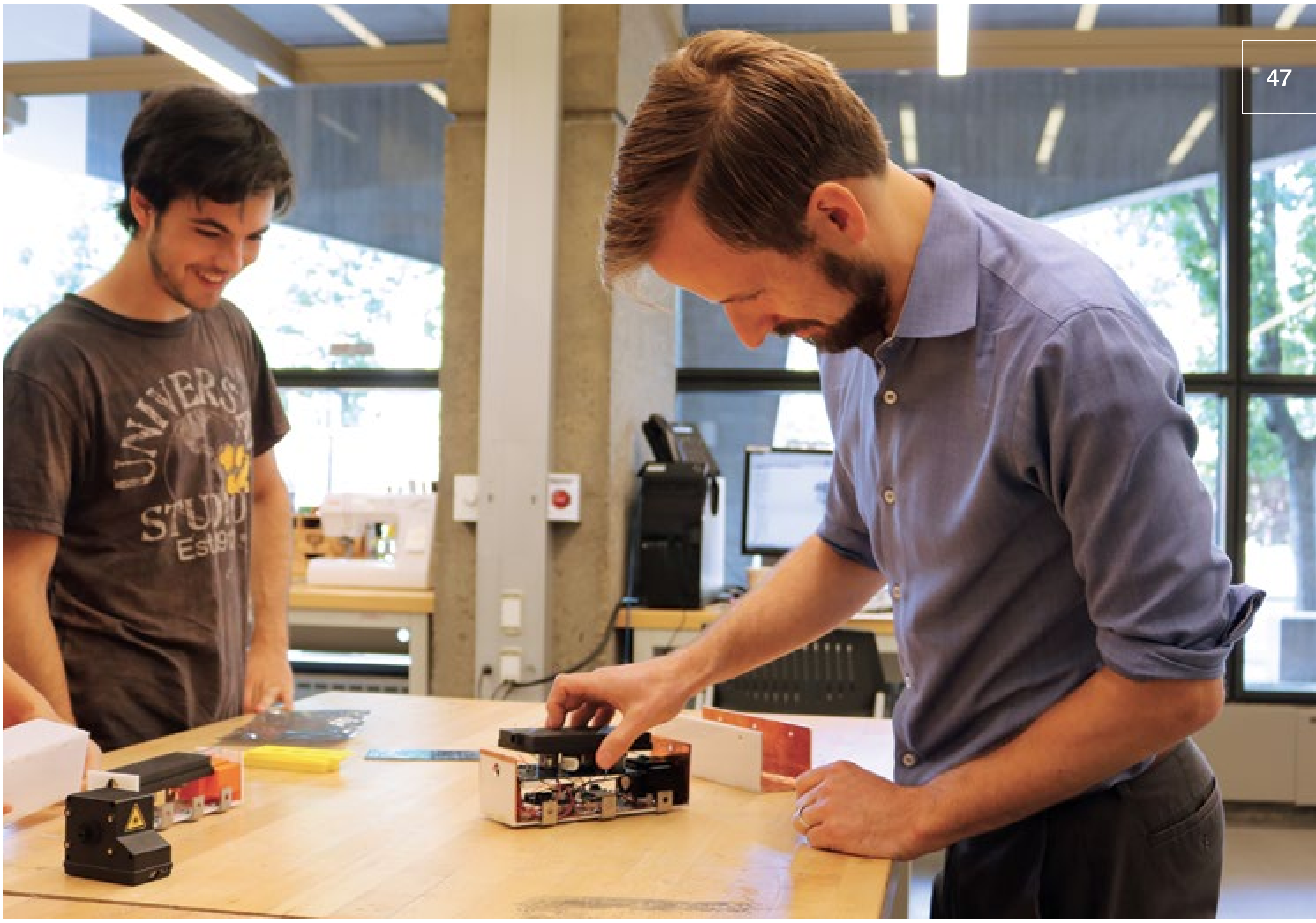
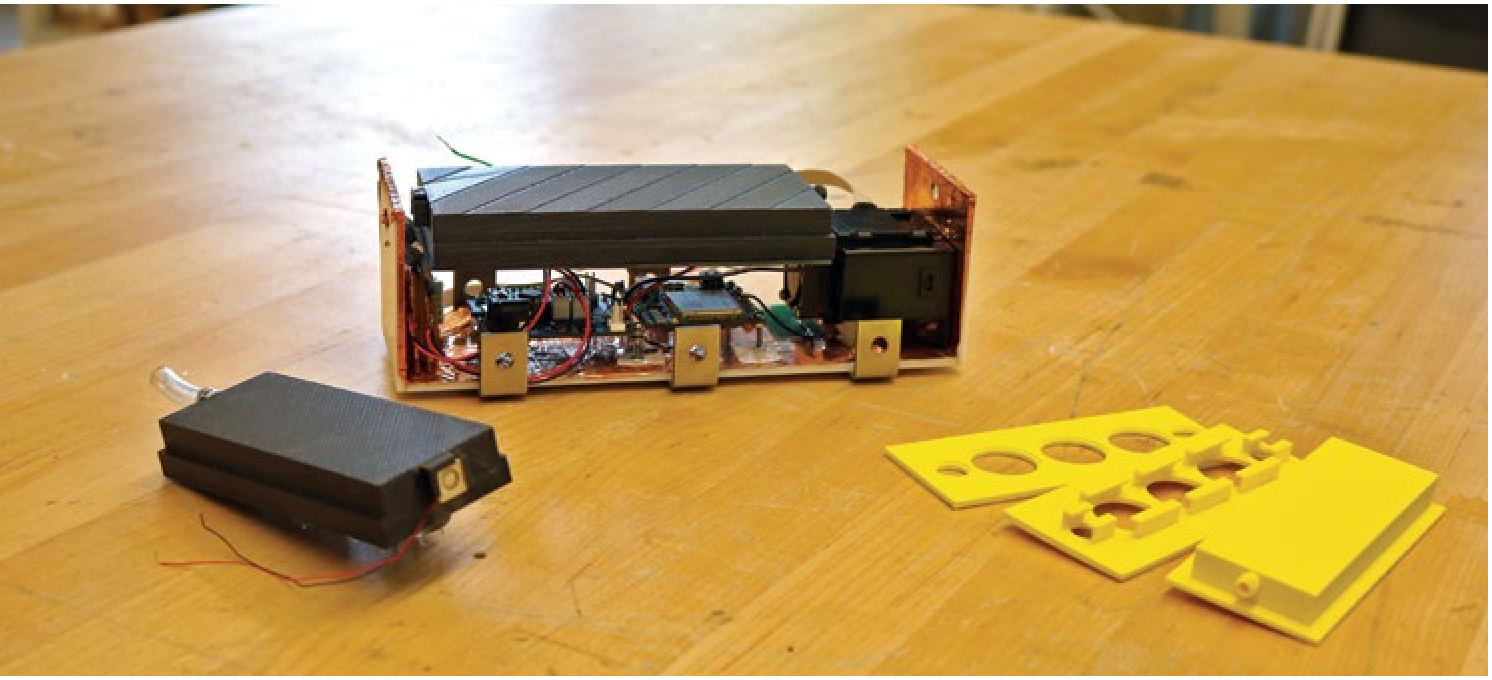




half-century or so, he said, the makeup of the atmosphere has proved to be remarkably complex, and "with every advance in instrumentation, we uncover new chemistry and a deeper understanding."

Getting to the next level of knowledge requires taking some novel approaches. In addition to his group's work with cutting edge analytical chemistry equipment, they have a project focused on spatial and temporal variability of air pollution. That means designing and building a new generation of low-cost, air quality monitoring devices. At the Center for Engineering Innovation & Design (CEID) this year, Gentner and his students have been working on portable devices that will be worn by volunteers in Baltimore as they go about their daily routines. For the same project, Gentner and the students are also making stationary sensors, each smaller than the size of a shoebox.

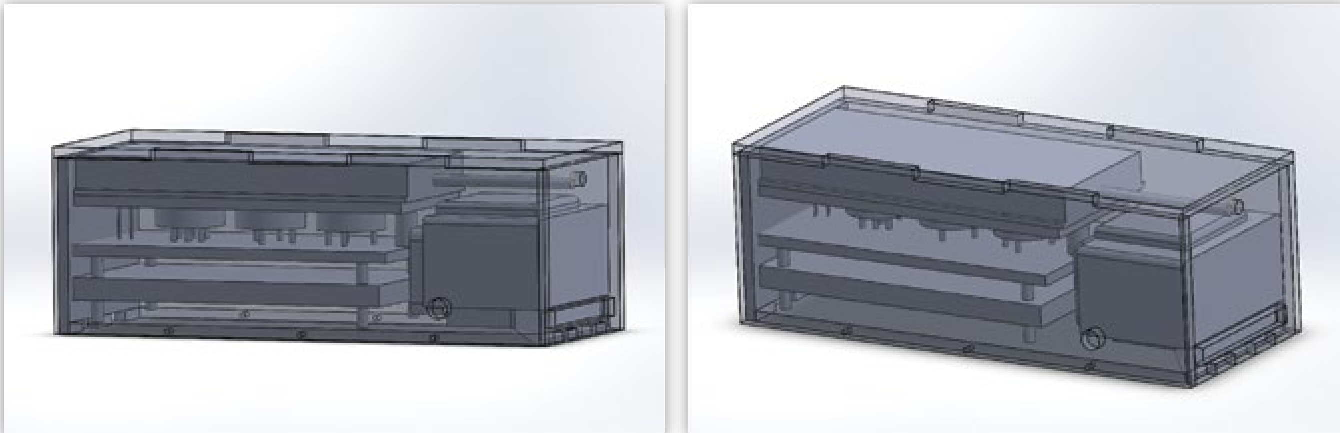
The effort is one of four core projects of the new Solutions for Energy, Air, Climate, and Health (SEARCH) Center, created with a five-year, $10 million grant from the U.S. Environmental Protection Agency (EPA) to study the relationships between air quality, energy policy, climate change, and public health. Michelle Bell, the Mary E. Pinchot Professor of Environmental Health at the Yale School of Forestry & Environmental Studies, serves as the director of the multidisciplinary research center. Johns Hopkins University and other institutions will serve as partners. It is one of only three centers funded by the EPA.

The high-resolution air pollution sensor networks and wearable sensors are being designed to give real-time data on common air pollutants. If all goes according to plan, the devices could help usher in a new generation of air quality studies.

Most cities have a handful of stationary field sites to monitor air quality. "Single-point measurements of air pollutants have historically been used to represent a whole region or city, and that's been a limitation for air quality studies," Gentner said, adding that "new opportunities abound as low-cost sensors become more accurate and precise." The stationary and portable monitors will make for some very detailed networks that will provide valuable information for studies on pollutants, how they are transported through the air and the level of human exposure to them.

Making the sensors small enough for volunteers to wear daily, and sophisticated enough to do everything Gentner wants, takes some work. Genevieve Fowler '16 was part of the first of two groups of students to work on the sensors. "It's been exciting to be working on something that could have such an impact," she said.

Fowler said the prototype they developed is a good start, but the second group of students (working on the sensors this semester) has its work cut out for them. With more design work ahead of them, Fowler said they will "have to



Facing Page: *One challenge for Gentner's lab is making the devices small enough to wear every day.* Above: *Early CAD renderings of Gentner's sensor.*

think about waterproofing and general durability for the housing. I think those are the biggest things."

The stationary sensors will be located in representative locations around the city: roads, schools and other places where people spend a lot of time. "With these networks, we'll have real-time measurements, 24 hours a day with fine spatial and temporal resolution on the air pollutants responsible for detrimental effects on human health and climate," Gentner said.

When the portable sensors are complete, the volunteers will wear the sensors at home and whenever they leave their home. One of the challenges is designing the sensor so users can carry the devices without even thinking about it.

The researchers chose Baltimore as the site for the sensors partly because of the proximity to SEARCH partner Johns Hopkins University. It also means that people from a wide range of backgrounds can take part in the study.

"It will allow us to look at a diverse group of people interacting with the built environment in different ways," Gentner said. "As part of the center, we're very interested in energy-related impacts — how do personal choices and regional-scale choices related to sustainability affect exposures to air pollution?"

Gentner said the portable sensors should be ready for use in 2017. They'll collect the data for two to three years and further analyses will look at how individual and broader policy choices affect air pollution and human exposure.

"This is a big effort going through the end of the decade and we're really excited about it," Gentner said. "These sensors have the potential to not only have an impact on this study, but also future studies with powerful methods for elucidating air quality."

EDUCATION

Beyond the Lab

Students in AGLP broaden their skills beyond academic research

Pursuing a Ph.D. in engineering can be arduous but extremely rewarding work, delving deeply into one topic and often taking the research to places never before explored.

But it's also good to occasionally look up from your microscope, get out of the lab and broaden your skill set. That's where the SEAS Advanced Graduate Leadership Program (AGLP) comes in. It's a competitive program designed to provide doctoral students with experiences and training outside of their specific area of research. The idea is to widen participants' career opportunities, particularly in academia, policy and public service, and business.

Launched in 2009 with a grant from the Goizueta Foundation, AGLP provides participating students a coursework sequence in the Yale School of Management or a semester-long internship designed to fit their career aspirations. We spoke with four AGLP members — all currently pursuing their Ph.D.s — about their experience with the program. Their work with AGLP has launched start-ups, helped Connecticut in its efforts to keep millennials in the state and brought the Yale philosophy on makerspaces to the White House.

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Jonathan Chen

In the early part of his work toward a Ph.D. in biomedical engineering, Jonathan Chen worked on a device designed to measure the immune response of cells at the single cell level. The researchers went on to receive a patent for the device, which became the foundation for the Yale start-up Isoplexis.

"Being a part of that process and seeing all of that unfold was really inspiring, and I wanted to learn more," Chen said. "Not just the science of it all, but what it takes to take something that started in a lab and bring it out to the greater society."

Chen got a chance to see that side of the innovation process this past semester with an internship with Elm Street Ventures, a New Haven-based seed and early stage venture fund with close connections to Yale. He did research there for a number of projects, which involved looking into technologies and competing companies. He then drafted internal reports based on that information.

His efforts mainly focused on the launch of Elm Street Ventures' latest spin-off, Osmol Therapeutics. On that project, he worked with Brian Dixon, an Elm Street Ventures partner and the CEO of Osmol. Like many of the venture fund's investments, it's based on research done at Yale — in this case, by Barbara Ehrlich, professor of pharmacology and cellular and molecular physiology.

Chen worked on internal memos about the company, wrote up explanations of the clinical need for the product, details about the science behind it and an assessment of risk factors. Rob Bettigole, a managing partner at Elm Street Ventures, said Chen was a big help in getting everything ready for the September launch of Osmol.

"Jon's pretty familiar with a lot of the science of what we're working on, so he's starting at a pretty high level," he said. And what he didn't already know, Bettigole said, Chen got up to speed quickly.

It's one thing to have great ideas and great research, but innovations also require practical know-how to get them to market and make a real difference. In that regard, Chen said working with Elm Street Ventures was "an awesome opportunity."

"I think everyone's ultimate goal for their research is to help as many people as possible and to turn your research — or help turn someone else's research — into something that's going benefit the public," he said. "That's something that really drives me, and sometimes people don't know the avenues. A firm like Elm Street Ventures can help bring that to the table."

Outside of the internship, Chen said AGLP has been instrumental in shaping his interest in investments and entrepreneurship.

"We meet with industry leaders in different fields," he said. "We've partaken in a lot of discussions and we hear about conflict management, negotiating, and a lot of skills that are very applicable in pretty much any space."

Thomas Kwan

When he first came to Yale, Thomas Kwan was intrigued by the Center for Engineering Innovation & Design (CEID). Design spaces are traditionally appropriated for distinct disciplines and he initially thought the CEID was geared toward mechanical and electrical engineering.

"It wasn't until I was in the space that I really understood how welcoming and collaborative the CEID space and culture is," he said.

As a doctoral candidate in environmental engineering, Kwan was interested in how makerspaces such as the CEID can be leveraged for green design and education. One of the first projects he designed asked multidisciplinary student groups to fabricate two hand juicers in the CEID and assess their environmental impact if manufactured at a large scale. By employing a rapid life cycle analysis, the students were able to make informed design decisions sparking an innovative, experiential, and sustainable approach to modern making and design.

Three years later, Kwan was at the White House talking up the virtues of the CEID and other makerspaces.

Now, through the AGLP, Kwan serves as something of an ambassador for makerspaces, looking at ways that universities and other institutions can make the best use of the spaces. He has spent time meeting with managers of educational makerspaces, networking with government officials, and giving sustainable design talks and workshops at international conferences.

His efforts earned him an invitation to a symposium at the White House in June as part of the National Week of Making. There, he and CEID Assistant Dr. Joseph Zinter shared their thoughts on what makes a successful makerspace. They talked about CEID best practices, emphasized a culture of inclusion, and how makerspaces can fundamentally change higher education pedagogy.

Daragh Byrne, a founder of the MakeSchools Alliance, which organized the symposium at the White House, said Kwan's talk and his other work are going a long way to enrich the makerspace community.

"I think the work he's doing is really interesting," he said. "One of the great things he's doing is sharing his perspectives and showing what Yale's doing — and how those best practices translate to the larger community. I think there's been a real receptiveness to these ideas."

With his background in environmental engineering, it makes sense that Kwan also focuses on how makerspaces can foster sustainable innovation. Kwan said he'll continue to build on his work in the program by exploring different educational settings and how they influence learning.

"My experience with AGLP really enabled me to view education differently and how people learn in different ways," he said. "It's really changed my perspective on how we communicate information and the best ways to do that."

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Aaron Morris

Aaron Morris is working toward his Ph.D. in biomedical engineering, with a focus on biomaterials and tissue engineering. He's also interested in entrepreneurship, so he signed up for an AGLP internship at the Yale Entrepreneurial Institute (YEI).

One of his main tasks over the semester was working with EZ Ice, a start-up company from Yale that's developing ice rinks that can be built in the backyard. The company planned to promote the product at an event in Canada, but were advised to first file a patent before making any public statements about their innovation. That's where Morris' background came in handy.

"I'd never submitted a patent application before, but I'm an engineer, and it's something I was interested in learning how to do," Morris said. "I thought I could help them with it — and they needed help, because they needed to do it quickly."

They had about two weeks. Morris, who's read plenty of patents for his research, immersed himself in the world of personal rink innovations and drafted a patent application. He and the EZ Ice team — the principals are four undergraduate students — had several meetings with Anthony D. Sabatelli, an attorney with Dilworth IP, the intellectual property law firm that serves as a YEI corporate partner. Between Morris' text and the designs from the EZ Ice team, most of the draft was solid. Sabatelli made sure the phrasing was legally binding.

Morris said working on the patent was important in understanding the process, particularly, he added, "if I want to patent my own ideas or help someone else."

"I learned a lot through this process and I certainly learned a lot about breaking down a product," he said. "For a patent, you need to break a product down to a bunch of parts."

Erika R. Smith, the former deputy director of YEI, said Morris was "an amazing part of the program this year" and that his research background was instrumental in getting the patent together so quickly.

"His help was critical to the team because they were going out to promote their idea and without the provisional patent, they'd be giving their idea away," said Smith, who now serves as the Director of the Blavatnik Fund for Innovation at Yale.

In general, she said, the AGLP has served an important role for graduate students by allowing them to gain knowledge and skills that they might not be exposed to in their academic work, but could help them as they explore career options. And it's been a great benefit to YEI, too.

"The AGLP interns really help our teams advance with the expertise that they provide," she said.

Amanda Pellowe

As much as Amanda Pellowe enjoys pursuing a Ph.D. in biomedical engineering, she's also intrigued by the world of science policy. Unlike the long-term goals of academic research, she said, things can happen a little quicker in policy-making.

For her internship at Yale's Office of Federal Relations, Pellowe was charged with two main tasks. One was to conduct an analysis of tech transfer — that is, how innovations move from initial research to final product. She conducted case studies of small companies that have come out of Yale, and looked at how Yale resources are being used for these companies. She also put together timelines that chronicled those companies' growth, ultimately determining where they ended up and whether they have provided jobs in the area.

For her second project she worked with the Connecticut Department of Economic & Community Development (DECD) to figure out whether millennials are leaving the state and why.

"It's part of a talent recruitment project they're working on and they're very concerned that they're losing talent in the state," she said. "So I helped put together some focus groups with graduate students to understand those issues a little better."

Concerns about job prospects and a lack of public transportation were near the top of the list. But Pellowe was surprised to also hear the focus groups talk about family life. "When you read about millennials, it's all about how they want fun and you need to have networking," she said. "But a lot of people said the lack of child care and unaffordable housing prevents them from starting families and establishing roots here."

She put together a report for the DECD, which has a group working on some initiatives to address those issues. Richard Jacob, Associate Vice President for Federal and State Relations, said Pellowe's work was a significant contribution.

"She's very talented and has an energy and enthusiasm for policy," he said. "And her being a grad student helps, since we want to better understand how students perceive Connecticut as a place to stay."

The AGLP has been good for Yale, he said. "In the policy world, there's a dearth of technical and scientific expertise, so it's helpful for us to have a framework to work with on that."

Pellowe enjoyed the experience and is now looking at fellowships that would allow her to continue this line of work. She's also gotten involved with the Yale Science Diplomats, the policy group for graduate students at Yale. Without AGLP, she said, it would have been a lot harder to get an idea of how she would have taken to policy work.

"That's the struggle with a lot of graduate students, because you're really only trained to do academic research," she said. "I think this gave me a great opportunity to explore."

Yale

INTERDISCIPLINARY

The Minnesota Connection

UMinn alums Paul Van Tassel and Christos Hatzis meet to talk old times, fight cancer

Paul Van Tassel and Christos Hatzis.

You know how it is, when you meet up with old schoolmates decades later: Talk turns to old professors, campus haunts and other college memories. And before you know it, you're discussing how to develop polymer-coated nanoparticles, carrying cancer-fighting agents and equipped with bioactive receptors.

At least, that's how the reunion went between University of Minnesota alums, Paul Van Tassel and Christos Hatzis. Both received their Engineering doctorate degrees from UMinn in 1993. They don't recall ever meeting up with each other while they were there — it's a big school.

"But we had this common experience, a very common background," said Van Tassel, professor of chemical & environmental engineering and biomedical engineering. After all, he said, they took the same courses from the same teachers.

They had another thing in common — they both knew SEAS Dean Kyle Vanderlick from her days at UMinn. She earned her Ph.D. in Engineering from the school a few years before Hatzis and Van Tassel. Hatzis, assistant professor of medicine, said she was a teacher's assistant for one of his toughest courses.

Hatzis came to Yale in 2013 after working in the private sector for most of his career.

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"I noticed that Kyle was Dean of SEAS, and I made a point to email her," said Hatzis, also Director of Bioinformatics for Breast Medical Oncology at the Yale Cancer Center. "We happened to meet at one of the campus-wide bioinformatics meetings and we said 'Oh, we should meet up with Paul — you know, all the Minnesota people — and get lunch.'"

They did, and soon Hatzis and Van Tassel were talking about collaborating on a project to develop better ways of directing cancer drugs to diseased tissue.

"I was toying around with this idea and Paul was excited about it," Hatzis said. "We had our first discussion in November last year, and filed a grant proposal."

The two meet once a month to discuss the project. Hatzis' lab is concentrating for now on analyzing cell lines, specifically those related to triple-negative breast cancer. It's a form of cancer particularly difficult to treat, since it doesn't express genes for any of the three receptors that chemotherapies target. About 30 percent of all breast cancers are triple negative.

"All other subtypes of breast cancer have well-defined therapeutic strategies," Hatzis said. "But for triple negative breast cancer, we only have standard of care, which really just doesn't work."

With Vikram Wali and Gauri Patwardhan in Hatzis' lab, the researchers are sorting out basal, luminal and stem cell lines and monitoring their behaviors and reactions to different drugs over time. That way, they can identify the best anti-cancer agents for specific cancer types.

Van Tassel's role in the project is getting those drugs to tumors with a greater specificity than what medicine now provides, so that the drugs aren't also attacking healthy cells.

Van Tassel and Hatzis are collaborating to develop better drug delivery systems for breast cancer.

"One way to optimize this is to bring the agents directly to the cells, so you're not treating systemically," he said. "Once you know which drugs might be effective against different cell types, you could potentially target those drugs to those cell types."

Van Tassel specializes in biofilms — thin films with bioactive species. He said one possibility would be to create a liposome that carries the agents. "With Christos, we want to take these ideas and apply the anti-cancer agents he's been developing and put them in this particle."

Receptors on the surface would target specific cell lines.

"You want these things to have an affinity for the diseased tissue," he said. "There are ways to functionalize the surfaces, so that if it's a liver cancer, for example, it'll go to the liver."

One approach they're considering is putting a polymer film embedded with bioactive species around these liposomes. "They can be sort of cancer-specific ligand, so these guys could help bring the particles to the right location."

That way, the particle does a lot of the work automatically. "The chemical specificity is really nice, because it catches cells even if they've escaped and gone to a new location in the body," Van Tassel said. "If cancer has escaped and gone from the liver to the spleen, or in a location you don't know, this way the particle thinks for itself."

They're also considering embedding particles with smaller magnetic particles.

"If you did that, you might have the opportunity to manipulate these particles with magnets, which allow you to concentrate these particles to a certain area of the body," Van Tassel said. "This is potentially powerful — if you know the cancer is here, you can use these agents to direct the drug-carrying particles to that area."

It could also be used to minimize the toxicity of certain drugs used in cancer therapies. For instance, a magnetized imaging agent could be retrieved before it causes any damage to the body.

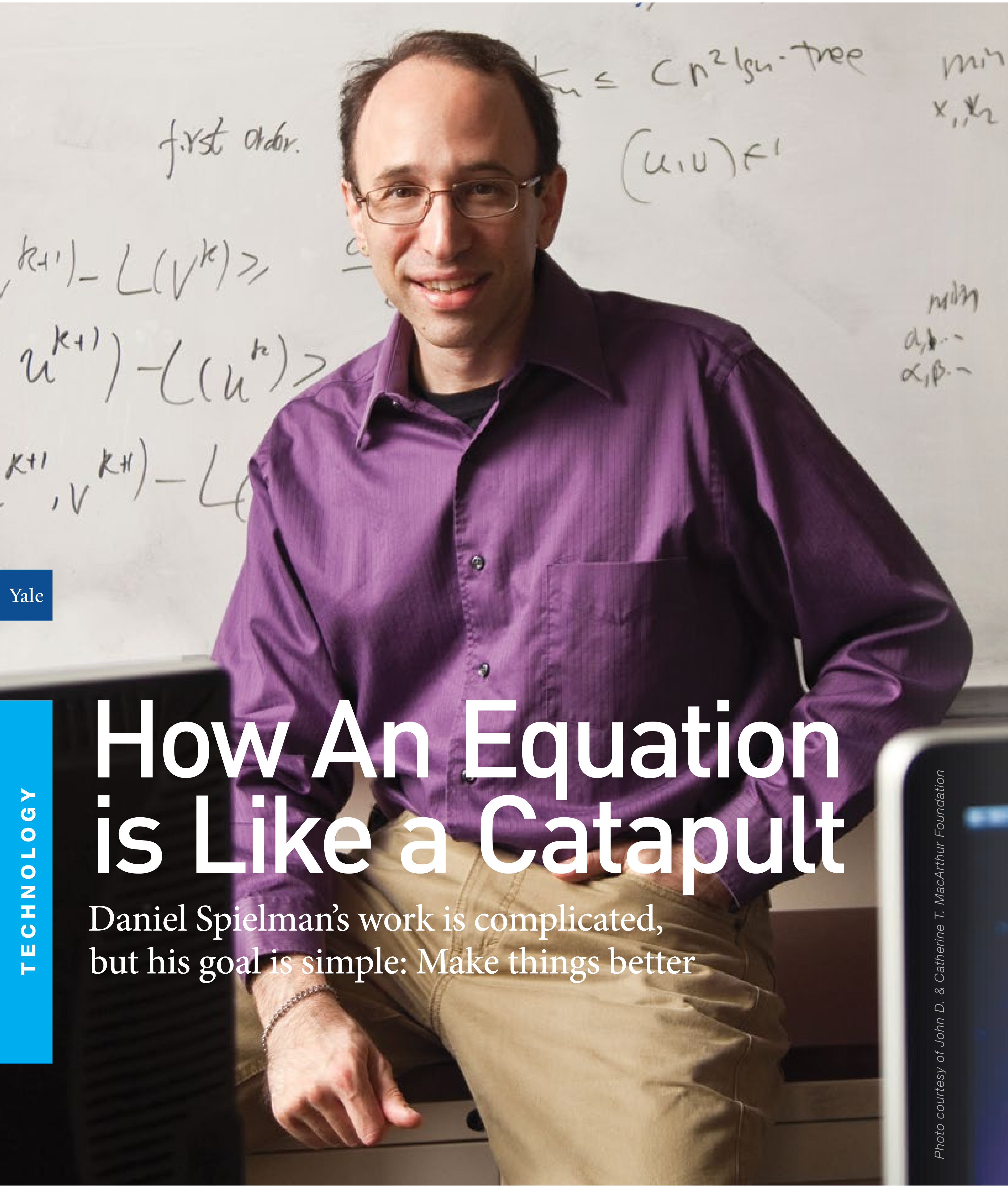
There are still a lot of things to figure out, Van Tassel said.

"There are a lot of interesting physical chemical questions there," he said. "If you have magnetic particles in this larger particle, how does that affect the release rate? How does that affect the uptake of this particle by these cells? It just changes things."

He said the magnetic particles would likely be about 30 nanometers — large enough to be magnetic, but small enough to pose no serious health issues.

Van Tassel and Hatzis stress that the project is still in its early stages, but they're excited about the possibilities. They have recently submitted a funding proposal based on an idea they developed for efficiently targeting and separating cancer cells.

It took them a while since their UMinn days to actually meet — but now that they've made that step, progress is moving swiftly.



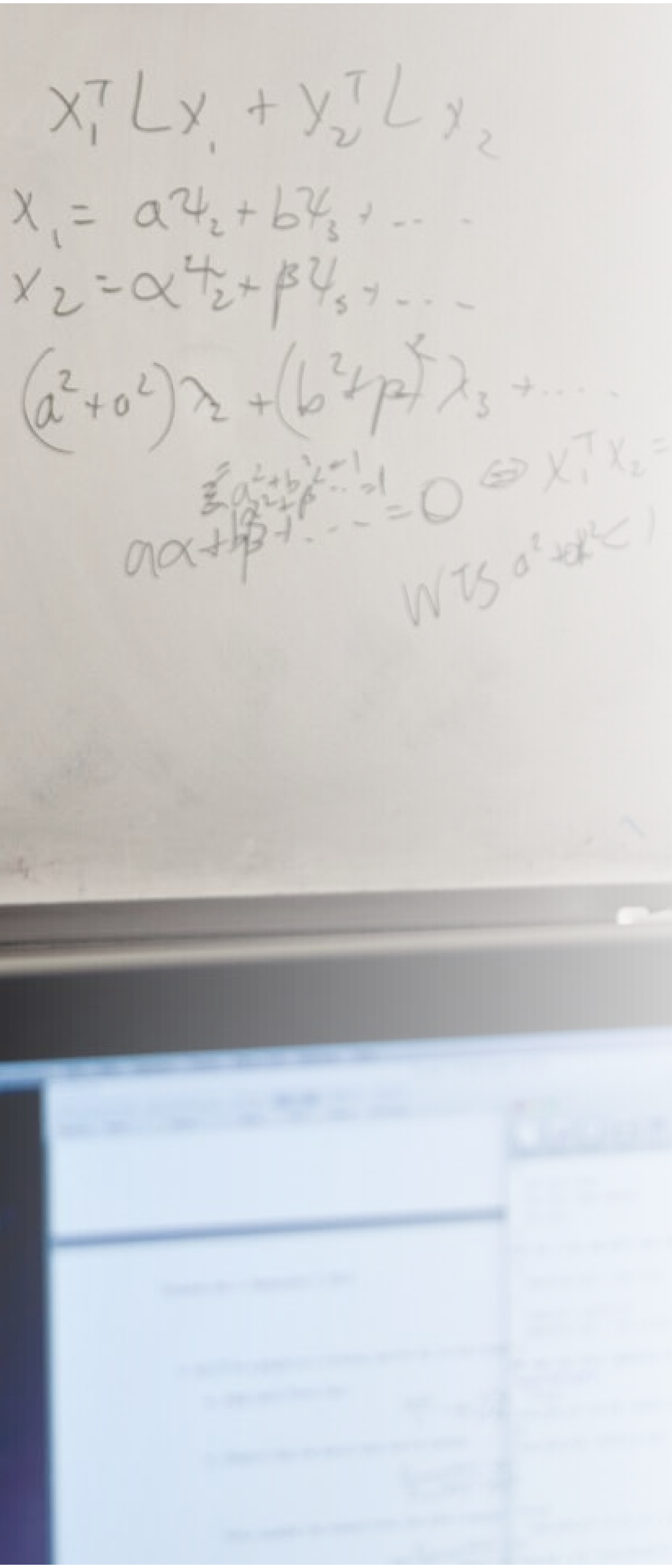
Yale

TECHNOLOGY

How An Equation is Like a Catapult

Daniel Spielman's work is complicated, but his goal is simple: Make things better

Photo courtesy of John D. & Catherine T. MacArthur Foundation



Lots of problems have already been solved. They just don't always have the best solution.

"By thinking about a problem, you can come up with a whole new way of solving it that might be much faster," said Daniel Spielman, the Henry Ford II Professor of Computer Science and Mathematics. "The whole field of algorithms is, to some degree, about finding new ways to solve problems. And people in this field, like me, really just like thinking of completely new ways to solve things."

He compares his research to someone who's trying to get better at throwing a ball. The conventional way is to practice throwing, lift weights and get bigger muscles. "A smarter person invents a slingshot — and an even better way of doing that is to use a catapult," he said, laughing. That's essentially what Spielman does, only with graphs, equations and computers. "One of my main projects has been designing faster algorithms for solving systems in linear equations, and then working on leveraging those algorithms to do other things faster," he said. "A lot of my life is dedicated to figuring out how we can compute things a lot faster."

In its raw form, Spielman's work is abstract, but the end results have led to countless applications from faster com-

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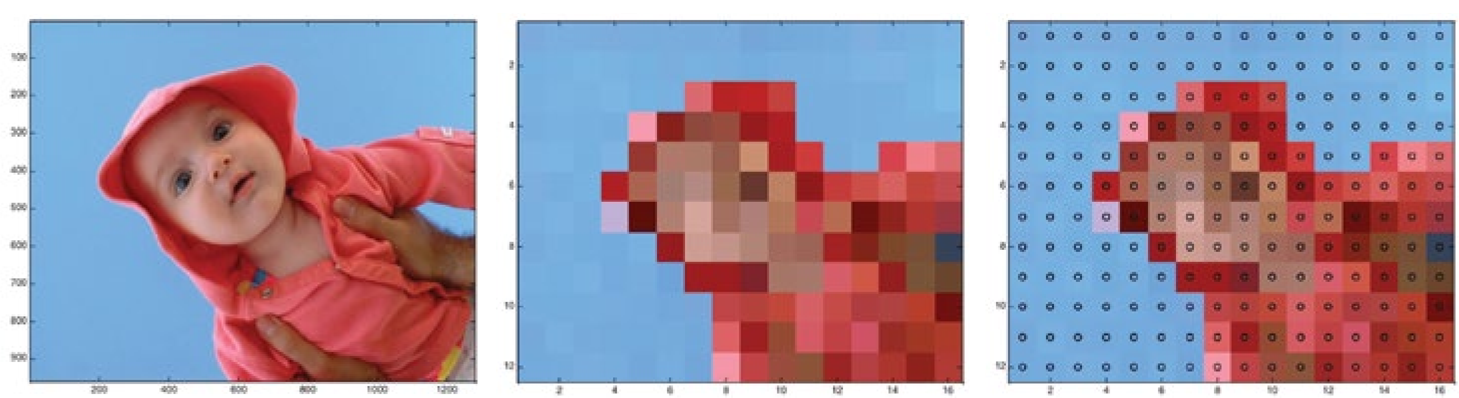
munication to medical imaging to how online retailers recommend products for you. His contributions to computer science and math have been enormous. His thesis work helped revolutionize the field of error-correcting codes, which allow communication devices to transmit information even if part of it is corrupted. That work has made communication faster and more reliable and has been used for broadcasting high-definition television.

In a separate line of research, Spielman was recognized for his work in what's known as "smoothed analysis," which has been credited with giving a more realistic understanding of how an algorithm will perform. The concept deals with the phenomenon in which some algorithms work better in practice than in theory. "We sort of proved that algorithms work as long as there's a little bit of noise in the input — because usually there's noise in real world data."

In 2013, he and two collaborators made international headlines when they solved the Kadison-Singer conjecture, a problem that had gone unsolved by mathematicians for more than 50 years. Its solution could have significant implications for the field of statistics.

Throughout his career, Spielman's work has earned him numerous accolades. The Simons Foundation named him to its inaugural class of Simons Investigators, providing Spielman and Yale's Department of Computer Science with $660,000 over five years. The same year, he was named a MacArthur Fellow, popularly known as the "genius" grant. He has also won the Rolf Nevanlinna Prize, one of the most prestigious awards in mathematics. And he's won the Gödel Prize — awarded annually for outstanding papers in the area of theoretical computer science — twice.

The most recent Gödel Prize, awarded in 2015, is connected to his work focusing on linear equations, particularly those related to what's known as Laplacian matrices, a grid of numbers representing a graph. They're used in computational sciences, optimization research as well as network analysis, which is directly related to Spielman's position as co-director the Yale Institute for Network Science (YINS). Working with frequent collaborator Shang-Hua Teng, the Seeley G. Mudd Professor of Computer Science and Mathematics at the University of Southern California, they created an algorithm that solves linear systems in what's known as near linear time — that is, the time it takes to run the algorithm increases in proportion to the size of the problem. Fellow mathematicians and computer



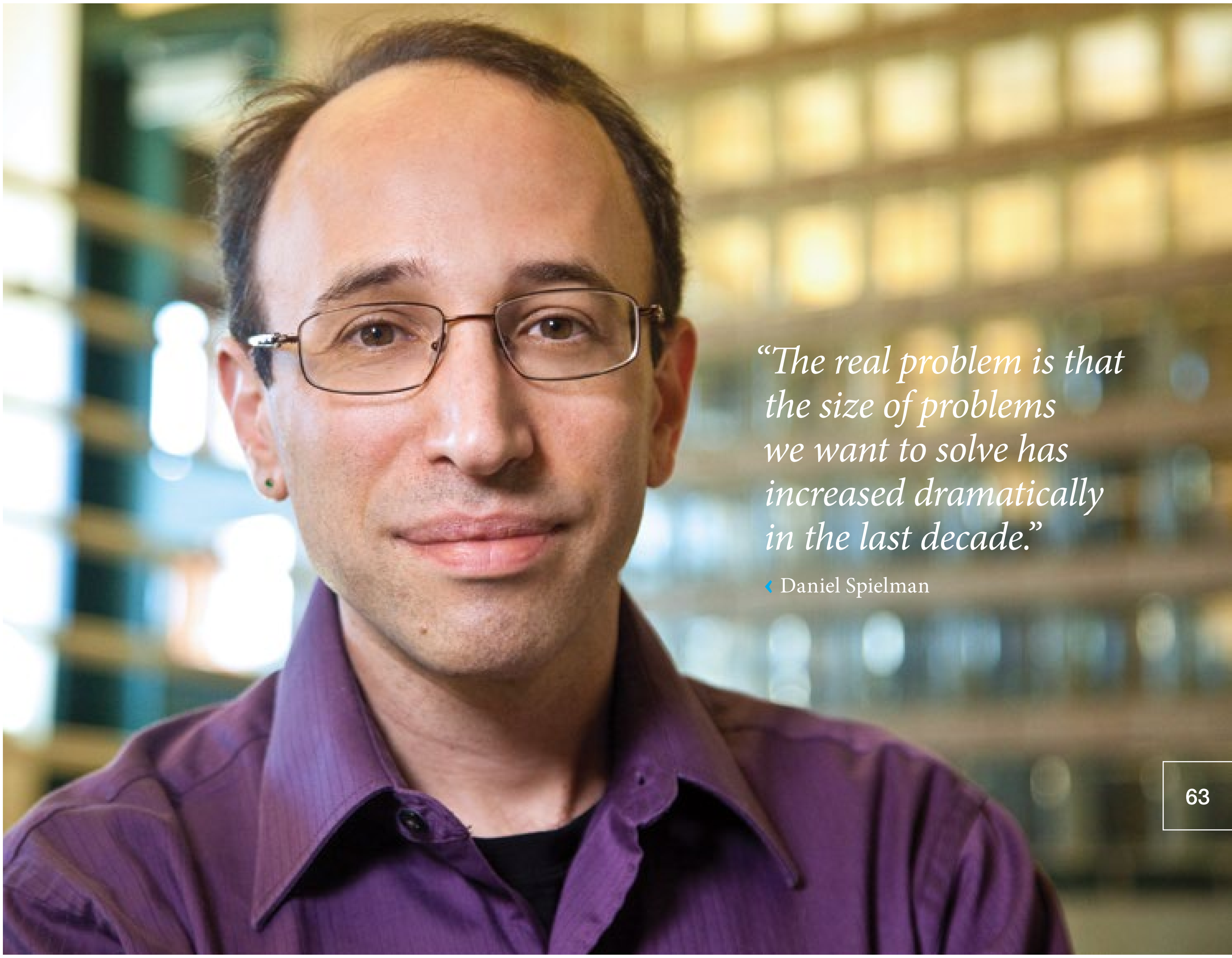


Photo courtesy of John D. & Catherine T. MacArthur Foundation.

"The real problem is that the size of problems we want to solve has increased dramatically in the last decade."

‹ Daniel Spielman

scientists have called the algorithm — aptly known as the Spielman-Teng algorithm — a "technical tour de force."

"I try to focus on fairly fundamental problems, the things that come up all over the place," he said. "My primary interest — my end goal — is really to understand what we can compute, and what we can't. I want to understand how quickly we can compute things we care about."

So when did he decide that he liked this line of work? It began partly when, as a teenager, he worked on puzzles. Not the normal way of putting them together himself, but

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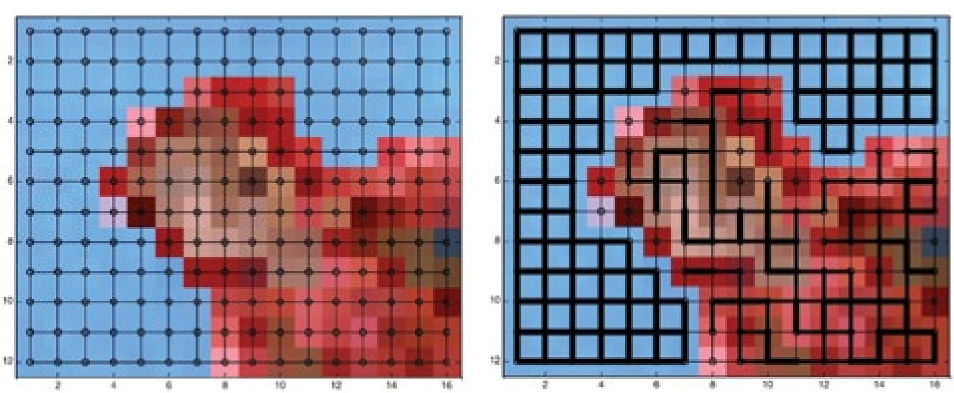
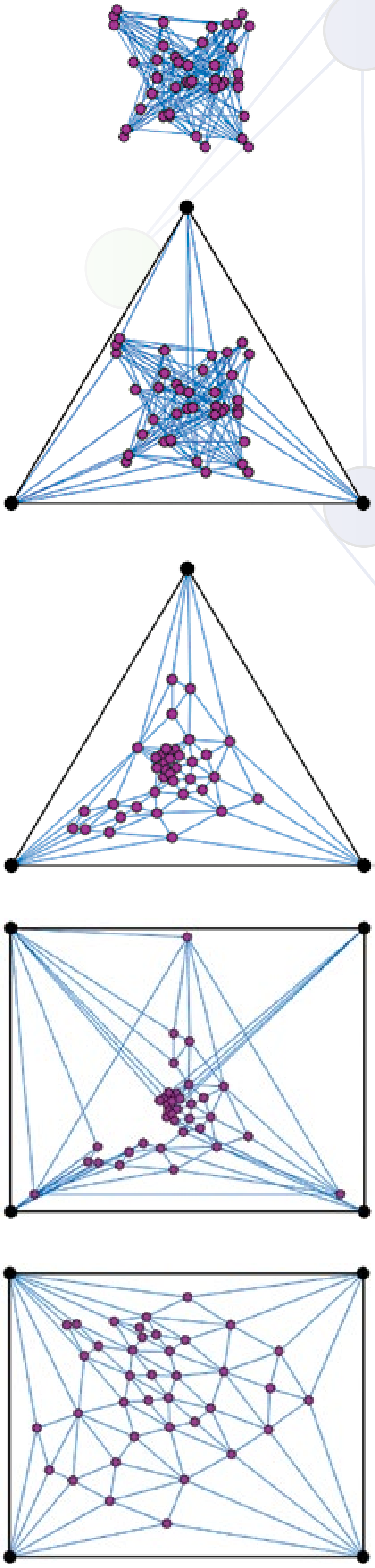


Left to right: *Segmenting an image by applying spectral partitioning to a graph connecting its pixels. Spielman designed a fast algorithm for computing certain aspects of these graphs.*

> *"We know that you can get better answers to problems with more data, but our data has scaled much more than our available computational resources."*
>
> › Daniel Spielman, Henry Ford Professor of Computer Science and Mathematics



by getting his computer to work out a solution for him. His interest was further stoked shortly after he arrived at Yale as an undergraduate.

"I took a course in algorithms as a freshman here at Yale and it was amazing to me," he said. "There are a lot of problems in which we know one way of solving them — often you can do it by hand — but by coming up with a better algorithm, you can do it infinitely faster."

One thing that appealed to him was that, not only do computers let you speed up what you would otherwise do by hand, they also give you the ability to implement more complicated algorithms. "The thrill of algorithms for me is that you look at a problem in which there is a straight ahead, brute force way of doing it, but with thinking, you can come up with something much, much better. And that's really what we're doing when we invent a new algorithm."

We're now in a time when our problem-solving ambitions have outpaced the increase of computing power. That makes better algorithms all the more crucial.

"We know that you can get better answers to problems with more data, but our data has scaled much more than our available computational resources," he said. "The real problem is that the size of problems we want to solve has increased dramatically in the last decade. That's partially because we have much more data — the world is now awash in data."

Besides, he said, increasing computer power isn't cheap.

"More computers, that costs real money. And if I can save all that money just by thinking and solving things better, then I'm a very happy person."

Left: *Drawing a planar graph by treating the edges as springs. The positions of the vertices on the outside are fixed, and the others are drawn in their equilibrium positions. Spielman designed a fast algorithm for determining where the vertices will rest, without needing to simulate the dynamics.*

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