Robots that Teach Us About Ourselves

For new insights into how humans think and move, Yale Robotics is at the head of the class

An Environment for Growth

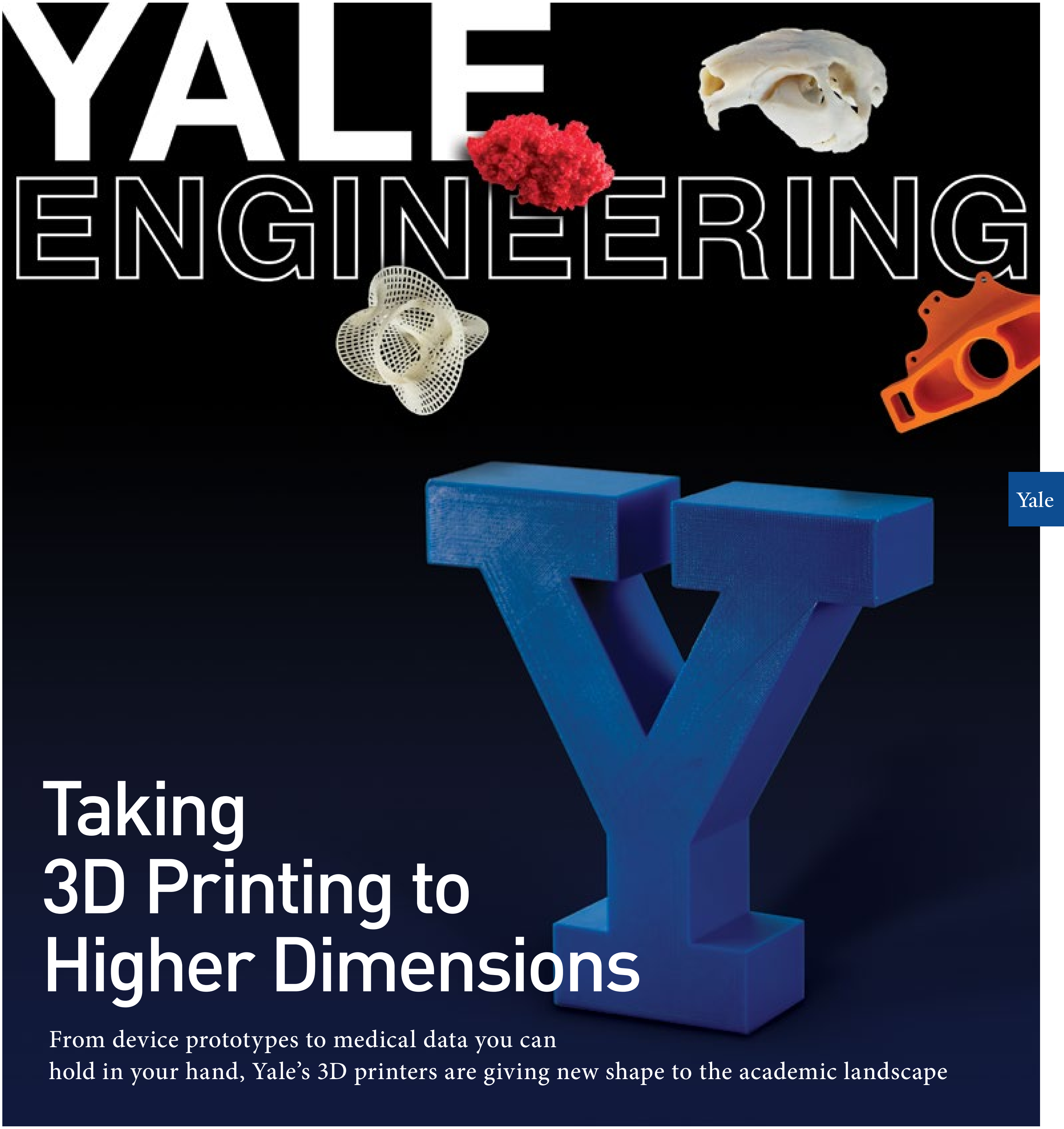
With three new hires, Yale's environmental engineering program is rising to the next level

A Better Class by Design

In the CEID's wildly popular courses, students innovate the campus around them

2014-2015

YALE ENGINEERING



Taking 3D Printing to Higher Dimensions

From device prototypes to medical data you can hold in your hand, Yale's 3D printers are giving new shape to the academic landscape

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

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FEATURES

Front Cover: *Yale Engineering's 3D printers produce objects of all shapes and sizes: (clockwise from far left) a string theory model, a folded protein, a rat skull, and an upright used to support Bulldog Racing's hybrid car body and components.*

Back Cover: *The world's first 3D printed neuron.*

EDUCATION   SUSTAINABILITY   INTERDISCIPLINARY   MEDICAL INNOVATION   TECHNOLOGY

YALE ENGINEERING 2014-2015

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Message From the Dean

Talk is cheap. And even so, there's just not enough talk about engineering from an educational perspective. It's no wonder that college-bound students often have limited, even misguided, notions of what an engineering education can offer them, especially at a place like Yale. It wasn't long after coming to Yale as Dean, to continue the revitalization of engineering at this magnificent university, that I came to appreciate our geographical placement on campus centered between the humanities on one end and the sciences on the other end. And so the idea of describing engineering as a *"bridge"* between the sciences and humanities came into being, and I talk about it all the time. I've found it to be a powerful and compelling way to describe the essence of engineering to prospective students. This metaphor also serves as a guiding framework for advancing our School of Engineering — so that we walk the walk, and not just talk the talk.

We are making all kinds of footprints as the School marches forward. Feet are tapping this fall semester as students in a new class are learning the physical principles of sound, composing music, and fabricating musical instruments in our Center for Engineering Innovation & Design (CEID). Meanwhile, the fresh tracks emanating from the French department belong to a professor of french literature, Morgane Cadieu, who is bringing her students into the CEID to make physical realizations of objects described in nineteenth century French novels. They seek to determine the level of technical information that is buried within convoluted literary passages written to describe various machines and manufactured objects associated with the industrialization of France. These are just two examples, but you will find many more in this magazine — stories that showcase how Yale engineers are using scientific principles to advance the human condition. *Vive le pont!*

T. Kyle Vanderlick
Dean, School of Engineering & Applied Science

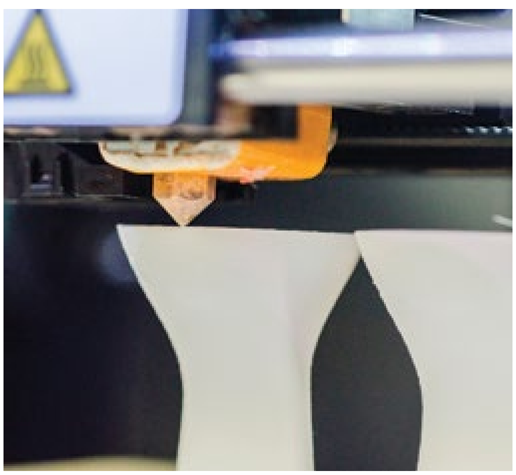
Year in Review

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

2013: September ›

Safer Chemical Design

Over the next four years, Julie Zimmerman, associate professor of chemical & environmental engineering and forestry & environmental studies, will lead a group of scientists developing computer software that helps molecule designers create safer, less toxic chemicals. “The idea,” said Zimmerman, “is to train chemists and toxicologists about these approaches early in their college careers so that chemists actually learn what toxicology is and toxicologists learn how to use their knowledge to help chemists.”



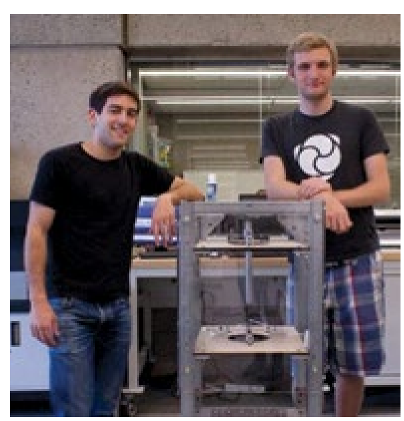
‹ 2013: October

Deployment in 3D

Aaron Dollar, the John J. Lee Associate Professor of Mechanical Engineering & Materials Science, is stretching the functionality of 3D printing to create parts with higher strength, multi-material components, and complete electromechanical systems. As recognized by a 2013 Young Faculty Award from the Defense Advanced Research Projects Agency, these advances could be used by military personnel for rapid field fabrication of necessary parts — even if the soldiers don’t have extensive backgrounds in engineering.

2013: November ›

Houston, We Have Success



Undergraduates Glen Meyerowitz and Patrick Wilczynski, both “alumni” of the Yale Undergraduate Aerospace Association, successfully tested a 100% reusable small-scale hybrid rocket engine. Using a hollowed out PVC rod (a polyethylene rod was also tested) as the solid fuel and nitrous oxide as the oxidizer, the rocket was more efficient, reusable, and safer, too. But to really get the rockets launching, Yale Entrepreneurial Institute’s Venture Creation Program stepped up to provide funding that could help Meyerowitz and Wilczynski use the technology for a completely self-contained rocket motor.

2013: December

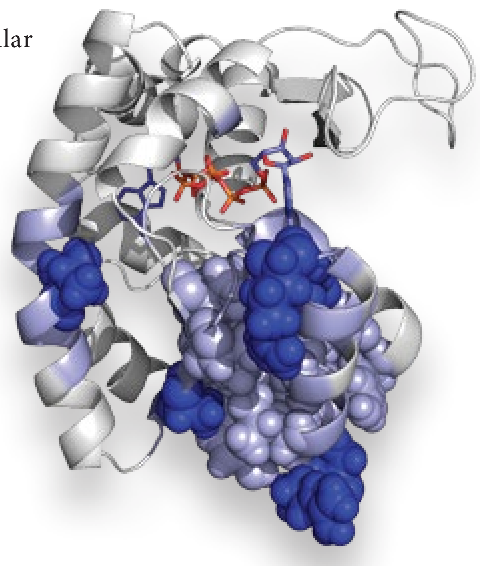
Asthma, Microbe by Microbe

Asthma development is associated with microbial exposure, though researchers have a hard time determining which microbes are to blame. That's why associate professor of chemical & environmental engineering Jordan Peccia turned to house dust. Using DNA barcoding — a next-generation method of DNA sequencing — to analyze the dust, his lab found that asthma development might instead be associated with lack of early-life exposure to large fungal diversity. Exposure to a large diversity of microbes, or at least to the "right" microbes, may inhibit development.

2014: January

Hot Enzymes

Like Goldilocks, enzymes don't tolerate extreme conditions: Too hot and the enzyme loses its structure; too cold and the enzyme's reaction slows to the point of uselessness. So, assistant professor of chemical & environmental engineering, biomedical engineering, and molecular biophysics & biochemistry Corey Wilson's lab began designing enzymes that function at specific temperature ranges. These enzymes could be used in the many industrial reactions that are performed at temperatures outside the enzyme's normal temperature range. Now, any temperature is just right.



2014: February

Cold Engineering

Undergraduates Levi DeLuke, Maren Hopkins, Dan Rathbone, Jack Rockaway, and Chris Segerblom created a device that could photograph the ice core crystals that serve as our best records of historic climate conditions. But as ice core scientists know, the cold storage temperature of -35 degrees C presents a serious engineering challenge. The design of the Yale device improves on current technology with higher-resolution cameras and more efficient imaging, and the team's device also incorporates at least one low-tech, albeit significant, improvement: The large components can be used while wearing gloves.

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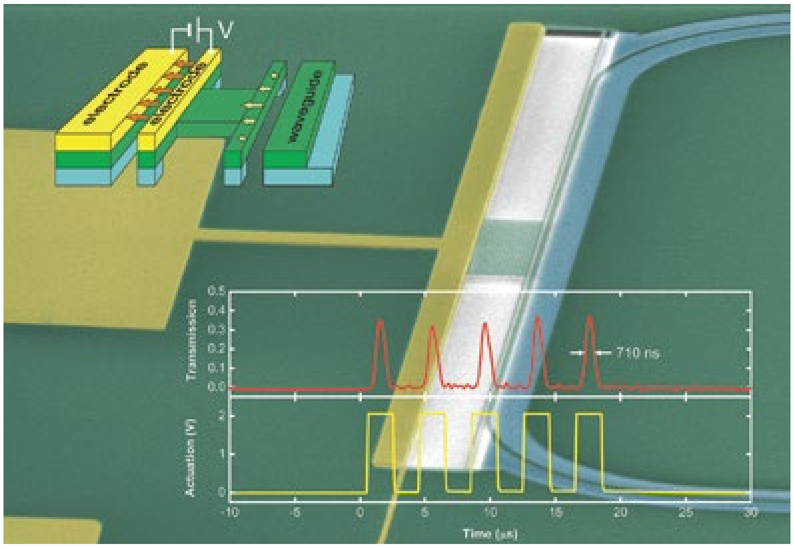
Year in Review



2014: March

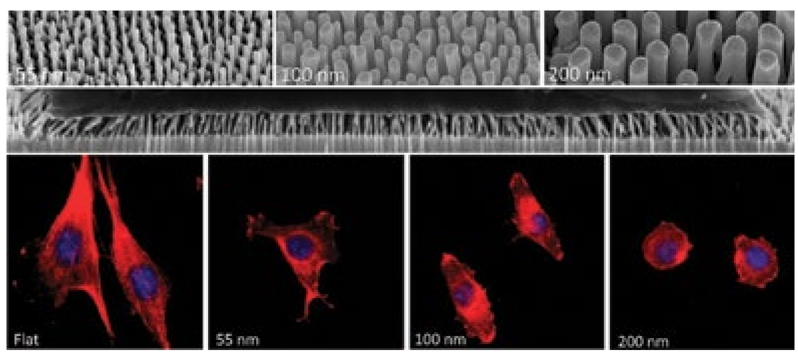
Light Communication

With modern communication relying more and more on messages encoded in pulses of light, fiber-optic cables now connect even the relatively close components inside a smart phone. But why bother with a cable? Associate professor of electrical engineering, physics, and applied physics Hong Tang developed a device that places the optics directly onto a silicon chip — a process that reduces coupling losses, enhances the device stability, and makes the entire system easily scalable. Tang's device encodes information in optical signals by modifying the phase of the light field.

2014: April

Engineering + Dance

Music! Lights! At Becton Engineering Center's Ground Café, Sho Matsuzaki's senior project controlled the speaker system and LED canvas with simple hand gestures, enabling an audience member "DJ" to change the musical texture and manipulate the LED screen's color and intensity with the wave of a hand. In front of it all, a live dancer grooved to the flexible beats in call-and-response sync with the DJ's musical commands. "Technology can show us an integral part of the human experience," said Matsuzaki. "That's the technology that is changing the world."



2014: May

Nanopatterned Implants

The worst outcome for a medical implant is to be rejected by the body's immune system. So associate professor of pathology and biomedical engineering Themis Kyriakides and professor of mechanical engineering & materials science Jan Shroers found a way to manipulate the immune system response using patterns of ultra tiny bulk metallic glass rods. Such nanorods — which are nearly a thousand times narrower than a human hair — could be fabricated on the surface of medical implants, leading to implants with lower rejection rates than even current "state-of-the-art" technologies.

2014: June

Intelligent Vehicles

The Yale Undergraduate Intelligent Vehicles team was named Rookie of the Year at the annual Intelligent Ground Vehicle Competition. The competition evaluated how each team's autonomous robotic vehicle navigated through a series of GPS waypoints, all while staying within a pair of white painted lines, avoiding traffic cones, and interpreting driving directions signaled by blue and red flags. The Yale team — newly founded this year — earned the award while competing against more than 40 international teams.

2014: July

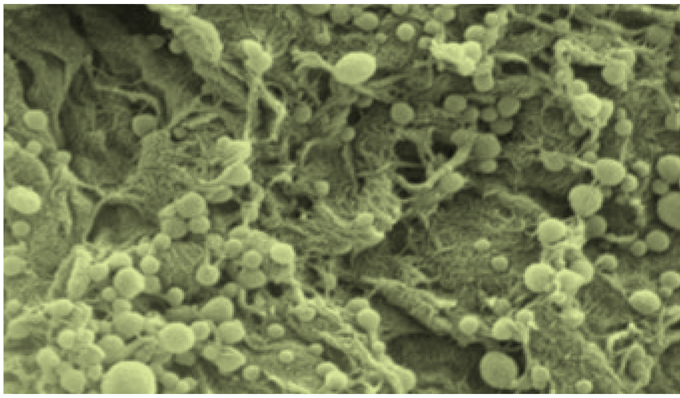
Soft Robots

Eric Dufresne, associate professor of mechanical engineering & materials science, began a new project to create novel, biologically inspired synthetic materials that can generate and respond to forces in the same way cells do. The project, a collaboration with scientists from Yale and the University of Chicago, will create materials that can autonomously stiffen, change shape, self-heal, or stretch in response to mechanical forces. Such materials could be used for wound healing or even for soft actuators that can control flexible robots.

2014: August

Cancer-Fighting Nanomaterials

The newest cancer-fighting tool isn't a new drug, it's your own immune cells. Associate professor of biomedical engineering Tarek Fahmy discovered that incubating immune cells outside the body on top of carbon nanotube-polymer composites could encourage growth by a factor of 200 within two weeks, at which point they can be injected back into the blood to boost immune response or fight cancer. Additionally, the nanotube surface could be seeded with molecules that signal to the growing immune cells which cells should be attacked, making for effective superkillers.

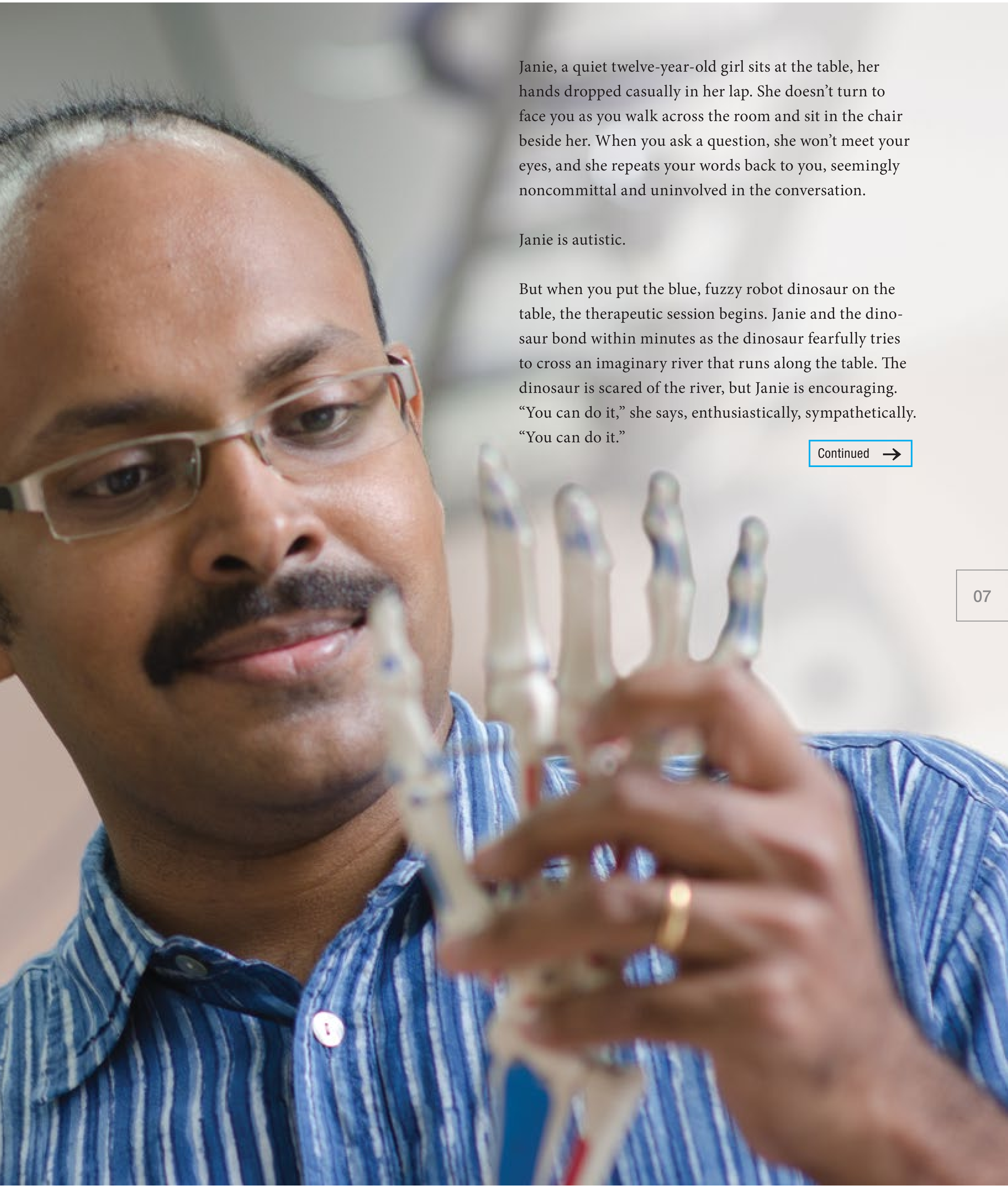


Yale

TECHNOLOGY

Robots that Teach Us About Ourselves

For new insights into how humans think and move, Yale Robotics is at the head of the class



Janie, a quiet twelve-year-old girl sits at the table, her hands dropped casually in her lap. She doesn't turn to face you as you walk across the room and sit in the chair beside her. When you ask a question, she won't meet your eyes, and she repeats your words back to you, seemingly noncommittal and uninvolved in the conversation.

Janie is autistic.

But when you put the blue, fuzzy robot dinosaur on the table, the therapeutic session begins. Janie and the dinosaur bond within minutes as the dinosaur fearfully tries to cross an imaginary river that runs along the table. The dinosaur is scared of the river, but Janie is encouraging. "You can do it," she says, enthusiastically, sympathetically. "You can do it."

Continued →

Brian Scassellati

Brian Scassellati, professor of computer science and mechanical engineering & materials science, designed this session to teach autistic children how to use appropriate tone of voice — one of many ways Scassellati's Social Robotics Lab uses technology to study people and improve their lives. "I'm more interested in people than I am in machines, and the robots we build all serve a purpose," he says. "That purpose is to help kids."

In that sense, the most interesting new behavior that children in such sessions develop is a deeper connection to people. Viewing a recording of a session similar to the one with Janie, Scassellati notes how the child keeps glancing over and making eye contact with the therapist, a behavior known as social referencing. "Before this moment, we've never seen him do that," Scassellati says. "And just five minutes later, he talks to the therapist. He's still orienting away from the table, but despite two-and-a-half days together of one screening test after another, this is the first time he's actually had a conversation with his therapist." In other words, while the child has successfully learned more about tone of voice, his reaction is positive in ways outside of the lesson's intent.

Scassellati does not yet understand why such changes happen — just that they do. "Believe me," he says, "we've tried so many different things over the years to figure out how it works." His experiments, conducted over the past 13 years, have shown a robust and repeatable positive response to robots in a surprising number of difficult situations for children: teaching nutrition to first graders, and English to first and second graders who speak Spanish or Portuguese at home; presenting options for children who deal with bullying; working with teenagers who have behavioral

disorders and anger management troubles. Using a $10 million grant from the National Science Foundation, Scassellati's lab has explored these expanding applications — and more — with a variety of robots, from the commercially available NAO humanoid robot to a custom-built dragonbot that sports wings fabricated by a Sesame Street puppeteer and a face displayed on the screen of a removable Android smartphone. "We need robots that can change and grow with the child," he says, "something that can be personalized to the particular child, something that can recognize what the child knows and doesn't know, and then something that can tailor the experience towards the parts they need. That's the goal."

As an example, he points to Keepon, a robot that looks like an 11-inch high, bright yellow rubber snowman. In one experiment, Keepon tells a story about the robot's imaginary dog, pausing to ask a child who speaks Spanish at home to translate a command for the dog from Spanish into English. Keepon analyzes the child's responses and can recognize which constructions are fully understood and which are not; Keepon then tailors the story to concentrate on the constructions the child doesn't yet fully grasp. "It's personalized tutoring," says Scassellati, adding that initially the child responds quickly because he wants the fun of interacting with the robot. However, after a week of similar sessions, the child learns where the difficult issues are. "And then," says Scassellati, "he works *really* hard, even if he still doesn't get how to overcome those issues. The excitement doesn't wear off, but he's willing to put that excitement on hold in order to work hard for the robot, which is what we want."

SEAS's newest roboticist, assistant professor of mechanical engineering & materials science Madhusudhan Venkadesan, also studies people, though as a biomechanist his particular interest is in how each part of the human body — muscles, tendons, joints, nerves — functions together. For example, one of his experiments explored how our fingers tap the

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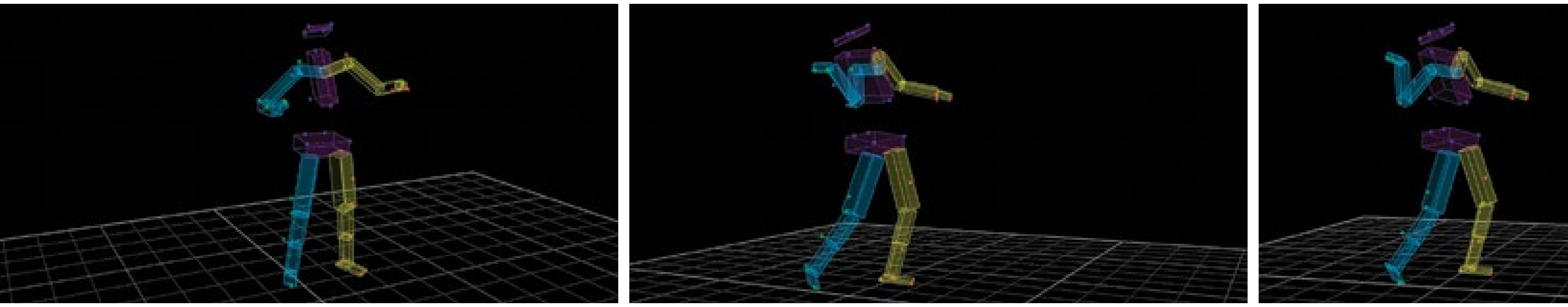
NAO humanoid robot (opposite page), Keepon robot (left), and Dragonbot robot (above)

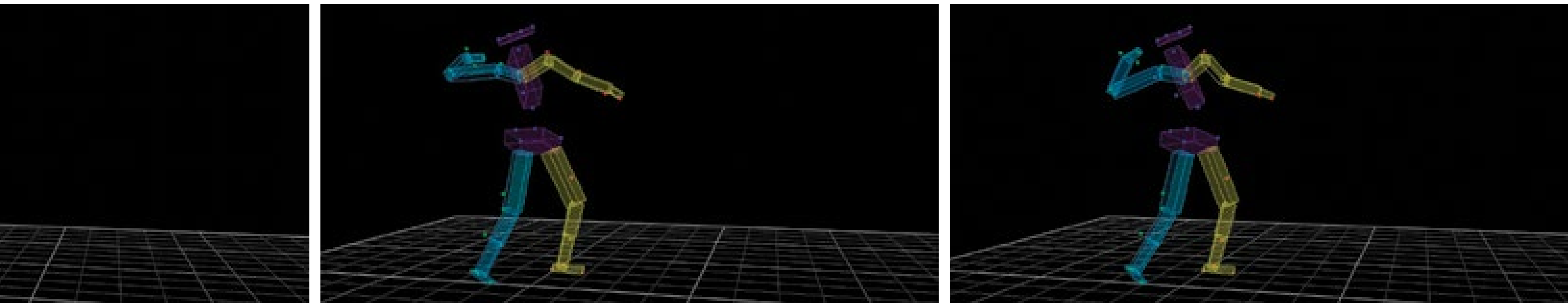


surface of a tablet or smartphone. Mechanically, the task seems simple, but in actuality, touching the screen requires a tricky bit of muscle coordination to shift from pushing your finger forward to holding your fingertip still: switch too early, your finger lands in the wrong place; switch too late, your finger's going to slip. "It turns out people are extraordinary estimators of when contact is going to happen and they switch the strategy 60 milliseconds before the finger lands on the surface," says Venkadesan. "The timing is incredibly precise."

As a larger part of his lab's research, Venkadesan has observed similarly precise neuromuscular coordination in the human ability to throw. Throwing well played an important role in shaping human evolution through our ability to hunt with a spear, and no species can throw as well as humans — even chimpanzees are incapable of throwing faster than 20 miles per hour. Venkadesan explores the foundations of our throwing ability, asking to what extent it's determined by our large brains or by the strength and flexibility of our musculature. "Understanding the mechanical, muscular, and neural basis of high speed throwing is clearly pertinent for sports such as baseball pitching," he says. "Pinpointing the ligaments, tendons, and muscles that experience high stresses during throwing could help us understand and perhaps reduce injuries suffered by even the most highly skilled pitchers."

At Yale, Venkadesan plans to build robots using such insights about human actions, human musculature, and even human evolution — creating machines that emulate human behaviors like tapping a screen or throwing a baseball, though without necessarily mimicking the human body's geometric structure. "By studying and distilling the complexities of human action," he says, "we can learn how the evolved and specialized morphology of humans makes us not only good at what we do, but also energy efficient while doing these things. Then we try to implement these principles on robots." His goal is twofold:

Left: *Madhusudhan Venkadesan;* Above: *When tapping a surface, precise timing produces a stable finger (left) and incorrect timing produces a buckled finger (right)*



Above, left to right: *High speed imaging for analysis of throwing biomechanics*

create better, more useful robots by applying the design principles learned from studies of human subjects; and use insights from the mechanisms of successful robots to sharpen the understanding of how neural control and evolution work together to help humans move in efficient and stable ways. For example, the principles that enable a robotic finger to tap on a tablet surface — perhaps accomplished using a human-inspired approach — might be used in industry to apply stickers to fragile objects, in prosthetics to create a more responsive robotic hand, and in medicine to help regain dexterity after injury or disease. “It’s humans helping robots helping humans,” he says.

In addition to looking at hands and arms, a large focus of Venkadesan’s research — and robotic inventions — centers on the foot. Almost a quarter of the human body’s bones are located in the feet, making it pliable enough to accommodate the shifting balance of walking and running on diverse and inconsistent terrains, while still rigid enough to support weight without injury. Looking at this interplay of flexibility and stiffness, Venkadesan’s research seeks to understand how the bones, muscles, tendons, and even signals from the nervous system contribute to maintaining stability during locomotion, especially while running at a marathoner’s pace.

Robotic feet built by Venkadesan will contribute to his research by imitating select elements of the human structure and neuromuscular interactions while avoiding direct reconstruction of all the human foot’s intricacies. “Each robot has to have a well-defined purpose, a single goal that answers a specific question,” he says. “Although the structure of the human foot is incredible, is flexible and versatile, trying to replicate it in complete detail would likely result in me tweaking parameters for the rest of my life — and still without getting anywhere.” Instead, Venkadesan might build a robotic foot just to study how the internal structure of the foot and the way it lands on the ground affects its compliance and flexibility. Stability could then be examined by attaching this foot to simple robots that run on rough ground and soft ground, sand and cobblestone. A different robotic foot could do the same tests to show how changes in morphology or mechanical properties of the foot affect running. Venkadesan then starts the cycle over, each foot spurring new questions about human body mechanics.

“Building a robot is a more definitive test of a design principle than anything I can do in biology,” Venkadesan says. “If I believe this ligament or that tendon is responsible for energy efficient running, or for stability, I can’t remove the ligament in your body to test my theory. But with a robot, I can. I can do that, and I can use any insights from that to better understand you while you’re running.”

And especially as the number of runners involved in recreational sports grows, Venkadesan hopes his insights can help people exercise more safely. “Every marathon I see, it’s this huge mass of thousands of people running, and many of these runners will go on to suffer injuries that can affect locomotion and ultimately cause significant lifestyle problems,” he says. “That’s why I want to better understand the body, and perhaps suggest ways to prevent such injuries. I believe learning to design effective robots can teach us about ourselves.”

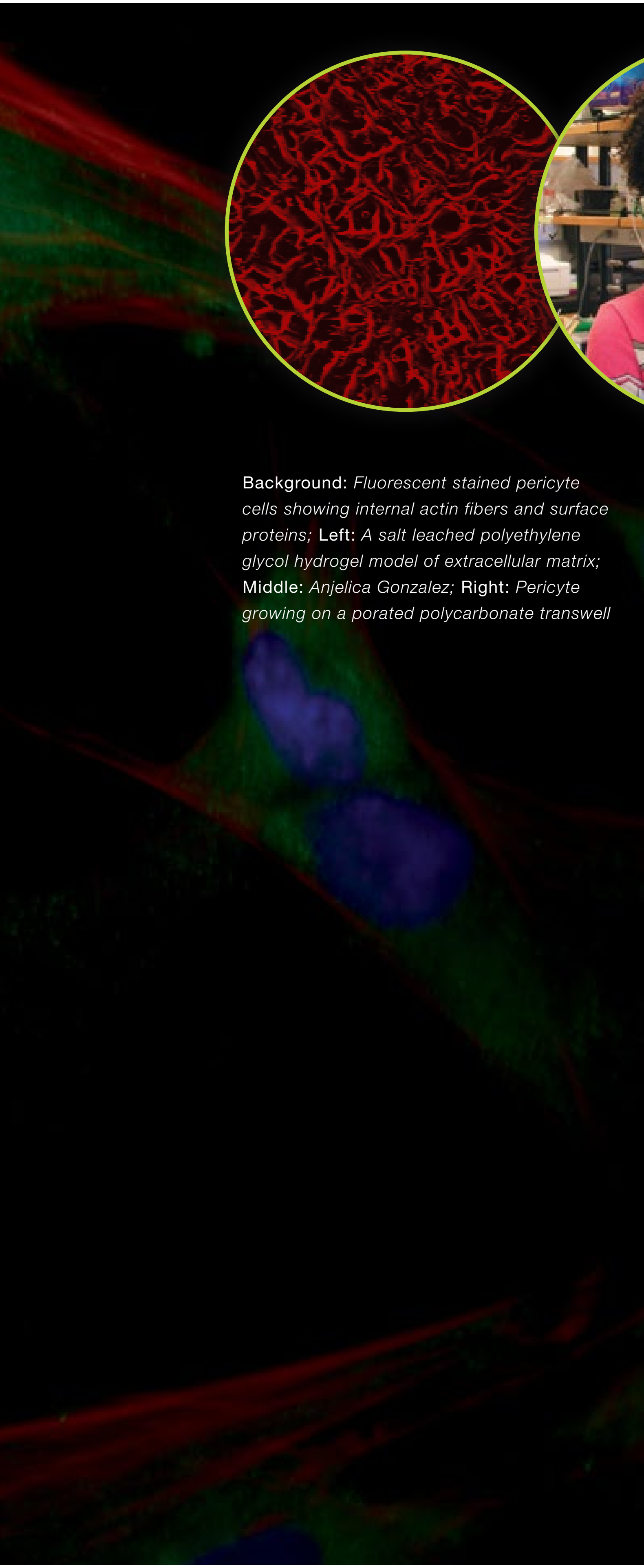
Whether tapping touch screens and walking on cobblestone roads, teaching nutrition and commanding imaginary dogs, the robots created by Venkadesan and Scassellati are already providing answers to that question: They’re enlivening our classrooms, demystifying our bodies, and ultimately showing us a path over our individual limitations, towards our best human selves.

Yale

MEDICAL INNOVATION

Going with the Flow

Anjelica Gonzalez is opening new pathways through her development of humanized blood vessels



Background: *Fluorescent stained pericyte cells showing internal actin fibers and surface proteins;* Left: *A salt leached polyethylene glycol hydrogel model of extracellular matrix;* Middle: *Anjelica Gonzalez;* Right: *Pericyte growing on a porated polycarbonate transwell*

Flow. It's how water moves through irrigation ditches into the fields, and how blood moves through your veins. It's the transmission of information from teacher to student, and the sometimes startling movement from one career path to another. It's everything converging in one direction, towards one goal.

"Flowing" is also how you might describe the goals for the lab of Anjelica Gonzalez, the Donna L. Dubinsky Assistant Professor of Biomedical Engineering. "For many researchers, there's a fixed line between hardcore basic science and hardcore application and therapeutic design," she says. "But I always want my lab to be a one-stop shop, with resources and information moving freely back and forth between basic science and translation. Everything we learn helps us improve our models for basic science, and it also informs how we should improve design of therapeutics."

Foundational to this task are the lab's two artificial tissues, both of which have already advanced the study of inflammation. "Inflammation research has basically been at a standstill for a few decades," says Gonzalez. "Scientists figured out long ago many of the molecular interactions that lead to leukocytes getting stuck on the vessel lining, then crawling through the vessel wall and into the tissue. But the vessel is much more complex than we'd previously thought."

To study such complexities, Gonzalez's "humanized vessel," which exists outside the body, is uniquely engineered with multiple human cell types, an advance that enables Gonzalez's team to evaluate how the cells signal each other

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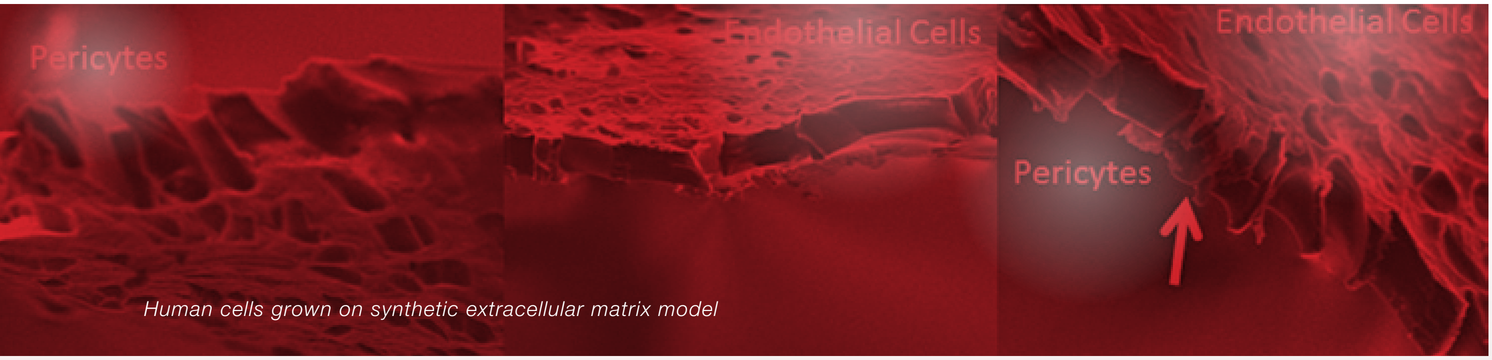


Human cells grown on synthetic extracellular matrix model

through cell-cell contact, the release of soluble signals, or the deposition of the connective proteins. The model has already yielded insights into how leukocyte recruitment — the basic mechanism behind inflammation — is influenced by communication between the cells lining the inside of the vessel and the cells lining the outside of the vessel. "We're already working on the next generation," says Holly Lauridsen, a doctoral candidate in Gonzalez's lab. "So we're making everything even more physiologically relevant, taking it one step closer to what an actual human vessel is like instead of an artificial system."

Although also designed to better our understanding of complex cellular interactions, Gonzalez's model of the body's "extracellular matrix" (ECM) is notably different from the humanized vessel because it's constructed entirely from polyethylene glycol, a polymer commonly used in medicine because of its compatibility with the body. This material, however, is still similar to the usual composition of ECM, which is made up of nonliving connective tissue like fibronectin, collagen, and laminin. As well, Gonzalez's artificial ECM has the significant added capability of being structurally, mechanically, and biochemically tuned to replicate not only healthy tissue but also various states of diseased tissue.

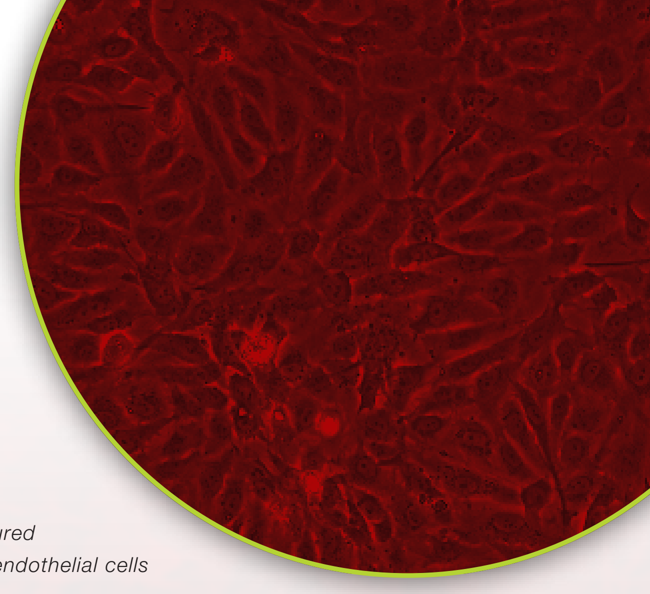
But while the ECM model has been used for basic investigations into how cells crawl in tissue and replicative substrates, it's also the key component in therapeutics for wound healing. As a biomaterial for healing large wounds and burns, it mimics the amniotic membrane that surrounds the sac a fetus develops in, a tissue already commonly used for healing skin and eyes because it heals without any scar. "The reason we have scars everywhere," Gonzalez says, "is because a lot of immune cells go in to clean up the wound bed, releasing enzymes that slow the growth of the skin cells and of the vessels. This material

"Artificial ECM has the significant added capability of being structurally, mechanically, and biochemically tuned to replicate not only healthy tissue but also various states of diseased tissue."

suppresses that immune response so that you don't have a lot of leukocytes invading, gumming up the works. Instead, the body is able to allow for new vascularization, reduced inflammation, and wound closure in a much more rapid fashion than traditional models."

Combining basic science and engineering principles, always trying to integrate that next level of complexity — it's perhaps not surprising to learn that Gonzalez had an early interest in problem solving and puzzles. More surprising, though, is the fact that Gonzalez discovered her passion for solving biomedical problems almost by chance. "I went to my undergraduate college to get an irrigational engineering degree — as in irrigation systems, sprinkler systems, and water flow," she says. "I had grown up in a small valley outside Las Vegas, where in order to run the irrigation systems that watered the crops, my grandfather had to check the reservoir's water levels every day of the week, multiple times a day, day and night, summer and winter. Even as a high schooler, I realized that, in regards to both man hours and to water, there was probably a more efficient way of organizing the system."

But her future in irrigation was not to be. In the spring of her junior year, she found an advertisement for a summer research opportunity while looking for a summer job. "Long story short," she says, "without knowing that it was actually a very competitive summer medical research



Above: *A cultured monolayer of endothelial cells*

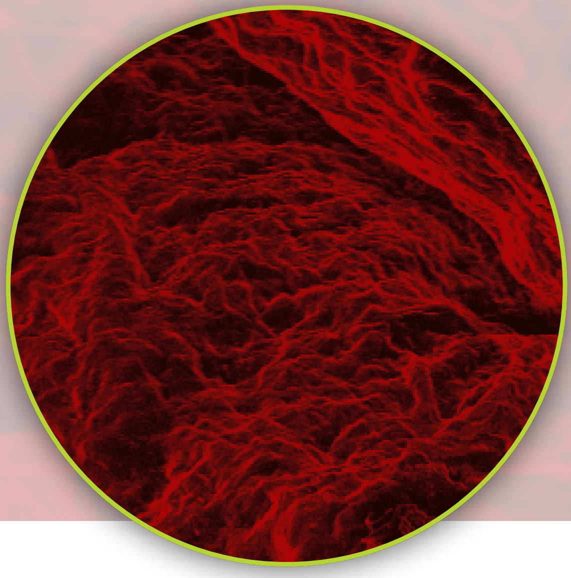
Below: *Synthetic extracellular matrix model containing human proteins*

training program at Baylor College of Medicine, I applied, and somehow I got in.

"I had no idea what I was doing, and didn't really know how irrigational systems were going to contribute to biomedical research. But they put me in a lab specifically about lung mechanics and they asked me to use computer programming to simulate the inflation and volume change in the lung when the diaphragm isn't functioning well. And I thought, 'Mechanics! I can do this!' And I remember it was my first time thinking that something I'd learned in the field with my grandpa could be applied to something other than irrigating fields."

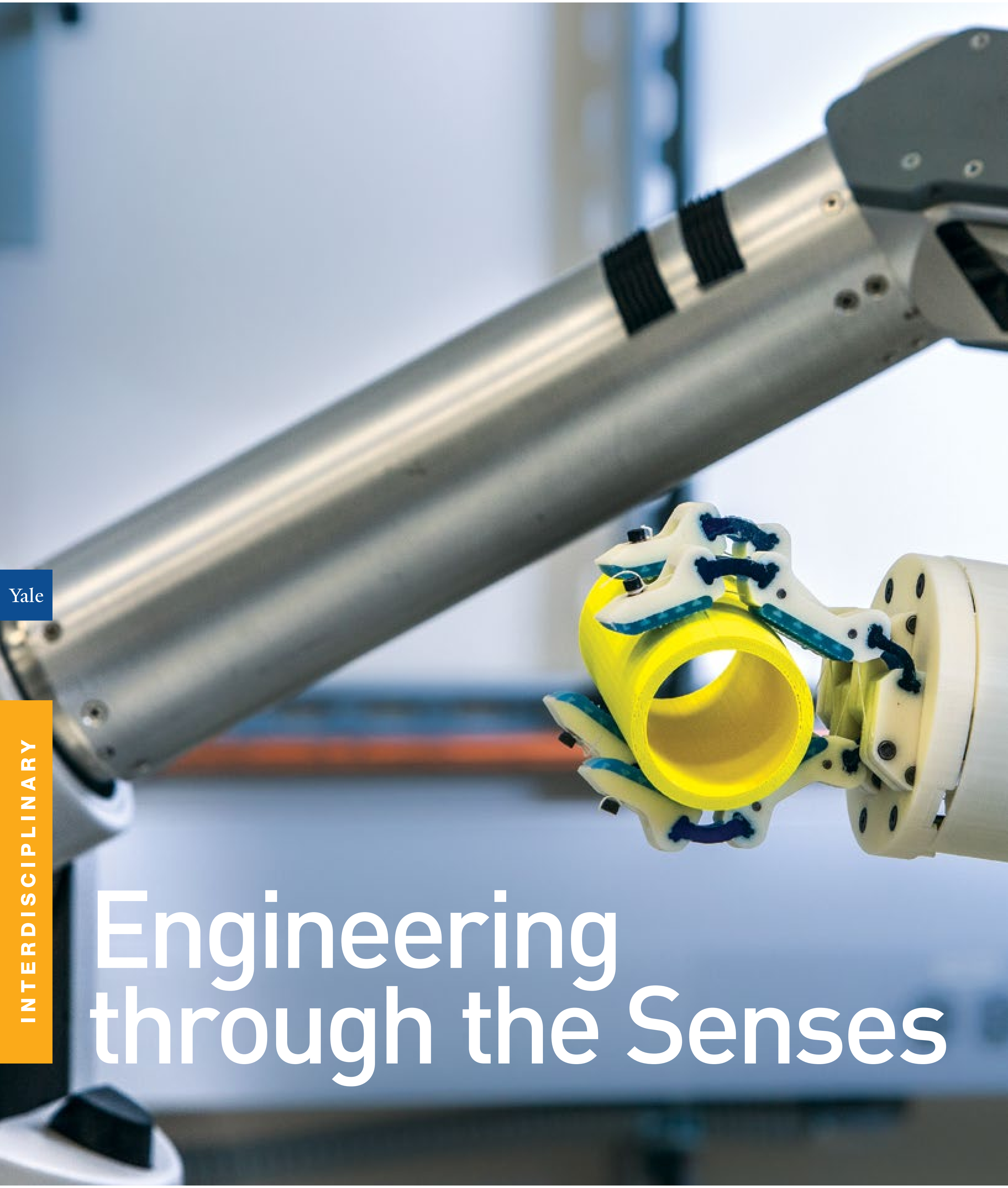
Gonzalez — who was recruited to join SEAS just after finishing her doctorate — keeps this memory fresh in her mind, a reminder that sometimes other people are more insightful than she is about what she can accomplish. In fact, it's a humility that subtly informs her entire approach to her career. "Through that experience, and a few others along the way, I learned that it was OK to expose my own vulnerabilities," she says, "and I think that knowledge changed my interactions with my colleagues, and with my peers, and with my collaborators. I realized that I could have a conversation about my struggles and about real life stuff, and I didn't have to feel like any less of a scientist because of it."

In fact, Gonzalez has opened the door for such talks among her graduate students. Although each of her students comes from a quite different background and is working on fairly different research, she encourages open suggestions and resource sharing during weekly lab meetings. "We have to be very collaborative in our own way, with our projects but also with our time. So I think it's been great to have students willing to share their expertise," she says.



Lauridsen, Gonzalez's doctoral student, agrees: "Everyone talks to everyone else about the projects, so you're constantly getting feedback even though a lot of the projects are really different in the day to day. But we still collaborate a lot, at least with sharing information. For example, one of the other grad students is doing a lot of work with cancer lines and exosomes, which has nothing to do with my work. But a couple of weeks ago, I was struggling with one of my assays, and because he had done something similar, he was able to give me a bunch of tips. So even though the application might not be the same thing, a lot of the fundamental methods are really similar."

And Gonzalez wants them to keep thinking that way after they've graduated. "Perhaps encouraging such collaboration is just one more way that I want my lab to advance science, one more way I want us to contribute to both basic science and translation," she says. "The way I see my students' research programs is that we have people who are developing new tools for the clinic, and we develop those things for the clinic by becoming better informed about the basic science of how cells differentiate into different kinds of cells, or how tissues becomes inflamed. And we do all of that under the same roof, one aspect flowing into the next."



INTERDISCIPLINARY

Engineering through the Senses

As the tools of perception, our first knowledge of the five senses is intuitively experiential: children delight in seeing, smelling, tasting, touching, and listening to the world around them, often with no thought for the sensory tools themselves. But as adults, many of us interrogate our senses more fully, through ophthalmological exams and wine tastings, fire-walking and avant-garde concerts. For scientists, such interrogations manifest more formally, perhaps in experiments to determine which regions of the tongue can differentiate sour from bitter, or in analyses of how our sense of smell diminishes with age. For SEAS faculty, the senses also provide inspiration for new devices that can help us overcome our limited perceptions and elucidate the mysteries of human sensation.

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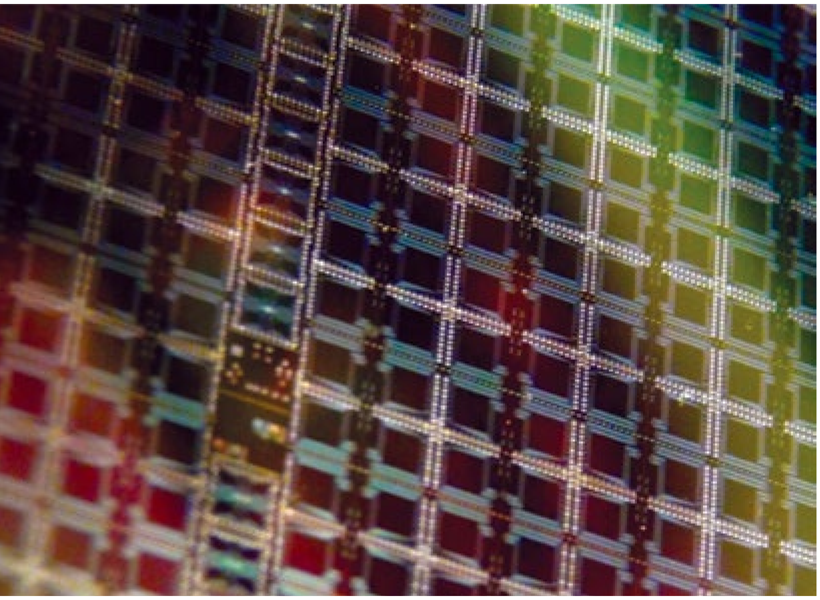

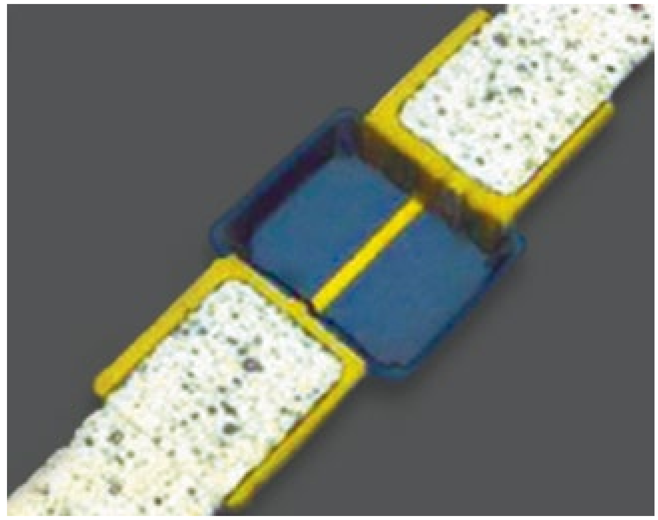

Left: *Reed's nanosensors on a wafer.*
Right: *Close-up of Reed's nanosensor.*

Sniffing Out Cancer

Nanosensors in Mark Reed's lab can identify a single desired target molecule, such as a particular disease marker, amid a full bouquet of cells, proteins, and ions; each nanosensor is like a technological nose sniffing out a particular aroma in a complex perfume. "We do the same type of recognition that the human nose does," says Reed, the Harold Hodgkinson Professor of Electrical Engineering, "except we do it in fluids, and we quantify the results electronically."

Reed's latest nanosensors, made from silver nanowires modified with self-assembling molecular monolayers that act as surface receptors, are particularly good at detecting a broad range of biological and chemical species. For example, sharks have a legendary sense of smell, with some species capable of detecting prey-emitted chemicals in concentrations as small as one part per ten billion — the equivalent of a single drop of those chemicals in an Olympic-sized swimming pool. But while such a response is impressive, Reed's nanosensors are orders of magnitude more sensitive, with the ability to detect a single grain of salt in the water of 1000 Olympic-sized swimming pools.

Perhaps more than their sensitivity, however, the nanosensors are notable for being reusable. Going against the common nanosensor construction strategy of using covalent bonds to bind the surface receptors to the nanowires, Reed's nanosensors utilize supramolecular interactions — non-covalent bonding forces inspired by biological systems — to create a densely packed self-assembled monolayer that attaches to the nanowire surface and that can complex with a variety of targeted hydrophobic organic molecules. Once the nanosensors have been triggered, the surface receptors can be easily rinsed and reattached, a unique technological development that not only has strong economic benefits but also permits accurate calibration prior to measurements and repeated use of the same calibrated device. "For example, a doctor could calibrate the sensors prior to measurement — and then use the same calibrated device," says Reed. "So you have better repeatability, better reliability, and a longer sensor lifespan. It's like being able to take another sniff if you weren't sure the first time around."

This combination of sensitive detection and regenerative capability makes Reed's nanosensors ideal for the clinical environment, where their ability to identify even a miniscule amount of pathogens in the body could mean the difference between discovering a small handful of cancerous cells in the blood stream and other tests discovering that same cancer spread throughout the body a year later. "These sensors measure what's in your blood, sorting through the proteins and ions to find, say, the earliest hint of cancer biomarkers," says Reed. "With their level of sensitivity, all you need is a little pinprick and just like that, we can tell you all the things going on with you."

Collision-Free Hearing

Professor of electrical engineering Roman Kuc is well known for his love of bats, with research often inspired by echolocation. Perhaps it's only natural, then, that in addition to sonar, Kuc would eventually become interested in flight. "As our understanding of bat sonar improves, we start to see new, interesting avenues for applying that knowledge," says Kuc. One avenue he identified is the unmanned aerial vehicles (UAV) that have recently surged in popularity among RC enthusiasts — particularly the quadcopters, which because of their ease of control, high maneuverability, and ability to hover have had significant commercial applications in the field of aerial photography. But as quadcopter use increases, the airspace might become crowded, increasing the chance of UAV collisions. "In thinking about this problem," says Kuc, "we discovered that what quadcopters needed was a sensor to prevent collisions."

And so Kuc turned back to his favorite subject: bats. He needed the quadcopter to be able to gather all the necessary information for 3D localization, including range, elevation, and azimuth. Such information could possibly be acquired through a ping sonar emitter and some "ears" — in this case a type of integrated chip, preamplifier, and microphone known as a MEMS microphone — to record the returning echo. But the trouble was in the placement on the quadcopter. "Have you ever wondered why your cat has its ears pointed outward naturally, but bats do not? It turns out that if my ears are pointing straight ahead, then when I turn my head, both ears decrease in amplitude," he says. "But if I have them slightly turned out, then as I

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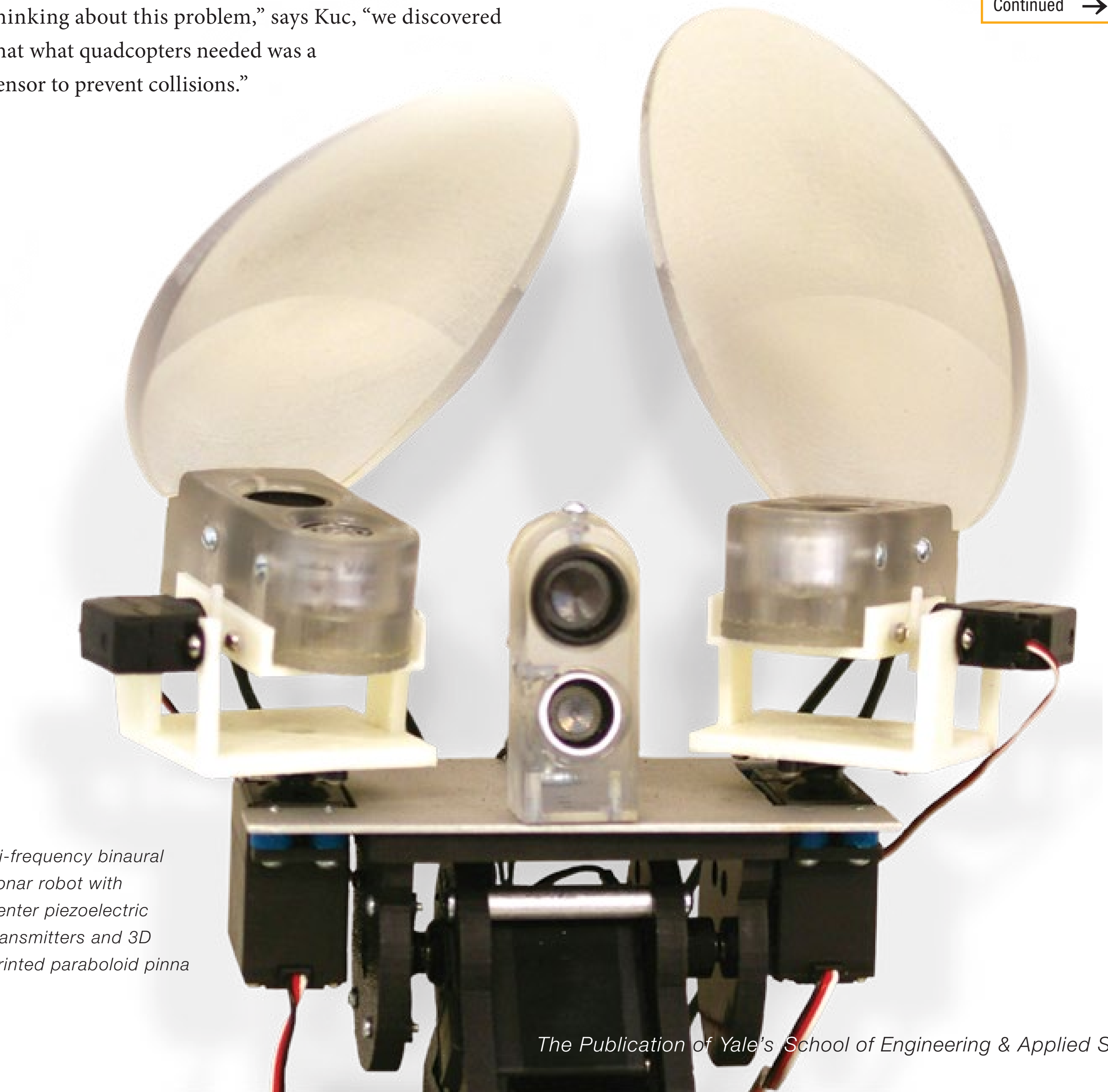


Bi-frequency binaural sonar robot with center piezoelectric transmitters and 3D printed paraboloid pinna turn from the source, one ear gets louder and the other gets quieter."

That information enabled Kuc to determine not only the optimal placement on the quadcopter for these microphone "ears" but also that to get all the information he needed, he'd actually need three of them. "Comparing the signal strength for each microphone ear helps us locate the object — if the left one has a stronger signal, the object is on the left. The problem is that if you have only two microphones side by side and they pick up the same strength of signal, there's no way to tell if the object is higher or lower." But if you add a third receiver, placed two inches higher, the extra data point fills in the blanks.

"And that," says Kuc, "is how you hear an object's location precisely."

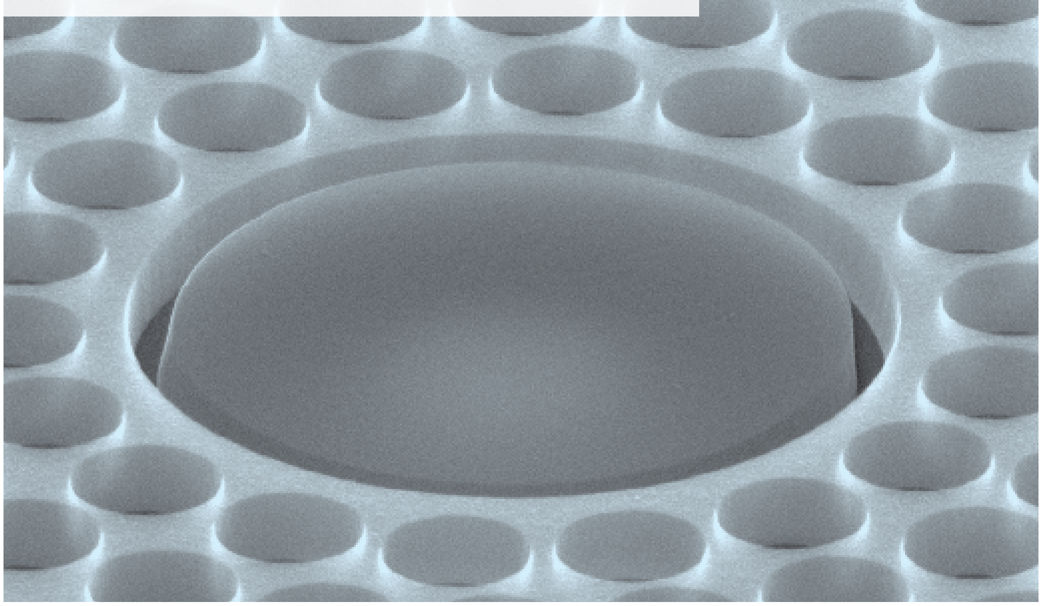
Seeing in the Near Dark

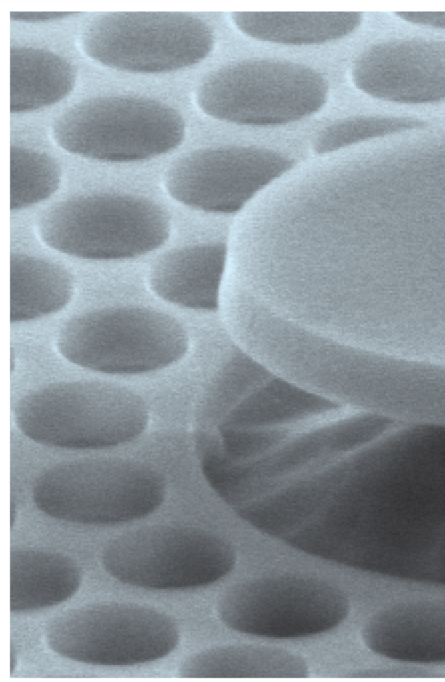
In a whispering gallery, even the quietest sounds can be heard across great distances, the acoustic waves following the curve of a wall or domed ceiling. Operating on similar principles, microdisk resonators are nanoscale discs that capture and trap light waves, heightening what we see instead of what we hear. However, though the high quality light they capture makes them useful components in optical communication, biosensing, and nonlinear optics, the scale of such devices is limited because light travels in a straight line and resists being bent. Therefore, as the disk becomes smaller and the internal reflection increases, the quality of the light degrades and may start to leak out from the edges of the resonator.

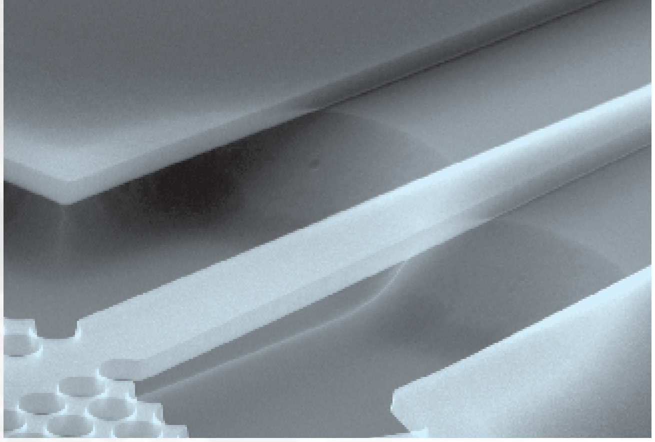
That limitation doesn't sit well with Hong Tang, an associate professor of electrical engineering, physics, and applied physics who leads the Yale Nanodevices Laboratory. "There is sometimes a trade-off between being small and being powerful," says Tang. "But to make advances in optomechanics, we need both qualities."

Tang's solution is to surround the microdisk resonator with a photonic crystal, a nanostructure that uses an arrangement of regularly repeating regions of high and low electric permittivity to prevent light photons from passing through — an arrangement that looks somewhat like a sunflower. Light can only enter and exit the resonator by traversing the photonic crystal along narrow raised waveguides, essentially trapping the light until it is of

Left to right: *States of central acid-etched microdisk resonator*







Microdisk resonator in a sunflower-type photonic crystal

use. "With the photonic crystal, the light has nowhere to go, and it will stay there for an extended time, even if you turn off the source," says Xufeng Zhang, a doctoral student in Tang's lab. "And this makes the energy of the light go higher, so you have the possibility to do things that were impossible before, like a very high sensitivity for detecting nanomechanical motion."

In that sense, this incredibly small device accomplishes Tang's mission — without sacrificing light quality, the microdisk resonator at the center, for example, has a diameter of only 2.32 microns, just barely larger than the 1.55 micron period of infrared light used by most fiber optic telecommunications systems. Each hole in the photonic crystal is only a single micron in diameter, and the entire device measures just 20 microns from end to end. The entire device is created from a slab of silicon sitting atop a silicon dioxide substrate. Undesired portions of silicon are etched away with acid, cutting away all of the silicon dioxide from below the device except for an extremely narrow column near the center. "The wet etching is precisely timed such that the photonic crystal is fully released while the microdisk still has a center pedestal underneath for support," says Tang. "We have to time the acid right or the disc will fly away." In fact the only thing connecting the photonic crystal to the outer bank of the silicon slab are six specially designed clamps that relax the material stress, which would otherwise cause deformation and degrade the device performance.

The result is a device that is both small and powerful, enabling the amplification of a light source while pushing the boundaries of how small a microdisk can be made.

A Helping Hand

With a mix of 3D-printed parts and flexible resin, Aaron Dollar's robotic hands are like no other hands on the marketplace. "We try to keep things as simple as possible," says Dollar, the John J. Lee Associate Professor of Mechanical Engineering & Materials Science. "In our

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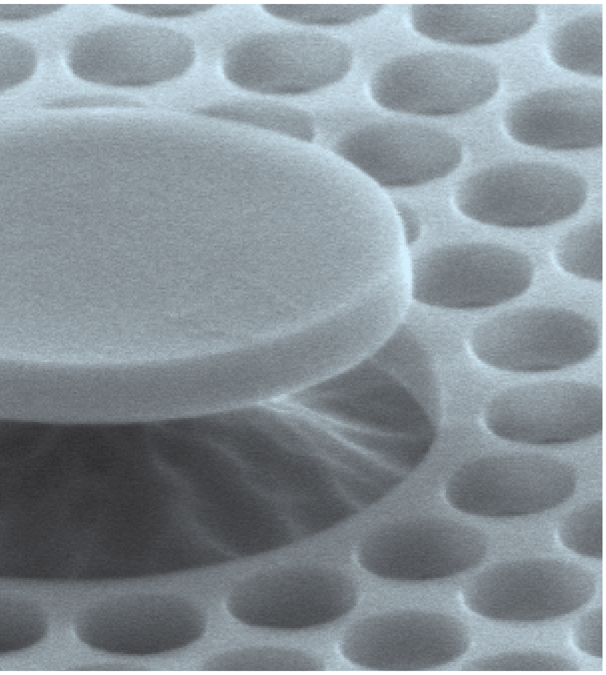
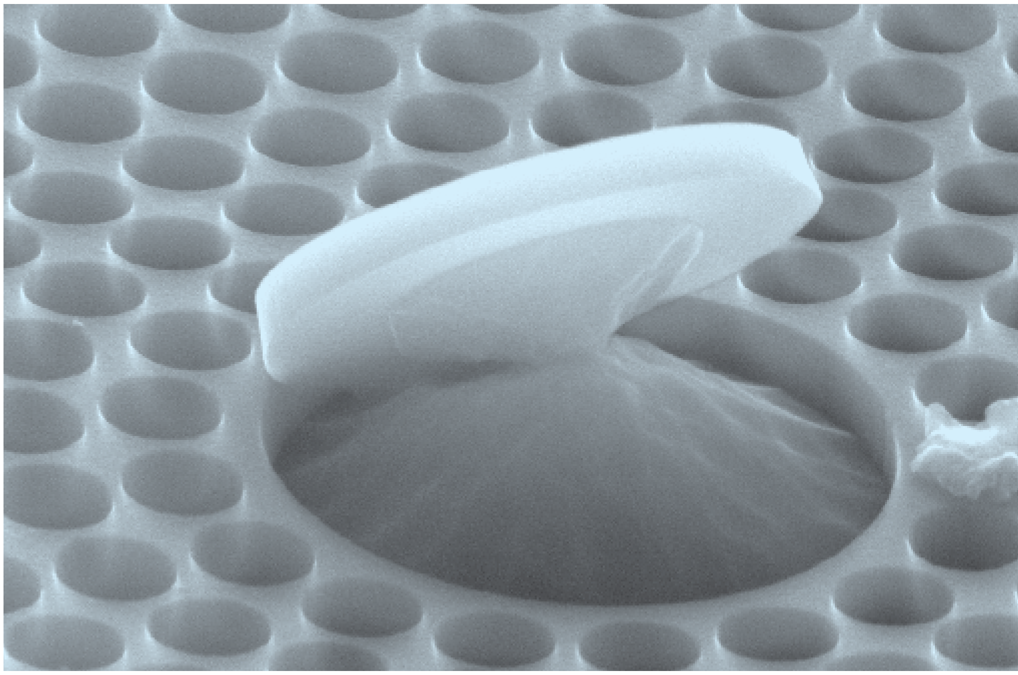


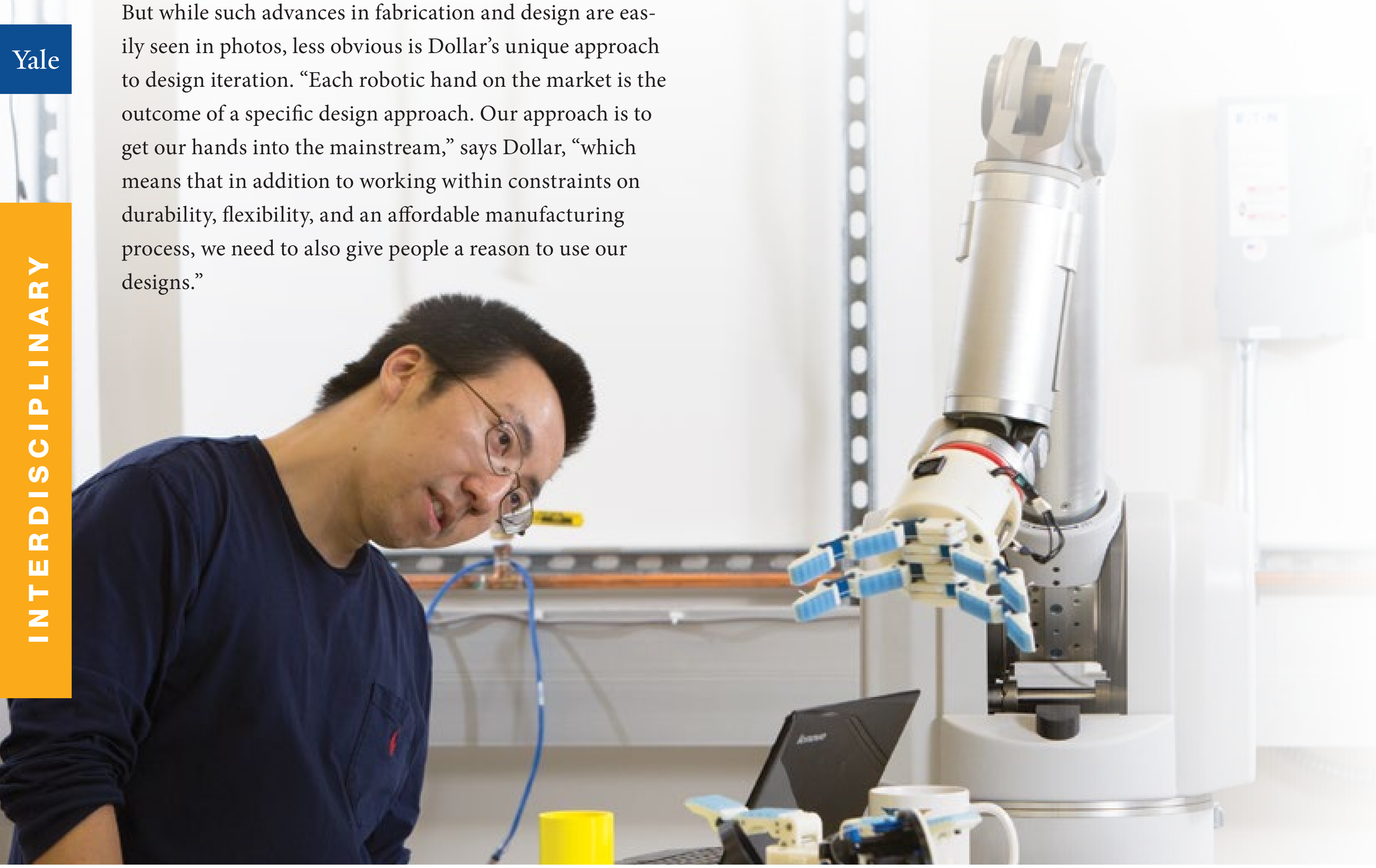


philosophy, robotic hands need to perform real-world tasks and grasp real-world things — and they need to do so without significant expertise or risk of breakage."

Much of Dollar's innovation has therefore focused on the grasping mechanism itself, particularly in the use of underactuated fingers, which have fewer motors controlling the finger movements than there are possible motions among the finger joints. In most of Dollar's robotic hands, for example, each finger is controlled as a single unit, with only one motor and one tendon — despite each finger having two or three joints. As a result, the fingers grasp much in the same way a human hand might catch a baseball: as the fingers close around an object, the base of the fingers are the first part of the hand to touch the object, and the tension in the tendon then curls the fingertip around the object to complete the grasp.

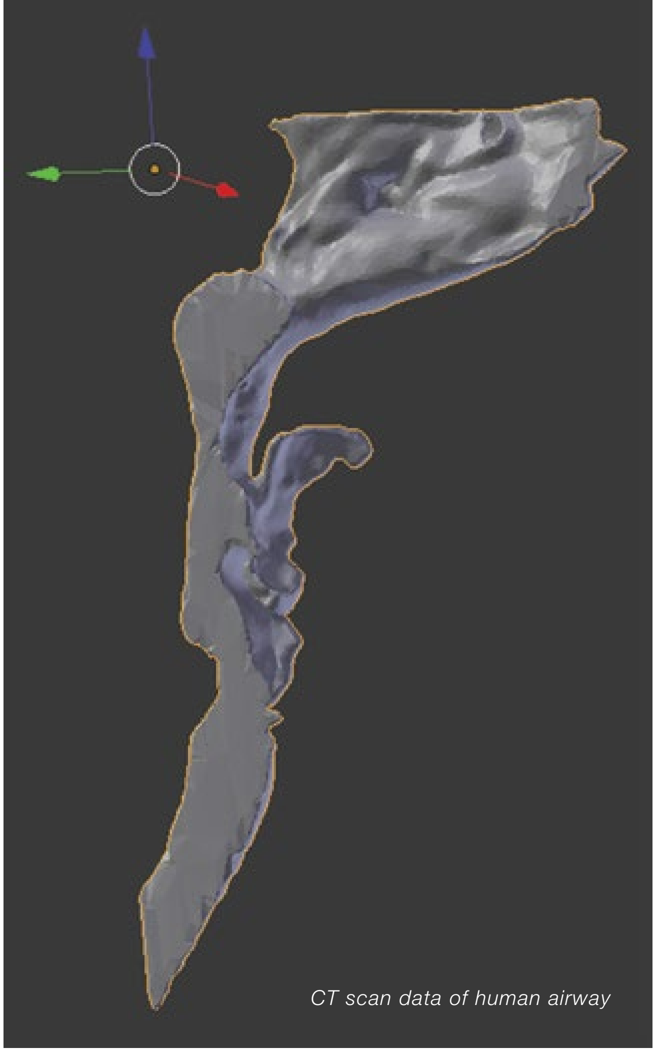
Grasping technique of underactuated robotic hand

But while such advances in fabrication and design are easily seen in photos, less obvious is Dollar's unique approach to design iteration. "Each robotic hand on the market is the outcome of a specific design approach. Our approach is to get our hands into the mainstream," says Dollar, "which means that in addition to working within constraints on durability, flexibility, and an affordable manufacturing process, we need to also give people a reason to use our designs."



The result is the OpenHand Project, a movement to advance the design of robotic hands through inexpensive, open-source rapid prototyping. As part of the project, roboticists interested in using hands from Dollar's lab can freely download detailed instructions and 3D files from the OpenHand website to build whichever design best fits their needs; moreover, OpenHand users are encouraged to modify the plans as they see fit, then offer feedback on everything from the functionality to the manufacturing process. Dollar's lab continually responds to such feedback through new iterations to the designs and the building instructions, hopefully making adoption as easy as possible.

"Open source can be difficult because you not only need users, you need users who talk to you," says Raymond Ma, a doctoral student in Dollar's lab. "This approach to robotic design has never been done before, and we've been lucky enough to have a relationship with a number of labs using our hands and helping us refine the design more quickly than would be possible if we'd gone a more traditional route."



CT scan data of human airway

A Taste of Future Research

When we think of tasting, we think of the tongue. But actually, the tongue has only very basic sensors, says Nick Ouellette, associate professor of mechanical engineering & materials science. "Most of our sense of taste comes from the odor sensors. You chew food with your mouth closed, causing volatile chemicals to be released inside the oral cavity, and when you breathe out, some of those chemicals are entrained into the retronasal flow and pushed past the odor receptors." In other words, there's a real possibility that most of our taste sensations come not from our tongues, but from our noses.

This theory, however, doesn't explain why humans, who have a better sense of taste than most animals, have a comparably bad sense of smell — something you may have noticed while walking your dog. That contradiction is what led professor of neurobiology Dr. Gordon Shepherd, who has long been interested in the coupling of taste and smell, to ask Ouellette if flow dynamics might be shaping our taste experiences. For example, the airway between the oral and nasal cavities is not symmetric, which may have consequences in terms of how well we can smell when breathing in through our nose versus how well we can taste when we breathe volatile chemicals out. "Plus, velocity might have something to do with it," Ouellette says. "When you sniff something, you make high-velocity, short-duration inhalations, which is very different from the more measured breaths you exhale while chewing."

To better understand the mechanisms, Ouellette is 3D printing a model of the human airway using CT scan data from one of Shepherd's actual patients. Ouellette will then measure how air flows — or possibly doesn't flow — in both directions past the odor receptors, paying particular attention to any places where the fluid or air gets dynamically trapped. What does he expect to find? You'll certainly hear a touch more on the SEAS website, after he's seen how we smell and taste.

The Magic of 3D Printing at Yale

From device prototypes to medical data you can hold in your hand, Yale's 3D printers are giving new shape to the academic landscape

Yale

TECHNOLOGY

A captive audience gathers around Ellen Su, their attention rapt for the magic trick. The immunology resident to Su's left adjusts his glasses, while the lighting designer, the DJ, and the MBA student all inch closer to the computer screen. Su, for her part, is casually confident and well-versed in her patter, having performed this simple trick hundreds of times since becoming a Design Fellow at the Center for Engineering Innovation & Design (CEID). She adds a few details to her digital file, and with a final click of her mouse, the trick is set in motion: in just fifteen minutes, ten blue Y-shaped keychains, one for each onlooker, will have been made seemingly from nothing.

But this performance, part of the CEID's weekly orientation for students who wish to use the 3D printers, is about demystifying how the "magic" works, revealing that what seems miraculous is just the latest addition to the modern engineer's toolbox. "The 3D printer now sits alongside more conventional tools as a staple of enabling technology," says Joe Zinter, assistant director of the CEID. "It's become a tool of creation and innovation just as valuable as a laptop or a pencil."

Over 800 students at Yale have completed training on the 3D printers and earned a "Y" keychain, resulting in nearly

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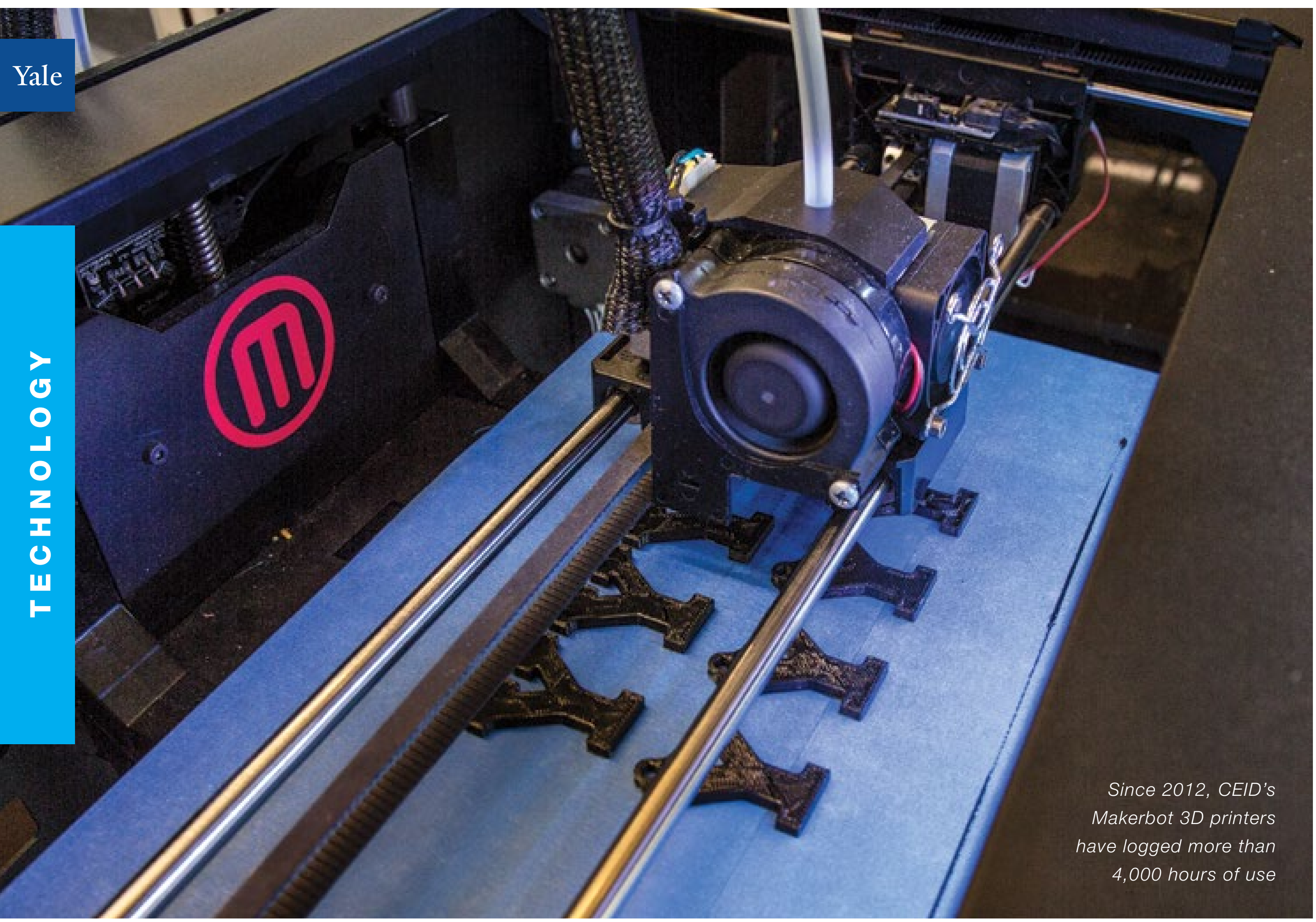
15% of the Yale College population qualified by the CEID to use the Center's three entry-level MakerBot printers. These students work from 3D digital files that, when uploaded to a 3D printer, can create tangible physical objects out of materials like plastic, plaster, or metal alloys. But unlike drilling, cutting, and milling, which create objects by stripping the material away, 3D printers add material layer by layer in only the space where it's needed to form the desired object. So in the eyes of a 3D printer, most complex or unusual shapes are as easy to produce as simple, more common shapes. In fact, the printers can essentially create any shape imaginable.

These creative possibilities drive students into the Center to use the machines for homework assignments and class endeavors, for club-sponsored competition entries and personal passion projects. "We don't limit the use of the MakerBots, so you can essentially print whatever you want on them, whenever you want, within reason," says Su, referring to the Center's entry-level printers. In fact, even with rules that prevent printing jobs from taking longer than three hours to complete, the Center's three MakerBots have logged over 4,000 hours of use — all since the CEID opened in August of 2012. Additionally, students can submit 3D printing request forms if they wish to have a file printed in higher resolution or with more durable material on one of the CEID's two higher-end machines. "We've had hundreds of jobs printed on each of these machines," Su says, "often by people who are using them for the first time."

It's that final caveat that makes the CEID's printers unique. Although 3D printers are among the most talked about technologies of the new millennium, most printers are still sold to a niche group of consumers — though this isn't to



Since 2012, CEID's Makerbot 3D printers have logged more than 4,000 hours of use



CEID members use the 3D printers to produce objects of all shapes, including the inner ear of a dolphin (left), a folded protein (center), and models of pelvic fractures (right)

say the market is stagnant. Rapid technology improvements have lowered the technical bar for ownership considerably in the past four years; as well, the increasing ease and availability of 3D modeling software and the growing number of web resources for sharing 3D files have paved the way for even further adoption. And yet, with printers only recently being sold for under $1,000, 3D printing still hasn't reached the tipping point that could make it a "one in every household" technology.

The result is that the average user, at least for now, is generally someone creatively adventurous, someone technically confident enough to explore a nascent technology, and an early adopter unafraid to do their own troubleshooting when something goes wrong. CEID users are these early adopters, exploring and pushing the limits of 3D printing technology for countless uses.

While 3D printing has been better at capturing America's imagination than America's wallets, SEAS has witnessed a dramatic rise in 3D printing use among its students, especially in the interdisciplinary, design-based engineering classes taught in the CEID (for more information, see page 44 for our article on CEID courses, including a profile of each course).

"CEID courses are the interface between theoretical teaching and practical implementation," says Tarek Fahmy, associate professor of biomedical engineering who has taught classes in the Center. "It's easy for students to say, well, here's how you *would* design a specific mechanical gadget to do something, but it's different when the students actually go out and create it themselves, printing out the different parts. That situation is much more pleasurable to teach in because students have a greater understanding of the problem."

However, because CEID classes are competitively sought-out not just by students from engineering but by students from all disciplines — anthropology to economics to political science — professors teaching in the CEID understand that not all of their students will have the same level of technical skill; instead, students in these classes are trained to use the CEID's many technologies, including the 3D printers. "For a lot of students, a project for a CEID course is the first time they're picking up a hammer or using a

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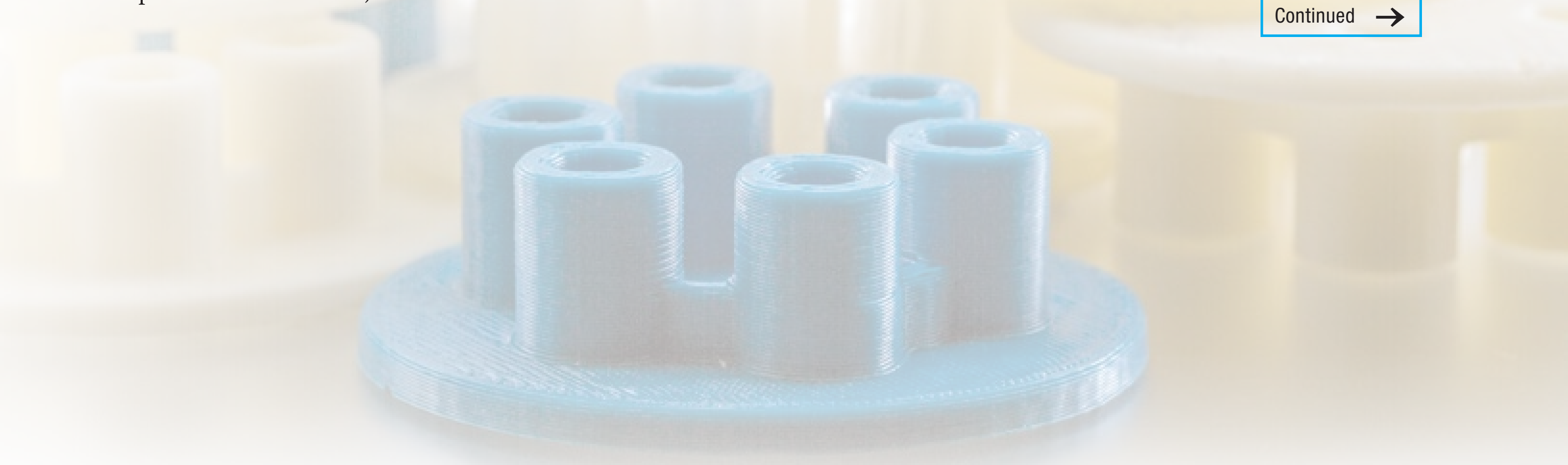


3D printed prosthetic hand capable of dexterous, multi-functional use in everyday tasks

drill press," says Zinter, "and that becomes important to the class, too, to show them how the physical world works. We don't open the doors and say, 'Go ahead, do whatever you want to do.' We coach, we mentor, we provide trainings — we provide all sorts of things in addition to access to equipment."

One of those things, says Levi DeLuke, a mechanical engineering student who graduated this past spring, is the ability to make things you don't otherwise have the skills to produce — an ability that comes from the use of 3D printers. "I love machining. It's an art and a really fun thing to do," says DeLuke. "But when I was new to engineering, often I could imagine a really cool design, but didn't have the technical background to make it. 3D printing was an empowering tool because it allowed me to make most anything that came to mind, with only a few limitations. And though my machining skills have improved, 3D printers are still a foundational tool, allowing me to spend time designing a better system. For example, sometimes it's hard to find the time to go and fabricate something in the shop, and so 3D printing enables you to spend time working on other parts of the project. It allows you to create designs that otherwise wouldn't be possible."

One such device was created by a student team in "Medical Device Design & Innovation," a class taught in the CEID by Zinter. Working with Dr. Boris Paskhover, a resident at the Yale School of Medicine, the team created a tool to assist surgeons operating on the base of the tongue and skull to remove cancerous tumors. Such operations currently require that a patient's head be placed at an extreme angle and are performed either by invasively cutting through the jaw to gain access to the operating site or by using the da Vinci surgical robot — an expensive surgical tool that requires significant set-up time in the operating room and that isn't available in all hospitals. Paskhover suggested that the students invent a simpler surgical robot to perform such procedures. The students, however, came up with an even simpler solution: a robust surgical tool designed specifically to reach the area of interest.

Thus was born the first of several prototypes. "I like to call them thinking prototypes," says team member Dan Rathbone, another mechanical engineer who graduated last spring. Starting with an early conceptual prototype constructed with little more than drinking straws, string, and some pipe cleaners, the group soon moved onto functional prototypes made using 3D printed parts and a system of small cables and pulleys running through the device. "By that point, the prototype looked like the final product, though at a slightly larger scale than necessary for the design requirements," says Zinter. "So they continued to refine and iterate the design, and by the end of just one semester they had a working device ready for presentation and further iteration — a device that functions the way that it should, rigidly locking into place at the appropriate angle.

"And this is amazingly well engineered," he adds, noting that the final device was presented at the August, 2013 conference for the Engineering in Medicine and Biology

Society. "In each prototype, they were able to quickly address feedback, and by their final iteration they had created about as impressive a student project as you will see out of anywhere."

The ability to prototype and iterate quickly is in fact one of the most commonly praised benefits of using a 3D printer instead of other fabrication methods. From GE to GM, Hasbro to Hershey's, 3D printing has become the go-to technology for quickly progressing through the many failures that pave the road to success. "You learn a lot through the building process," says Su. "Most of what I've learned is by making something that doesn't work and then realizing how many things I left out, or learning that I was making assumptions that weren't actually true. So for us, the faster we can fail, the faster we can improve."

The "us" in that sentence refers to 109 Design, a company Su, DeLuke, and Sebastian Monzon founded while students at Yale. Together, they've developed an "intelligent strap" designed to improve the medical treatment of scoliosis. The strap, which attaches to existing scoliosis braces, uses sensors to gather data on the quality and hours of brace wear. Braces are often not worn for the time prescribed by a doctor and even when braces are worn, they are often not tight enough to be fully effective. The strap provides patients the feedback they need to maximize treatment and ultimately reduce the progression of their spine curvature.

"We printed our first designs on the MakerBot," says Su. "We started with a very large case, basically just a box that had holes in the right places. And then one of our first priorities was to move smaller, so we got aggressive and decided to make it as small as possible. We printed a new case — and it didn't work. But that was fine, just another part of the development process. We tweaked the design to have just a bit more room, and the new case worked perfectly. No other production method could have given us that kind of change so quickly, especially important when meeting the design requirements for building a medical device."

Dr. Mark Michalski would know. As a resident and Holman Research Fellow in the radiology department at the Yale School of Medicine, he's used CT and MRI images to create 3D prints that have applications for everything from patient education to surgical drill guides to preoperative surgical planning. "Primarily what we do is build knowledge about complex pathophysiology," he says. Last year, he worked with CEID staff to produce a high quality 3D print of a knee with a large tumor growing in it — a tumor that Dr. Dieter Lindskog, an orthopedic surgeon at Yale, was planning to remove. Lindskog planned the complicated surgery using Michalski's 3D printed 1:1 scale model, which included the femur, fibula, tibia, patella, tendon, and tumor.

Clinicians, however, are not the only ones in the hospital being helped out by 3D models. "It turns out that many patients want to see their pathophysiology, especially around complex decision making," Michalski says. "Doctors, unfortunately, very rarely have a definitive answer when it comes to really, really tough choices, and a lot of what we do on a day-to-day basis is helping patients make informed decisions. But if you can make their disease tangible and physical, something that is easy to demonstrate, then I think it has an effect of making the patient more invested in making good decisions around their care. If I had to pick one thing that we're doing right now that can happen in the near term and that I'm most excited about, it's that."

Continued →


3D printed rat skull

"We've leveraged 3D printing to provide a new way to visualize information, a critical added dimension that I suspect will change how we perceive, understand, reimagine, and create the world around us."

– Joe Zinter

World's first 3D printed neurons

A few blocks away from Michalski's lab is the office of Dr. Gordon Shepherd, professor of neurobiology and one of the founders of the field of neuroinformatics — and the first person in the world to 3D print a neuron. On his desk sits his latest print: a pyramidal neuron printed using sintered nylon. Approximately 1,000 times bigger than the actual neuron in the hippocampus, the flexible dendrites spider out from the top and bottom of the central cell body, like a tree and its roots.

Progression of surgical tool prototypes, including one with 3d printed parts (center)

Working with Zinter and Robert McDougal, a post-doctoral fellow in Yale's Department of Neurobiology, Shepherd made the print in the CEID based on data he's collected for a database of 3D neuron simulations, which is viewable on a computer screen. "But once we had the data," says McDougal, "we realized that we didn't have to look at it on the computer anymore. And that's how we ended up at the CEID talking to Joe Zinter."

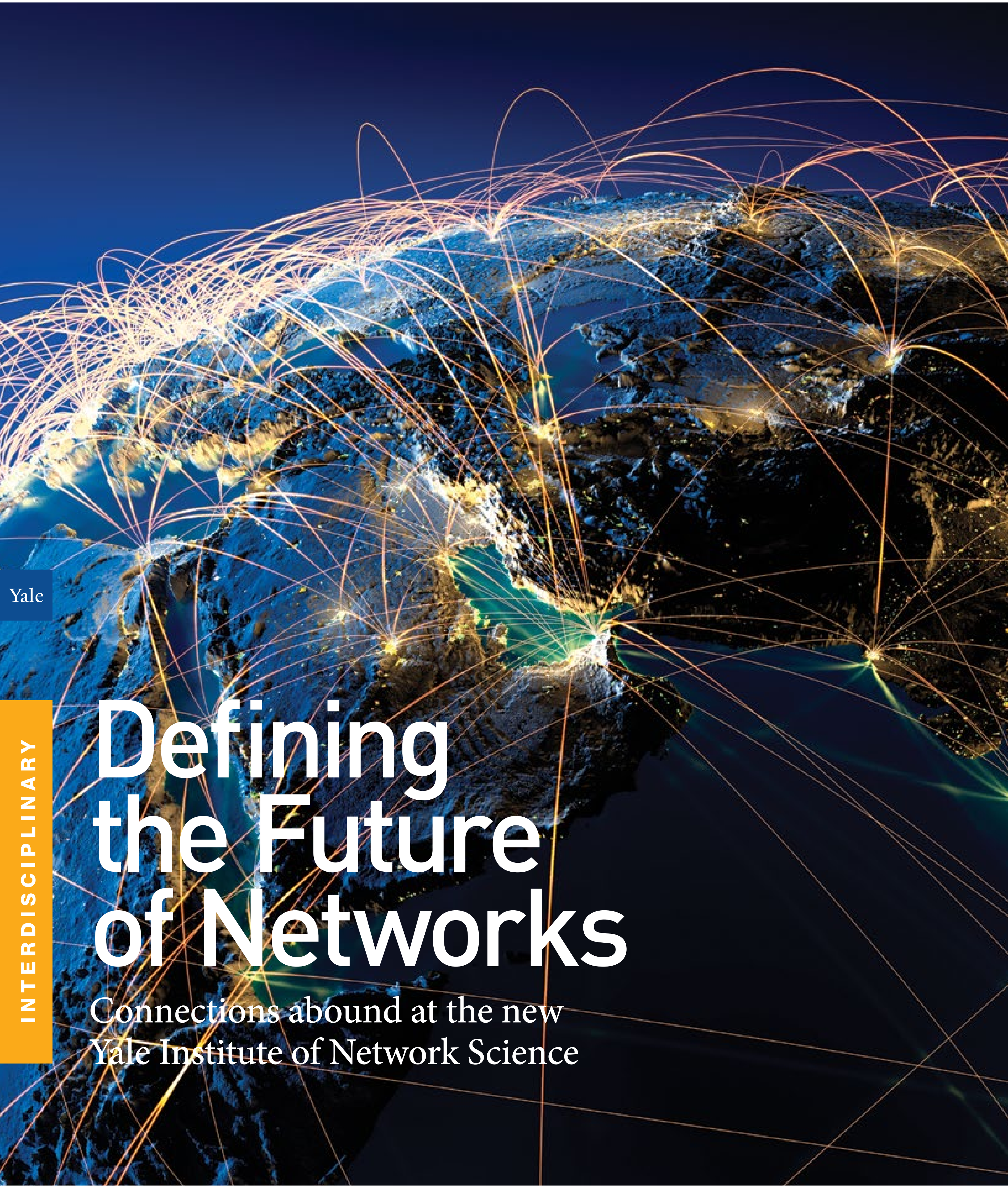
While Shepherd and McDougal admit that the print is fun, of more interest is how this particular way to see their data has informed their understanding of the neuron itself: when holding the print, it's obvious that the dendrites appear slightly flattened, spreading out much more to the right and left of the neuron than to the front and back. "We never noticed that just looking on the computer," McDougal says, "but as soon as you're holding it, you see all the details you missed before."

"Which brings up the question," adds Shepherd, "is this the way it actually is in your brain? Or is it that when the cell was stained to show this form, it had actually come from a slice of tissue so thin that bits of the cell got nipped off? If we've amputated a significant number of branches, that's going to change our estimation of what the resistance is to an electric current, our estimation of how big the cellular responses are, how they get integrated — it's something we have to take into account."

Zinter, who helped Shepherd print that first neuron, agrees, pointing out that data visualization is one of the unique ways 3D printing is used in a university setting. Sure, he says, we use it to prototype and iterate just as many others do. "But at Yale," he continues, "we've leveraged 3D printing to provide a new way to visualize information, a critical added dimension that I suspect will change how we perceive, understand, reimagine, and create the world around us.

"Just the other day, I saw one of my students who graduated this past spring, an economics major from my class, 'Appropriate Technology for the Developing World.' She and her teammates from that class won $25,000 in seed money to develop their product commercially, and they've just returned from India to pilot their life-saving technology. On this day, she was giving a tour to her family, and of all places to visit, she takes them to the CEID's 3D printers — a 30-minute stop. She explained how they worked, how they helped her studies. And being there in front of them, being able to touch the printers, they understood a bit more of what she'd done this year.

"And they were enamored," he adds, "as if it was magic."



Yale

INTERDISCIPLINARY

Defining the Future of Networks

Connections abound at the new Yale Institute of Network Science

net•work

| ˈnetˌwərk | *v.* 1. to connect to a network.

Each Wednesday around lunchtime, an audience gathers at the Yale Institute of Network Science (YINS) for the "Meet YINS" seminars. Faculty, staff, and students mingle while they grab plates of food and take their seats, ready for the session's two faculty presenters to delve into the questions, methodologies, and insights that have defined their respective research careers.

However, though the two presenters are always from different disciplines, with unique data sets and often disparate research methods, their back-to-back lectures feel connected. If the first presenter, for example, draws upon his neurobiology research to show how complexly associated neural pathways govern a chimpanzee's ability to see a red apple in a collection of green apples, then the second presenter, an electrical engineer, might discuss how wifi routers and data centers efficiently sync a Netflix queue across a smart phone, a desktop computer, and a TV set-top streaming box. Both researchers investigate the speed at which information travels and which factors disrupt or corrupt such transmissions; both researchers highlight how different interfaces receive and interpret that information. These connections are the essence of network science, which studies the communication patterns between different "nodes," be they people or computers, disease transmission or historical trade routes — and the Meet YINS seminars reveal how YINS professors, individually and collectively, are innovatively defining what can be accomplished in the network science field.

Continued →

net•work

| 'net,wərk | *n.* 1. an association of individuals having a common interest, formed to provide mutual assistance and helpful information. *v.* 2. to organize into a network.

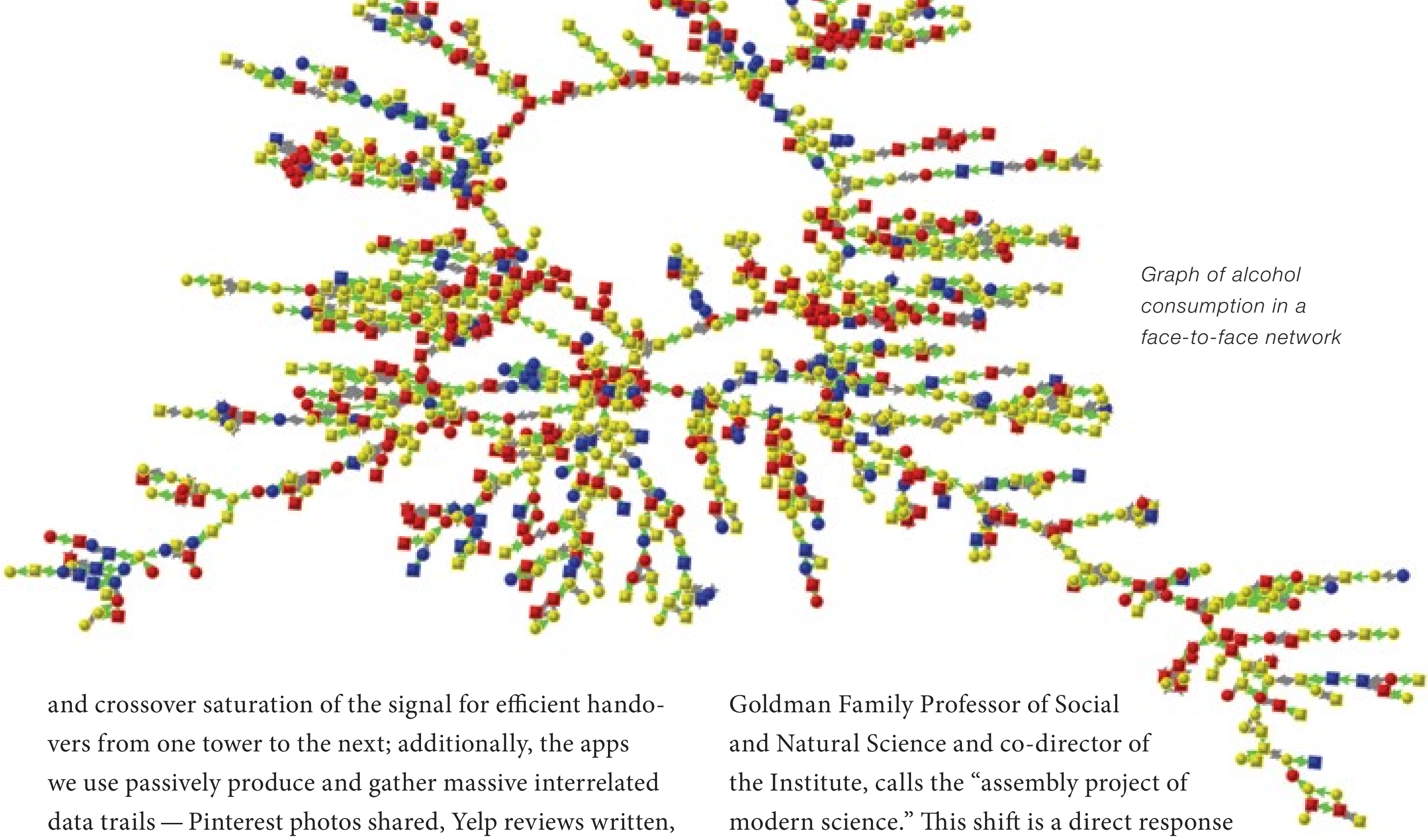
The idea for YINS took shape in the fall of 2012 with a group of faculty in engineering, computer science, economics, management, and sociology committed to the belief that Yale could dramatically accelerate the field of network science forward by establishing a central institute to facilitate network research being conducted across all disciplines at Yale. Daniel Spielman, the Henry Ford II Professor of Computer Science and Mathematics and co-director of the Institute, hopefully suggested in those early meetings that even ten network scientists gathered together in a room somewhere could significantly advance the field. "But what I discovered," he says, "is that more than fifty of us were already studying networks — and we were going to need a pretty big room."

Officially launched on February 5th, 2014, YINS is now an interdisciplinary community that actively encourages collaboration among engineering, the social sciences, and the natural sciences to further the study of complex networks of all kinds. Located in the newly renovated building at 17 Hillhouse, YINS is also a physical location where that collaborative culture permeates hallway conversations and inspires cross-disciplinary research partnerships.

SEAS represents the largest faculty population in the Institute, with four resident faculty (three of them hired specifically to join YINS) and four affiliated faculty. "The engineering faculty bring to YINS a rich set of methodologies, statistical techniques, and data modeling approaches that we believe will complement those of our colleagues in the social sciences and natural sciences," says Sekhar Tatikonda, associate professor of electrical engineering, who in addition to being one of the thought leaders who first proposed the creation of YINS is now also one of the YINS resident faculty.

As an example of such a partnership, you might think about how a new product is marketed to a target audience, a task that relies on both advertising strategies and optimal pricing to generate appropriate consumer demand. But no matter how many ads are placed or how low the price is, that demand is determined, in part, by how far word-of-mouth diffuses information across the target population — a diffusion that can be described using a mathematical technique known as a random walk, where the probability a person talks about a product is a function of how much they like the product and the price. Associate professor of economics and YINS affiliate Arthur Campbell is already utilizing these statistical analyses, but such computations could potentially be optimized or even augmented by findings from other faculty in YINS. In particular, Tatikonda and assistant professor of electrical engineering Amin Karbasi — another YINS resident faculty — are developing new graph algorithms to speed-up information diffusion via local message-passing schemes in a variety of networks. These analyses could help companies take better advantage of the targeted website ads that today are only generated using our browser history but that could in the future be further tailored to our relative connectedness within online social networks. These opportunities for transformative, cooperative research, says Tatikonda, are what make YINS "one of the most exciting and important new initiatives at Yale. And SEAS is a founding member."

One reason for that excitement is the growing ubiquity of networks in contemporary culture. Consider how we use our smartphones: such devices connect to a cellular network composed of individual towers that, in order to keep us "only a call away" throughout our travels, must be efficiently designed for maximum signal strength and coverage, taking into account the effectiveness of the cell tower hardware, service load due to population density,



Graph of alcohol consumption in a face-to-face network

and crossover saturation of the signal for efficient handovers from one tower to the next; additionally, the apps we use passively produce and gather massive interrelated data trails — Pinterest photos shared, Yelp reviews written, eBay auctions won, Netflix movies queued — that provide empirical evidence of how each of us interconnect in the multiple, overlapping social networks that influence, shape, and even sometimes determine our behaviors. In fact, nearly everything we do, touch, or interact with can be studied from a network science perspective.

It's perhaps not surprising, therefore, that YINS is addressing some our most universal experiences — including matters of life and death. Associate professor of sociology and YINS affiliate Andrew Papachristos observes how our shared cultural witnessing to tragic mass public shootings has made common the perception that violence is both pervasive and random, that it can happen anywhere or to anyone. However, Papachristos has shown that not only are young, minority males the most likely victims of gun homicide, but such violence is also severely concentrated within small social networks of individuals in high-crime communities and populations. In a recent study of one Boston, MA, community, Papachristos found that 85% of all fatal and non-fatal gunshot injuries occurred in a social network of less than 6% of the community's population. So while networks are everywhere around us, our position within them can strongly influence how they affect us.

But in addition to the ubiquity of networks, network science has also achieved a growing prominence because of the intellectual shift towards what Nicholas Christakis, the Sol Goldman Family Professor of Social and Natural Science and co-director of the Institute, calls the "assembly project of modern science." This shift is a direct response to centuries of scientific achievements that have seen scientists progressively reduce their objects of study into ever finer parts. In life sciences, for example, life has been disassembled into species and organisms, then organs, then cells, then macromolecules, and then genes. At the same time, the scientific professions themselves have become increasingly specialized and fragmented, with intellectual and professional barriers that today often discourage cross-disciplinary collaboration and prevent researchers from recognizing the common technical and scientific challenges they face.

"We're seeing diminishing returns to discipline specialization, and scientists in every discipline are struggling to put the parts back together," Christakis says. "However, rather than accede to such discouragement, we're now also seeing the emergence of new disciplines interested in complexity and interconnection — and intellectually, these are the fields that are about to explode."

To this end, YINS is leaping over the walls that divide research specializations, encouraging a culture where conversation between the disciplines is standard practice. In addition, YINS aspires to be the home for the growing number of cutting-edge scientists whose research doesn't comfortably belong in any single discipline.

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"Network science is a perfect axis for the growth of Yale's School of Engineering & Applied Science," says Kyle Vanderlick, the School's Dean. "Through our foundational support for YINS, we're formally strengthening and nurturing faculty research connections that previously may have been difficult to recognize, let alone establish."

Yale Institute of Network Science provides a hub for innovative researchers

net•work

| 'net,wərk | *v.* 1. to cultivate people who can be helpful to one professionally. 2. to distribute widely.

In addition to encouraging active research collaboration, YINS is also already becoming a powerful tool for faculty and student recruitment, and three new SEAS faculty have joined Sekhar Tatikonda in residence at YINS: the John C. Malone Professor of Electrical Engineering Leandros Tassiulas, assistant professor of electrical engineering and computer science Wenjun Hu, and assistant professor of electrical engineering Amin Karbasi. "Of the fifteen electrical engineering faculty, four of us are now in residence at YINS," says Tatikonda. "That shows how important networks have become to engineering, and it's also strong evidence of the University's belief in the future of networking at Yale."

The three new hires represent a broad and complementary approach to computer networking efficiency. Tassiulas has more than 20 years of network research experience, with a recent focus on increasing the efficiency of wireless networks by better utilizing the wireless spectrum and adapting to unpredictable environmental variation; this results in novel internet architectures that can be utilized by even ad-hoc networks of nearby devices. On the other hand, Hu's approach to efficiency relies on empirical measurements and analysis of the hardware that makes up a network, thereby pinpointing bottlenecks in the data flow; as a self-identified experimentalist, she optimizes a network by testing prototype improvements until the network user is satisfied. Finally, Karbasi researches at the intersection of large-scale networks, learning theory, and optimal information processing; for example, a method his team developed based on metric analysis can be used to create interactive content search algorithms that can link small networks — such as a group of close friends — with extraordinarily large data sets to help a user more efficiently find relevant and desirable content.

However, more than mere communication patterns between each computer node, what makes these three researchers appropriate as YINS faculty is the human decision-making aspects related to each problem they address: the effectiveness of Tassiulas's ad-hoc cell phone networks is influenced by the distribution of the cell-phone owners; Hu's wifi bottlenecks might result from the network owner's desire to keep the router in the hallway and the laptop in the living room; and the effectiveness of Karbasi's algorithms lies in how they augment more conventional metadata search techniques with, say, the results that your friends found useful when conducting similar searches through the same data. "More and more," says Tatikonda, "engineers must account for real-world behavior — and humans and animals aren't particularly rational or things you can design. Being at YINS provides us access to researchers outside our field who have studied human beings, who have studied animals, and who can help us make more informed design decisions. It's a conversation that goes both ways."

Tatikonda's words ring even more true for the other SEAS faculty affiliated with YINS. Stephen Morse, the Dudley Professor of Electrical Engineering and Computer Science, creates algorithms for groups of autonomous mobile robots to form specific patterns or accomplish sensing

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tasks — patterns often modeled on animal behavior, such as flocking birds. Nicholas Ouellette, associate professor of mechanical engineering & materials science, uses his background in fluid dynamics and particle tracking to collect empirical data on midge swarming habits in order to understand what causes the midges to aggregate and what keeps individual midges from straying from the swarm. Mark Saltzman, the Goizueta Foundation Professor of Biomedical Engineering, Chemical & Environmental Engineering, and Physiology, designs smart vaccine delivery systems that use biocompatible polymeric materials capable of adapting to different locations and conditions within the body. Steven Zucker, the David & Lucile Packard Professor of Biomedical Engineering and Computer Science, models the hierarchical organization of neuronal connections in the primate brain to understand how and why animals perceive color. And Tatikonda himself is concerned with how each node in a network learns to makes decisions to most efficiently achieve a global objective, research that can be applied to statistical machine learning and the optimization of data distribution. For these engineers, whose research bridges into disciplines as widespread as entomology and political science, YINS provides a hub for connecting to potential collaborators, both at Yale and beyond, through the sharing of data and methodologies, through the increased public visibility that the Institute promotes, and through the resources that YINS makes available for coordinating and supporting interdisciplinary grant applications.

In this regard, YINS faculty are not only discovering how networks in diverse fields function, they are inventing new ways to use their understanding for improvements in technology, public health, and public policy. They are harnessing their respective backgrounds to derive new insights into social processes, economic systems, and fundamental sciences, to increase the adoption of innovations and to optimize communication systems. "We're creating a full-spectrum research pipeline," says Spielman. "We have people producing the ends that are the public goods — the new inventions, medicines, policy recommendations — and people producing the mathematics and the statistics and the analyses that enable those ends to happen. All these researchers together in one place will have an opportunity to influence each other's work, to improve each other's work, and to learn from what each other is doing." They are thus also laying the foundation for a body of knowledge that can be accessed by all of Yale, a data library relevant to network science methods that is then transmitted through interdisciplinary graduate and undergraduate courses with broad appeal to the Yale community, and promoted in lectures, workshops, and conferences — including the Meet YINS seminars and a distinguished lecture series that brings leading scientists and innovators to Yale.

Or as Tassiulas puts it, "YINS is very timely, and maybe even ahead of its time. And that's a good thing."

An Environment for Growth

With three new hires, Yale's environmental engineering program is rising to the next level

Jaehong Kim

Drew Gentner

Desirée Plata

Yale's environmental engineers have a unique synergy with their chemical engineering colleagues. Whereas traditional environmental engineers work within civil engineering departments to perhaps analyze drought patterns, develop sustainable construction materials, or invent new methods for remediating legacy environmental contamination, Yale's environmental engineers work in the Department of Chemical & Environmental Engineering, a setting that reinforces the faculty members' focus on creating molecular-level solutions that aim to prevent tomorrow's environmental problems by reshaping the industrial and environmental landscape of today. "The projects we're working on now," says Menachem Elimelech, the Roberto C. Goizueta Professor of Chemical & Environmental Engineering, "are addressing the problems of ten or fifteen years into the future."

Elimelech, who founded the SEAS environmental engineering program in 1998, is a perfect example of this unique focus. Rather than assessing historical groundwater contaminants near industrial areas, Elimelech's membranes for forward osmosis make new water sources available around the world, incorporating nanomaterials into thin polymer films to create innovative improvements to water desalination that reduce both the energy cost for purifying water and the amount of fouling from particles in recycled wastewater. Instead of attempting to mitigate an oil spill's aftereffects, his membranes for pressure retarded osmosis are a novel technology for reducing our oil dependence, generating energy from the mixing of salt water with fresh water, both in locations where that mixing occurs naturally and in closed-loop industrial systems. Such research has made Elimelech, a member of the prestigious National Academy of Engineering, among the most highly cited researchers in his field.

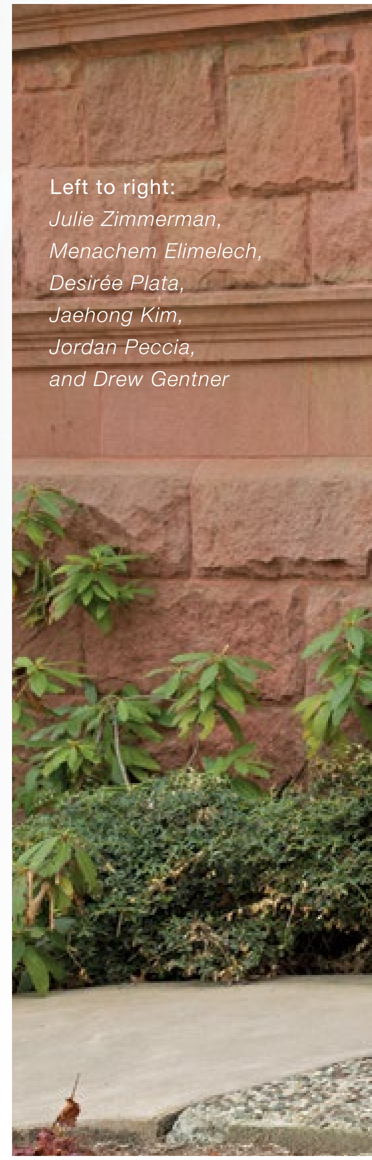
Under his guidance, progressively greater acclaim has been bestowed on the Yale environmental engineering program, and the links between Yale's environmental engineers and chemical engineers are continually strengthened through creative collaborations among the faculty. Newly-synthesized nanomaterials find applications in "greener" solar cells; challenges in managing atmospheric particulates inspire new methods of chemical analysis. As a result, almost within a decade of Elimelech's arrival, Yale was top-ranked in the National Research Council's data-driven evaluation of 130 civil and environmental engineering programs, based upon the 21 criteria that scholars say are most important — criteria that measure research activity, student support and outcomes, and diversity of the academic environment.

However, such acclaim, notes Paul Van Tassel, isn't surprising to anyone familiar with Yale's dedication to a sustainable relationship with the environment. "An interest in broader, societal issues is part of the Yale culture," says Van Tassel, department chair and professor of chemical & environmental engineering and biomedical engineering. "With a shared focus on the future of energy, the environment, and sustainability, there's a synergy between chemical engineering and environmental engineering that makes them ideally linked in one unifying department. We benefit from having both chemical engineers who consider the bigger environmental picture and environmental engineers who utilize innovative chemical and molecular science."

Continued →

In fact, much of the environmental engineering program's reputation comes from the impact of faculty research. For example, associate professor of chemical & environmental engineering Jordan Peccia's analysis of agricultural applications for treated domestic sewage sludge, termed "biosolids," has produced recommendations for changes to EPA soil regulations that would limit pathogen exposure for residents who live near biosolid land application sites. As well, his research into large-scale microalgae production addresses fundamental questions associated with creating efficient sustainable biofuel systems. Julie Zimmerman, professor of chemical & environmental engineering and forestry & environmental studies, has explored similar uses of algae for fuel in addition to utilizing algae to produce chemical surfactants, and her research in evaluating and developing materials for use in water and wastewater treatment has resulted in high-performance materials that also align with the principles of sustainability. Additionally, she has made groundbreaking achievements in advancing the rational design of chemicals and nanomaterials that are less toxic to humans and the environment.

Such research is a natural extension of the decades-long concern for sustainable innovation and global perspectives that has been a cornerstone at Yale. And from that foundation, the environmental engineering program has further strengthened its dedication to energy, the environment, and sustainability through the hiring of three new environmental engineering faculty: Jaehong Kim, Drew Gentner, and Desirée Plata.

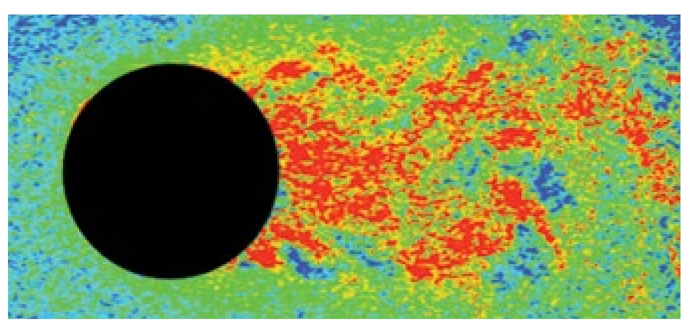


Left to right:
Julie Zimmerman, Menachem Elimelech, Desirée Plata, Jaehong Kim, Jordan Peccia, and Drew Gentner

Left: *Kim measures photoluminescence property of upconversion phosphor;*
Right: *UV disinfection process inactivates a virus*

Water

Generations of engineers have considered water access in the developing world to be an extremely low-tech problem — something best solved with a well, pipes, and proper sewage treatment. But as crucial as wells, pipes, and sewage treatment are, Jaehong Kim, the Barton L. Weller Associate Professor of Chemical & Environmental Engineering, believes that kind of thinking won't solve the problem entirely. Instead, he suggests that environmental engineers think a little "smaller," perhaps while looking at their smartphones. "Years ago, a computer as powerful as your iPhone would have been the size of a building," says



Kim, “and that’s the size of many water treatment facilities now. Like the iPhone, I want to know how we can bring water treatment down to a small but sustainable scale.”

Kim’s solution is in new materials that destroy harmful chemicals and kill germs in water. These materials — photon upconversion phosphors and photocatalysts — either absorb low-energy visible photons and produce high-energy ultraviolet light or they generate reactive oxygen species. Such materials can be molded into any variety of shapes, including a water bottle that cleans the water inside it simply by being placed in the sunlight. These materials can also be used for larger-scale water treatment in the developing world.

“A lot of the challenge of my research,” he continues, “is thinking far enough ahead, working specifically to provide high-tech solutions for these low-tech problems. Low-tech solutions can be done anywhere, but at Yale, we have the right technology, the right caliber of students and colleagues, and the right level of support to think twenty years ahead, to dream up the solutions that not only solve the problem but actually change the paradigm. A cheap water bottle that disinfects its contents just by sitting in the sunlight? It’s simple, but it’s also very futuristic.”

Yet Kim is quick to point out that while the solution is forward-looking, perhaps even exotic-sounding, the problem very much needs a solution today, with millions of people dying each year from water-related diseases. “The number is staggeringly high,” he says. “Maybe I’m dreaming a little too big to think we can change the world, but I and the students in my research group are extremely motivated toward that goal.”

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Air

Every time Drew Gentner visits a big city, he thinks about the air he's breathing. "Hundreds of millions of people live and breathe in the world's megacities," says Gentner, assistant professor of chemical & environmental engineering and forestry & environmental studies. "And across a range of cities — Beijing, New Delhi, Paris, Los Angeles — there's a mix of emerging and continual air quality problems that represent some of the biggest pollution challenges in the world today. And they affect us all."

Gentner's research aim is to provide a clearer picture not only of the air's chemical composition but also of the ways in which our technologies affect air quality. In one study, for example, he compared the potential for gasoline and diesel emissions for organic aerosol formation, an atmospheric particulate that is detrimental to human health. The chemical compositions of the fuel samples, characterized using a coupled gas chromatograph and mass spectrometer, revealed that diesel exhaust is seven times more efficient at forming dangerous aerosol. Moreover, Gentner demonstrated the applicability of his research by comparing the results to diesel fuel regulations in California (where the measurements were taken) and to weekday/weekend road usage for gasoline- and diesel-powered vehicles.

However, while vehicle emissions are a well-recognized air pollutant, many of Gentner's research subjects are often missing from conversations about air quality. In one study, he compared the spatial distribution of emissions from petroleum operations and dairy operations, suggesting that the emissions are important data to regional modeling but that they do not lead to dangerous aerosol production; he has also shown that the spring flowering in orange orchards is a major emission event, with significant potential to impact regional air quality. With so many varied and undocumented contributors to air quality, Gentner likens the process to deep sea exploration: a vast, little-understood expanse that's difficult to fully measure and is full of clues hinting at the existence of understudied chemicals.

"I like to think of my research as addressing critical issues at the nexus of air quality, climate change, and human health," he says. "I'm trying to provide the information necessary to make policy-relevant decisions, because with a better understanding of the chemistry and sources of pollution, we can design more effective air quality mitigation strategies to reduce the concentrations of pollutants that have large effects on human health."

Energy

Desirée Plata's research, which shares many of Gentner's concerns for the air, often focuses on one element: carbon. How do nanocarbon formations develop? How do they disperse? How can their environmental effects be mitigated? To answer these questions, Plata provides free emissions estimates to manufacturing and energy companies, a mutually beneficial act that offers the companies much needed data about their environmental impact and gives Plata further data about nanocarbon formation mechanisms. She then applies the basic science principles from her lab to help a company change its industrial practices, in ways big and small: "We can offer the company improvements in energy efficiency, reductions in production costs, and better quality control over the product —

Left: *Gentner measures aerosols emitted from motor vehicles;* Middle: *Photoreactor used to study novel routes of nanomaterial activation;* Right: *Algal biomass grown for fuels and value-added chemicals*

all in addition to reducing their environmental impact," she says. By focusing on "green improvements" that also improve the metrics industry leaders most value (such as the bottom line), Plata makes it easy for companies to be environmentally sustainable.

That approach has earned Plata, assistant professor of chemical & environmental engineering, a unique alliance with industry, and enabled her to cross traditional us-versus-them barriers between the environmentalists and the oil & gas companies. She sets out to help them improve their production of the current necessary fuels for our society, and in doing so is able to help protect the environment by reducing harmful carbon emissions.

Plata also pursues innovations that can enhance the viability of alternative high-density renewable fuels. Here, too, carbon is crucial, and she suggests that the ability to controllably form nanocarbons will enable environmentally critical technologies that have direct implications for energy storage via novel capacitors, supercomputing, mechanical strength applications, and smart materials. For example, she says, imagine an airplane made from stronger materials than any currently available and that can also dissipate electrical charge if struck by lightning, report its own defects, and de-ice itself in bad weather.

Such technologies are plausible, suggests Plata, when the construction of carbon nanotubes becomes significantly more efficient and better controlled. "We're trying to figure out how these bonds are put together, atom by atom, with a goal of achieving complete molecular control," she says. "This would enable not only enhanced efficiency and reduced emissions, but also help realize all of the promise that carbon nanotubes hold for future environmental technologies."

Plata says she's not sure when that breakthrough will happen, but she has an idea of where. "Yale is a place where top-tier students can take this kind of research to the next level, not just through their great intellectual skills but also through their interpersonal skills — a critical talent when you're trying to work with industry. You have to be charming and still have the guts to go after these really difficult intellectual problems. Yale is a unique place where all these skills are coupled with groundbreaking goals in mind for the environment and for society."

EDUCATION

A Better Class by Design

Building a surgical tool? Redesigning a museum exhibit? Just another day for students enrolled in the Center for Engineering Innovation & Design's wildly popular courses

The Center for Engineering Innovation & Design (CEID) is a hive of creativity: Utilizing every inch of the 8,500-square-foot space, students can be found in the CEID at all hours of the day enthusiastically converting passion projects into reality, conducting original research, and dreaming up — then creating — unique club-directed inventions. But these same students, and many others, are also at work on homework assigned as part of the CEID's growing lineup of project-based, interdisciplinary courses. From a freshmen-centered introduction to engineering and design to an intense upper-level course team-taught by faculty from SEAS and the Jackson Institute for Global Affairs, these wildly popular courses represent some of Yale's most unique and challenging opportunities for engineering accomplishment.

A key element of CEID courses is their use of real-world team-based projects, many of which are proposed by actual clients seeking solutions that they can implement. Leveraging the greater Yale community's awareness of where technological innovation might have a significant positive impact, such clients are often drawn from within the university's diverse departments, institutes, and projects: doctors at the School of Medicine who have encountered a surgical procedure that could be less invasive with the proper tool, curators at the Yale University Art Gallery who wish to increase their technology offerings through a mobile app and RFID scanner, the manager at the Yale Marsh Botanical Gardens who require a smart irrigation system to prevent overwatering, and faculty from other Yale departments who have identified unique opportunities for inventive engineers to engage with and shape the world they inhabit. CEID instructors, while preparing their courses, tap into this network

Continued →

of colleagues and coworkers to identify and assess many potential projects, then select the challenges that will best inspire students to semester-long innovation. "Project-based courses are so tremendously different from lecture-based courses or lab courses," says Eric Dufresne, associate professor of mechanical engineering & materials science, physics, and cell biology, and director of the CEID. "You're giving students the opportunity to be creative and solve problems that don't have simple, obvious solutions. Those problems must be compellingly difficult, but they can't be unfocused or overwhelmingly broad."

In spring of 2013, two such problems were proposed by the Mara Project, a collaborative initiative between Yale University and the Cary Institute of Ecosystem Studies that researches how diverse native wildlife shape the Serengeti ecosystem and food web dynamics of Kenya's Mara River. Graduate students from the Mara Project — Chris Dutton and Amanda Subalusky — met with two teams of students from Dufresne's "Introduction to Engineering, Innovation, & Design" course to present their needs: a protective case for water quality sensors, and an inexpensive depth logger to measure the volume of water flowing in the river. Both devices would also need to be built with a consideration for the unique challenges of the Mara ecosystem and location — the heat, the hippos that would step on the water sensor case, the tons of natural detritus and animal feces that float down the river daily, and the availability of the construction materials in Kenya for on-location repairs. As the clients, Dutton and Subalusky would provide in-process feedback on the student prototypes, and the finished solutions would be implemented in Kenya.

While real-world projects like these are often the main focus for students in a CEID course, the day-to-day classwork that happens alongside the projects is just as unique. At any given moment, the students can move easily from the classroom to the studio space, and the resources for any practical exercise — planned or unplanned — are sitting just 25 feet away from the desks. This flexibility translates into a classroom loaded with possibility, says Bo Hopkins, a lecturer at Yale's Jackson Institute for Global Affairs who co-teaches "Appropriate Technology for the Developing World" with Joe Zinter, assistant director of the CEID. "We can take any learning opportunity that presents itself and walk over to the benches for a hands-on demonstration," Hopkins says. "That back and forth cements the philosophy of what we're trying to do with the engineering tools to do it."

In addition to classroom demonstrations, CEID courses also use the nearby studio space to develop students' skills on the Center's cutting-edge technology, much of which

Left: *Water sensor in hippo-proof sensor housing being deployed to Mara River;* Center and Right: *Ultrasonic depth logger positioned on bridge over Mara River* they'll use for their final projects. Professors might take class time to complete design exercises on the 3D printers or assign "homework" resulting from a laser cutter training session with a CEID staff member. These hands-on activities are for many students the first step in their engineering education; for others, they are a final complement to everything they've learned at Yale about creative engineering-based problem solving. But all students, no matter their proficiency at the beginning of the semester, learn foundational technology skills that can be used well beyond the classroom doors, in engineering careers and in daily problem solving. Students leave the course trained to design new inventions, then build them.

Although real-world projects and class-wide technology trainings create an exciting and accessible curriculum, CEID courses also stand out for their intellectually diverse student enrollment. "In the CEID, we work on big, real-world problems," says Zinter, "and we think the best way to solve those complex, multidimensional problems is to bring together students from all different backgrounds — innovation is a team sport, and the best teams are always interdisciplinary." Any given team, for example, might consist of a mechanical engineering major, a classics major, a molecular biology major, and a graduate student from the School of Management — each handpicked from the large number of students who apply for each available spot in a CEID course, despite the fact that most CEID courses are not required by any major for graduation. "This year in 'Introduction to Engineering, Innovation, & Design,' I had 140 students apply for 45 spots — and I had already increased enrollment from 30 spots the year before," Dufresne says.

Looking again at the Mara Project teams offers a window into such diversity in practice. Mechanical engineering and global affairs alumnus Charles Stone was a junior on the team designing the protective case for water sensors. Kendrick Kirk, then a freshman economics major, was part of the depth logger team. Although in different years, with different backgrounds, and working on different projects, Stone and Kirk shared information about the region's environmental challenges and international economics, and their teams worked in concert to meet their clients' needs. Ultimately, the teams constructed both a stronger hippo-proof sensor housing out of a lightweight, internationally-distributed aircraft-grade aluminum alloy, and a battery-powered depth logger equipped with ultrasonic sensors and a SIM card that could transmit real-time water-level data to an internet database every 15 minutes; the water sensors, protected by their new case, could safely remain in the water, and the depth logger could be positioned on a bridge above the river, beyond the ravages of floods and large animals. "Through their close collaboration, both teams made a huge difference in our ability to use our meters effectively," says Dutton. "Work they did has even formed the basis for how we measure other parts of the Mara Basin."

With students in every CEID course achieving such high technological and educational success — and so many more students hoping to get in — it's no surprise that the Center continues to develop additional courses to be offered in future semesters. And as the following profiles of some of the current CEID courses show, already the CEID classes are introducing students of all disciplines to the challenges of globally minded, real-world engineering.

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Yale

EDUCATION

ENAS 118

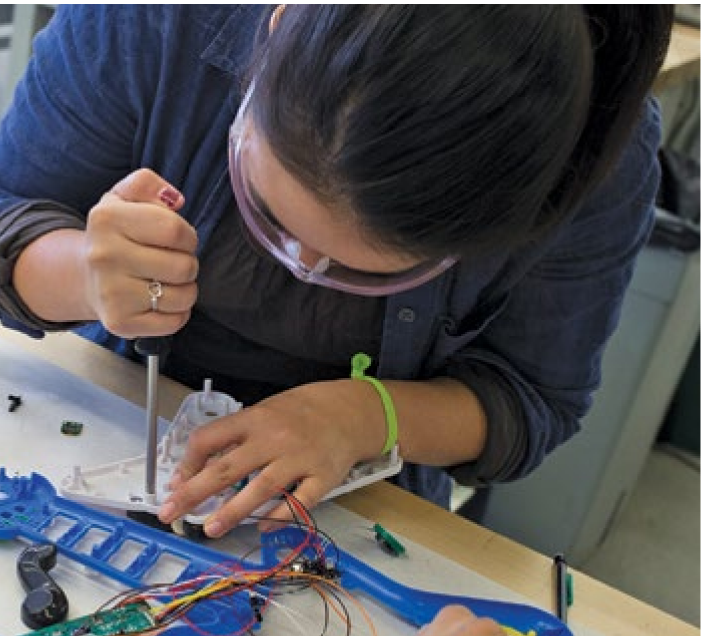
Introduction to Engineering, Innovation, & Design

On any given day last spring, student teams from "Introduction to Engineering, Innovation, & Design" might be bending pipe cleaners into the shape of an initial prototype, testing sensors for their ability to record soil temperature, and using a computer-controlled router to cut wooden tiles. Created to give engineering newcomers insight into each of the core engineering disciplines — with freshmen given priority enrollment — the course exposes students to the principles of engineering and design through an appealing mix of lectures, team-based class activities, and time spent on their final projects. "We take full advantage of how flexible the CEID space is," says Eric Dufresne, associate professor of mechanical engineering & materials science, physics, and cell biology, and director of the CEID. "While I'm providing feedback to a group sizing an electric motor for a robot, another group might be at the next table writing code."

That variety extends even to the students' final projects, which are always proposed by real-world clients drawn from within the broad reaches of the Yale community, including researchers in the School of Forestry & Environmental Studies, the manager of the Yale Farm, faculty in the department of mathematics teaching introductory calculus courses, and the managers of Ground, the engineering café. But where other CEID courses are geared to specific frameworks (medical devices, sustainability issues, developing world challenges), projects in "Introduction to Engineering, Innovation, & Design" can address any sufficiently compelling topic, heightening student interest while meeting the needs of the Yale clients through an impressive number of ready-to-implement inventions from the course. "The course brings students who have no engineering experience to the front line of available materials, technologies, and skills, putting them in the fire and seeing how they innovate," says Tarek Fahmy, associate professor of biomedical engineering, who co-taught the course last spring with Dufresne.

One of the latest "Introduction to Engineering, Innovation, & Design" projects to be adopted now resides in the Yale Peabody Museum of Natural History. David Heiser, head of the Peabody's education and outreach, needed a way to regulate the temperature and humidity of the leafcutter ant exhibit. "And because the display is in the extremely popular 'Please Touch' room," he says, "any solution needed to not get in the way of viewing while holding up against a lot of little curious fingers."

In response, the students developed a new environmental control system with custom software, an Arduino microcontroller, and a number of sensors. As well, while researching the ants' preferred environment, they also realized that a different layout of the ants' Plexiglas containment box would make the ants more likely to hang out near the ground. "We created a 'playground' for the



Left to Right: *Students in CEID classes build prototypes of their final projects*

ants," says freshman team member Jessica Lee, "so that they'd want to live where younger visitors could easily see them. The idea for it came right out of what we'd learned about environmental engineering, and the museum is really excited to see it in action."

MENG 404

Medical Device Design & Innovation

"Over in the School of Medicine," says Richard Fan, "a physician might say, 'I wish I had a tool that did X.' But most physicians don't have the skills or resources or time to invent that tool." So Fan, a former associate research scientist at the Yale School of Medicine, and Joe Zinter, assistant director of the CEID, created "Medical Device Design and Innovation," a course where physicians would act as clients and mentors for student design teams. The course is also an opportunity for students to work alongside Yale physicians to develop solutions for unmet clinical needs.

Such solutions emerge out of the course's two core elements — an introduction to everything "med tech" and a design and engineering component where students conceptualize, develop, and test prototypes in the CEID. The first element provides contextual information on the medical device design process, healthcare economics, the modern hospital (including a field trip to the Yale-New Haven hospital operating suite), the different types of surgical procedures, the various methods of medical imaging, what it's like to work at a medical device company, and even a visit from an FDA representative. Alternating with these information sessions, the students are given studio time throughout the semester to design and refine their final projects, most often building the components of their prototypes using the CEID's computer-aided design software and 3D printers; as they prepare for progress updates and receive individual feedback sessions from both their client and from Fan and Zinter, they use the same technology to create multiple iterations of their device, each more complex and fully developed than the last.

Between this rich problem-directed context and focused feedback, the final projects become working solutions to real-world problems — solutions that could be refined and further developed into market-ready devices to improve patient outcomes. One such device in last fall's course aimed to significantly improve the ability to transplant the small intestine, a notoriously delicate organ that breaks down rapidly when out of the body. The Yale team bettered current transportation options by keeping the organ "in use" throughout transport by pumping a nutrient-rich solution through the main intestinal track as well as the surrounding vasculature, simultaneously supplying the organ with

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Left: *Small intestine transplant device gets final presentation;* Center and Right: *Team "Khushi Baby" field tests vaccination record amulet in India*

necessary nutrients to prevent organ death and preventing harmful waste products from accumulating. Working with their client, Dr. John Geibel, professor of surgery and of cellular and molecular physiology, vice chair of surgery, and director of surgical research at Yale-New Haven Hospital, and three Yale transplant surgeons, the team has continued to improve their device outside the course. In addition to winning first place and $10,000 in the National Collegiate Inventors and Innovators Alliance BMEStart Competition, the device has been approved by multiple New England organ banks for experimentation with human tissue.

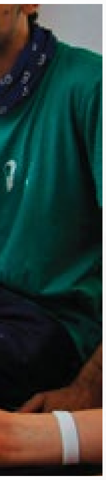
ENAS 360

Green Engineering & Sustainable Design

Between Yale's vibrant environmental engineering program and a campus culture that values sustainability, it's no surprise that "Green Engineering & Sustainable Design" has been a popular course since professor of chemical & environmental engineering and forestry & environmental studies Julie Zimmerman first began teaching it eight years ago. From the beginning, the course was a product design course within a sustainability context — a course that addressed how to solve sustainability challenges, like energy or water or packaging, without causing harm to the environment or to human health. That forward-thinking philosophy still drives the course today, preparing Yale students of all majors and backgrounds to solve problems in the context of globally aware environmental mindfulness.

However, with the CEID's resources surrounding them, "Green Engineering & Sustainable Design" is now a very different experience. In place of traditional homework assignments, current students explore the course's sustainability principles through design challenges that also teach students how to use essential CEID equipment. Those same tools have also made possible new depths and ambitions in the students' final projects. "Instead of reaching the end of the semester with only a concept, students are now developing robust prototypes and testing their ideas," says Zimmerman. "The resulting creativity, ingenuity, and passion of the students is impressive."

When the course was offered last spring, one such final project was a folding box, an e-commerce packaging design that could be reused again and again. Capable of bending without breaking or even significantly degrading over time, the polymer-based folding box could be used to ship goods to high-volume customers, such as Amazon Prime subscribers, and then sent back to the company for reuse. Moreover, the folding box also eliminated packing tape waste by integrating thermoformed fasteners into the design — a feature brought about through careful consideration regarding how to reclose the box and ensure that it's not opened by anyone other than the intended recipient. Growing out of the principles of the course, the folding box guarantees safety and security while reducing the human footprint. "Our interest in this course," says Zimmerman, "is really big innovative ideas that solve really important global problems. The students are challenged with developing solutions — sustainable solutions — that may not have ever been thought of before."



MENG 491

Appropriate Technology for the Developing World

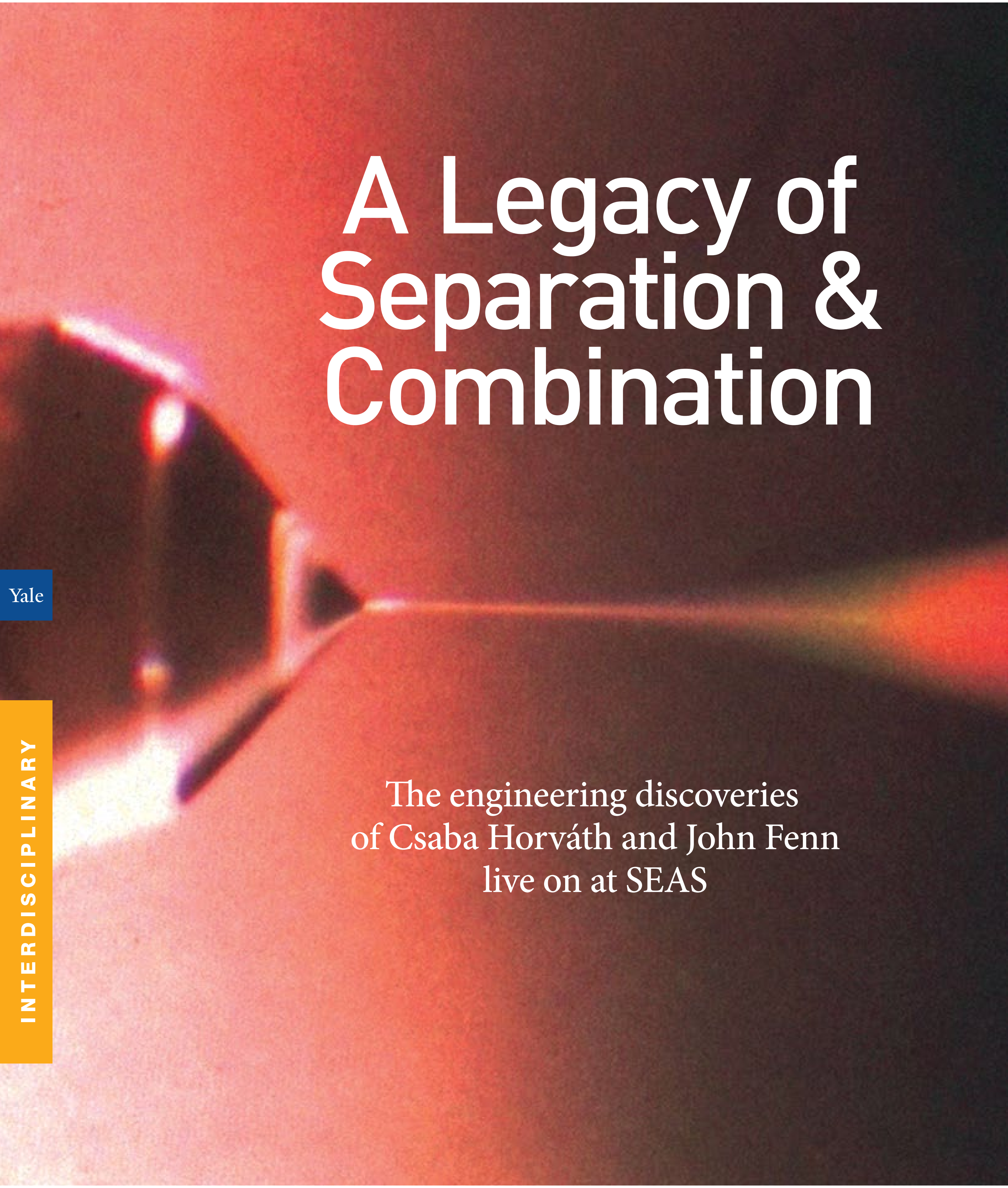
It's a startling fact: 1.5 million children die each year from vaccine-preventable diseases. But that fact took on a new meaning for students in "Appropriate Technology for the Developing World," when they were asked to find ways to lower that number.

Co-taught by Bo Hopkins, a lecturer for Yale's Jackson Institute of Global Affairs, and Joe Zinter, "Appropriate Technology for the Developing World" leverages the resources at Yale to develop solutions for a new global challenge each year. "It might be related to agriculture, it might be drug delivery, it might be electricity — it could be anything," says Hopkins. "The students have to figure out how they might develop viable solutions for some of the world's most complex problems."

This year, the students were divided into four teams and asked to improve the technology for rural vaccine delivery, specifically focusing on what's known as "the last mile." While vaccines are easily maintained at the proper storage temperature for their journey from manufacturer to storage to regional hospital, in many resource poor settings, those vaccines are then transported to villages — the "last mile" that may actually be many miles, over roads that are often impassable by car. When vaccines arrive at these rural destinations, their effectiveness has often been diminished or eliminated entirely by temperature fluctuations during transport; though the on-site clinicians administer the vaccines, there is no way to tell how much protection — if any — the patient will receive.

The four student teams in the course developed diverse solutions that each targeted a different aspect of the problem. One team invented a small, low-cost, real-time temperature monitoring system that uses text messages and a GPS tracker to report when and where portable vaccine storage containers get too hot to be effective, while another team developed a modular packaging design that stays at the ideal vaccine temperature much longer than the conventionally used Styrofoam coolers and ice packs. The third team rethought even the vaccine injection, creating an easily stored and cooled pre-dosed single-use vaccine syringe wrapped in a high-capacity thermal sleeve. Finally, the fourth team embedded a near-field communication chip inside a small amulet, creating an inexpensive, durable, and color-customizable piece of wearable tech for an infant's vaccination record to be stored digitally on a necklace; the amulet eliminates the need for mothers to keep a paper record that can be accidentally lost or destroyed, and allows for mothers to receive automated SMS messages of upcoming vaccinations. This 'Khushi Baby' team — which won the 2014 Yale Thorne Prize for Social Innovation in Health and a $25,000 cash prize — spent the summer in India working with their partner, nonprofit organization Seva Mandir, to field test their amulet, and they hope to conduct phase one trials in early 2015.

The opportunity to engage with such difficult and important problems appeals to students in many disciplines — and that interdisciplinary collaboration is key to innovative solutions the students develop. "We bring people from the arts, from architecture, from computer science, from management, from molecular biology," Hopkins says. "The best thing about the CEID is getting that diverse cross-section of students in here, and the best thing about teaching in the CEID is interacting with those students on these big real-world problems. With those students in this space, I know we can do anything."



A Legacy of Separation & Combination

The engineering discoveries of Csaba Horváth and John Fenn live on at SEAS

Even almost fifty years after high-performance liquid chromatography (HPLC) was invented at Yale by chemical engineer Csaba Horváth, scientists around the world continue to discover novel applications for the technique: detecting drugs in bodily fluids, determining the caffeine content in coffee beans, precisely measuring out pharmaceuticals for experimental analysis or drug preparation.

But HPLC's usefulness — and connection to Yale — has been magnified through the use of electrospray ionization, an innovative interface technique for use with mass spectrometry developed by Horváth's Yale faculty colleague and fellow separation scientist, Nobel laureate John Fenn. Like HPLC, electrospray ionization mass spectrometry (ESI-MS) has become a vital method for the study of proteins and other molecules, such as when diagnosing certain genetic metabolic disorders. Through these technologies, Horváth and Fenn's scientific contributions continue to be foundational for further scientific advancements in a number of diverse fields.

But at Yale, where both scientists provided decades of service, their legacies also live on in other ways: though the annual Horváth Lecture Series, world-renowned separation scientists enrich the Yale community by sharing their work with our faculty and students; as well, SEAS faculty members Alessandro Gomez and Juan Fernandez de la Mora continue to extend Fenn's electrospray innovations.

Dan Rosner helped found the Horváth Lecture Series in 2009, and he has been among its strongest advocates since. "Horváth's impact has been enormous," says Rosner, a professor emeritus of chemical & environmental engineering with 45 years of service, now remaining active at Yale as a research professor. "In part that's because of the remarkable number of students he had: he attracted over fifty doctoral students and postdoctoral researchers, who are now dispersed around the globe, making their own contributions. While this lecture series has enabled us to bring prominent people to Yale — superstars in the separation field — all of them have a connection to Horváth, as his students, as his collaborators, or as scientists who directly engage with his work."

Those "superstars" represent a wide diversity of separation science research, and their lecture topics have been equally varied: Ann Lee, a former student of Horváth's who is now senior VP of Genentech, spoke about how chemical engineers can contribute to oncology drug innovations; the year prior, Edward Cussler, now an emeritus professor at the University of Minnesota, discussed how to design new chemical products, from commodities like ammonia to chemical devices like Horváth's chromatograph — with a particular focus on nanostructured products such as aircraft anti-icing chemicals and the fish paste used in imitation crab. The first two lecturers — C. Judson King, director of the Berkeley Center for Studies in Higher Education, and emeritus professor Edwin Lightfoot Jr. of the University of Wisconsin-Madison — provided critical reviews, respectively, of the entire field

Continued →

Csaba Horváth

John Fenn

of separation processes and of the recovery and purification of high-level biologicals. And in 2013, Fenn's student Matthias Mann, now director of Germany's Max-Planck Institute of Biochemistry and among the most highly-cited researchers in his field, focused on Horváth's HPLC in tandem with Fenn's ESI-MS, reporting improvements to those techniques that have made it possible to analyze nearly the entire yeast proteome — the entire set of proteins expressed by a genome, cell, tissue, or organism — and much of the human cell line proteome in only a few hours. With such innovations to Horváth and Fenn's methods, he said, "proteomics is now ready to directly answer questions of clinical relevance."

This year, the sixth annual Horváth Lecture was presented by Douglas Frey, a former collaborator of Horváth's who spent nine years as a Yale chemical engineering faculty member and who is now a professor at the University of Maryland, Baltimore County. After a short reminiscence about Horváth's precision ("For Csaba, every word in a paper was a like a drop of blood."), Frey's lecture focused on an inventive use of HPLC called chromatofocusing. In regular HPLC, a sample mixture is forced by a pressurized liquid solvent through a narrow column; interacting with the adsorbent material, the sample components separate, ready to be identified and quantified as they exit the column. Chromatofocusing, noted Frey, extends HPLC by using a series of solvents with progressively lower pH, causing particular components of the sample to separate at a "focused" pH. The technique is helpful in purifying protein variants that are similar except for their charge difference, as Frey has done when analyzing the heterogeneity of antibodies in our immune system.

Frey's lecture was the latest illustration of how Horváth's innovations in separation science still enrich the Yale community. As a world leader in chromatofocusing techniques, Frey has expanded upon methods Horváth pioneered — along with developing his own methods — and Frey's visit offered those in attendance firsthand exposure to techniques not otherwise being researched at Yale.

"This lecture series expands upon Horváth's impact," says Rosner. "He was one of the leading lights in separation science, and through this series, the very best separation research in the world is brought home to Yale Engineering, where so much of it began. And perhaps not coincidentally, when we look at the groundbreaking researchers in this field, searching for future lecturers, many of the best candidates are Horváth's students — his influence lives on not just through his scientific contributions, but also in everyone he taught at Yale."

For that particular aspect of his legacy, Horváth owes no small debt to John Fenn: After joining the faculty in 1967, Fenn was the one who ultimately recruited Horváth to Yale engineering two years later — the same year Fenn also recruited Rosner. And like Horváth, Fenn's scientific innovations continue to be integral to Yale's engineering culture, most notably through the work of Rosner's own recruits: professors Alessandro Gomez and Juan Fernandez de la Mora.

"I'm one of the scientists carrying the electrospray torch for Yale since Fenn's departure," says Gomez, professor of mechanical engineering & materials science. In Fenn's technique, a sample (perhaps as it exits the HPLC column) is combined with a highly-conductive solvent then pushed through a small needle; the needle has an electric charge applied to it, causing the mixture as it exits the needle to form a cone, the tip of which breaks into a finely sprayed mist of small, stable, charged droplets. In mass spectrometry, the charged droplets evaporate, releasing solute ions that then enter a vacuum where they can be analyzed based on how their trajectory is deflected by the pull of electric or magnetic fields. "Electrospray, because it doesn't produce much product, essentially has had only one core application — mass spectrometry," says Gomez. "So I've spent a considerable amount of time 'multiplexing the electrospray,' using multiple electrospray sources that behave identically to increase the throughput."

A significant portion of Gomez's research has focused on using electrospray to controllably deposit particles on a surface. For example, he has used the technique, which involves pushing a desired substance through a multiplexed electrospray with a solvent, to create uniformly sized biodegradable polymers for controllable drug delivery, as well as for manufacturing cheaper solar cells. "The current photovoltaic panels you see on the roofs of homes and office buildings tend to be built in a relatively costly way," says Gomez. "The prices have gone down quite significantly, but still they're costly because they require clean rooms — it's like building a chip for an electronic device. And one of the less expensive alternatives is dye-sensitized solar cells."

Such cells, says Gomez, entail making a small cell out of titanium particles that have been coated with a catalyst that allows the titanium to absorb the visible radiation coming from the sun. Most research in this field, including by other faculty at Yale, has focused on the development of the optimum catalyst for the energy conversion. "We feel that with multiplexed electrospray, we have a new angle," says Gomez. "We can control the deposition of the titanium particle deposit, looking at how a greater or lower velocity from the spray affects the deposit structure and ultimately the efficiency of these cells. And we'll continue to refine that technique to see what happens."

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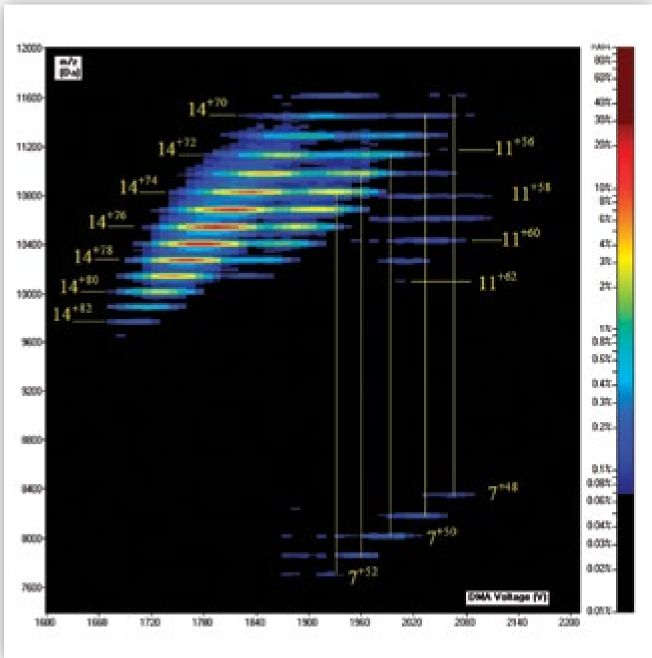
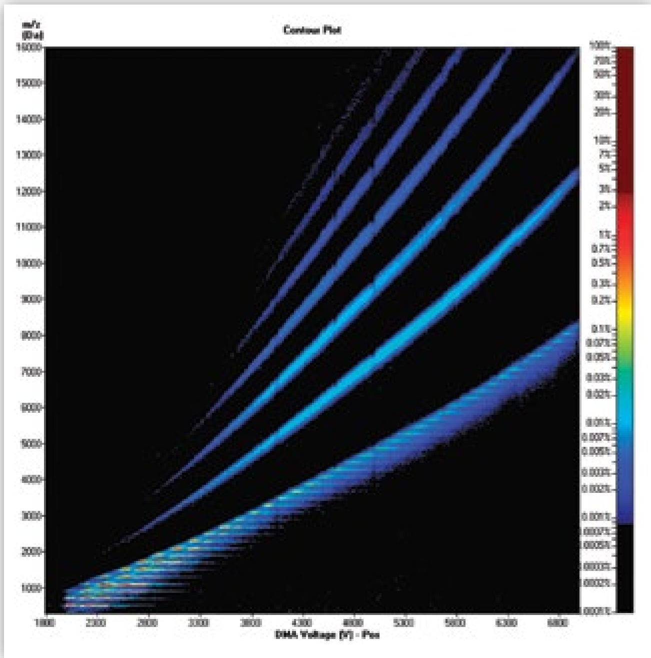




Spectra results from compounds separated in differential mobility analyzer

From High-Temperature to High-Pressure

Dan Rosner celebrates 45 Years of engineering innovation

Since joining the Yale University faculty in 1969, Dan Rosner, professor emeritus of chemical & environmental engineering, has been associated with energy. As director of Yale's High Temperature Chemical Reaction Engineering Laboratory, he's earned international recognition and numerous awards for research on transport processes in multi-phase chemically reacting systems, chemical surface reactions in high temperature flow systems, and the combustion synthesis of nanoparticles. His research has also provided a deeper understanding of heterogeneous chemical reactions under extreme conditions — research that directly influenced the design of the leading edge and nose-cap materials for the NASA Space Shuttle Orbiter Vehicle.

In recent years, Rosner has turned his research focus toward gas anti-solvent precipitation (GASP), a technique that exploits high-pressure CO_2 vapor to generate ultrafine powders of active pharmaceutical ingredients that can dissolve quickly in the body.

Yale

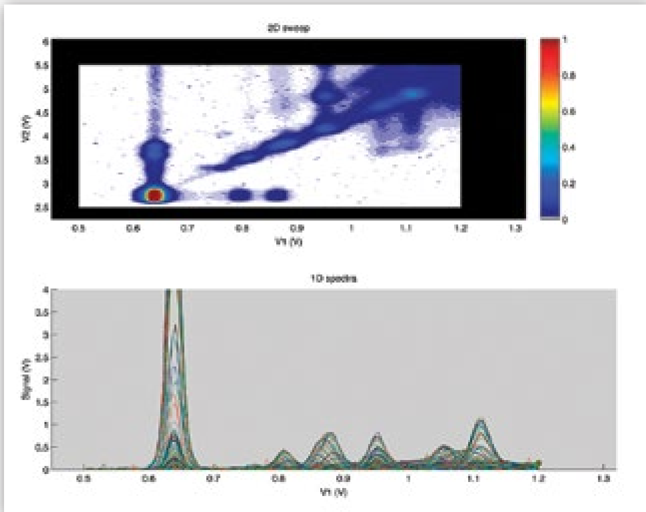
INTERDISCIPLINARY

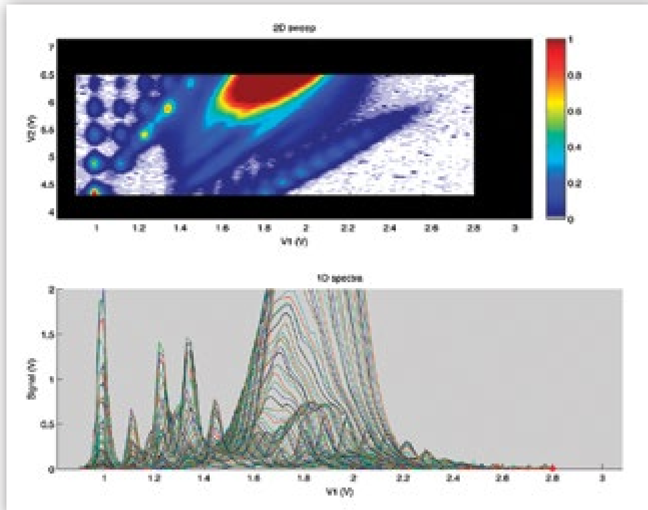
While many methods exist for creating very small pharmaceutical particles, GASP is significant because it doesn't dismantle the drug in terms of activity, and its circumvention of mechanical milling limits potential drug contamination. Instead, GASP begins with a course powder of the pharmaceutical, which is dissolved in a solvent then sprayed into a high-pressure CO_2 environment; the solvent hosting the pharmaceutical ingredient becomes swollen at a high rate by the influx of CO_2, driving the drug out of solution in the form of micron-sized particles.

"But you don't simply get particles of a single size—you get a spectrum of sizes," says Rosner. "We're interested in predicting what factors affect the size of these particles. For example, what size distribution results from operating the process under a certain pressure? How do variations in droplet size change the results? Essentially, we're creating a mathematical description of this anti-solvent precipitation — a comprehensive, practice-ready predictive model for optimizing this process. Such a model would facilitate the adoption of this process by the pharmaceutical industry."

Rosner believes he's very near a sufficiently comprehensive process model, having already discovered and published significant novel features of GASP, including one of the first practical examples showing how the rate constant for coagulation of small particles is reduced by the host fluid's rate of dilation. He has also reformulated the crystal growth rate law to enable reliable predictions under these transcritical conditions, as described in a recent issue of the *ACS Journal: Crystal Growth & Design.*

In this way, even 45 years after he began working at Yale, Rosner is still creatively innovating. Although retiring from the Yale faculty this summer, he has chosen to remain at Yale, where he will continue to improve the mathematical modeling of high-intensity multi-phase chemical and physical processes through his position as research professor. "Through my research," he says, "I continue to connect to the community of scholars at Yale and to the many global scholars in this field — researchers in Spain, Italy, Japan. I can't imagine stopping now: I enjoy this research, and I look forward to further interacting with my colleagues."





2D mobility spectrum in which clusters are selected in first differential mobility analyzer (horizontal axis), given some reaction time to be converted into something else, reanalyzed in a second differential mobility analyzer (vertical axis).

Controlling the velocity of the spray is equally crucial to a project Gomez has developed with professor de la Mora: the ion propulsion system for a ten-by-ten-by-ten centimeter microsatellite. Such satellites are deployed into space using chemical rockets, says Gomez, "but for tiny adjustments to keep them aligned, you need a thruster that can last for a long time, typically years, and that also can be operated on and off every so often. Multiplexed electrosprays that generate nanodroplets propelled at very, very high speed are one viable way to make these adjustments."

The small size of the electrospray drops was in fact one of the original attractions for de la Mora, professor of mechanical engineering & materials science. "They are beautiful," he says. "Ionized water projects very intense blues and reds from light scattering in the drops. And when the drops become small enough, you can't even see the drops themselves because they're smaller than a wavelength of light." These incredibly small droplets — some as small as a single ion, depending on the conductivity of the material being sprayed — can move the microsatellites with such exacting precision that NASA plans to employ these electrospray thrusters to detect gravitational-wave induced strains in space-time by measuring changes of the separation between three spacecraft 5 million kilometers apart.

But in addition to his interest in electrosprays, de la Mora has also followed in Fenn and Horváth's footsteps through contributions to separation science he's made using differential mobility analyzers. "To get a complete chemical description of a complex mixture, HPLC may take one or two hours to separate all the components," he says. "A differential mobility analyzer does the same thing almost instantaneously."

It all begins with an electrospray: the sample is charged and sprayed through a tiny slit towards a charged plate a short distance away. However, as the sample exits the slit, a stream of gas comes from the left side — the particles are attracted to the charged plate, but carried downstream by the gas. "The particles spread in a fan depending on how fast they move in the electric field, which has to do with their drag," de la Mora says. "Particles that have a big drag will move more slowly. And there's another slit in the far panel, so essentially, you fix the voltage of the panels and measure the masses of all of the ions that come through the opposite slit. Change the voltage and you get a different range of masses. Change it again, and again, and you can separate thousands of different classes. Then the mass spectrometer, which has a higher resolution, separates them into a hundred-thousand different classes."

De la Mora suggests that in some cases, the differential mobility analyzer could be a substitute for Horváth's HPLC, though because of the electrospray lead-in to a mass spectrometer, "perhaps it's more a continuation of the Fenn tradition." Or as a combination of both, it's de la Mora picking up where the two researchers left off, furthering the field of separation science at Yale in their absence. Either way, Gomez suggests one more lesson he and de la Mora received from Fenn and Horváth: "We learned from both of them that so long as we keep having fun and training students, then it's worth it."

EDUCATION

AGLP Fellows Today, Industry Leaders Tomorrow

Alumni of the Advanced Graduate Leadership Program are translating experience into top jobs

Students earning engineering PhDs are taught by university professors to conduct research that meets the rigorous standards of academic science, that is written for an academic audience, and that is published in journals that might have a theoretical focus. For all these reasons, it's easy to assume that upon graduation, many, if not all, engineering doctoral students become university professors themselves.

But in truth, the majority of engineering doctoral students find careers outside of academia. They become inventors and entrepreneurs, they serve as technical experts for companies large and small, and they use their scientific knowledge to pursue passions in related fields: healthcare, chemistry, finance, communications, politics. In short, engineering students need to be prepared for the veritable cornucopia of options that lie before them.

Launched in 2009 with a grant from The Goizueta Foundation, the SEAS Advanced Graduate Leadership Program (AGLP) was established to connect doctoral students' time at Yale to their later career possibilities,

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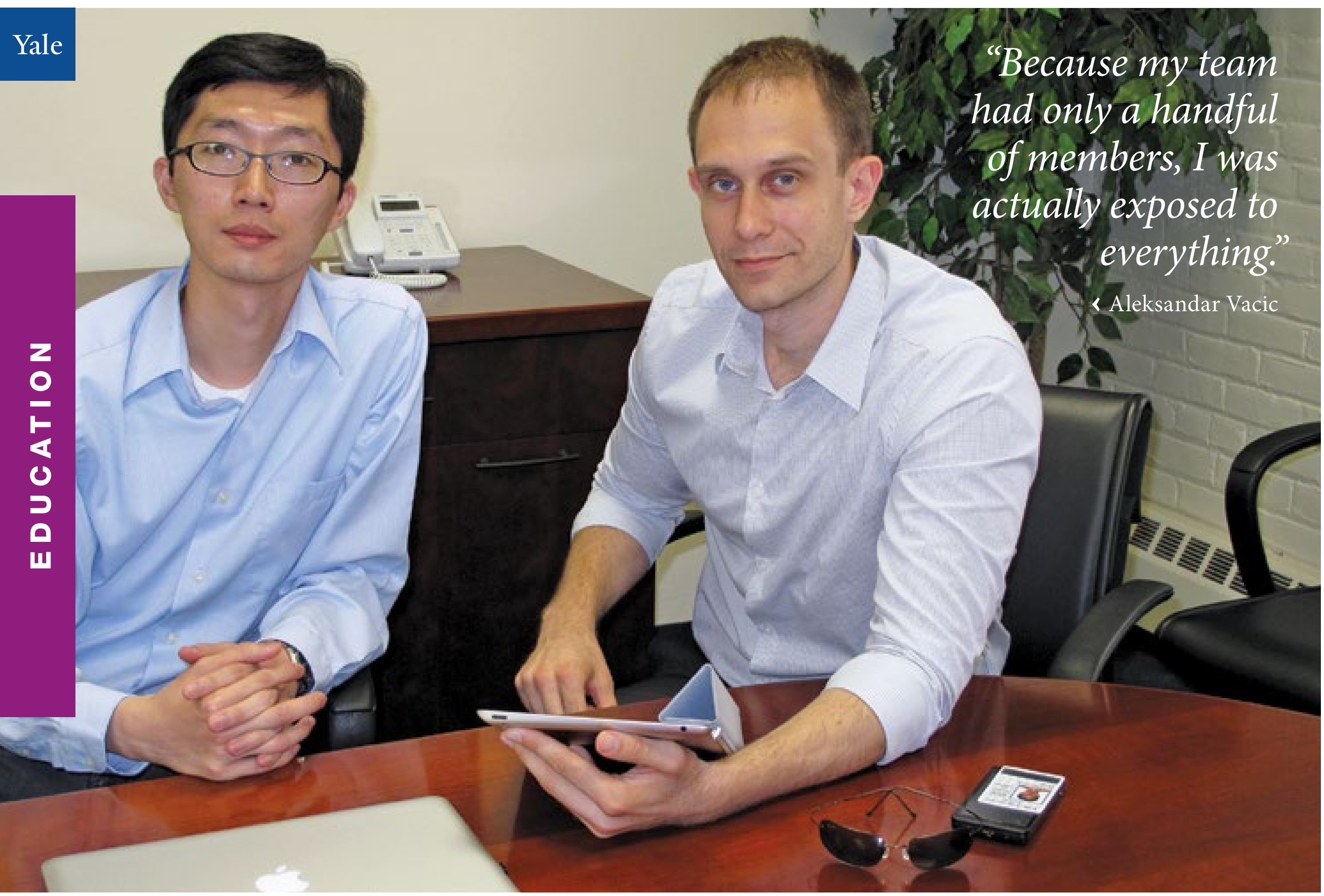
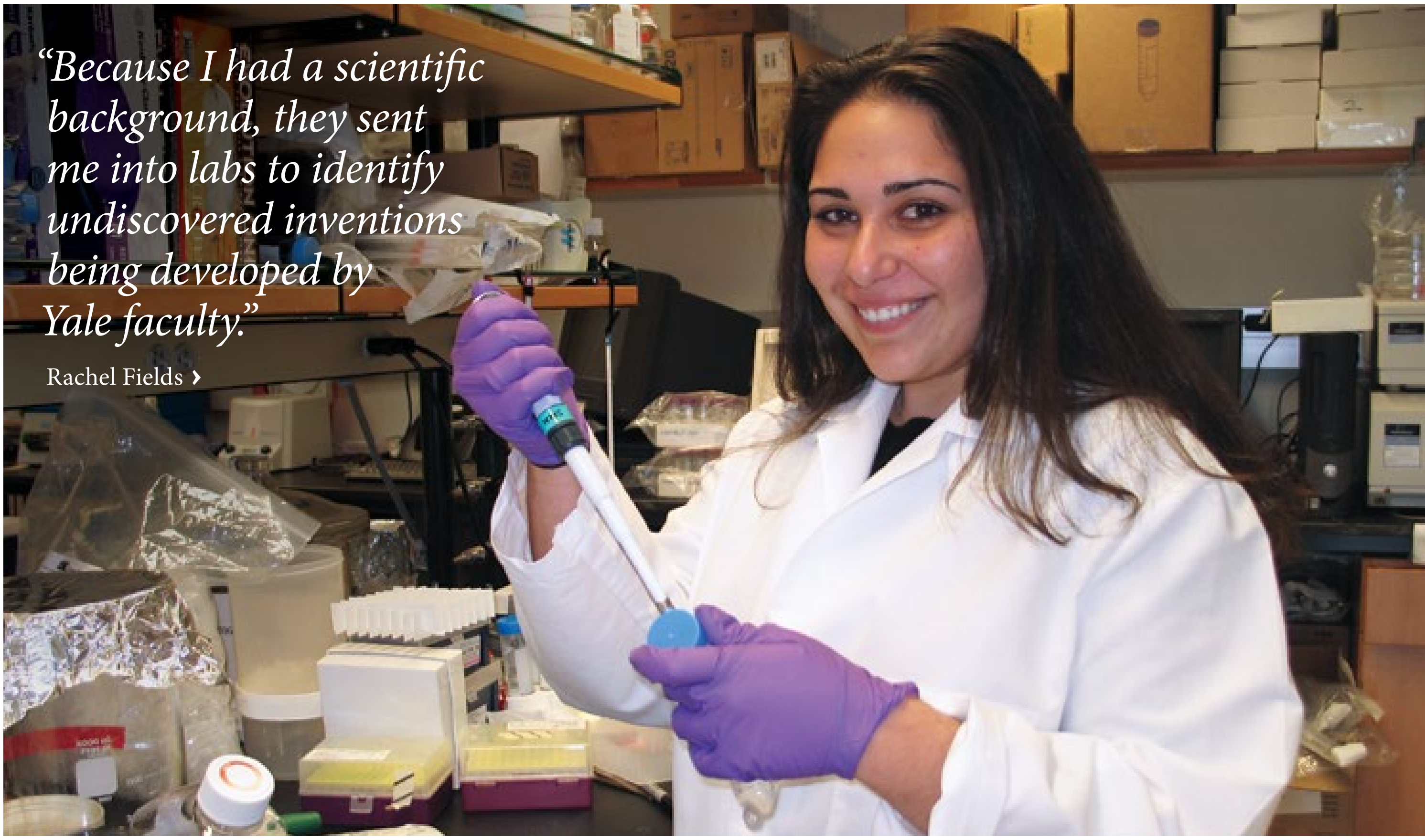
providing a select group of SEAS graduate students with beyond-the-lab training and experiences. The core curriculum — consisting of either a coursework sequence in the Yale School of Management or a semester-long internship — is tailored to a student's own professional aspirations within three broad areas of interest: academics, business & industry, and policy & public service. In addition, AGLP Fellows have access to a year-long career strategies workshop series, individual leadership coaching, and funds for additional professional development, all of which further prepare them for the many forms of life after SEAS.

After graduating from Yale, chemical engineer and AGLP alum Fang Fang began working at a tech startup — though it's not a position she would have ever considered if she hadn't completed the AGLP, including an internship with the Yale Entrepreneurial Institute (YEI). "The Fellowship opened my eyes to other career paths, to real industry activity," she says. "The learning curve at my YEI fellowship was fast and exhilarating, and I was able to leverage all of my graduate studies, even while broadening my perspective from pure scientific thinking into a combination of science and business." It's perhaps no surprise then that Fang graduated from SEAS knowing she wanted a position where she could grow with the company.

Now at Mezocliq, a startup focused on Big Data analysis, Fang's most important assets for addressing her clients' needs are the problem-solving skills she learned during her doctoral research: she begins by framing the problem she's trying to answer, then compares variables across different projects and tries to find a narrative that can be programmed to produce meaningful results — just as she did during her PhD experiments. And with her AGLP experience, she is able to translate those same skills to other aspects of her position. "With a startup," she says, "you're



"Because my team had only a handful of members, I was actually exposed to everything."
‹ Aleksandar Vacic



forced to stretch into other areas, such as assisting the client services team or the programming team. But more than that, I've succeeded here because the AGLP taught me to be well-rounded and to accept every challenge the day brings."

Like Fang, electrical engineer and AGLP alum Aleksandar Vacic found a job immediately after graduation, making the leap from SEAS doctoral student to Senior Device Physicist at 1366 Technologies. But Vacic's AGLP Fellowship in YEI's student ventures program prepared him for life after SEAS in unique ways. Through YEI, Vacic was able to get experience as the physics and engineering anchor for a technology startup, using his scientific training to solve problems as they arose. "Because my team had only a handful of members, I was actually exposed to everything," Vacic says. "I gained experience raising money and then dealing with all the problems that come with it, I was asked to help improve the business plan — I even participated in the IP research and the competitive analysis."

Vacic now leads an R&D group at 1366 Techonologies that is responsible for optimizing each of four subprocesses that make up his company's solar cell manufacturing technique — a diverse set of problems that keeps him constantly challenged as an engineer. However, as a senior-level scientist, he is also the crucial link between the science team and the business managers, doing many of the same things he did during his AGLP internship. "I end up traveling around the world," he says, "taking part in dealmaking, planning negotiations, working with other engineers and with other companies. These are real-world skills that not every engineer has."

Vacic and Fang both sought out Fellowships to face the diverse challenges of being engineers at a startup company. Some students, however, hope their internship might diverge from the path even farther, illuminating post-graduation next steps that might not be directly engineering-related.

Rachel Fields was one such student. Among the first students accepted into the AGLP when it was founded, she was excited to apply everything she'd learned in graduate school to something science-related in the biotech world. "But I also knew that the right 'something' wouldn't be in doing the science itself," she says. A biomedical engineer with extensive training in novel polymers for gene

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therapy, Fields' core AGLP experience was in a combined internship in Yale's Office of Cooperative Research (OCR) and in YEI — an internship experience that didn't require her to "engineer" anything. At OCR, she learned to write intellectual property documents and provisional patents, while also getting an introduction to licensing deals. "Because I had a scientific background, they sent me into labs to identify undiscovered inventions being developed by Yale faculty," she says. "I'd talk to professors to see if we could come up with commercial aspects worth pursuing." At YEI, she trod a complementary path, reviewing seed funding applications from undergraduates founding their own companies.

Now Fields works as an assistant account executive for Russo Partners, a boutique healthcare communications firm in New York City with global clients in the biopharma, medtech, diagnostics, and healthcare IT sectors. She credits her doctoral education as critical to her preparation for this position: whether managing the press coverage for a client's new cancer therapy or leveraging social media to raise awareness of a client's new smartphone app, her first challenge is understanding the technical capabilities of her clients' innovations and services. However, her job would be incomplete with only the science. "The AGLP taught me how to translate the knowledge I gained in the lab into opportunities outside the lab," she says. "In my work, clients' messages have to balance the needs of the science with the needs of the business, and that's just as true when developing high-level corporate communications strategies as when interacting with customers on Twitter. If I didn't understand my clients' scientific breakthroughs *and* their business strategies, the job would be impossible."

The AGLP internship, while central to the Fellowship, is only the beginning of the program's support. Monthly workshops gather the Fellows together around a communal theme, and their small size allows for advice tailored to each individual's needs. "The workshops lend themselves to building your own confidence and your own skill set," says Leanne Gilbertson, a chemical engineer and AGLP alum who graduated this past spring. "They've covered a huge variety of topics around yearly themes — communicating, negotiating, and marketing yourself — all of which directly influenced my personal development."

Left to right: Julie Zimmerman, Leanne Gilbertson, and Dean T. Kyle Vanderlick

Prior to arriving at Yale for her doctorate, Gilbertson taught high school chemistry, and she approached her time at SEAS as an opportunity to explore non-academic engineering careers. By the time she enrolled in the AGLP, however, she was certain that being an educator was an important part of her identity, and so she looked to see how the AGLP could better prepare her as a future faculty member. In one example, through her internship in the Office of New Haven and State Affairs, she developed a K-12 science outreach program in collaboration with a local engineering and science high school. As well, through the career workshops, she determined that a postdoc position at Yale would best set her up for her next career move. "Certain skills are universal," she says. "In being a professor, there's an outreach aspect, a negotiation aspect, a leadership aspect when you build your lab group. The Fellowship gave me the skills to get where I want to be, and through connections I made

with other Fellows, I already have a professional network that could be a competitive advantage in the job market."

In that regard, the AGLP, while still relatively young, is already impressive: AGLP Fellows consistently find meaningful, challenging employment after graduation, with the majority of the career trajectories directly correlated with their AGLP internship experience. Moreover, the skills learned in the AGLP provide a foundation for addressing the challenges of all career stages after that initial position. That, at least, has been the experience of chemical engineer and AGLP alum Nan Li, who right after her graduation in 2011 was hired by the Boston Consulting Group. Since then, Li's career trajectory has been anything but timid. After building experience at Boston Consulting Group, she joined Primus Green Energy as their business development manager. Even more recently, she was offered a position at BASF as a Senior New Business Development Manager. With every career move, she says, she's thought back to things she learned in the AGLP. "Through the program, I received weekly leadership coaching, and I was able to quickly develop interview skills that I would otherwise have had to learn through trial and error. These things were incredibly helpful and prepared me for everything I was going into after graduation."

At BASF, Li is responsible for optimizing change among all BASF businesses, looking at what goes in and what goes out of every BASF location. Like the other alums, she's found that her position requires a careful mixture of scientific acumen and business insight. "My job is to ask, 'does it make sense to buy something or to make it?'" she says. "Looking at it from that high level, I might find that the byproducts of one business process can be the stock for another business. So it's a position where I'll make a significant difference."

Already Li's noticed one significant difference at BASF: "Every other employee at this same level in the company is ten years older than I am. I feel like the AGLP has accelerated me in my career that much."

Engineering Is Not

It's been called the unlikeliest title game in NCAA hockey history: against all odds, the 15th-seeded Yale Bulldogs knocked off opponents left and right — including two No. 1 seeds — to earn a face-off against their crosstown rivals, the top-ranked Quinnipiac Bobcats. Then, just four seconds before the buzzer could end the second scoreless period of the game, biomedical engineer Clinton Bourbonais slapped the game-winning shot between the Bobcat goalie's legs. Rallying with excitement, Yale scored three more unanswered goals to claim the 2013 championship in a 4-0 win.

Bourbonais, who graduated this past spring, is only the latest SEAS student to successfully balance the high-energy physical demands of varsity athletics with the mentally taxing rigor of Yale engineering's academic programs. Engineering graduates have dueled for Yale fencing and caught the wind with their fellow sailors, tumbled for our gymnastics squad and shutout opponents pitching for Yale Softball. Here's a look at some of the top scholar athletes from the class of 2014 who came to Yale for the win.

JUSTIN BERL PHOTOGRAPHY

Hockey

Clinton Bourbonais

Biomedical Engineering

Fencing

Peter Cohen

Environmental Engineering

Field Hockey

Emily Schuckert

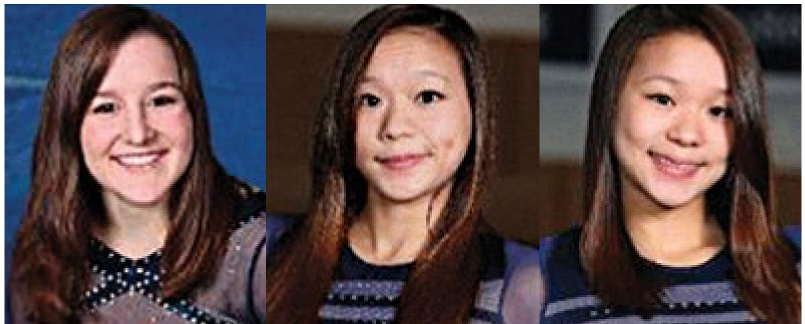
Environmental Engineering

Their Only Goal

Football

Greg Carlsen
Biomedical Engineering

Jack Bechert
Electrical Engineering



Gymnastics

Maren Hopkins
Mechanical Engineering & Economics

Nicole Tay
Biomedical Engineering

Tabitha Tay
Biomedical Engineering

Lacrosse

Dylan Levings
Environmental Engineering

Sailing

Christopher Segerblom
Mechanical Engineering

Marissa Pettit
Biomedical Engineering

Squash

Gwendoline Tilghman
Electrical Engineering & Economics

Soccer

Peter Jacobson
Chemical Engineering

Softball

Chelsey Dunham
Biomedical Engineering

Swimming

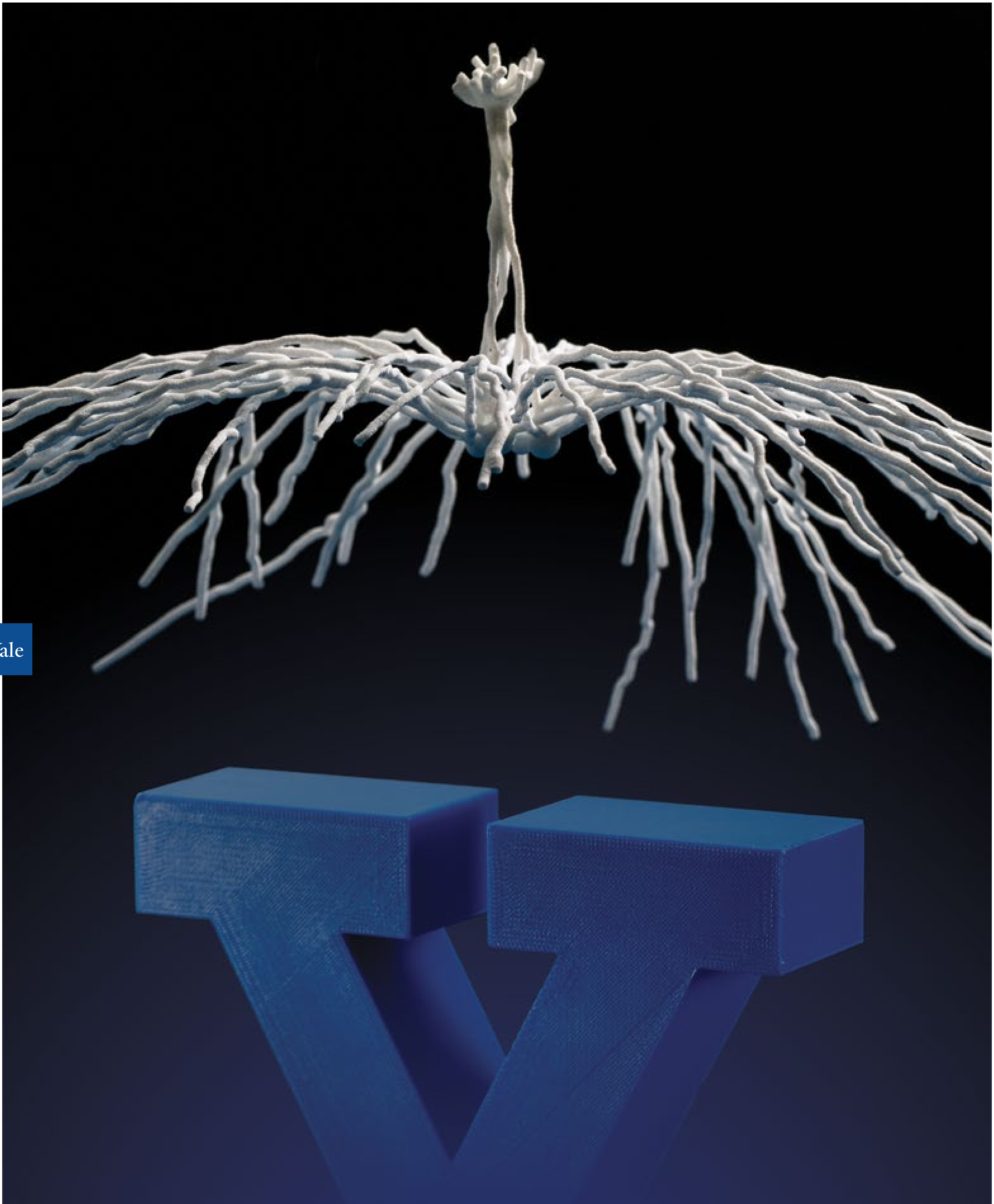
Allison West
Mechanical Engineering & Political Science

Paschall Davis
Electrical Engineering

Tennis

Patrick Chase
Electrical Engineering & Computer Science

Yale



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