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

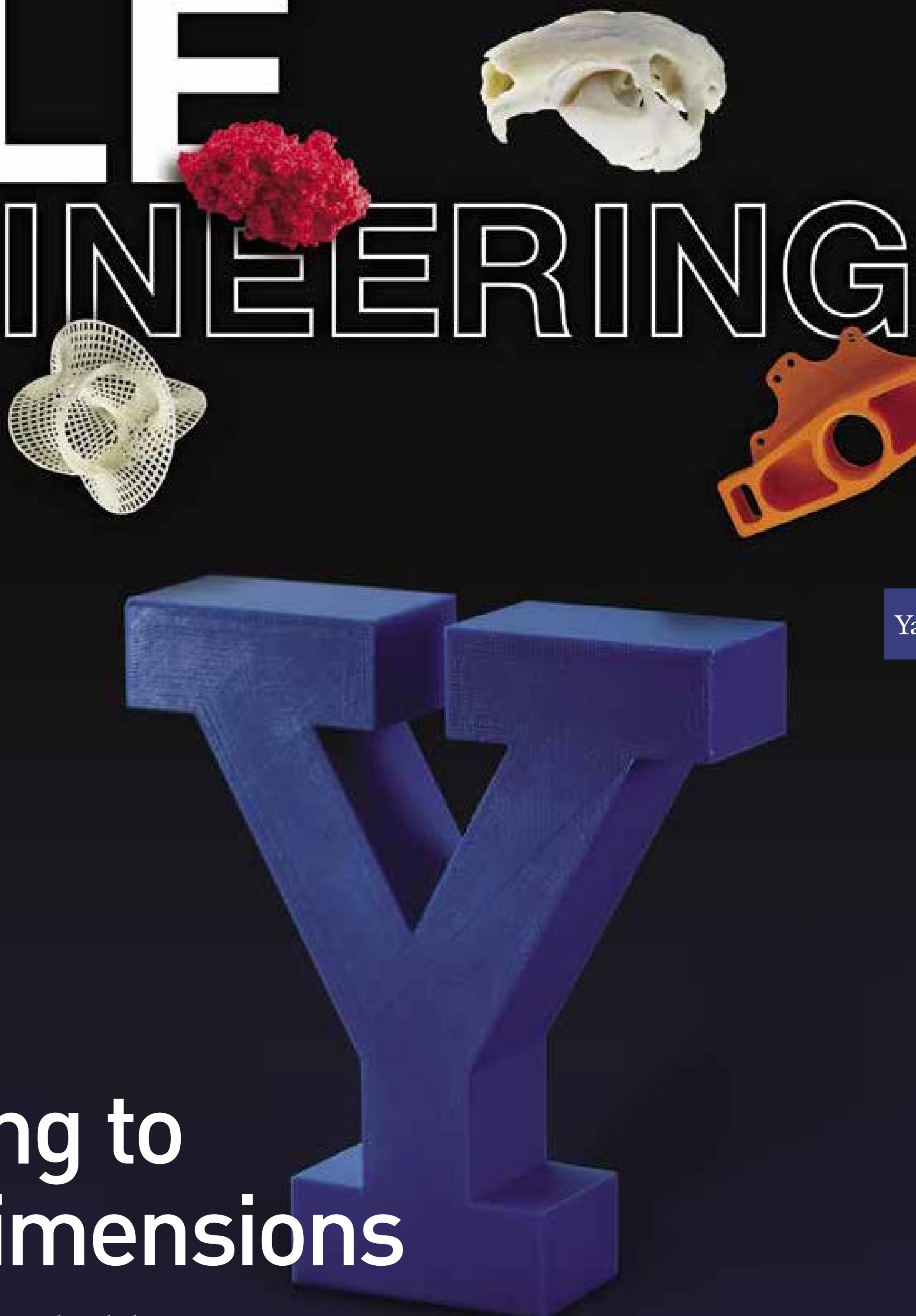
With three new hires, Yale's environmental engineering program is rising to the next level

A Better Class by Design

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

2014-2015

YALE ENGINEERING



Yale

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

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

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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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ENAS 118

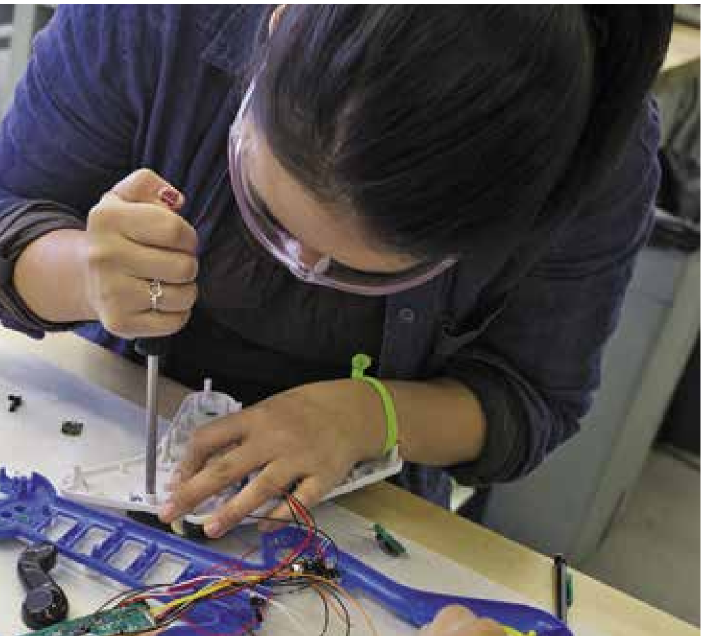
Introduction to Engineering, Innovation, & Design

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.

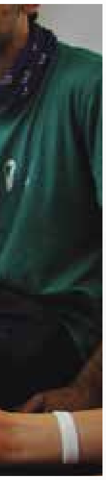
ENAS 360

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

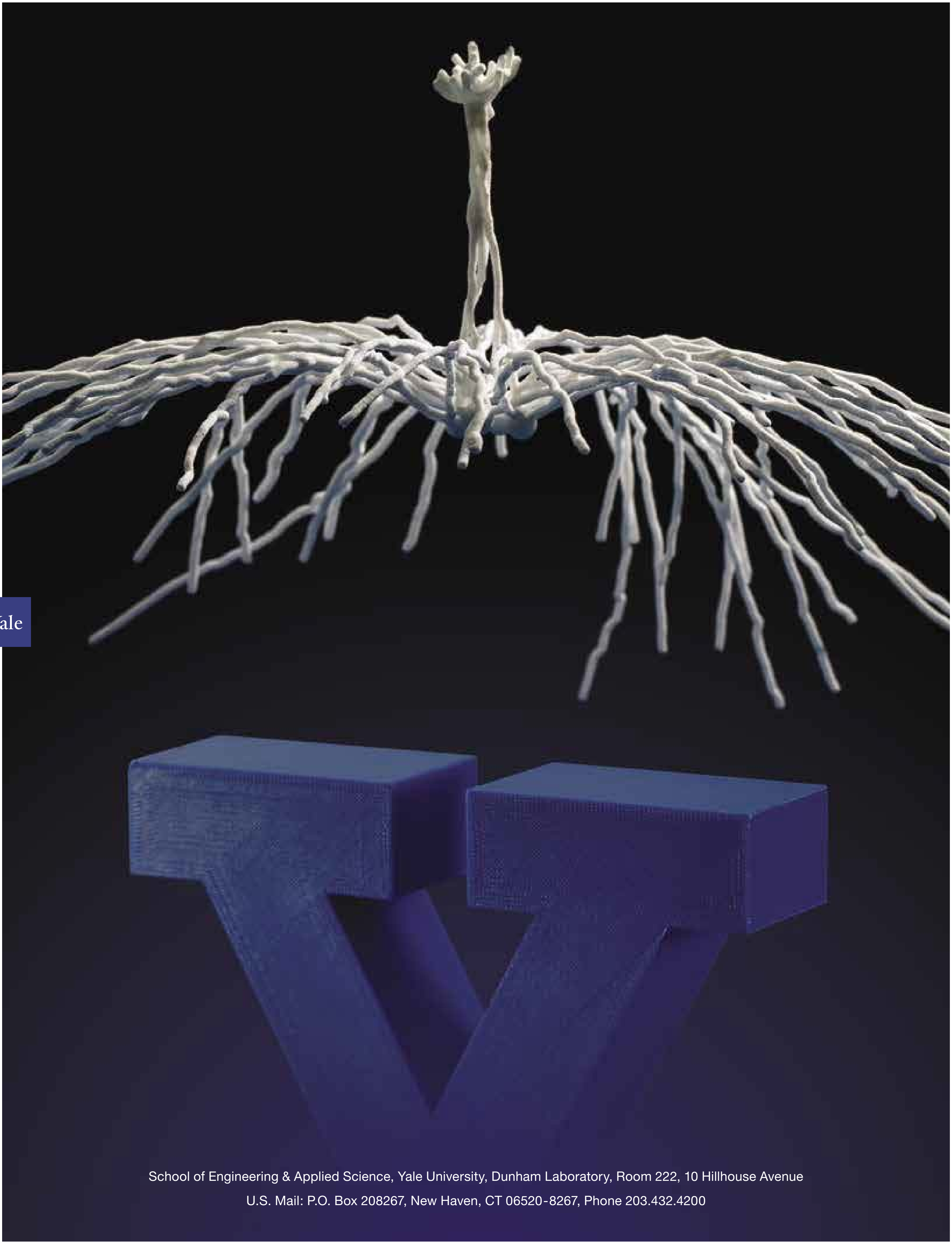
It's a startling fact: 1.5 million children die each year from vaccine-preventable diseases. But that fact took on a new meaning for students in "Appropriate Technology for the Developing World," when they were asked to find ways to lower that number.

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."



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