Worldwide Undergraduate Collaboration

Utilizing today's technology, innovative research doesn't stop when the school year ends

Moving Molecules to Create the Materials of Tomorrow

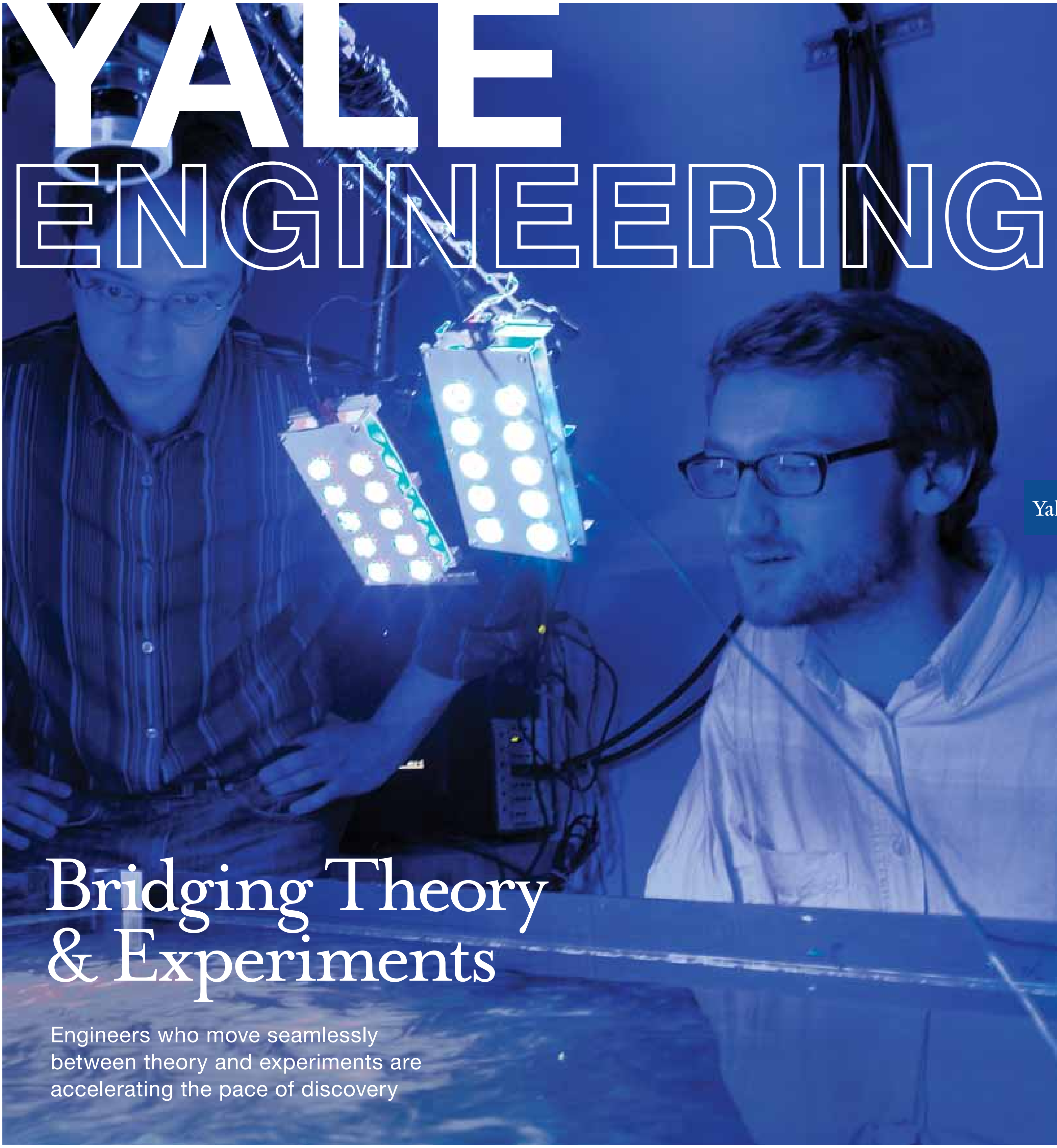
Efficiencies gained by aligning nanometer-scale components in composite materials

Moving from the Classroom into the Marketplace

Yale team awarded Grand Prize for improving food safety

2011

YALE ENGINEERING



Bridging Theory & Experiments

Engineers who move seamlessly between theory and experiments are accelerating the pace of discovery

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

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YALE ENGINEERING
2011

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Message From the Dean

Though rarely described this way, engineering is the bridge between the sciences and humanities. Simply put, engineers apply scientific principles to advance the human condition. Their success relies as much upon an understanding of physics and math as an appreciation of history and psychology. Engineering bridges the limits dictated by science (e.g., the laws of thermodynamics) with the limitless nature of human talents and passions.

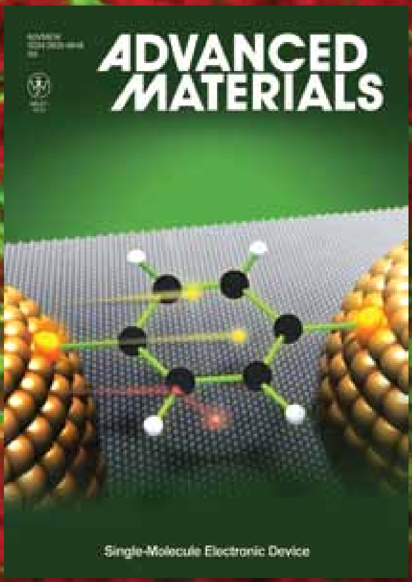
It is a shame that engineering is not usually put into this context. Instead engineers are often portrayed as über-science introverts or as nerdy tinkerers. (These stereotypes usually supplanting the childhood imprint of engineers being associated with trains!) Is it any wonder that only about 5% of college graduates in this country are choosing engineering as their major?

By framing engineering as the intellectual bridge that it is, we will not only draw in the best young minds but also the diversity of minds that represent our collective existence. How can we truly expect to advance the human condition through technological progress by engaging only a small non-representative sample of the population?

It is going to take a great deal of effort to change the populist notions about engineering, especially as an education. Not all history majors become historians; not all chemistry majors become chemists; and certainly not all engineering majors pursue careers as professional engineers. But engineering majors have invested in an education which ties the sciences to the humanities, which develops quantitative thinking, and which teaches design and problem solving in the face of incomplete knowledge. Engineering is the quintessential liberal education for the technologically driven world in which we live.

And given that a bridge is only as sturdy as its footings, it is hard to imagine a more ideal setting for the study of engineering than at Yale (where even geographically we are located between the humanities and the sciences). As we grow and advance the School of Engineering & Applied Science here at Yale we have no more important mission than to lead by example, developing and showcasing engineering as the interconnect that it is.

We hope you enjoy this edition of *Yale Engineering* – a view from the bridge.

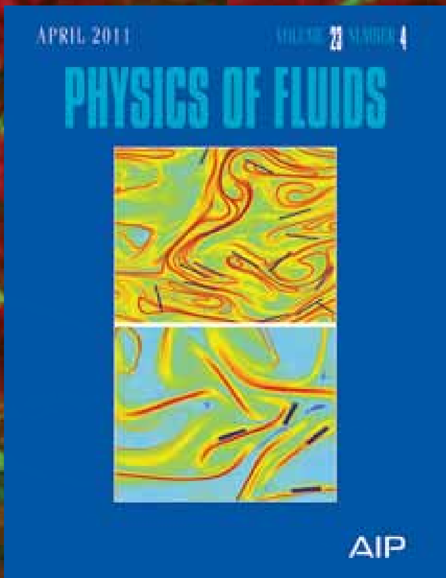


Yale

INTERDISCIPLINARY

Yale Engineering Cover Models

Leading journals depend on Yale engineers for cover stories



International scientific and engineering journals often feature leading research as their cover stories. This year, Yale School of Engineering & Applied Science researchers were highlighted on the covers of numerous publications.

MARCH: *American Journal of Physics*

Assistant professor of mechanical engineering & materials science Nicholas Ouellette describes the use of a particle-tracking apparatus developed in his lab to introduce undergraduates to modern image processing and particle tracking methods for understanding instability in fluid flow.

APRIL: *Advanced Materials*

Mark Reed, Harold Hodgkinson Professor of Engineering & Applied Science & Electrical Engineering, and colleagues review experimental aspects of electronic devices made with single molecules.

APRIL: *ACS Nano*

Jan Schroers, associate professor of mechanical engineering & materials science, and André Taylor, assistant professor of chemical & environmental engineering, describe a new fuel cell catalyst system using nanowires made of an innovative metal alloy that boosts long-term performance by 2.4 times compared to current technology.

APRIL: *Physics of Fluids*

Nicholas Ouellette and colleagues use video particle tracking to study the dynamics of rod-shaped particles in 2D electromagnetically driven fluid flows, and compare two separate types of flows that exhibit chaotic mixing.

JUNE: *Trends in Biotechnology*

Associate professor of biomedical engineering Tarek Fahmy and colleagues review recent advances in immunology and biomaterial engineering that have brought particulate-based vaccines to reality, and describe some of the most common biomaterial elements – liposomes, solid biodegradable polymers, and natural polymers – used in vaccine applications.

SEPTEMBER: *Langmuir*

Assistant professor of chemical & environmental engineering Chinedum Osuji and Lisa Pfefferle, C. Baldwin Sawyer Professor of Chemical & Environmental Engineering, show that nanowires of single-crystal zinc oxide spontaneously form nematic phases in organic and aqueous media. The results provide critical insight for the utilization of semiconductor nanowires, enabling the use of solution-based routes for fabricating optoelectronic devices.

Yale

TECHNOLOGY

The "Blue Beam" Semiconductor: A New Fabrication Method

Innovating in the space between traditional disciplines

Gallium nitrate is a material that has proven to be very useful in electronics despite significant limitations associated with its complex manufacturing and resulting high cost. Recognized for its ability to emit light, the gallium nitride semiconductor is what enables a Blu-ray Disc player to read data and an LED flashlight to shoot an intense blue beam. This semiconductor is also quietly forcing a revolution in lighting industries, enabling a conversion from the decades-old incandescent and fluorescent technologies to solid state. In fact, the high-tech uses for gallium nitride are many, and its potential uses—in wireless data transmitters, solar cells, power grid switches, and microwave ovens, to name a few—are wide spread.

In hopes of enabling some of those future applications, a team of electrical engineers at the Yale School of Engineering & Applied Science is perfecting the processing of this valuable technology.

The key to gallium nitride's usefulness lies in the fabrication of small, thin membranes that are half the surface area of a dime and just 1/60th the width of a strand of hair. Trouble is, the compound known as GaN is extremely hard, which makes processing these membranes difficult, time consuming, and expensive. Because of these complexities gallium nitride has been a challenging target for materials scientists for more than a decade. In light of these materials science and economic barriers the success of the Yale team, led by professor of electrical engineering Jung Han, is particularly satisfying.

Han and his colleagues developed a simple, efficient, and inexpensive electrochemical method for creating small, stable gallium nitride films. By drilling nanometer-sized pores into the material's surface—a technique called "nanoetching"—they developed a technique to essentially weaken the composite structure to then allow thin layers to be peeled off the base material.

Not only did their work succeed in simplifying the fabrication of gallium nitride films, it produced a unique type of "nanoporous" semiconductor, opening up opportunities for new approaches to the design and manufacture of high-frequency transistors, sensors, and other electronic devices. Han's research team, which is principally comprised of electrical engineers, benefitted by the materials science expertise that permeates all fields at the Yale School of Engineering & Applied Science. Their innovation is one example of the technological advances that result from investigating the interfaces between engineering disciplines.

EDUCATION

Worldwide Undergraduate Collaboration

Utilizing today's technology, innovative research doesn't stop when the school year ends

Left to Right *Elizabeth Asai, Elliot Swart, and Nickolas Demas*

For Yale Engineering undergrads armed with Skype and Google+, leaving campus for the summer doesn't mean taking a break from being innovative. Two teams of student engineers who experienced tremendous success with independent projects during the 2010-2011 school year continued their collaborations while summering in locales as far-flung as Beijing and Tel Aviv. They returned to campus ready to launch the next generation of their innovative technologies.

Hanging Out on Google+

Yale Engineering juniors Elizabeth Asai, Nick Demas, and Elliot Swart found out in June that their early melanoma detection device had bested competitors from around the country to win $100,000 in a national contest hosted by Boston's Center for Integration of Medicine and Innovative Technology (CIMIT). Their "Stereoscopic Plug-and-Play Dermatoscope and Web Interface" is a small, user-friendly, low-cost camera designed for use by a doctor or patient to capture and upload 3D pictures of skin lesions to a web-based directory. Dermatologists can then log in to remotely analyze and monitor the topography and volume changes of abnormalities such as skin moles.

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Asai, Demas, and Swart, who met as freshmen in Morse College and collaborated as sophomores to engineer a laparoscopic surgical probe, said the idea for a mole scanner came to them during a late-night conversation. They wondered how the 3D visualization employed in their surgical probe could be useful to a technology that would qualify for entry to the CIMIT contest.

During the school year, they dedicated up to 30 hours a week to the project, working independently of any Yale engineering courses. They developed the prototype in their dorm rooms, used the Engineering School's 3D printing resources to fabricate ergonomic plastic parts, conducted a clinical study in partnership with Yale Dermatology Associates, and filed a provisional patent for the device.

After being notified that they were finalists for the CIMIT competition, the sophomores finished the school year and then put in three weeks of 15-hour days to meet CIMIT's May deadline before leaving campus for the summer. Asai,

a biomedical engineering major, departed for an internship in DC, and Swart, a computer science/electrical engineering major, headed to Johns Hopkins University to participate in neuroprostheses research, while mechanical engineering major Demas stayed in New Haven to work on sensor upgrades for the international ATLAS High Energy Physics Experiment.

When the $100,000 prize was announced in June, progress on the dermatoscope continued as the three convened twice a week using Google+ Hangouts to discuss their next steps. In DC, Asai explored regulatory issues and investigated how the team might obtain FDA approval for their instrument without becoming incorporated. Swart spent evenings on his PC refining the instrument's web interface for patients' at-home use. And Demas built a $1,200 MakerBot—a 3D printer from a kit—and used it to fabricate a physical model of the next-generation dermatoscope.

Now back on campus for their junior year, the three say they are concentrating on improving upon their prize winning prototype based on the advice of dermatologists and guidance gleaned from clinical tests. Their goal is a mass-producible device that is user-friendly such that anyone could use it without training. With 3.5 million cases of skin cancer diagnosed annually, an easy-to-use dermatoscope could become as ubiquitous as the home blood pressure monitor, so getting patent rights is also a top priority for the team this year.

The group's determination continues to pay dividends as demonstrated by their third place showing in the Institute for Electrical and Electronics Engineering Medicine and Biology Society Wyss Award for Translational Research. With first place awarded to a Harvard Medical School physician's lab and second place going to an MIT postdoc's research, the three Yale Engineering undergrads faced seasoned competitors during this first year of research. The fact that the Yale team was the only undergraduate team chosen as a top finalist out of the 77 applications is testimony to the team's innovative spirit, methodical design, and thorough testing.

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Watch the Video Online

http://seas.yale.edu/publication

Summer on Skype

The four undergrads who founded the Yale Undergraduate Aerospace Association in early 2011 also stayed virtually connected over the summer. Earlier in the year, the team designed a system to photograph the earth and accurately track their helium-filled launch vehicle and payload during ascent and descent. Through e-mail and video conferencing, they kept their high altitude balloon project on track throughout the summer and managed to submit an application to an international design contest as they toiled at internships on three continents spanning 12 time zones. YUAA president Israel Kositsky '13, says, "We planned out the framework for the fall so our executive board could hit the ground running when we came back to campus."

Via Skype from outposts in Beijing, Moscow, New York, and Tel Aviv, the group collaborated to create a video for a James Dyson Award application, explored ideas for structuring future projects, discussed shortcomings of their previous launch, and strategized on what they considered their main challenge for the first two weeks of the semester—to recruit new members with particular scientific and engineering expertise.

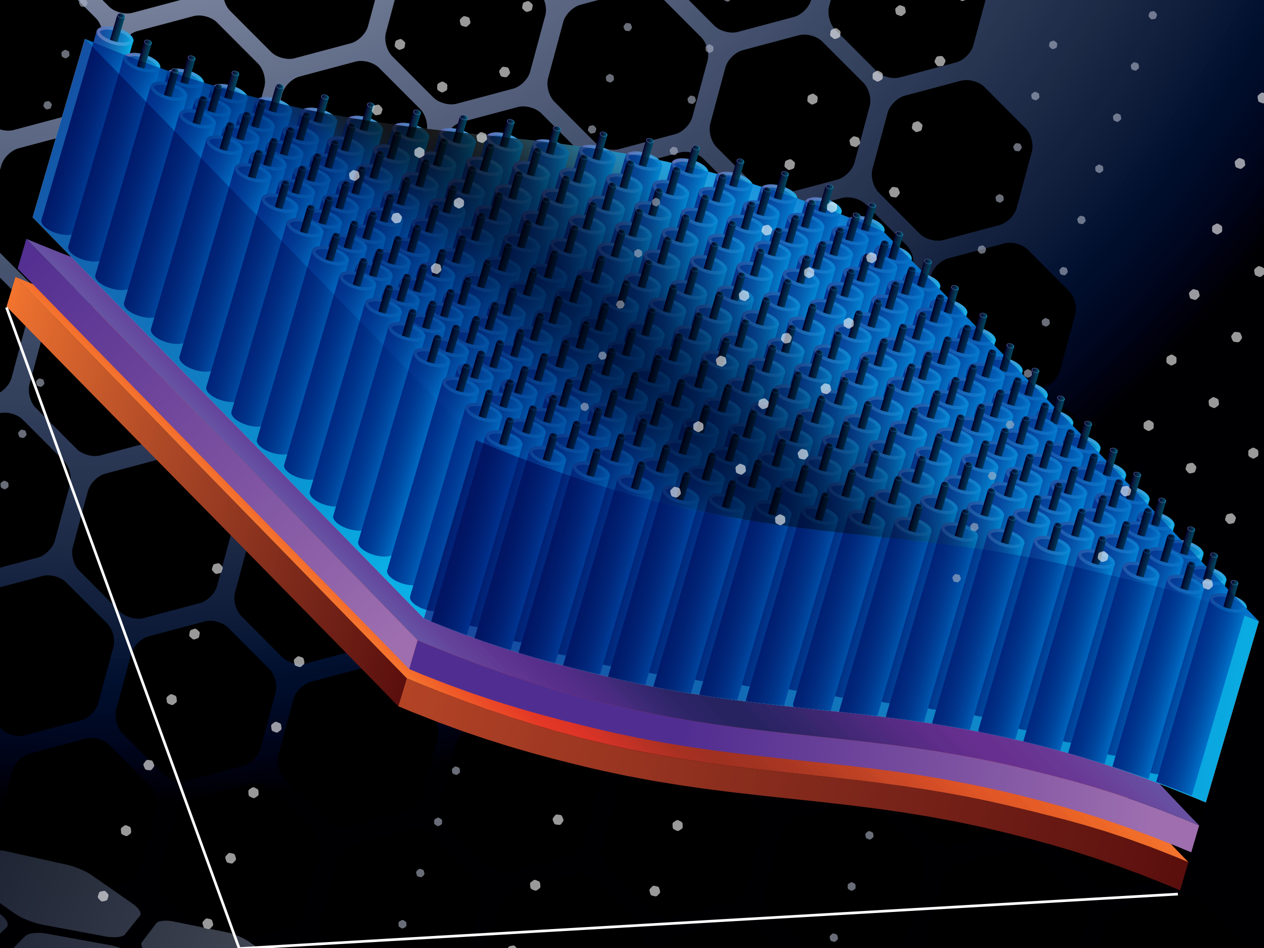
The efforts have paid off. Their unmanned vehicle was one of 10 national finalists in the Dyson competition, and YUAA expanded its membership from 8 to more than 20 before the end of September. With new members who will be devoted to particular physics, math, and engineering questions, Kositsky says, "We will be able to pursue more advances this year."

In particular, Kositsky says the group wants to launch version 2 of the YUAA Horizon that he and a team that included YUAA co-founders Jan Kolmas (mechanical engineering '14), Stephen Hall (mechanical engineering '14), and Michael Magdzik (political science '13), launched last Spring. The group took amateur space exploration to a new level of sophistication, capturing images of the earth from an elevation of 50,000 feet and transmitting altitude and location data to a receiver like a satellite would. Potentially a low-cost alternative to satellites, the Horizon cost under $1,600 to fabricate and operate.

The Yale Undergraduate Aerospace Association:
Israel Kositsky (physics, '13), Jan Kolmas (mechanical engineering, '14), Tanjim Efaz (electrical engineering, '14), Stephen Hall (mechanical engineering, '14), Glen Meyerowitz (physics, '13), Jack Rockaway (mechanical engineering, '14), Ian Vorbach (electrical engineering, '13), Michael Magdzik (political science, '13).

Now, with an expanded team, they hope to upgrade the vehicle's command center. The original Horizon consisted of an eight-foot-diameter helium-filled balloon supporting a payload and a recovery parachute. A small styrofoam box housed the vehicle's instruments, which included a homemade GPS tracking device, a camera programmed to snap images at seven-second intervals, and a hand-crafted antenna to transmit real-time altitude and location updates every second from an on-board microprocessor to a laptop on the ground. A custom iPhone app charted the balloon's course allowing the team to follow it by car. The vehicle ascended into the stratosphere and travelled for nearly three hours and 35 miles northwest before the helium's expansion burst the balloon.

The plans for Horizon II call for updated electronics, a more powerful processor, a carbon fiber body, new on-board sensors for detecting temperature and radiation, and an air-intake for collecting air samples at high altitude. Some YUAA members have been tasked with investigating how to perfect the balloon's helium ratio, and others will optimize its wireless technology to transmit more accurate signals. Kosinsky says Horizon2 will be lighter, smaller, and smarter, and backed by much better technology. YUAA co-director of engineering Stephen Hall adds, "We're striving to push not only what we can do but what these balloons and aerospace projects can do."



Yale

SUSTAINABILITY

Moving Molecules to Create the Materials of Tomorrow

Efficiencies gained by aligning nanometer-scale components in composite materials

Assistant professor of chemical and environmental engineering Chinedum Osuji is not just developing better batteries, photovoltaic devices or filtration membranes, but rather he is making the materials that these technologies depend on better. Developing the enhanced material properties that will give rise to what Osuji refers to as "materials of tomorrow" will require controlling the microstructure—how the molecules are arranged. Osuji has demonstrated that this arrangement can be done in some materials using magnetic fields and that the results are scalable to larger applications.

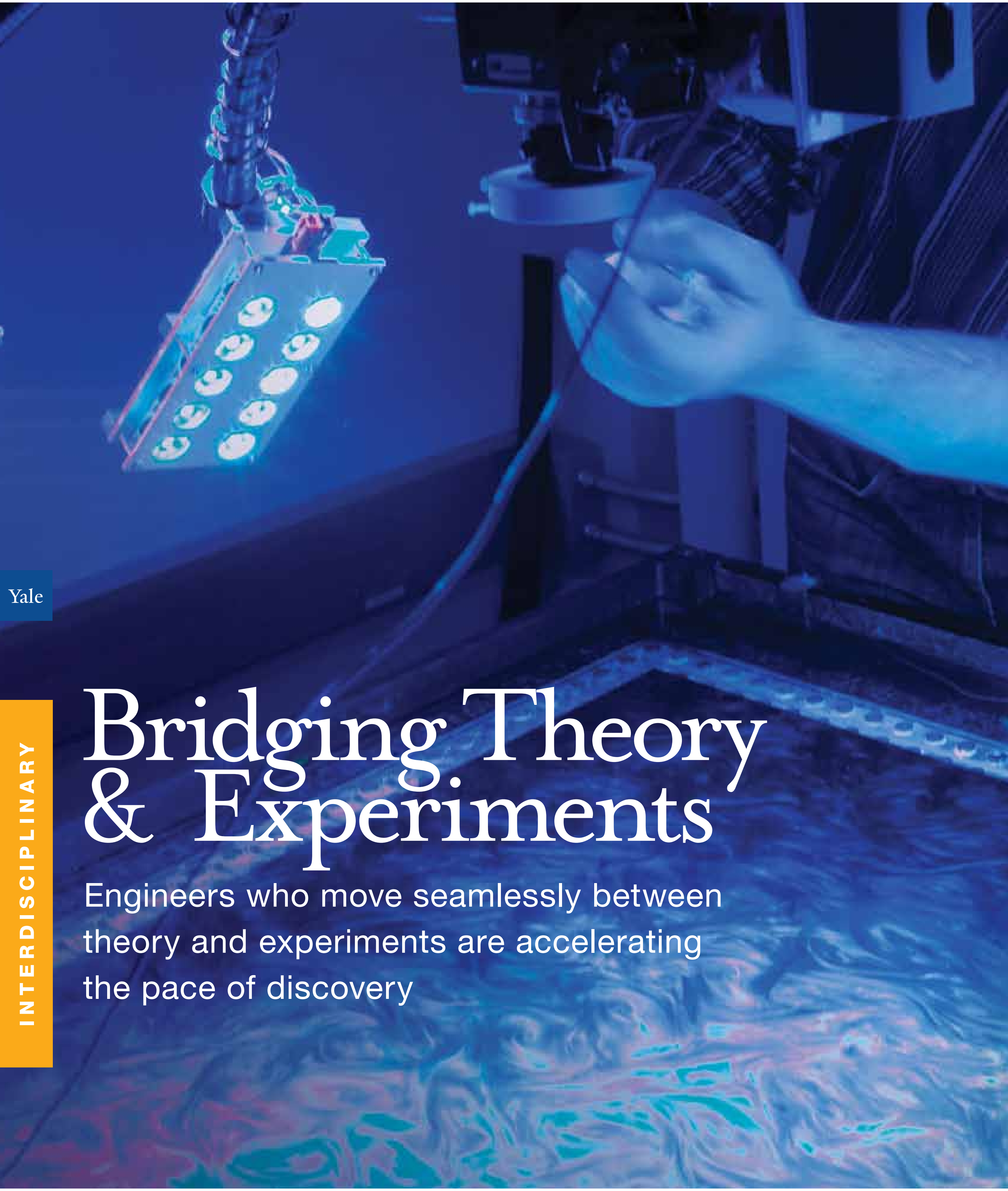
One of the materials is polyethylene oxide (PEO)—a polymer that finds widespread applications ranging from biomedical engineering to Lithium-ion rechargeable batteries which power most consumer electronics. "For many years, industry has sought a solid electrolyte to overcome issues of safety and mechanical stability inherent with current state-of-the art liquid electrolyte technology," says Osuji.

Solid electrolytes offer several advantages for Lithium-ion batteries, including a thin profile (less than one millimeter or about the thickness of a credit card), light weight, and the absence of the safety hazards associated with liquid electrolytes. Unfortunately, the development of solid electrolytes faces a significant challenge—they don't conduct electricity as well as liquid electrolytes. A clever solution to this problem involves the use of self-assembly whereby small nanometer-scale cylindrical pores of liquid-like PEO are surrounded by a continuous matrix of a solid-like polymer. The composite material behaves like a tough solid and the nanometer-scale liquid-like channels provide a means for conducting ions and electrons. Unfortunately the organization of these self-assembled channels is far from perfect. The challenge is to align all the cylindrical PEO pores to provide the most direct route for Lithium-ion conduction from one side of the material to the other. This maximizes conductivity and optimizes the battery's performance.

This is where Osuji's work comes into play. His lab focuses on directed self-assembly of such systems, ensuring that highly aligned materials can be produced from the randomly oriented structures produced by undirected self-assembly. Says Osuji, "Controlling the microstructure allows you to control the performance of the membranes." By applying very large magnetic fields produced by a superconducting magnet (the fields are about 100,000 times as strong as the earth's magnetic field), Osuji has demonstrated that ion conduction channels based on PEO can be aligned in a single direction, creating direct routes for Lithium-ion transport and improving the material's conductivity by ten times.

While a considerable advancement, Osuji's research stops short of pushing the applications. He is, however, working closely with those who do use materials in specific applications, including Roberto C. Goizueta Professor of Chemical & Environmental Engineering Menachem Elimelech, who is developing water desalination membranes which involve the magnetic alignment of single-wall carbon nanotubes in polymer membranes Osuji is also collaborating with a team of researchers led by Lisa Pfefferle, the C. Baldwin Sawyer Professor of Chemical & Environmental Engineering, and including André Taylor, assistant professor of chemical and environmental engineering, Phillips Professor of Mathematics Ronald Coifman, and associate professor of applied physics & physics Sohrab Ismail-Beigi to design more efficient and cost-effective solar cells.

"If you can align the channels," says Osuji, "you can do many other things including synthesizing materials inside the domains, such as gold nanowires, semiconducting nanomaterials or anti-microbial agents." With this ability to control the orientation within the material, Osuji says, the possibilities are far-reaching.



Yale

INTERDISCIPLINARY

Bridging Theory & Experiments

Engineers who move seamlessly between theory and experiments are accelerating the pace of discovery

To illustrate the symbiotic relationship between theorists and experimentalists, Nicholas Ouellette, assistant professor of mechanical engineering & materials science, points to the Nobel Prize: “With rare exceptions, theories don’t win prizes until they’re confirmed by experiments, and experiments don’t win without theories to explain them.” To Ouellette and most in his profession, it’s plainly obvious that scientific understanding is achieved by reconciling theory and experiment.

Historically, it has been rare to find engineers who are comfortable doing both cutting-edge computational modeling and experimental work. Lately, however, more sophisticated approaches to engineering and applied science are integrating these two steps of the scientific method. Especially in an engineering culture such as Yale’s, which places a priority on discovering engineered solutions to humanity’s most pressing problems, the union of experiment and theory is increasingly common.

Enabled by massive data storage banks, computers that effortlessly process terabytes of information, and high-speed imaging technologies that can capture experimental data and update computer models instantaneously, engineers are moving from theory to simulation to experiment and back again in near real time.

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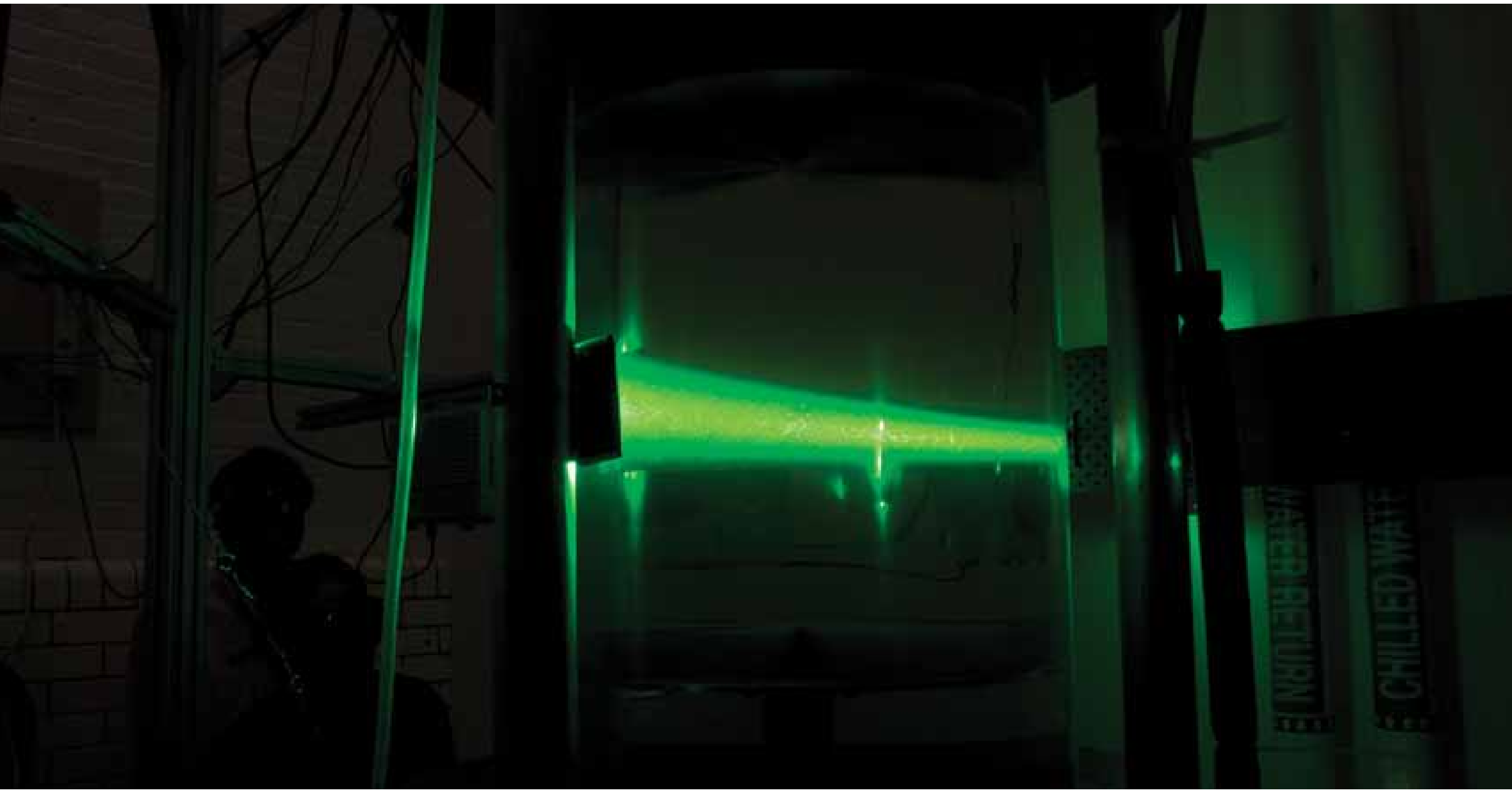
Some Yale faculty members play the dual role of theorist and experimentalist. Other faculty members who excel in one area recruit the other type of expertise to their labs and foster day-to-day interaction between experiment and theory. And in other cases, specialists collaborate across labs and departments. However the two come together, Yale engineers agree that tight coupling between experiments and modeling leads to rapid progress where experiments help benchmark and validate models, while simulations can guide experimental development.

Ouellette, who studies fluid dynamics, tries to put experimentalists and theorists in the same room to help ideas percolate faster. "Theorists can ask for additional information, and experimentalists can focus their experiments to get what's really needed. What you want is to have them leapfrogging each other," he says.

Associate professor of mechanical engineering & materials science Corey O'Hern, a theoretical physicist with expertise in granular media, colloids, polymers, and proteins, has partnered with experimentalists in Yale's Mechanical Engineering & Materials Science, Chemical & Environmental Engineering, Molecular Biophysics & Biochemistry, Applied Physics, and Physics Departments. He says he has come to consider theoretical models without experimental validation to be of little value. "I want to make sure my work is making contact with experimentalists all the time instead of rarely," O'Hern says. "Most of my papers are now written with experimentalists."

O'Hern says interactions between experimentalists and theorists have evolved in lockstep with the supporting technology. "Computer power is growing exponentially, so we can run simulations for longer times over larger scales than we have in the past, and we can study problems that make direct contact with experiments." In his work, there is constant dialog between experiments and simulation. "By doing this, we will make much more rapid progress than if experiment and theory proceeded independently," he says.

Assistant professor of biomedical engineering Kathryn Miller-Jensen, whose group applies quantitative, systems-level approaches to study signaling aspects of viral infection and develop novel anti-viral therapies, says her field has also benefited from a closer theory-experiment interface. "Biology has increasing access to high-throughput data, and better measurement techniques," she says. "By bridging the gap between the people who conduct the experiments and those who use math, computation, and theory to synthesize quantitative data, you can understand your experiment in the framework of the theory, or you can rethink your theory to match the data."



Adds Miller-Jensen, "That's why people in grant-making and editorial positions like to see theory and experiment proposed or published jointly—it can maximize the information you're getting out of research."

To be sure, access to funding and a better chance of getting published are strong incentives for theorists and experimentalists to join forces. Jan Schroers, associate professor of mechanical engineering & materials science, who collaborates with colleagues across the engineering school, says, "In order to get funding you need to have a strong theoretical aspect to your work and an experiment that people care about." Adds Ouellette, "Papers that get published by the high-impact journals tend to have both pieces—either you're finally testing a theory that's been around for a while, or you've developed a model to explain what's going on in an experimental result. One without the other has less impact, because someone has to do more work to validate what you're saying."

Funding agencies such as the National Science Foundation and the Department of Energy that began encouraging interdisciplinary collaborations in recent decades are also strong proponents of mergers among theorists and experimentalists. And, knowing that partnerships between theorists and experimentalists won't happen without a catalyst, the most forward-thinking research institutions foster a culture that supports these kinds of collaborations. At Yale, for instance, interdisciplinary research groups such as the Integrated Graduate Program in Physical Engineering and Biology and the Yale Institute for Nanoscience and Quantum Engineering are providing opportunities for experimentalists to tackle problems in tandem with theorists.

The following profiles reveal the ways that several Yale Engineering faculty are benefiting from working at the interface of theory and experiment.

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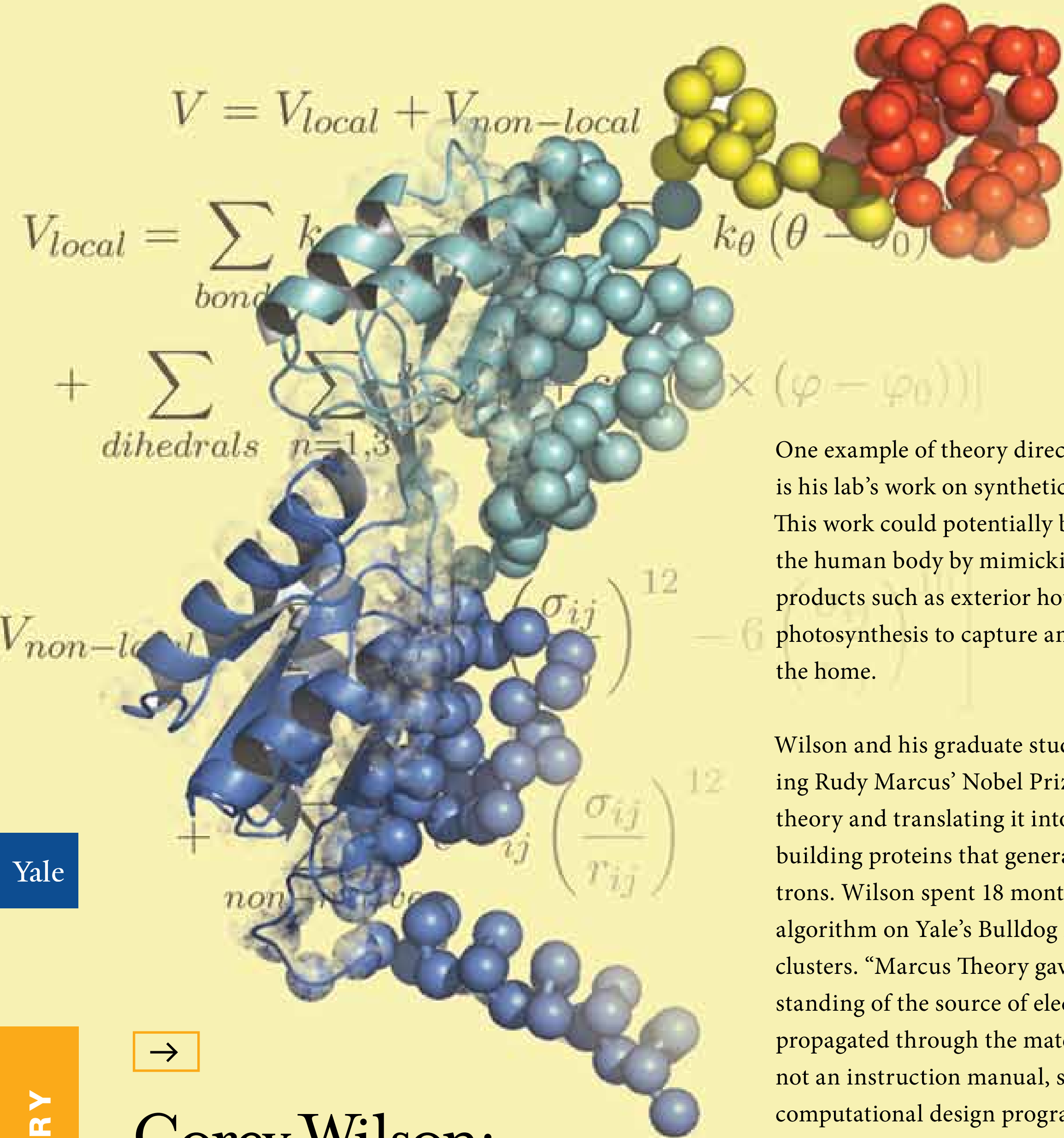

Yale

INTERDISCIPLINARY

Corey Wilson: Extrapolating Marcus Theory

Corey Wilson, assistant professor of chemical & environmental engineering, is a classically trained biophysicist who did postdoctoral research in a computational protein design lab. In his lab in Yale's Malone Engineering Center, he integrates experimental and modeling approaches to understand protein folding and function and to design macromolecules and higher order biosensors.

One example of theory directly informing experiment is his lab's work on synthetic electron transfer systems. This work could potentially be used to generate energy in the human body by mimicking cellular respiration or in products such as exterior house paints that could imitate photosynthesis to capture and translate light to power the home.

Wilson and his graduate students began by deconstructing Rudy Marcus' Nobel Prize-winning electron transfer theory and translating it into a schematic design for building proteins that generate naturally occurring electrons. Wilson spent 18 months implementing the design algorithm on Yale's Bulldog high-performance-computing clusters. "Marcus Theory gave us a fundamental understanding of the source of electrons and how the energy is propagated through the material," Wilson says, "but it's not an instruction manual, so we had to write one. The computational design program leverages our understanding of the atomic properties of protein structure and function, allowing us to generate putative macromolecules that can accommodate charge-transfer."

Blueprint in hand, the experimental engineering work commenced. To date, Wilson's team has succeeded in designing functional proteins that can propagate electrons and continues toward the goal of creating respiratory and photosynthetic mimics. "In a nutshell, we build functions of interest in silico within a protein scaffold, then we test the output experimentally. A second critical benefit of this work is that it allows us to benchmark almost any theoretical framework related to protein function," he says.

Kathryn Miller-Jensen: Bridging the Gap Within One Lab

Kathryn Miller-Jensen describes her team as "engineers who look at cell and molecular biology with a quantitative approach." Miller-Jensen, who joined Yale Engineering a little over a year ago as an assistant professor of biomedical engineering, says, "We're still in the early stage, but we're interested in using data-driven modeling to understand how viruses change the way cells respond to stimuli—to understand how a system works, and then to manipulate that system."

"In biology," Miller-Jensen says, "very seldom do you know a mechanism in detail. Things are not linear. It's rarely an A-goes-to-B-goes-to-C pathway. There's feedback and crosstalk or an E-F-G pathway affecting A-B-C." For that reason, she begins with an assumption, for instance, that there is a functional quantitative relationship between how cells sense HIV and how they respond to HIV. Through experiment, she takes dynamic measurements in response to different stimuli, and tries to model those stimuli and responses.

"For example," Miller-Jensen says, "if you build a model for how a cytokine induces cell death, you might be able to predict how a drug or virus that blocks a particular pathway could increase or decrease cell death. If you get it right for that particular drug, you've likely captured important functional information. But if you don't get it right, that's okay too, because then you know you're missing a key piece of information and you can figure out what else you need to measure to improve the model and your understanding of the biological mechanism."

"In terms of theory and experiment," she adds, "we look at viruses as a way to test fundamental theory about how cells interpret information."

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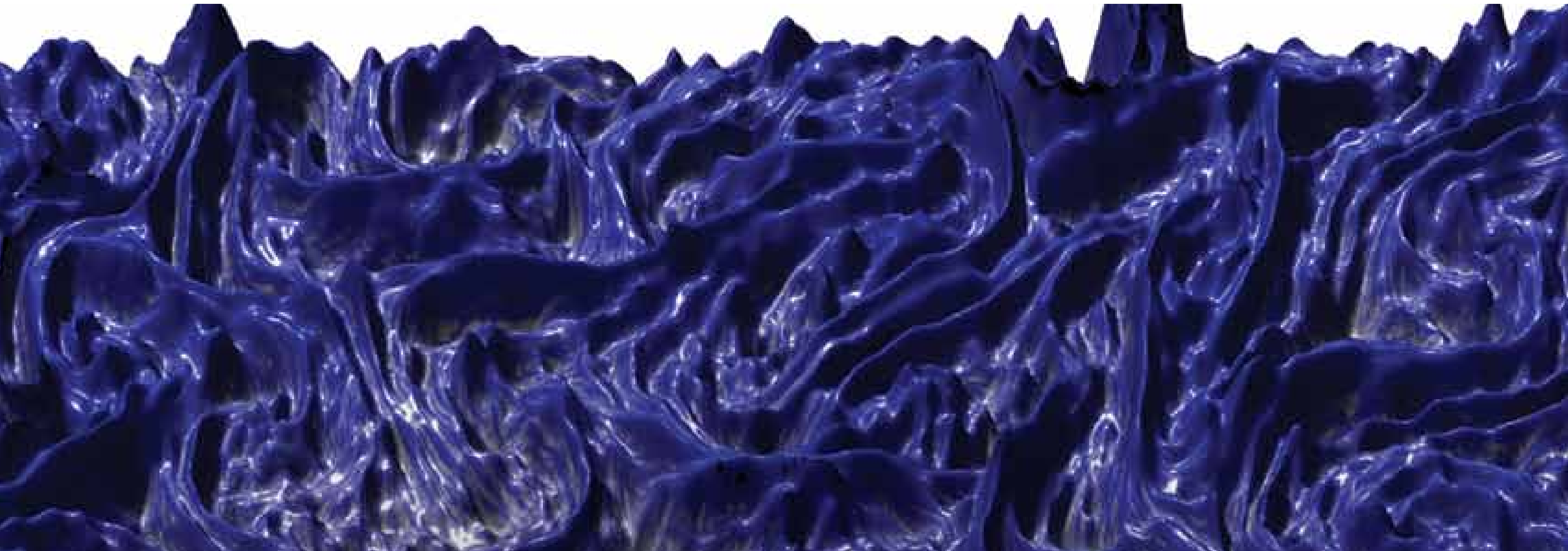


Nicholas Ouellette: Experimentally Guiding New Fluid Dynamics Theory

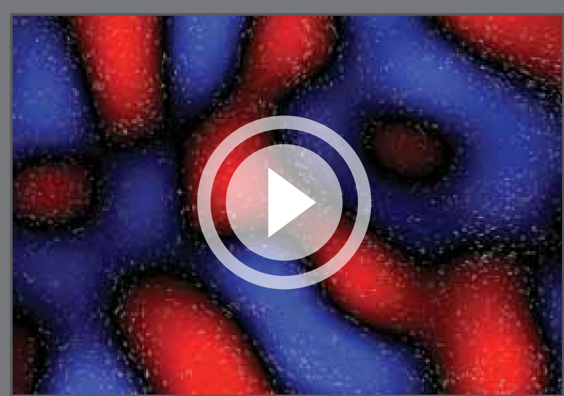
Nicholas Ouellette credits the revolution in high-speed imaging technology with enabling a merger between theory and experiment in his fluid dynamics work. "The time scales over which large fluctuations happen in turbulence are at the millisecond or microsecond level. While I was in grad school, really fast cameras came onto the market, and over the past decade we've come a long way in being able to generate data by acquiring images really, really fast," Ouellette says. With terabytes of disk space and multi-core processors, he now has the computational horsepower to process the data.

In his lab, Ouellette has developed an experimental system to understand the basic properties of turbulent flow based on particle tracking with 3D cameras. By tracking particle movement, his team can probe the fluid mechanics with resolution that wasn't possible even a decade ago.

"In turbulence," Ouellette says, "a lot of fundamental science remains to be done before applications can be perfected. When we don't have enough information to constrain our performance requirements, we have to over-engineer. Developing better models first allows you to build systems more precisely and make applications more efficient."

As an experimentalist, Ouellette sees his role as providing the information that will hint about how to constrain those models. "With these new technologies, we can provide new information that's getting at things people didn't know the answer to before. My hope is to drive the development of totally different kinds of models."

Watch the Video Online



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Corey O'Hern: Engineered Birds' Nests

Associate professor of mechanical engineering & materials science Corey O'Hern is a theorist working closely with several experimentalists at Yale and elsewhere to understand the internal structural and mechanical properties of birds' nests. Despite the fact that nests appear to be constructed haphazardly using debris, they are remarkably strong and durable. One of their long-term goals is to identify robust design principles for composite fibrous materials that are lightweight yet extremely strong.

The project's three components combine experiments, theory, and computation. First, O'Hern is partnering with Richard Prum, professor of ornithology, ecology, and evolutionary biology at the Yale Peabody Museum of Natural History, to generate x-ray CT scan images of the interior of nests built by birds including the Yellow-billed Cuckoo and the Mourning Dove. He's also working with experimentalist Mark Shattuck from the Physics Department at City College of New York to build artificial nests using materials with variable density, roughness, and stiffness, such as wood, plastic, and metal rods. They'll image the artificial nests with CT scans, then vibrate and shear them to assess their mechanical stability. O'Hern and colleagues will also perform coordinated computer simulations of random packings of rods with large aspect ratios, which will allow them to study parameter regimes that are difficult to achieve in nature and experiments.

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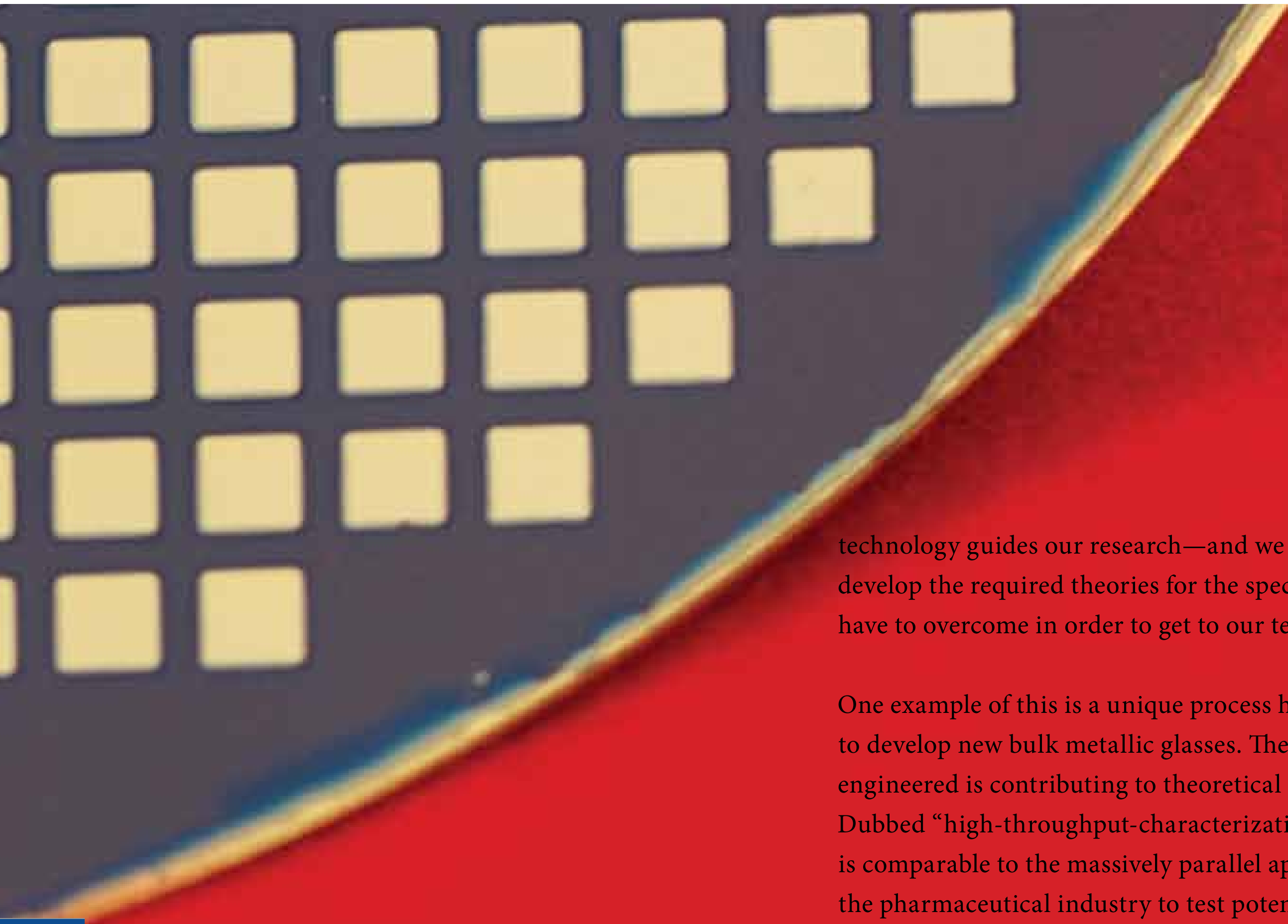


Yale

INTERDISCIPLINARY

Jan Schroers: Contributing to Society

Jan Schroers, associate professor of mechanical engineering & materials science, is guided by a simple principle: "We get money to do research that is of measurable value to society. In applied science, if you don't have a theoretical background, you don't make progress. And if you're in love only with theories, you're not placing a priority on advancing understanding in a field."

He didn't always see things that way. "I used to start in theory and almost accidentally got into applied science," Schroers says. "Now, we put the problem first—the technology guides our research—and we go back and develop the required theories for the specific problem we have to overcome in order to get to our technological goal."

One example of this is a unique process his team created to develop new bulk metallic glasses. The process they engineered is contributing to theoretical advancements. Dubbed "high-throughput-characterization," the method is comparable to the massively parallel approach used in the pharmaceutical industry to test potential drugs. But instead of screening libraries of chemical compounds for effectiveness in treating disease, Schroers and colleagues are systematically creating large composition libraries of materials and characterizing them to find properties of interest.

In the past, Schroers' five-person team spent a year and $500,000 to develop a single new bulk metallic glass. The process entailed alloying various amounts of metals such as gold, silver, palladium, copper, and silicon, and characterizing the material to iteratively improve the alloy composition. Working fast, Schroers says the team produced one new alloy per day, and produced one combination a day for a year to come up with the one that could be blow-molded as a bulk metallic glass. Now, with their high-throughput approach that sprays four different metals in various ratios onto a substrate, they can process 750 new combinations in a day.

"We can gather vast information and produce stronger experimental data points to compare our theories against," Schroers says. "This has the potential to revolutionize the understanding and development of materials."

Eric Dufresne: Overturning Theory

Eric Dufresne's title reflects the highly interdisciplinary nature of his work: He's the John J. Lee Associate Professor of Mechanical & Materials Science Engineering, Chemical & Environmental Engineering, Physics and Cell Biology. He also extols the value of constant communication between theory and experiment. "Successful engineering relies on theory to define the limits of what's possible, optimize designs, and model a system on paper or computer before building it," he says.

An experiment that his lab published earlier this year in *Physical Review Letters* sits at the junction of theoretical physics and mechanical engineering. The work capitalized on advances in imaging technologies to reconcile a long-standing conflict between two theories from the solids and fluid mechanics communities. Their results redefined the theoretical limit of what's possible when a drop of water sits on a soft solid surface.

Solid mechanics theory predicts that the droplet will deform the surface. But the surface tension effect, described by fluid mechanics, holds that a water droplet takes a spherical shape to minimize its own surface area. Taken together at face value, Dufresne says, "you get an absolutely absurd prediction that you know can't possibly be true."

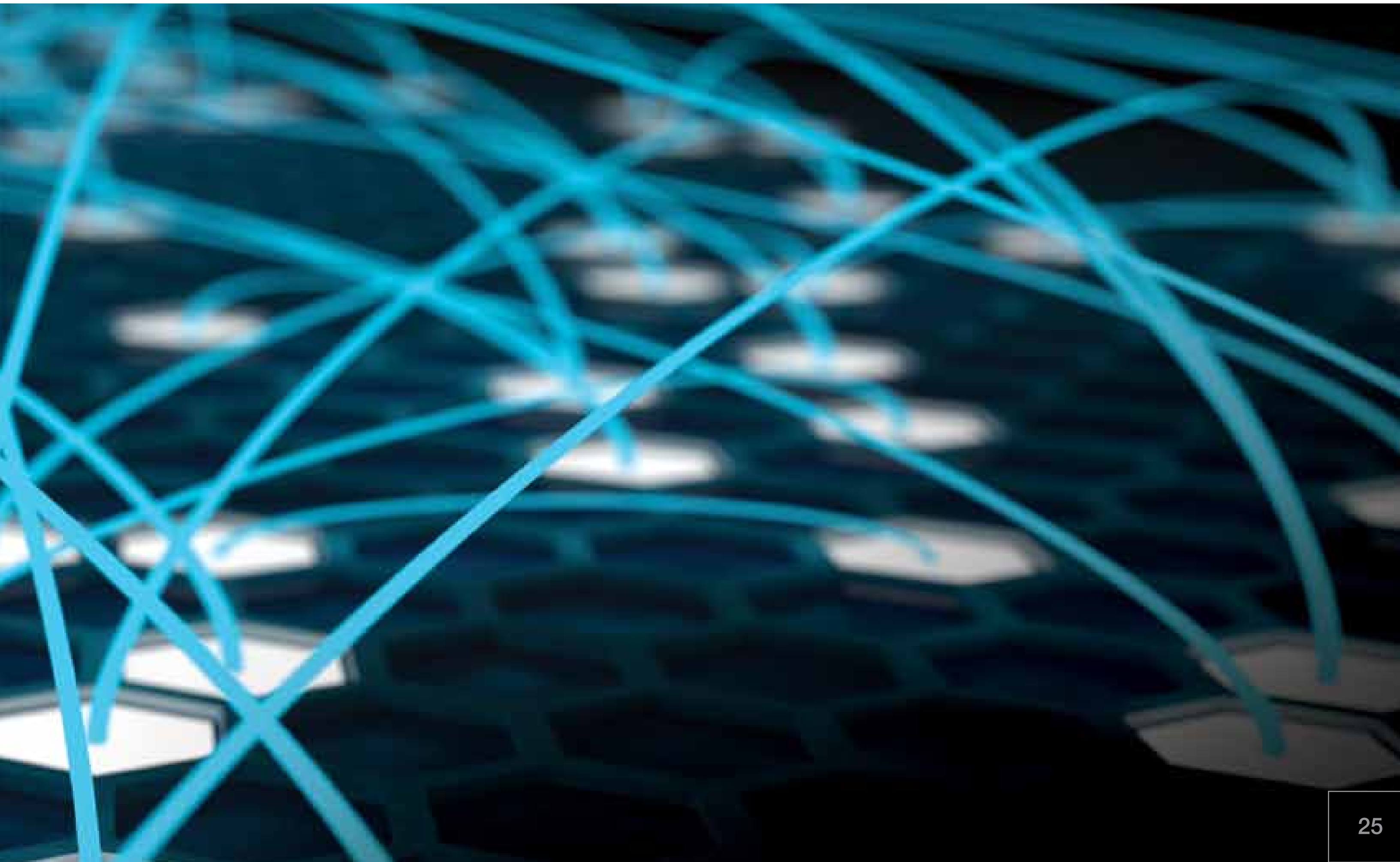
With high-powered imaging, Dufresne's team observed a ridge where the edge of a water droplet touched the solid surface. They discovered that the fluid actually pulls up the host surface to reduce its own surface area.

Dufresne says the bottom line of the finding, which has implications for print, paint, and even skin care applications, is that solids have surface tension too and that is essential to describing how the surface deforms. "By starting with an experiment, we put forth a unique theory that was better than what was out there," Dufresne says.

TECHNOLOGY

Making Sense of a Constantly Changing Environment

Developing structures for tomorrow's communication networks



Consider developing a system to allow for communication amongst thousands of devices without any centralized coordination. How would you ensure there are enough resources to transport voice and data without delay? How would you ensure that different users consume resources fairly?

Sekhar Tatikonda, associate professor of electrical engineering, applied mathematics, computer science, and statistics is solving these questions by applying network theory to cases where multiple users communicate in dynamic settings. In doing so, Tatikonda is developing communication schemes for the next generation of communication networks, including completely wireless "ad hoc" networks.

Unlike today's wireless communication network, the ad hoc network does not require extensive infrastructure, such as base stations. The ad hoc network flexibly adapts to changes in the environment and the motion of users. While not ideally suited to replace current cellular communication, ad hoc networks offer advantages to numerous applications that require flexibility and mobility – from search and rescue missions to military applications. Ad hoc networks are also appealing for a variety of sensor networks with applications ranging from homeland security to in-home medical monitoring for elder care.

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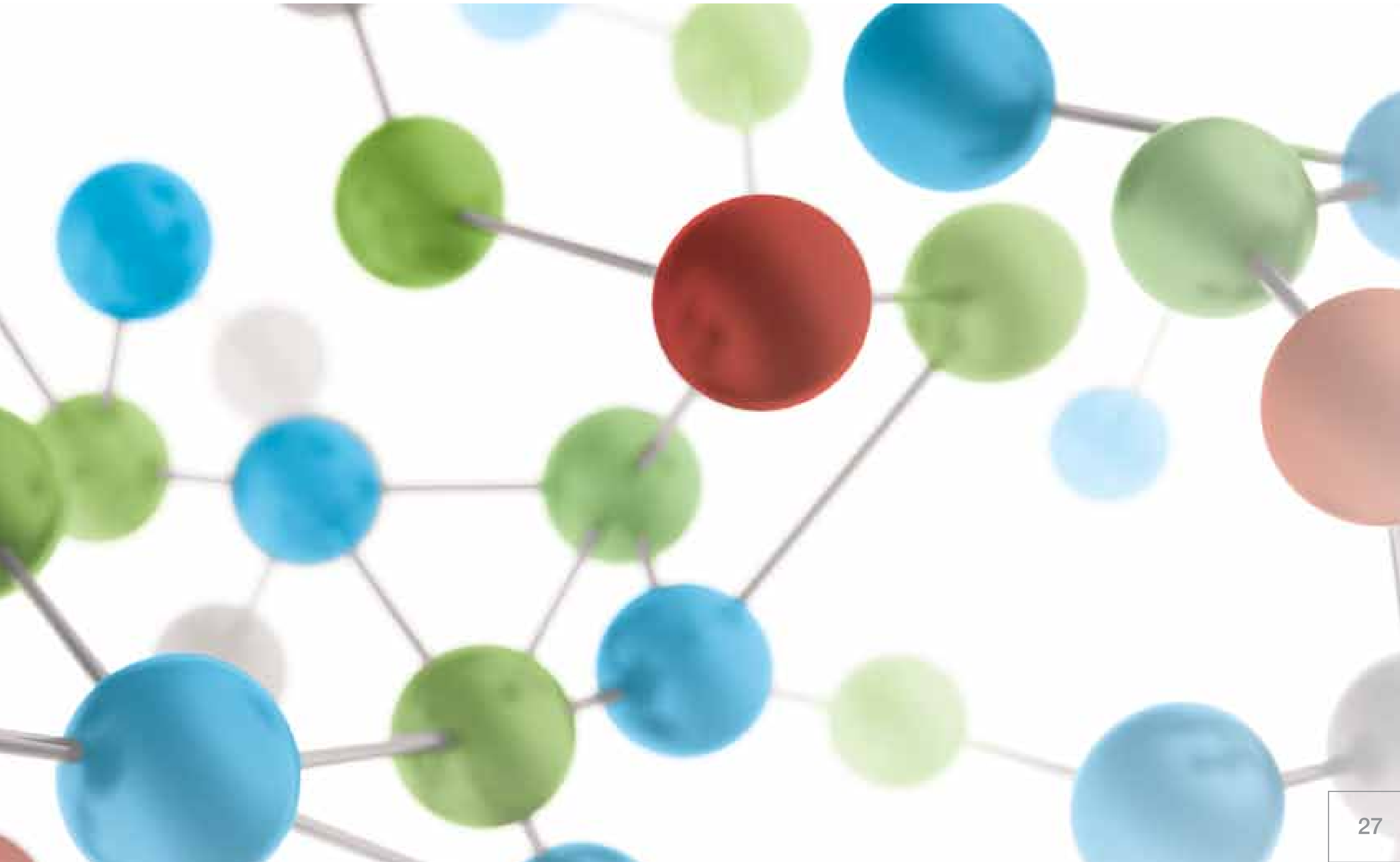
The major challenges of ad hoc networks are no different from the cellular communication networks and include limitations on bandwidth or frequencies that can be used to minimize interference and ensure that power budgets are maintained. It's akin to attempting to hold a conversation with someone in a noisy restaurant. As the volume of the room increases, so does your voice to overcome interference. You are transmitting the same data, but expending more energy in doing so. This conflict is what Tatikonda is trying to minimize.

Without the coordinating capability of a base station, however, an ad hoc network has the additional challenge of managing decisions about frequency usage on a local level between individual nodes.

As a simple example, consider how one could allocate the spectrum to five users, or nodes, located on a straight line. To prevent contention or interference, nodes located 100 meters or less apart must use different frequencies. Without overprovisioning (assigning more frequencies than actually required), nodes 1, 3, and 5 could be assigned one frequency and nodes 2 and 4 a second frequency. A technique known as color graphing is applied to help optimize frequency distribution, in this case red is assigned to the first frequency and blue to the second. But, what happens when you add a sixth connection between nodes 2 and 3? If you assign node 6 as the color red or blue, it will set off a chain reaction of color changes in either direction. Alternatively, you could color it green, but such overprovisioning consumes resources.

To extend the example, what if the number of nodes expanded to 10,000, were scattered over a 3-D region, and had the ability to move? Complicating the analysis is the reality that some users are communicating by voice, some are transmitting data, and others are streaming video. Each communication method has different requirements for quality and delays.

The above complicated scenario describes the complex problem Tatikonda is working to solve. He aims to optimize decentralized wireless ad hoc networks where the network parameters are constantly changing – nodes are frequently moving and the type of transmission (data or voice) varies.



"There are lots of easy algorithms," says Tatikonda in referring to scheduling time and assigning frequencies for a small number of users. "But what you want is an algorithm that is scalable, efficient, robust to changes, and local." The optimal algorithm must be able to accommodate numerous users without exhausting the number of available frequencies. Also, the network must be able to handle multiple time-varying parameters without requiring communication across the entire network.

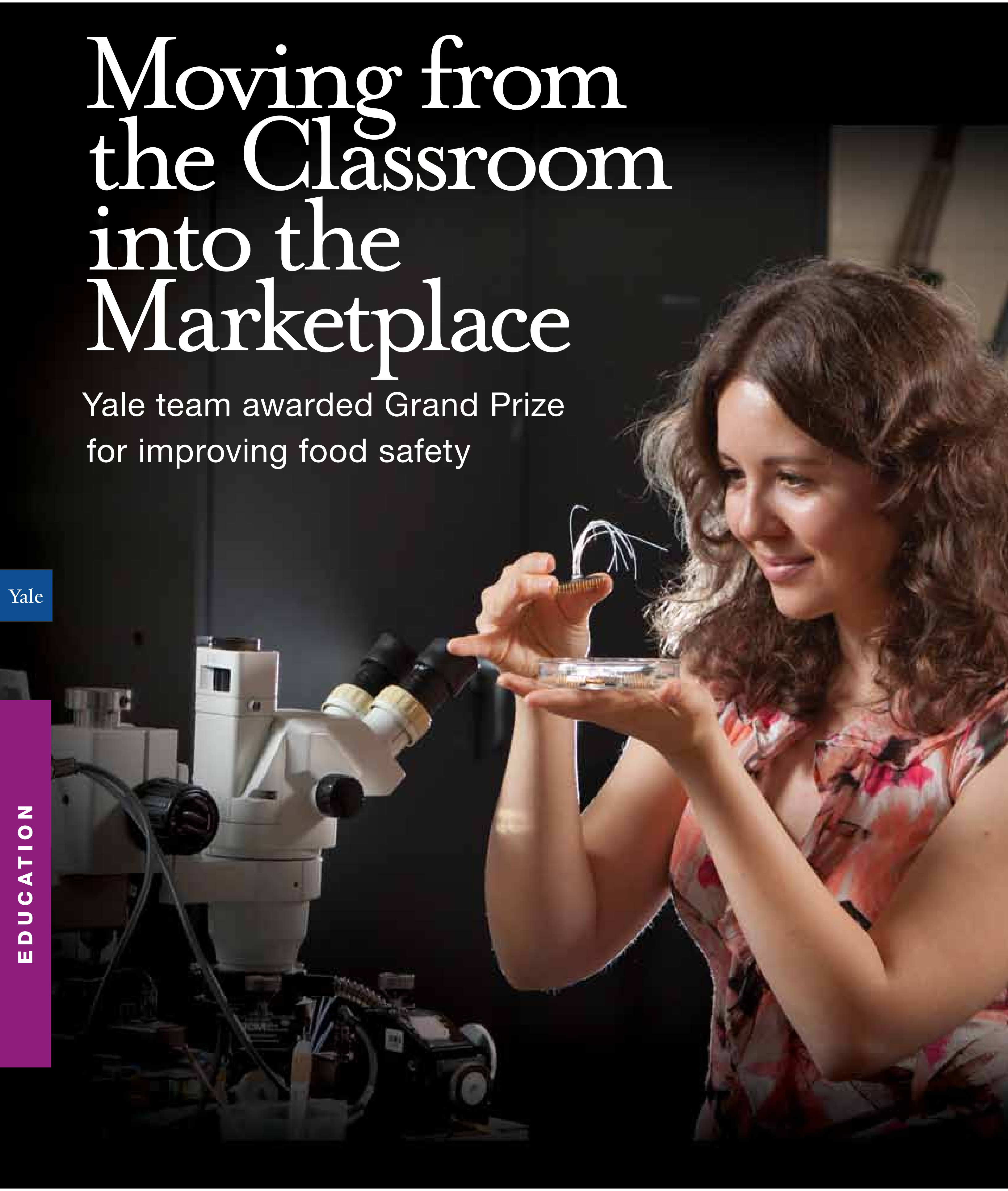
This last point is what Tatikonda means when he refers to the algorithm being "local" and it is a very important criterion. When one node moves within contention range of another, it could set off a chain of frequency shifts across the entire network. However Tatikonda believes nodes should not have to send their location to every other node in the network. Instead, each node should be able to look at their neighbors and determine what frequency is available based on that local data alone, independent of the thousands of other users in the network.

Each node should also be able to retain information about the past. "Current network algorithms are designed for static problem instances, where you partition time into slots and solve problems on a slot-by-slot basis, often starting from scratch each time," says Tatikonda. "It may be handy to keep information about second and third best solutions, as it could provide a good initialization, or first template, for a solution to the current problem – the past provides a 'warm start' for the present."

While Tatikonda focuses his research on what is known as the graph coloring problem, collaborators at the University of Texas-Austin are testing his algorithms using a set of of semi-autonomous robots. Those results, combined with his own, could validate these fundamental frequency sharing concepts and demonstrate the great utility of ad hoc networks.

Moving from the Classroom into the Marketplace

Yale team awarded Grand Prize for improving food safety



Monika Weber, a third year electrical engineering Ph.D. student, never thought that a homework problem could end up earning a $20,000 design competition prize, but that is exactly what happened when her team won the 2011 Create the Future Design contest sponsored by NASA Tech Briefs magazine. Weber, one of this year's new Advanced Graduate Leadership Fellows, and her classmates Christopher Yerino, Hazael Montanaro and Kane Siu Lung Lo were challenged to design a micro-electro-mechanical system (MEMS) as a homework assignment in last fall's course, MEMS Design. The problem posed by associate professor of electrical engineering Hur Koser was to design a MEMS device that could be developed into a commercial product.

Motivated by a recent outbreak of *E. coli* in German food supplies, Weber's team integrated ideas on bacteria detection supplied by physicians with her own experience with nanowire sensor systems for bio-nanotechnology applications gained while working in the lab of Mark Reed, the Harold Hodgkinson Professor of Engineering & Applied Science and Electrical Engineering. The team investigated using nano-electro-chemical sensing technologies that could be applied to bacteria detection and then optimized the general methods to rapidly detect blood samples of food in processing plants for bacteria. Each member of the team was responsible for individual components of the project, applying their expertise in electronics packaging, digital microfluidics, and medical diagnostics to the solution.

Following up on the course assignment, Weber continued to refine the design with additional assistance from Reed's lab. The preliminary design was fashioned into a prototype over the spring and summer to meet the competition's June application deadline. Their MEMS rapid pathogen screener for food-borne illnesses received the top prize among the 7,000 product design applications for the competition. The scanner separates any present bacteria from the red and white blood cells using dielectrophoesis. Nanowire field effect transistors (FET), capable of detecting low concentrations of biomolecules, serve as the sensors for the device.

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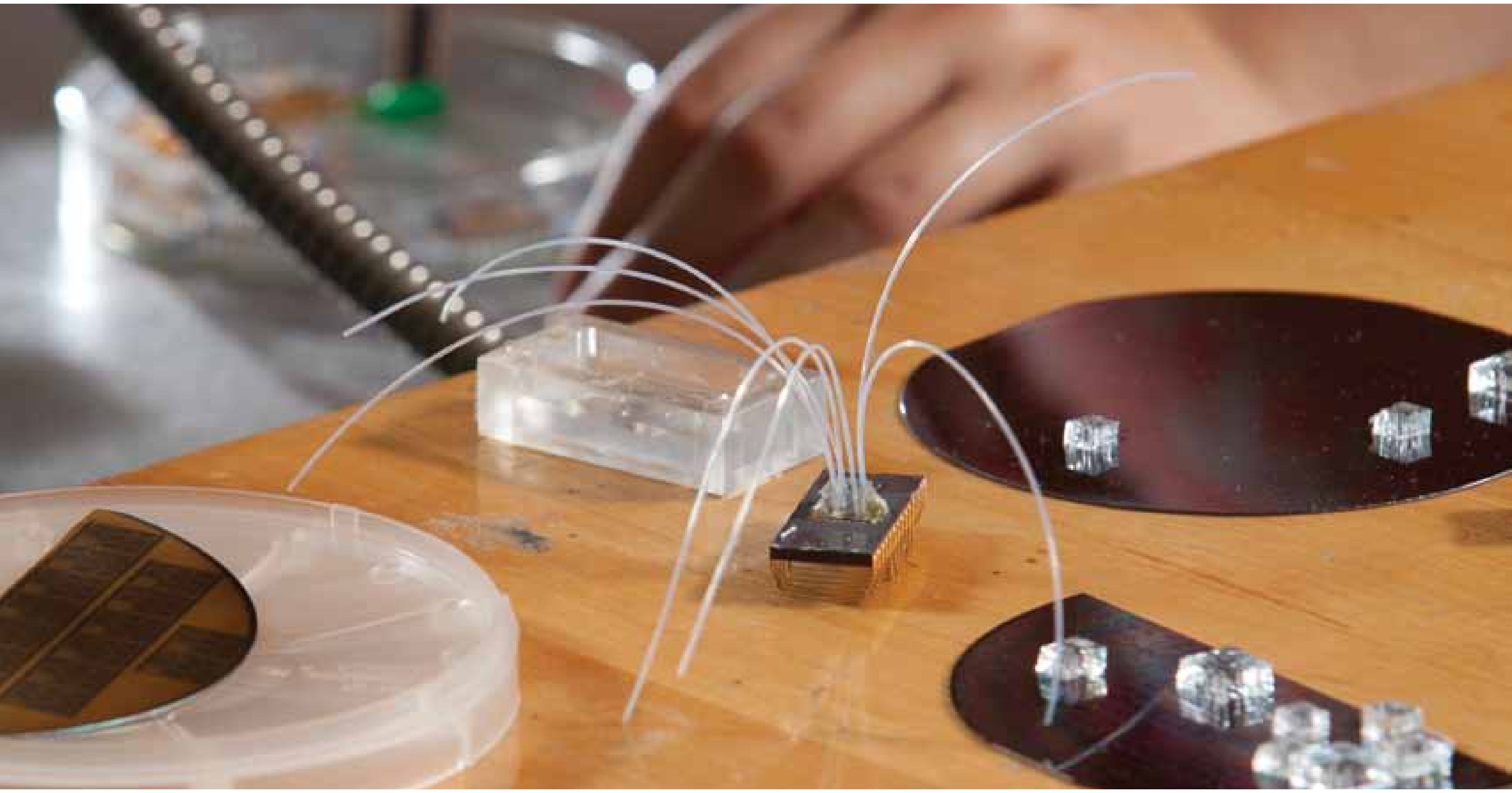

Yale

EDUCATION

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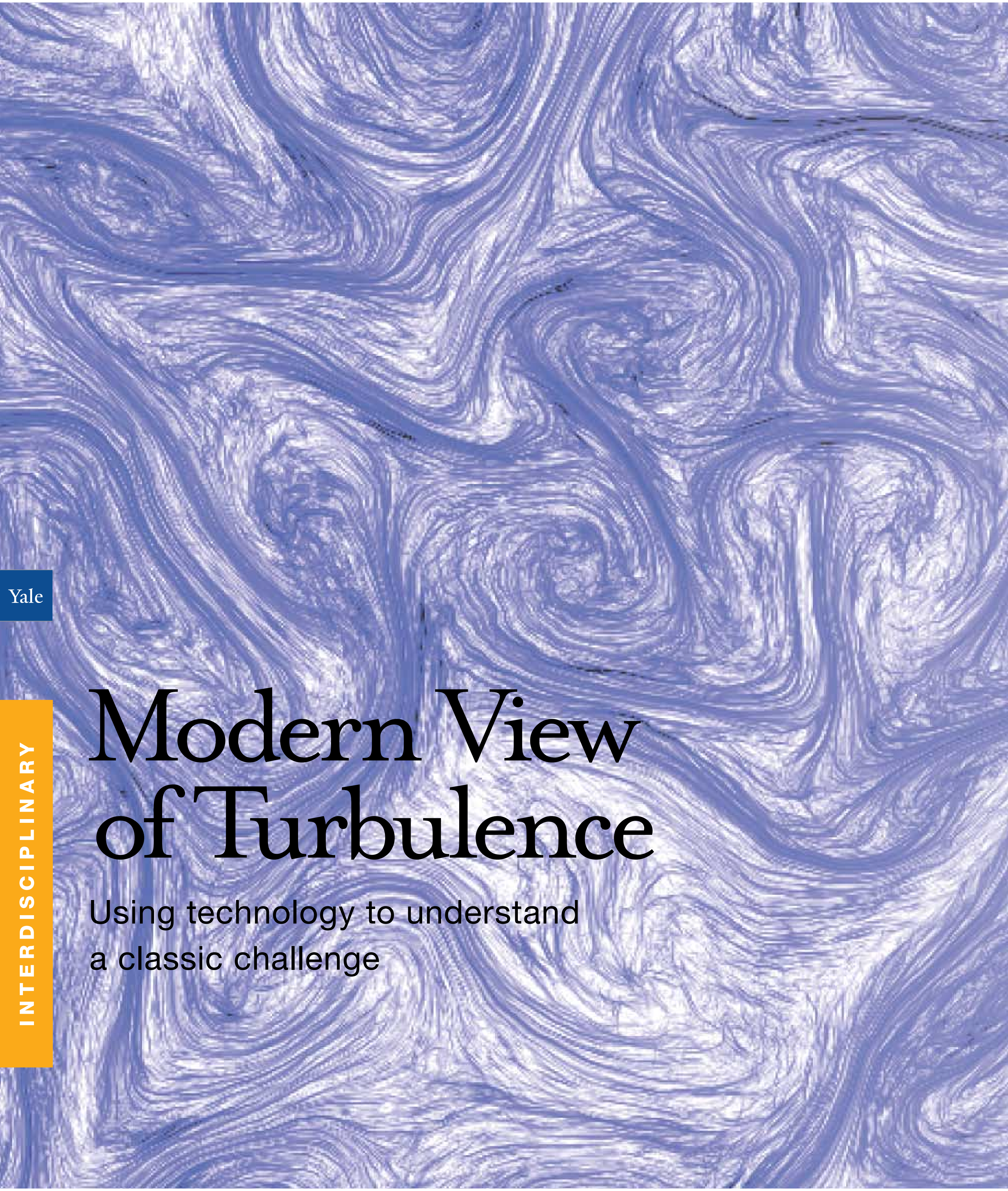
The team first modeled the bacteria separation system using multiphysics modeling and simulation software to examine the effectiveness of the potential solution. Components for the detector, including the FET sensors, were fabricated using optical photolithography and combined with the microfluidic separator that separates the bacteria from the sample. Their innovation can detect the presence of bacteria in less than a half hour, and can do so at a cost significantly lower than other testing methods.

Weber credits the team's success to the initial challenge posed by Koser and the open-minded approach towards research that is fostered in Reed's lab. Very much appreciating the latitude in establishing her own unique research interest, Weber commented that Reed "showed me some of the challenges and allowed me to pursue research that we had mutual interests in, in this case seeing how nanowire technology could be applied to my own scientific interests."

The team is now using the $20,000 prize to further refine and test their sensor, with the hopes of attracting additional funding to develop the design as a commercial product. Weber's participation in the Advanced Graduate Leadership Program is contributing to these efforts as she is active in opportunities to learn about entrepreneurship and the translation of ideas into products. After all, designing a MEMS device that has the ability to become a commercial product was the original starting point for this work. While the timeline for the project extended well beyond the semester, the potential impact of this project extends far beyond a single class.



Yale

INTERDISCIPLINARY

Modern View of Turbulence

Using technology to understand a classic challenge

"For millennia, scientists have been fascinated by the striking and beautiful patterns of flowing fluid," says assistant professor of mechanical engineering and materials science Nick Ouellette. From climate change to predicting the migration of an oil plume in the Gulf, the study of fluid mechanics is a critical piece in understanding some of today's most complex problems. Because of its complexity and largely unanswered questions, this field has captured Ouellette's interest.

"There are a lot of interesting and complicated components of fluid motion," says Ouellette, "but one would hope that they are not all equally important."

Take for instance, turbulence—the state of extreme chaotic flow that is often characterized by its dynamic structures, such as eddies and vortices, or the swirling fluids that captivate the eye. For years, researchers have studied turbulent flow using two methods of simplifying the dynamics: one that describes the system statistically to characterize the average dynamics, and one that takes an in-depth look at the dynamic structures (the eddies and vortices) themselves.

But, are these swirls of fluid really important? While visually stimulating, Ouellette is not convinced they are anything more than just that. "There is no evidence that they are statistically relevant to the flow," says Ouellette. "Certainly, something is making vortices form, but it's not obvious they should then couple back and influence the further evolution of the flow."

Ouellette believes that it's the places in between the vortices—points of inaction where all the forces come together and cancel each other out—that may provide a key to understanding turbulence.

"There are great sketches by da Vinci that look like our current understanding of turbulence," says Ouellette. "It may be the last great unsolved problem in classical physics." Using small plastic particles with the same density of water and a high-speed camera to capture movement, Ouellette and postdoctoral associate Doug Kelley track the particles to trace turbulent patterns, stagnation points, and other coherent structures to quantitatively measure the flow and make sense of what is and what is not important.

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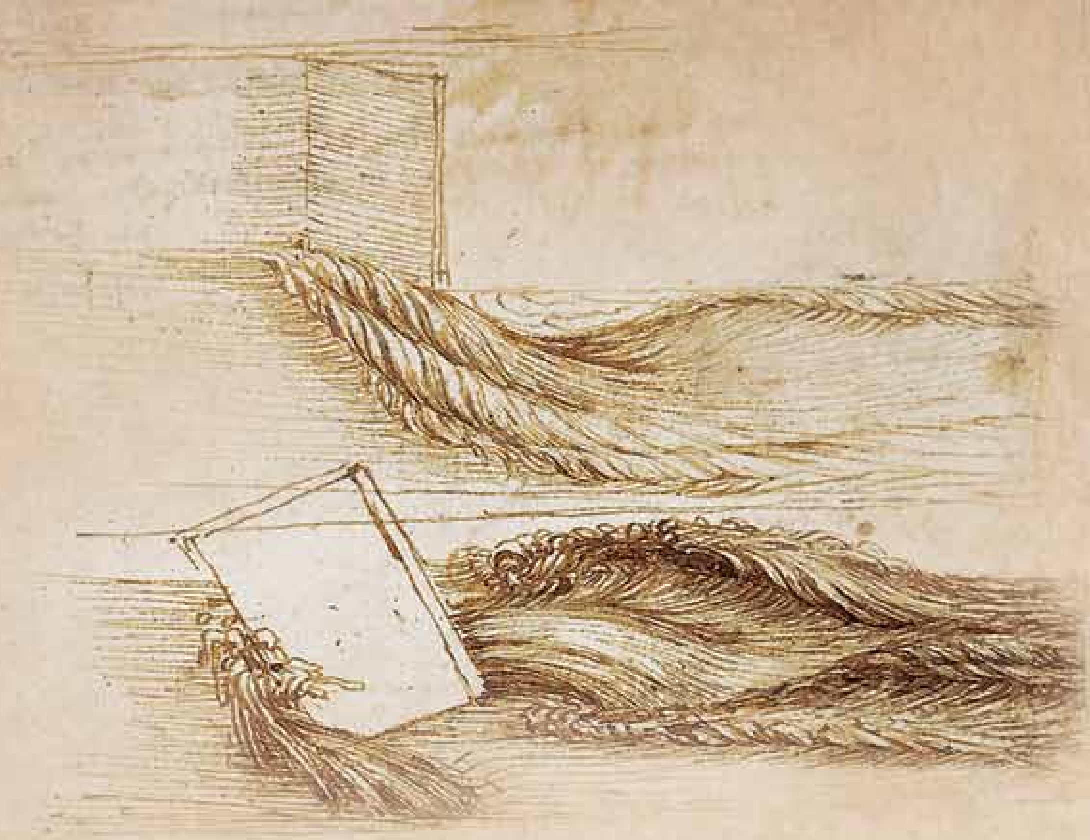


Yale

INTERDISCIPLINARY

This is a common theme in Ouellette's research which includes fluid mixing, transport, and the boundaries between different flows. Most recently, Ouellette and Kelley made a breakthrough in modeling chaotic advection—the phenomena responsible for large-scale mixing as could be observed in the Gulf of Mexico following the Deepwater Horizon oil leak.

When aerial images of the oil leak were analyzed, long, narrow streaks of oil that looked like threads on the ocean's surface were apparent. These streaks resulted from efficient mixing where the contaminant plume was repeatedly stretched and folded to expand its periphery and allow diffusion over a much larger scale. Ouellette compares the motion to making croissants, where the dough is alternately rolled and folded again and again, thereby, creating many thin layers.

Although stretching and folding have been qualitatively studied in real flows, researchers have never before been able to quantitatively decouple these phenomena because they didn't know how to capture the very important, nonlinear component of the fluid deformation—the folding. That was until Ouellette came across modeling that had been done on glassy solids and found that it could be applied to fluids.

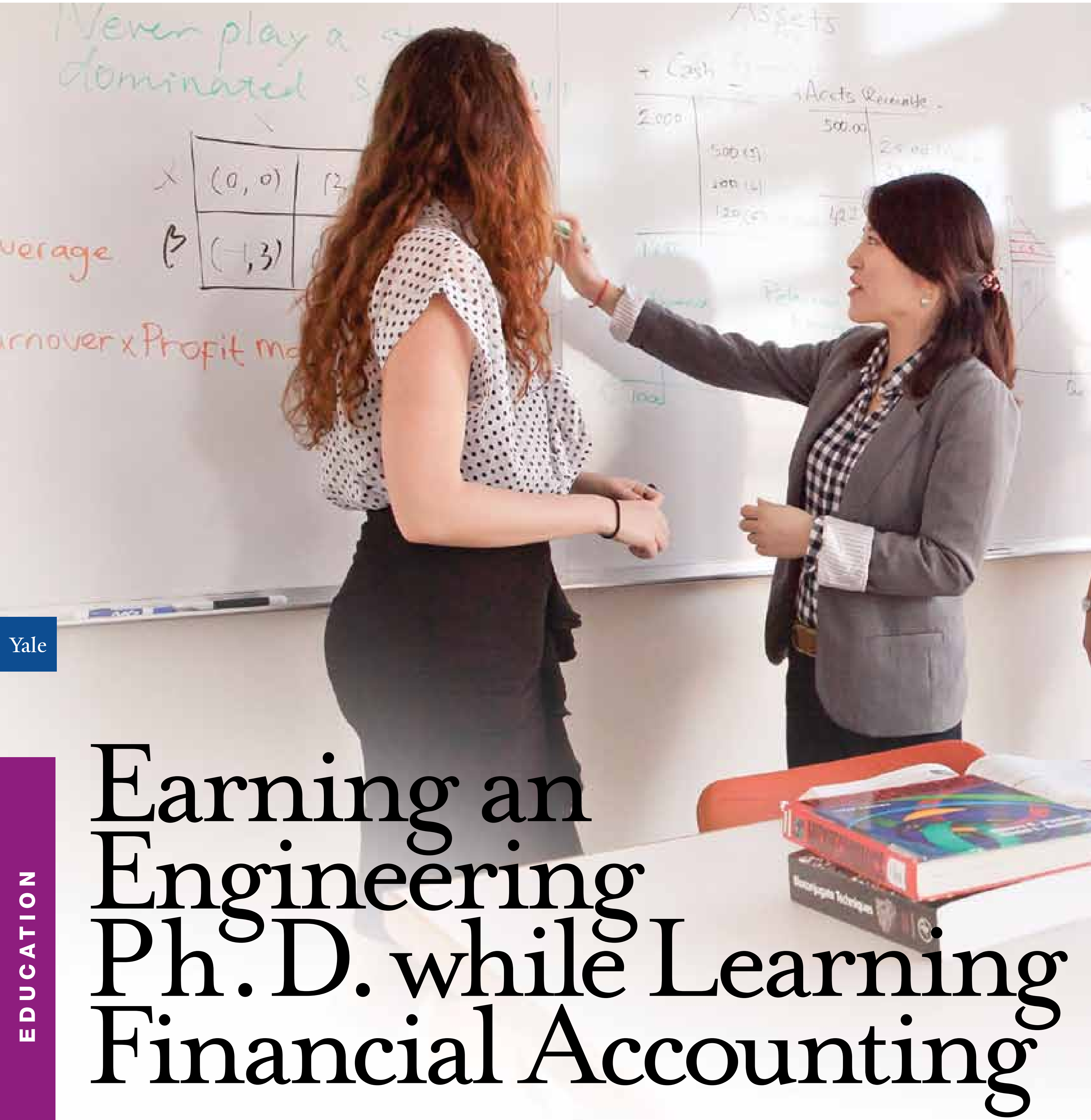
"It's rare to find researchers working in both fields," says Ouellette when asked why researchers hadn't applied this model before. Plus, he says few have the high resolution measurement tools that he has developed for collecting the necessary data.

"What we aim for is simplified models that have real predictive power by getting the important parts correct and letting everything else fall out," says Ouellette. "I have to remind people that all of this is very far in the future." While real progress may be slow in his field, Ouellette is certainly enjoying the challenge.

Watch the Video Online

http://seas.yale.edu/publication

Image courtesy of: *The Royal Collection* ©2011, *Her Majesty Queen Elizabeth II*



Yale

EDUCATION

Earning an Engineering Ph.D. while Learning Financial Accounting

Yale Engineering’s Advanced Graduate Leadership Program has produced its first few success stories—new Ph.D.s with experience beyond the lab

Since the Advanced Graduate Leadership Program launched in 2009 with the mission to avail the Engineering School's top Ph.D. candidates of professional development opportunities outside the lab, 27 Fellows have enrolled. Tarek Fadel and Jason Park were among the first class of graduating Fellows in 2011, and both say the program not only broadened their perspective, but taught them a new vocabulary. Others have been inspired by the first graduates and are now following the unique path these graduates established.

Fadel, a 2011 chemical engineering doctoral graduate, came to Yale with an understanding of the importance of market analysis and behavior economics. He spent three years as a product engineer at Hewlett Packard before pursuing his Ph.D. at Yale. In industry, he says, the engineers and research scientists he encountered typically interacted with marketing and finance teams to gain feedback and insights on product design. Once at Yale, however, Fadel says he came to see how easy it is for scientists in the academic research environment "to focus on technological restrictions and lose track of what the market wants." It's what attracted him to the Advanced Graduate Leadership Program, which is designed to address this very issue.

Of the 8,000 or so students who receive a Ph.D. in engineering in the U.S. each year, only about a third go on to employment in academia. For the rest, the transition to a job in one of many diverse career paths can

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be overwhelming. Graduate school traditionally emphasizes the research component of one's profession. Through participation in non-engineering internships, business courses, career coaching, leadership workshops, and face-to-face meetings with entrepreneurs and other engineers who took nontraditional routes, Yale Engineering Advanced Graduate Leadership Program Fellows are uniquely positioned to more easily transition from graduate school to careers in business, industry, policy, academia, and other areas.

Fadel and Park, a 2011 biomedical engineering doctoral graduate, were the first Fellows to take advantage of a unique offering of the AGLP: four semesters of course-work in Yale's School of Management. "I was so excited when I saw this opportunity," says Fadel. "I thought it would be a great way to get away from my narrow focus on the supply side of biotechnology and begin to understand the demand side. What I came away with was the ability to speak an entirely different language."

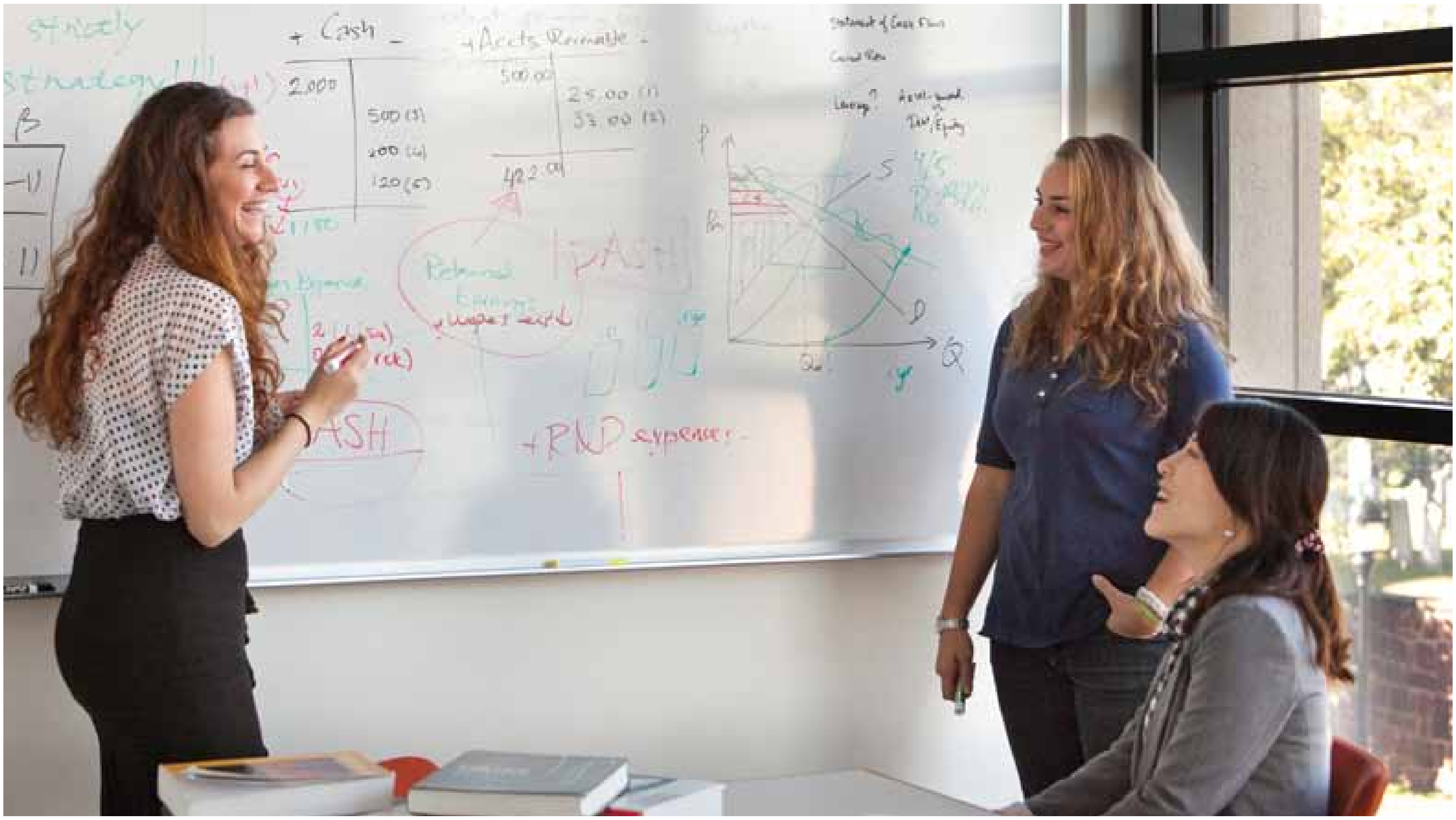
From basic numerical methods in accounting to the dynamics of finance, Fadel says he quickly became versed in business management parlance, which included expressing oneself with a certain level of confidence not typical of science and engineering professions. "As scientists, we're taught to question and have doubts," he says. "Even when we make breakthroughs, there is always more testing to be done—others need to reproduce our results before the scientific community accepts the findings."

Park, who says he has long known that his interest is in the financing and management of biotech companies, pursued the rigorous and demanding studies required for a Ph.D. in engineering as a path to obtain the critical reading, analysis, and quantitative reasoning skills that would be valuable to his business career. He says his newly acquired skill set combined with his understanding of finance, competitive strategy, and venture capital opened many doors. Consulting industry employers "don't expect engineering Ph.D.s to have this kind of training," Park says. Testimony to his uniqueness, Park won a spot as a consultant with the very selective Boston Consulting Group in New York following graduation.

Fadel, who professes to being a researcher at heart and is now carrying out postdoctoral studies in biomedical engineering professor Tarek Fahmy's lab, says the Advanced Graduate Leadership Program helped him articulate what is most important to him, to determine what drives him to achieve success, and to set and remain focused on his goals.

Watch the Video Online

http://seas.yale.edu/publication



The success of these and other AGLP graduates have increased interest in the School of Management option in the current group of Fellows. Biomedical engineering doctoral student Alyssa Siefert and chemical & environmental engineering doctoral students Diana Hu and Seyla Azoz are now following in Park's and Fadel's footsteps.

Siefert's professional goal is to establish biotech companies after she completes her Ph.D. She says her experience in the AGLP's School of Management option is helping her prepare for her future. "I've learned the benefits and pitfalls of microfinance, regulatory information for biotech startups, and how nonprofit organizations can stay afloat," she says. "What I am learning will guide and inform my long-term goals of founding biotech companies that will bring the best research products to the clinic, in the most streamlined ways, to benefit the largest number of people possible."

Azoz believes the experience is the critical link between her expertise and her professional ambition. "As engineering students, we have been exposed to all sorts of engineering problems throughout our studies," she says. "However, I believe it is not enough to only demonstrate engineering principles in the laboratory; they must also be applied in the real world. I believe that the information I am learning will bridge the gap between my research knowledge and my aspirations to become an entrepreneur. I feel very special to take part of such an amazing program."

MEDICAL INNOVATION

In the First Person

Setting the stage for the third revolution in modern biology

A year into his Yale appointment, professor of biomedical engineering, Jay Humphrey reflects on the culture that's catalyzing advances in his biomechanics research, in his own words, as told to *Yale Engineering.*

My Yale appointment is through the Faculty of Arts and Sciences, specifically in the School of Engineering & Applied Science. I am also affiliated with the interdisciplinary and interdepartmental Vascular Biology and Therapeutics Program at the School of Medicine. This program includes 45 faculty members from biomedical engineering, cardiology, cell biology, chemical engineering, immunology, pathology, pharmacology, surgery, and other departments. It is absolutely the best of its kind, so it was an easy decision for my Texas A&M graduate students to follow me here. With such a great opportunity for specific training in vascular biology and biomechanics, they all said, "Let's go!"

My area of interest is biomechanics, which, despite the name, is very different from mechanobiology. The two are distinct fields of study, but, in the spirit of interdisciplinary research, it's the bringing together of the two fields that's exciting.

Mechanobiology is that aspect of biology that focuses on how mechanical stimuli affect cell behavior. In the past, people who have worked in biology and focused on the effects of mechanical signals have not used mechanics. For example, they have not invoked Newton's second law. In contrast, biomechanics researchers often start with force equals mass times acceleration and formulate a biological problem in this context, such as how a red blood cell is transported within the aorta.

All cells have to respect Newton's law of motion, and we have to understand not just how the cell moves in response to a force, but how it changes its gene expression, and how it changes its activity. That's where the two fields meet. A colleague and I started a journal 10 years ago called *Biomechanics and Modeling in Mechanobiology.* Modeling helps to bridge the biology and the mechanics.

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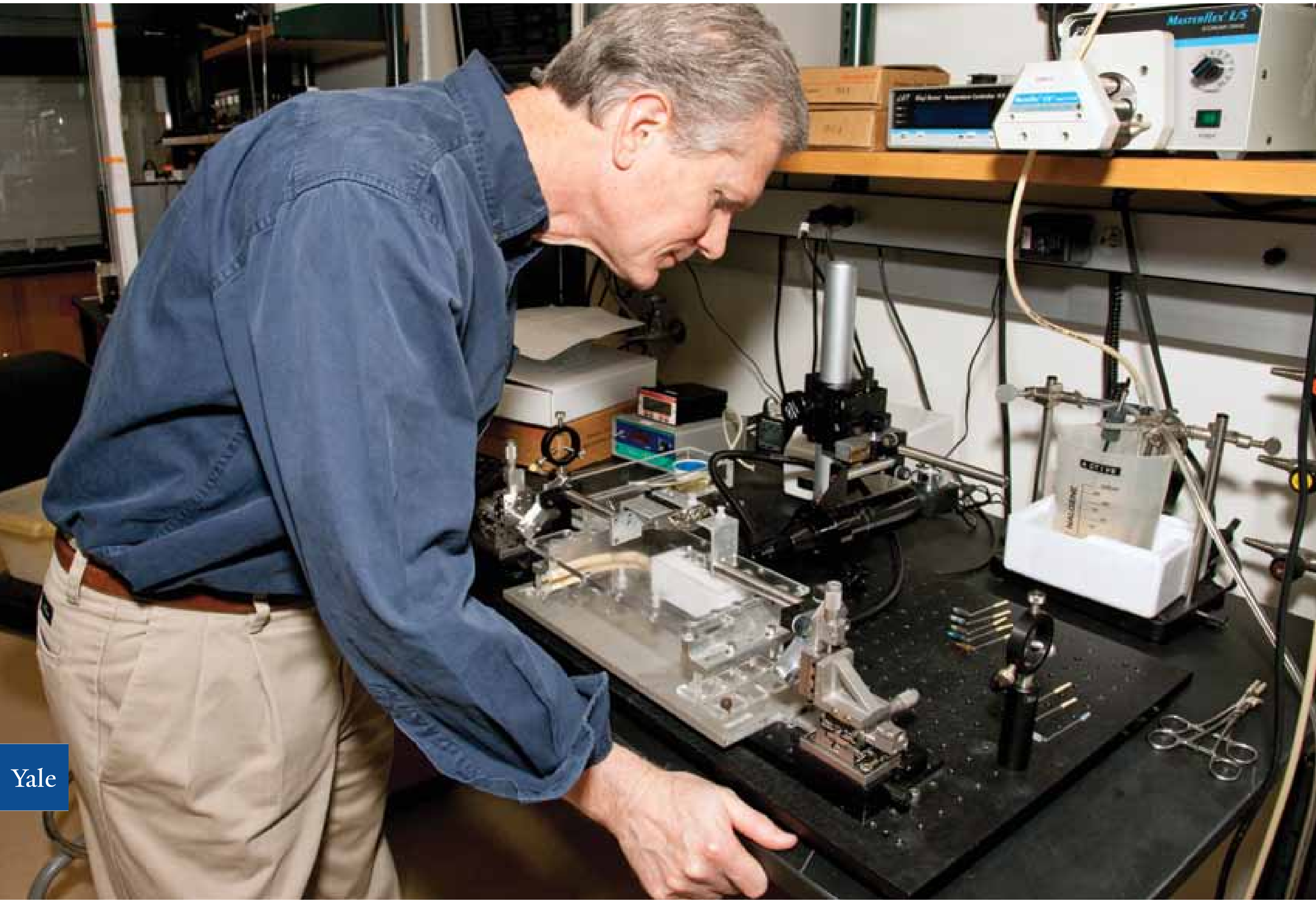
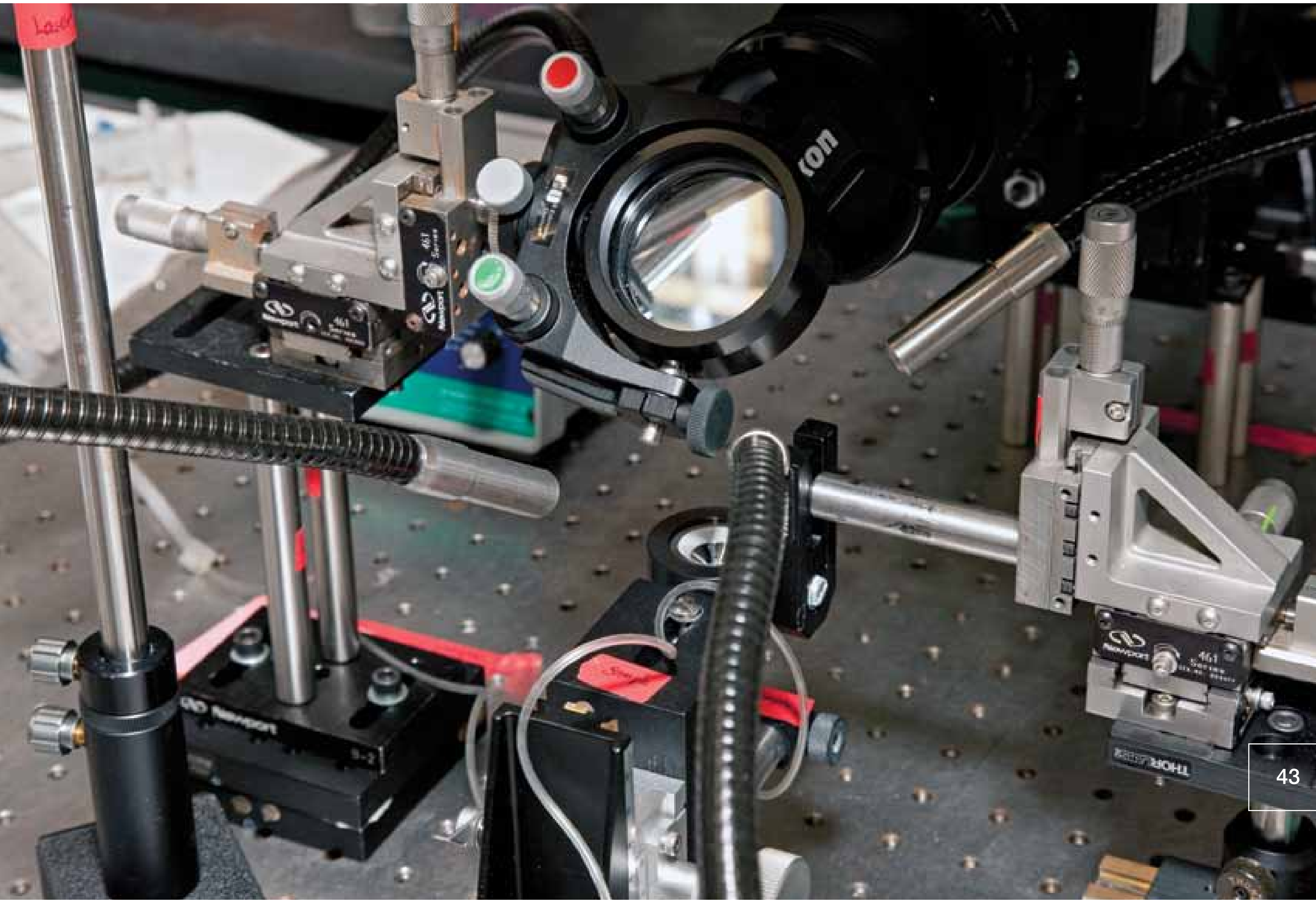


That's just one small example of the merging of physics, chemistry, biology, engineering, mathematics, and computer science that people are talking about. Computer science has already helped tremendously to unravel the complexity of the genome, but we need to go beyond data mining, sorting, and interpretation and develop predictive models. Many people refer to this need, this promise, as the third revolution of modern biology.

The first revolution in biology was signaled by the discovery of the double helix structure of DNA, which interestingly was made by Watson, a biologist, and Crick, who had a physics background. That they even considered a helical structure was thanks to Linus Pauling, a chemist, who was led to consider the helical structure because of a discussion in a graduate mathematics class. He even claimed that modern biology was possible only because of quantum mechanics—a branch of physics and theoretical chemistry. That was the early 1950's when mathematics and physics and chemistry and biology began to come together to increase understanding. And even then, the conceptual merging of disciplines was not new.

In the late 19th century, the French physiologist Claude Bernard attributed the day's advances in biology to the physico-chemical sciences—physics and chemistry. You can even go back to Descartes in the 17th century, before Newton, to find the argument that the physical self is subject to the laws of nature. At that time, the body of scientific knowledge was more manageable and scientists



were simply natural philosophers—one individual could practice mathematics, chemistry, physics, and biology. As knowledge has exploded, we've become much more compartmentalized.

Now, to solve the really tough problems in health, and similarly in energy and the environment, we have to re-synthesize all of this. In the human body, there's physics, chemistry, biology, and engineering. How do you understand all these things as a single-discipline trained scientist? You can't. This is the motivation of the third revolution in biology—with the first being Watson and Crick, and the second being genomics—to bring back together all of these subjects so that we can understand and predict biological processes, ultimately for the purpose of improving human health.

The FDA, in conjunction with the NIH and NSF, has organized annual meetings in my area of computational modeling for treating cardiovascular disease. The goal has been to get people from academia, government, and industry together to figure out how we can speed up medical device design and approval and how we can make devices more effective. Using computational methods is very important to this.

Boeing uses computational models to design next-generation aircraft. They can design a plane on the computer, build just a few prototypes, test them in a wind tunnel, and start flight testing much more quickly than in the past. The models are that good. The same is true in the automotive industry. We're not yet there in the medical device industry, but there is considerable promise.

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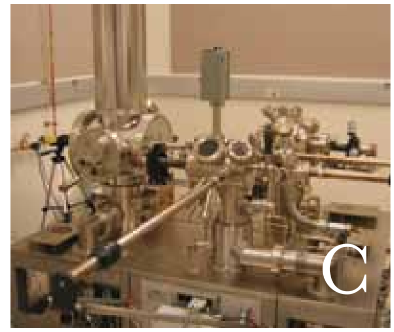
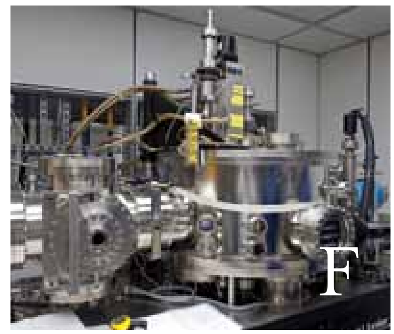
The new supercomputer that Yale acquired in March this year, Bulldog Omega, is the most powerful among the Ivies and is rated 146th in the world. This is an example of the computational tools needed for modeling in our field.

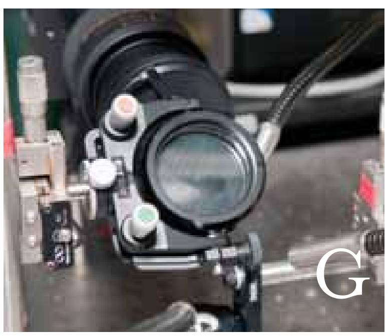
The main thing we're working on in my lab is a computer model that would tell us how diseased blood vessels change over long periods—weeks, months, and years—so that we can predict what might happen in the future if you've had a particular type of device implanted, a particular type of injury, or a particular surgical procedure. This project is in its infancy, but we know that it is the mechanics that will tell us what the mechanical stimulus is on the cell while the mechanobiology will tell us what the biological response will be at a cellular level, which in turn will manifest on a tissue and organ level. We're interested in whole arteries and aneurisms, not just the individual cell within that artery, but we need to understand how the cell behaves in order to make that prediction, and that's where the two come together.

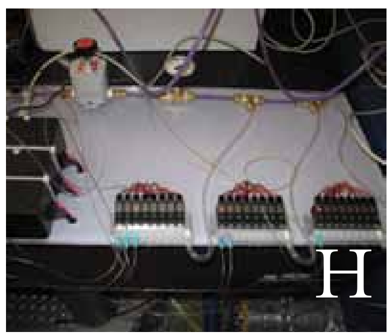
The NIH continues to push what they call "team science," which makes so much sense. Those of us in Biomedical Engineering who are affiliated with the Vascular Biology and Therapeutics program truly benefit from a "team science" approach because of the very collaborative environment at Yale. Every research institution likes to say "we're highly collaborative," but the reality is that's not always true. During my first year at Yale, however, I've seen that it's very true here. In Biomedical Engineering, there are wonderful opportunities to collaborate with basic scientists on Science Hill and researchers at the Medical School.

Why is Yale so good at this? Part of it is our size. At Yale there isn't an emphasis on being the biggest group; the emphasis is on having the best people in each area. And if you have a few people in each of several different areas, it's very natural then for them to work with each other. The other factor is Yale's culture. There's a tradition of collaboration here and as new people come in, they're very quickly integrated across campus. It's the ideal setting for staging the third revolution in biology.









Match Game

Can you match the equipment with the descriptions below?

1. This item is used to characterize the properties of transistors, diodes, and other semiconductor devices.
2. Known as the "MAD Machine," it is used to synthesize gate dielectrics in CMOS transistors
3. Housed in a SEAS facility and available to all students, this offers nine potential sources for materials evaporation using RF and DC sputtering and thermal methods.
4. This liquid chromatography system is used for protein purification.
5. Also located in a SEAS facility and available to all students, this unit creates complicated multi-layered thin films.
6. This atomic force microscope operates at temperatures near absolute zero. It is the only such microscope in the U.S. that is able to image the atomic structure of surfaces.
7. This Von Kármán cell is used to produce and optically measure intense turbulence.
8. This digital image correlation system quantifies regional surface strains on small specimens.
9. This device controls and regulates a separate microfluidic system.

Answers can be found at http://seas.yale.edu/matchgame

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