



A BROAD VIEW: Tiny lenses, inspired by insect eyes

Drawing inspiration from an insect's intricate eye, UW-Madison engineers have created miniature lenses with a vast range of vision.

Their novel approach allowed them to create the first-ever flexible, Fresnel zone plate microlenses with a wide field of view—a development that could allow everything from surgical scopes to security cameras to capture a broader perspective. Led by Hongrui Jiang, the Vilas Distinguished Achievement Professor and Lynn H. Matthias Professor, the researchers described the advance in the October 30, 2015, issue of the journal *Scientific Reports*.

The advance centers around a method for creating tiny lenses, each the size of a grain of salt, embedded within a flexible plastic polymer. This approach allowed the researchers to bend an array of multiple lenses into a cylindrical structure. An array of these miniscule lenses, each no larger than a head of a pin, can

capture an almost complete panorama, producing images from a 170-degree field of view. “We got the idea from compound eyes,” says Jiang. “We know that multiple lenses on a domed structure give a large field of view.”

He sees potential for this work to improve surgical scopes and security cameras—offering a wide range of vision for devices at a fraction of the size required by conventional lenses.

The imitation insect eyes not only capture a large field of view, they also contort and flex. Each tiny lens sits within a flexible plastic polymer material, which allows the researchers to freely reconfigure the shape of the lens array. Jiang and colleagues can manipulate their microlenses in this manner because rather than relying on conventional optics for focusing, they used Fresnel zone plates. “Usually flexible structures are incompatible with optics, but our lenses are small and the optical properties are fine,” says Jiang. *(Continued on page 3)*



John Booske

Incredible and wonderful things are happening here at UW-Madison's ECE department. As always, the key to our success is to focus. Our mission remains focused on a world-class education for our students,

and a world-class faculty who lead the nation in education and research.

Our faculty and students are leading the way to better living for humankind. Tiny compound eye lenses, inspired by, yet far superior to, nature's best results (after billions of years of evolution), will revolutionize scopes for micro-surgery and cameras for security or smartphones. Record-setting performance from flexible microelectronic chips, including some made almost entirely from wood, will shepherd in a new age of smart textiles and environmentally-friendly electronics. Smaller and smarter antennas, inspired by miniature insect auditory systems, will enable superior remote monitoring for greater national security both home and abroad. Advances in optimization based on novel decentralized control theories will pave the way for stable, safe and efficient self-driving cars.

It's no surprise that with a focus on research that addresses humanity's most basic needs and grand challenges, our faculty and students are garnering awards and shout-outs, including best paper awards, election to fellow membership in the most prestigious professional societies across the globe, the 2015 *Popular Mechanics* Breakthrough Award, and Sweden's prestigious Sven Berggren prize.

Meanwhile, the quality of a UW-Madison ECE education continues to be a gift that keeps on giving—giving back to society, that is, through the leadership and excellence of our exceptional students and alumni, as you will read about in the following pages. While our department consistently enjoys high rankings, we

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need your support to help us continue to excel. Your gifts help us:

- Hire and retain top-flight faculty and educators,
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- Support research that changes lives and creates a better world—today and beyond.

To that end, a huge thank you to all of you who have and continue to give back to our students with your financial generosity. Particularly generous gifts include the Splinter and Thompson Morgridge match professorships, as well as Qualcomm's Design Labs and the Education Innovation Scholar. Thank you for the confidence you place in the Department of Electrical and Computer Engineering as we look to a future of continued progress, groundbreaking research, and engineers who are excited and prepared to tackle any challenge. I appreciate all you have done for us—and continue to do, for our department.

As we look to the months ahead, please be sure to visit the department's 125th anniversary website, 125.ece.wisc.edu/. We will be celebrating ECE's rich history and exciting future the entire academic year of 2016-2017 with a variety of alumni events around the country, a distinguished lecture series and a department 125th birthday bash. We hope you can join us!

ON, WISCONSIN!

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Morgridge match yields new professorships

A historic \$100 million matching gift to UW-Madison spurred the creation of 13 new professorships in the College of Engineering. Among those are the **Karen Thompson Medhi Professorship** and the **Patricia and Michael Splinter Professorship**.

Jim Thompson (BS '85, MS '87 and PhD '91) established the former professorship to honor the memory of his sister, Karen, who earned a PhD from UW-Madison in industrial engineering. The Splinters' professorship focuses on increasing the number of women and people of color in the department. Mike Splinter earned his BS ('72) and MS ('74) from the department.

125 YEAR ANNIVERSARY

Make plans now to join us from **August 2016 through May 2017** as we celebrate the department's 125th anniversary with a variety of exciting events, including lectures, alumni receptions around the country, a kickoff party, and a special birthday celebration.

Watch for more details about how you can help us celebrate!
125.ece.wisc.edu

Tiny lenses *(Continued from front page)*

Typical lenses consist of stiff translucent materials, machined into concave or convex shapes; they obtain images by changing the trajectory of incoming light into a single focal point through refraction. Fresnel zone plate lenses, by contrast, focus light through constructive and destructive interference, or diffraction.



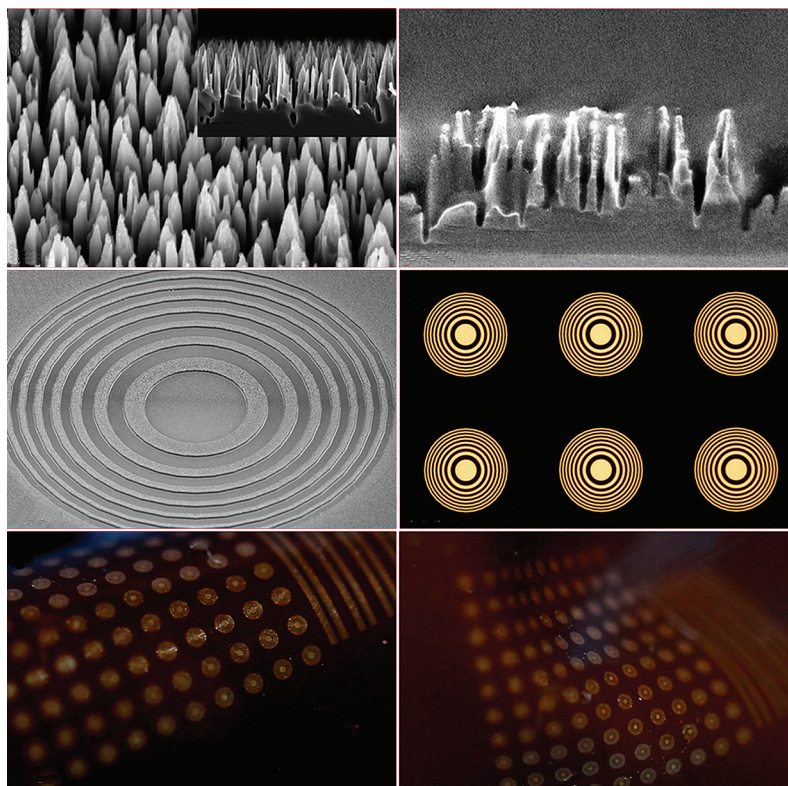
Each of Jiang's half-millimeter diameter lenses resembles a series of rings on the surface of still water emanating outward from a single point. In bullseye fashion, each concentric ring alternates between bright and dark. The distance between the rings determines the optical properties of the lens—and the researchers can tune the optical properties of a single lens by stretching and flexing it.

Previous attempts at creating Fresnel zone plate lenses have suffered from fuzzy vision. “The dark areas must be very dark,” explains Jiang. “Essentially, it has to absorb the light completely. It’s hard to find a material that doesn’t reflect or transmit at all.”

His team overcame this obstacle by using black silicon to trap light inside the dark regions of their Fresnel zone plate lenses. Black silicon consists of clusters of microscopic vertical pillars, or nanowires. Incoming light bouncing between individual silicon nanowires cannot escape the complex structure, making the material darker-than-dark.

Rather than laying down layers of black silicon on top of a clear backdrop, Jiang and his team took a bottom-up approach to generate their lenses. First they patterned aluminum rings on top of solid silicon wafers using lithography, and etched silicon nanowires in the areas between aluminum rings. Then they seeped a polymer between the silicon nanowire pillars.

After the plastic support solidified they etched away the silicon backing, leaving bullseye-patterned black silicon embedded in supple plastic. This approach gave their lenses unprecedented crisp focusing capabilities as well as the flexibility that enables them to capture a large field of view.

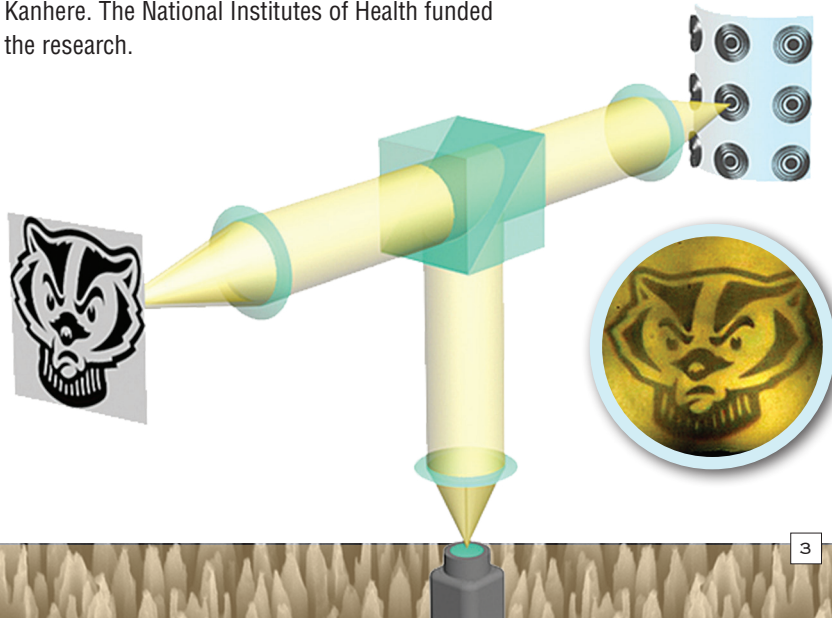


Tiny silicon nanowire towers make up dark regions of the flexible Fresnel zone lenses. Each individual lens resembles a bullseye of alternating light and dark. Arrays of lenses formed within a flexible polymer bend and stretch into different configurations.

Currently Jiang and his team are exploring ways to implement these microlenses into real-world applications. They are working to integrate the lenses into existing optical detectors and directly incorporate silicon electronic components into the lenses themselves.

Mohammad J. Moghimi, a postdoctoral scholar, was first author of the manuscript. Co-authors from the Jiang group included Jayer Fernandes and Aditi Kanhere. The National Institutes of Health funded the research.

Bringing Bucky into focus: Curved arrays of individual lenses allow small-scale sensors to perceive a broader picture. The cylindrical arrangement (below) allowed researchers to resolve a 170-degree field of view.





New Qualcomm labs enable more sophisticated learning

The ethic of teamwork, so vital in professional engineering, is being instilled in electrical and computer engineering students working on semester-long projects in the Qualcomm Design Labs.

“Students love it,” says Professor Parmesh Ramamathan who has taught in the labs. “Collaboration is absolutely essential, and this setting builds team skills.”

Teams of six students work at computer-equipped pods around the perimeter of each lab, mentored by faculty members. A pod at the center of the room allows for larger group meetings and teaching sessions.

The two labs, on the third floor of Engineering Hall, also allow students to experience the crazy-long hours it sometimes takes to complete projects on real-world deadlines. Team members are given 24/7 access to the secured labs and to their projects, which don’t have to be disassembled at the end of each session.

“It’s a variant of a makerspace,” says John Booske, ECE chair. “You need instrumentation. You need computers. You need parts. You need layout space. We’re really very fortunate that Qualcomm was able to provide a gift for a space that’s dedicated to this type of learning.”

Because so little of engineering today is done solo, the teamwork aspect is important for students and for the department, Booske says. “Having the chance to do this as teams means that students can really get their hands into something on a real-world sophistication level, as opposed to doing something more trivial with less facilities and infrastructure,” Booske says.



Jim Thompson

And, this active learning approach helps enhance the stature of the students in the eyes of employers. “Having exposure to making progress on something as a technical team is crucial to sustaining our students as among the top recruitment prospects for major employers,” Booske says.

Jim Thompson, executive vice president of engineering at Qualcomm, says the labs “bring a part of our company to UW to enable exploration and discovery resulting in new innovations that can change the world.” Thompson, a three-degree ECE graduate, said the project is built on Qualcomm’s core values of innovation, partnerships and execution.

As the semester begins, Ramanathan says students are often wary about working in teams. Many times, they are concerned that their teammates won’t share the load equitably.

“We teach team skills and strategies in hitting milestones,” Ramanathan says. “We try not to allow people to lag behind. But, working in a real-life scenario, they will encounter people who work at a different pace.”

Students using the labs are able to use the facility at all hours, and that’s often required. Ramanathan says the teams’ goals simply cannot be accomplished during class time alone.

Booske says that means students gain an appreciation for solving problems while meeting deadlines—essential workplace skills. The labs, he says, provide a margin of excellence for students and the department.

“We want them to complete their education successfully with the skills needed for them to be not just excellent engineers for society, but engineering leaders,” Booske says.

When it comes to protecting the men and women of the armed forces, Associate Professor Nader Behdad focuses his work on an obstacle most people wouldn't associate with combat: the physical limitations of low-frequency antennas.

For decades, the military has sought to take greater advantage of low-frequency radio waves. The long wavelengths and propagation characteristics of radio waves in the 3 to 300 megahertz range enable long distance communication, and can penetrate or diffract around natural obstacles—making them useful in many military communications systems.

This frequency range is also a crucial tool in electronic warfare—jamming an enemy's communications or, conversely, tracking down the source of a jamming signal in an electronic attack.

The laws of physics dictate that a conventional antenna has to get bigger as the wavelengths get longer. And when you're dealing with 10- to 100-meter-long wavelengths, the antennas get far too bulky to lug into real-world electronic warfare situations.

Behdad has received a \$1.3 million grant from the U.S. Office of Naval Research to tackle this problem. Building from previous research successes, he and his research group will explore how to make compact, powerful antennas for transmitting jamming signals in an electronic attack. They also will explore how to develop better antennas for finding the source of a hostile signal. "If you have a small platform and you want to put an antenna on it that works across this entire low frequency band, this antenna can't be a 10-meter-long antenna," Behdad says. "If you have an unmanned aerial vehicle that's flying, you don't have that kind of real estate. Even on a ship—a ship is huge, but there are so many things on it—finding that kind of space would be a problem."

On the transmission—or attack—side, Behdad is working to develop a 1-meter antenna that can send high-power signals at frequencies as low as 3 megahertz.

What the military is seeking will push Behdad's previous research—and the laws of physics—to the limit.

Behdad thinks he can achieve this short antenna with a combination of vacuum electronics, which can handle high-power transmissions, and the concept of non-Foster impedance matching, which essentially shows that antennas using negative-impedance converting-circuits can overcome some of the limitations that conventional circuits face.

The defense angle of the project also presents a problem of size. Again, convention says these antennas have to be large if the enemy is using low-frequency transmission and if the antenna needs to pick up that signal and determine where it's coming from.

For several years, Behdad has been tackling this problem by developing biomimetic technology inspired by the *Ormia ochracea*, a tiny fly that achieves



Smaller and smaller antennas for military use

excellent directional hearing with two closely spaced ears on its thorax—which to an antenna engineer resembles a tiny antenna.

Behdad's challenge is to adapt his previous successes to very small wavelengths. Success will mean military personnel can bring high-powered, low-frequency-range antennas into a greater variety of situations, gaining both a combat advantage and added safety.

"You can precisely figure out where your enemy is by listening to their communications and if they turn on any wireless device, you can figure out where they are," Behdad says. "And the electronic attack antennas that we develop can be used to jam all of these communications. Similarly, you can jam their radars to make them blind.

Finally, you can jam the signals used to remotely detonate improvised explosive devices to increase the warfighter's safety."



Nader Behdad

In the background of all of our electronic machines and devices are systems that sense and automatically compensate for noise, disturbances, and other unwanted behavior. These mitigations are the basis of feedback control systems, the principal focus of Assistant Professor Laurent Lessard, who joined the department in fall 2015.

Lessard, who grew up in Toronto, received his master's and PhD in aeronautics and astronautics (in 2005 and 2011, respectively) from Stanford University before traveling to Lund University in Sweden to work as a postdoctoral researcher in its Department of Automatic Control.

There, Lessard was able to work with a group of about 60 researchers who all specialized in controls, an area that spans many engineering disciplines, but doesn't have a basis in any specific field. He says he enjoys the opportunities his field presents. "I like not being tied down to one particular problem at a time," he says. "I like to think about what these various disciplines have in common—and more recently, where I think they're going to go in the future."

This is certainly evident in Lessard's background. He has worked in fields that include adaptive optics at Stanford, mechanical engineering at the University of California, Berkeley, and now electrical and computer engineering at UW-Madison. At the university, Lessard also is a controls theoretician within the Wisconsin Institute for Discovery (WID) optimization group.

Lessard is excited by the opportunity to work at UW-Madison, and with colleagues at WID, because the environment is highly collaborative and will allow him to pursue a variety of projects that interest him. The WID optimization group also maintains close ties with industry, ensuring that his research continues to have relevant applications.

He already has made advances in decentralized control theory, an area that essentially has been on hiatus for the past 40 years—in part because the problems are especially difficult. In decentralized systems, there may be multiple controllers and feedback loops. The controllers may be spatially separated and measure different information about the system. Nevertheless, the goal is to find strategies that allow the different controllers to effectively coordinate their efforts.

LESSARD'S GOAL: To build a strong connection between optimization and control experts, therefore broadening the possibilities and capabilities of future systems.

In Lessard's experience, however, not all of these problems are hard. In fact, what makes a decentralized control problem difficult has less to do with how many controllers there are and more to do with how the controllers share information with one another. The network architecture makes all the difference.

"Let's say there are two mechanical arms on a robot, each with a separate controller, and the goal is to have the arms work together to carry an object," Lessard says. "If the controllers don't share any information at all, that's not a tractable architecture. That's very difficult to solve. But if the controllers are able to share sensor measurements with one another in a particular way, the problem can be solved very efficiently. The key is to discover which types of information-sharing lead to tractable problems."

Although Lessard's work focuses on theory, it provides a platform for further research into decentralized control, and allows engineers to build large-scale systems more efficiently.

While he will continue research in decentralized control at UW-Madison, he currently is focusing on problems at the intersection of control theory and optimization.

LAURENT LESSARD at the cornerstone of control theory and optimization



Modern machines are changing dramatically: The self-driving car is a perfect example of how controls are evolving as these changes take place. Although cars already have control systems, a self-driving car requires powerful computers that can perform image recognition on the fly and learn a vehicle's surroundings as they change. Engineers from several disciplines are working on improving the self-driving car, and each type of engineer approaches the problem differently. While computer scientists consider it to be an optimization challenge, for example, control theorists view it as a feedback problem.

Lessard sees himself somewhere in the middle of the two.

In many ways, a self-driving car represents the sudden union of optimization and control. In traditional large-scale optimization problems such as personalized advertising and movie recommendation engines, large-scale algorithms can afford to be aggressive because the cost of making errors is low. With self-driving cars, errors are unacceptable, and engineers are forced to be risk-averse. That's where controls come in.

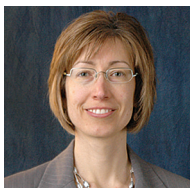
"In controls, performance is a luxury, and robustness is key," Lessard says. "Optimization is the other way around: Performance is key, and robustness has been a luxury. How do you design for these systems of the future that are going to involve not only a lot of feedback loops, but also a lot of very intense computation? You can think of a self-driving car as an example of wanting both high performance and luxury."

Lessard won't be working on the next self-driving car—but the example demonstrates his far-ranging goals: To build a strong connection between optimization and control experts, therefore broadening the possibilities and capabilities of future systems.

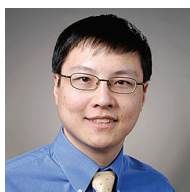
"I think you're going to have a lot more complicated systems being built," he says. "Will you be able to control them the way you would like, and will they do what you think they are going to do? That's the question."



Associate Professor **Azadeh Davoodi** and alumnus Hamid Shojaei (PhD '12) received the 2015 Association for Computer Machinery Transactions on Design Automation of Electronic Systems Best Paper Award in June 2015 for their paper, "A fast and scalable multidimensional multiple-choice knapsack heuristic," published in 2013 in *TODAES*.



Susan Hagness, the Philip Dunham Reed Professor and college associate dean for research and graduate education, received the Sven Berggren prize from the board of the Royal Physiographic Society in Lund, Sweden, in early October 2015.



Hongrui Jiang, the Lynn H. Matthias Professor and Vilas Distinguished Achievement Professor, was elected fellow of the Institute of Physics, the Royal Society of Chemistry, and the American Institute for Medical & Biological Engineering—honors that recognize the highly interdisciplinary nature of his work.



Jack Ma, the Lynn H. Matthias Professor and Vilas Distinguished Achievement Professor, received a 2015 *Popular Mechanics* "Breakthrough Award" for his and his collaborators' work in developing a unique, environmentally friendly microchip made mainly from wood.

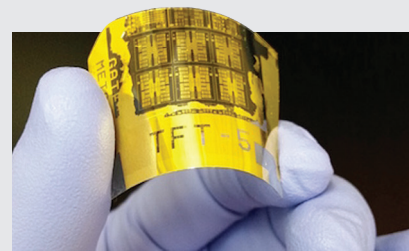


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IN THE NEWS

These three ECE faculty members are among those cited, mentioned or featured in the news:

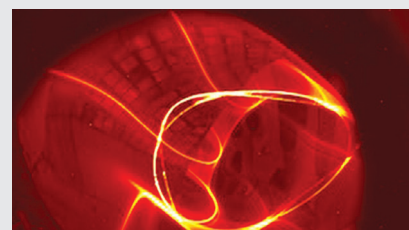
- **Hongrui Jiang**: "Tiny lenses inspired by insect eyes" (story and video in the *Wall Street Journal*)
MORE: go.wisc.edu/wsj-insect-eyes
- **Jack Ma**: "Scientists develop chips made almost entirely from wood" (video in the *Wall Street Journal*)
MORE: go.wisc.edu/wsj-wood-chips
- **Rob Nowak** ("Data scientist at the University of Wisconsin"): Cartoon lounge: Show me the funny (*New Yorker* video)
MORE: go.wisc.edu/ny-data-scientist



Record-setting flexible phototransistor

Developed by Lynn H. Matthias Professor & Vilas Distinguished Achievement Professor **Jack Ma** and research scientist Jung-Hun Seo, the innovative phototransistor could improve the performance of myriad products—ranging from digital cameras, night-vision goggles and smoke detectors to surveillance systems and satellites—that rely on electronic light sensors.

MORE: go.wisc.edu/flex-phototransistor



A step forward for fusion

With ECE expertise, German fusion experiment achieves major milestone In June 2015, the Wendelstein 7-X, one of the world's most innovative fusion experiments, marked a major technological achievement that likely will make it a viable candidate for producing energy from fusion. Jim and Anne Sorden Professor **David Anderson** contributed experimental measurements, compared with computational models, from his helically symmetrical fusion experiment.

MORE: go.wisc.edu/wendelstein-anderson

Willett named Spangler Faculty Fellow

In an effort to better understand how the brain actually works, Associate Professor **Rebecca Willett** will use funding from the award to explore additional ways to leverage varying sources of data about the brain.

MORE: go.wisc.edu/willett-spangler



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Advancing educational education in ECE

A teaching scholar hired to quarterback cutting-edge educational innovations in the Department of Electrical and Computer Engineering is expanding the power of instructional technology.

"There's an awful lot of educational transformation going on in the department and it takes a substantial amount of up-front time to prepare material," says John Booske, department chair. "We needed someone to be the guru."

The new role was made possible by an annual fund gift from Roy Thiele-Sardiña, a 1982 graduate who is managing partner at HighBAR Partners in Menlo Park, California.

His gift, along with income generated from a \$500,000 estate gift from 1958 PhD graduate Earl Lind and his wife Ellanette, provides full funding for the position, which is held by graduate student Yaman Sangar.

Using educational technology has been a department priority. More than two-thirds of the department's core required undergraduate classes have been converted to blended learning, where lectures are provided online,

allowing instructors more hands-on learning time students in labs and classrooms.

"Roy gets it," Booske says. "Roy has succeeded tremendously by doing, so he understands that value of learning through maximal time spent by doing and trying and experimentation."

Sangar will ensure that the department's efforts are

coordinated, that faculty and teaching assistants have access to training and an expert resource to help solve problems. Sangar will also be an important bridge if those teaching the blended courses change. "It's a key position that makes our efforts sustainable," Booske says. "It gives us the

margin of expertise to do enhancements, building on the expertise we've acquired during the first generation of innovations."

The position will also create a ripple effect, Booske says, enabling instructors to be more productive and make the classroom and lab experience richer for students.

"By supporting one person, the impact of this is just very broad-spectrum," says Booske. "Maintaining this awesome set of material liberates the instructor, especially the TAs, to be high-value-added coaches, rather than low-value-added graders."

Thiele-Sardiña says he hopes that the gift will give students a different, more practical outlook on engineering. "It gives students hands-on experience in how real-life engineering works," Thiele-Sardiña says. "The combination of online learning and strong teaching reflects how people work."

Booske credits Thiele-Sardiña for recognizing the importance of that role in a landscape of educational innovation.

"He's helping support us in a big way so that the next generation of students will continue to be the exceptional engineers that they deserve to be," Booske says.

