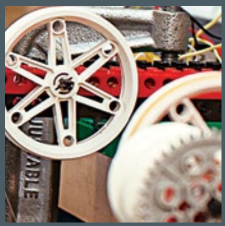

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A FOCUS ON LEHIGH ENGINEERING • VOLUME 1, 2017

A MATERIAL CONVERGENCE

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LEHIGH UNIVERSITY | P.C. ROSSIN COLLEGE OF ENGINEERING AND APPLIED SCIENCE

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VOLUME 1, 2017

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Envisioning our shared future

Welcome to the Spring 2017 issue of **Resolve*****—a magazine dedicated to research and educational innovation in the P.C. Rossin College of Engineering and Applied Science at Lehigh University.***

This issue arrives at an exciting time for the Rossin College and for our University as a whole. Within Engineering, the faculty is leading an envisioning process that will articulate specific, actionable plans to move our College forward. Discussion focuses on these areas—innovating our learning environments, enhancing our research impact, and developing areas of distinctive intellectual prominence for our future. There will be more to come as this process builds momentum, so please stay tuned.

Along the way, it has been crystal clear that Lehigh's interdisciplinary science and engineering research culture—the hallmark of our overall academic environment—serves as a powerful foundation for our future. In short, the most interesting, challenging, and pressing issues of our time require thinkers who are perfectly comfortable working outside of their comfort zones.

This issue of *Resolve* celebrates what can happen when teams of researchers, with varied expertise, integrate their skills and expand the boundaries of their traditional fields. Throughout, you will notice faculty researchers with related yet asymmetrical interests working together to find success.

The article "Advancing Materials for Health" (p. 10) features Lehigh research in an area of key importance to broader societal concerns in health and healthcare. Recent estimates have projected that the global biomaterials market will more than double by 2021, reaching nearly $150 billion. From a research perspective, it's a field situated squarely at an intersection of disciplines where Lehigh enjoys significant, demonstrable strength.

The "Q&A" interview with Lehigh chemical engineering alumnus and Trustee Dr. Michael Yaszemski '77 '78G is a strong reflection of how research in biomaterials, and biomedicine more broadly, can make a lasting impact.

"Stronger Soil through Bioengineering" (p. 16) discusses research that uses an enzyme, inspired by sea sponges, to develop stronger substructures and increase earthquake resistance: another strange-but-true product of interdisciplinary science.

The "Rising Star" (p. 24) in this issue, Dr. Brandon Krick, is a one-person interdisciplinary research machine. Relatively new to Lehigh, Brandon is already leveraging his expertise in tribology—the science of 'wearing and tearing'—in fascinating ways, contributing to a number of successful research projects with colleagues at Lehigh, and elsewhere.

To support such endeavors, we must continue to develop strong core facilities that enable groundbreaking research, coupled with shared spaces that encourage interdisciplinary interaction. These facilitate collaboration that leads Lehigh, as an institution, in exciting new directions.

"The most interesting, challenging, and pressing issues of our time require thinkers who are perfectly comfortable working outside of their comfort zones."

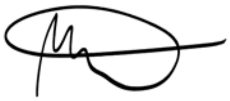
The feature article "Bringing Fusion into Focus" (p. 20) shows how sophisticated instrumentation, mixed with ingenuity, is key to unlocking new engineering knowledge and technical advancement in important fields—while creating cutting-edge learning opportunities for our students.

The "Educational Innovation" article (p. 22) highlights our work with KEEN, the Kern Entrepreneurial Engineering Network. While Lehigh is renowned for its thriving set of entrepreneurship education programs, the KEEN team's focus is different—a broad effort to fundamentally transform the undergraduate curriculum across all engineering majors. The goal is to instill in all Rossin students an entrepreneurial mindset that empowers them to identify opportunities and make an impact.

With support from KEEN, we are developing novel curriculum design techniques that get students thinking creatively about every aspect of projects they encounter, while adhering to the rigor of a classic Lehigh Engineering education. As you'll see, KEEN is helping to change the way everyone from senior faculty to incoming first-year students view the role of the modern engineer.

I hope you enjoy this issue of *Resolve*. For expanded articles, profiles, and video/animation of research in action, please visit the online version of the magazine at **lehigh.edu/resolve**.

Thanks for supporting the Rossin College; please drop me a line with your thoughts and comments.



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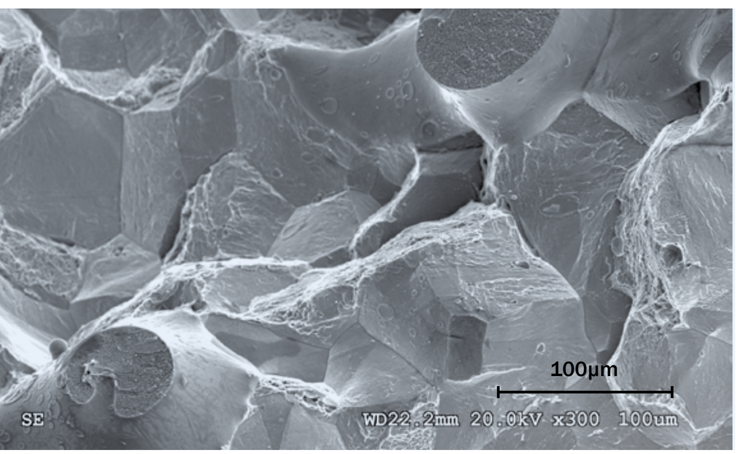
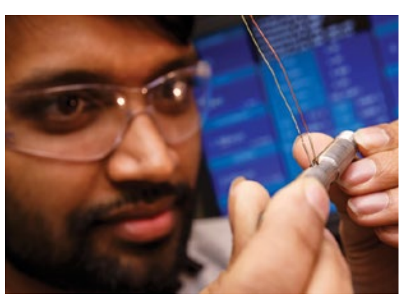
Joining for strength

National collaboration yields Ma^{2}JIC solutions for industry

Welding may be perceived as an established technology with little room for innovation, but its underlying principles are poised to guide the very future of manufacturing—from heavy-duty industrial components to children's toys.

"Welding remains one of the most complicated and important fabrication processes used by industry," says John DuPont, the R.D. Stout Professor of Materials Science and Engineering and co-director of Lehigh's recently established Manufacturing and Materials Joining Innovation Center, or Ma^{2}JIC. "And it turns out when you look at the additive manufacturing processes used for metals and alloys, they are really welding processes in disguise."





Above: Fracture surface of a nickel alloy; image acquired via Lehigh scanning electron microscope. Right: Ph.D. student Rishi Kant examines a tensile specimen in the Ma^{2}JIC lab.

Additive manufacturing—technologies that build 3D objects by adding layer-upon-layer of material—has entered the popular imagination via the proliferation of desktop 3D printers, and its wider impact in manufacturing science has been dubbed a "third industrial revolution" by *The Economist*, among other sources.

In 2010, Ma^{2}JIC began its efforts as Lehigh's Center for Integrated Materials Joining Science for Energy Applications. This Center was part of an Industry and University Cooperative Research Center (I/UCRC) supported by the National Science Foundation (NSF), a consortium that now includes The Ohio State University, Colorado School of Mines and University of Tennessee at Knoxville, as well as 29 industry and government partners.

As industry increasingly turns to additive manufacturing to improve the bottom line and mitigate environmental impact, Ma^{2}JIC has broadened its researchers' focus to tackle projects in additive manufacturing of advanced metals such as new stainless steel and nickel alloys, across a broad swath of industry sectors.

When dissimilar materials are welded together traditionally, DuPont explains, the properties of the alloys change abruptly, leaving the joints prone to failure. "We have found that when you join these alloys, they don't have the strength of the base metals," he says. "Due to an effect known as micro-segregation, the alloying elements are not distributed uniformly in the area of the joint."

This leaves industry with an expensive and difficult choice. For example, modern power plants seek greater efficiency by using less fuel and emitting less carbon, and thus engineers have designed plants that burn hotter and generate much higher steam pressures. Operators must undertake costly preventative maintenance programs to remove and replace joints before they fail, or endure downtime that can cost millions of dollars per day.

The Ma^{2}JIC of collaboration

Power plant designer Babcock & Wilcox, welding equipment provider Lincoln Electric, Shell Oil, and Brazil's Petrobras, along with the Electric Power Research Institute, are partnering with Ma^{2}JIC to solve the problem of cracking in heat-treated welds. According to DuPont, one way to deal with the weakness caused by micro-segregation in welds is to heat-treat the joint after welding. Rapid heating and cooling experienced during welding does alter the material's microstructure, and can cause defects; sometimes heat-treatment doesn't effectively relieve the stress, and the joint cracks.

Engineers must find the right combination of exposure time and temperature to strengthen the weld—"it's like baking a cake," DuPont says. Because trial-and-error costs time and a lot of money, a previous project experimentally validated software models from another partner, Thermo-Calc Software, to help determine optimal recipes. Through experiment and simulation, Ma^{2}JIC tests and compares alloys to identify the best combinations for a wide variety of industrial-strength applications.

"We worked with Ohio State researchers to develop a way to simulate the cracking process in the lab under controlled conditions," DuPont says. "We can take an alloy that would be used in the field and put it through any thermal cycle we want, and stress it at the same time," using a specialized piece of equipment known as a Gleeble® simulator.

With colleagues from UT Knoxville and Oak Ridge National Laboratory, DuPont and his team are fabricating what they call graded transition joins. By carefully controlling and adjusting the material composition of the weld, this technique yields stronger and longer-lasting components by blending the properties of the base metals gradually over a controlled distance.

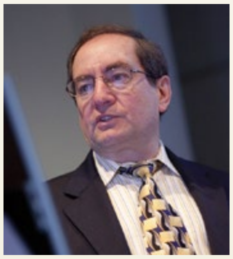
Ma^{2}JIC represents the second five-year bloc of support from the NSF for Lehigh's efforts within the I/UCRC. DuPont says that the broad I/UCRC collaboration is "a way to take our expertise and put it to work right away finding solutions for industry. It's a big benefit to us, because we attract more industrial support in the long run. Our Master's and Ph.D. students work on real-world research problems and get the chance to attend twice-annual meetings with center participants and members. And often they come away with job offers."

Catalyzing excellence

RESEARCH RECOGNITION

Dr. Israel E. Wachs, the G. Whitney Snyder Professor of Chemical and Biomolecular Engineering, has been named to prestigious lifetime achievement awards in the field of chemical reaction engineering.

The director of Lehigh's *Operando* Molecular Spectroscopy and Catalysis Laboratory, Wachs' contributions over three decades have been integral to the development of cutting-edge research, new technologies and emerging growth areas in chemical engineering. He has published more than 300 highly cited technical articles and holds more than three dozen patents.



Wachs formally accepted the R. H. Wilhelm Award during the 2016 Annual Meeting of the AIChE, the world's leading organization for chemical engineering professionals, with more than 50,000 members from over 100 countries. The Wilhelm Award is considered the top award in chemical reaction engineering research.

"There can be nothing more central to our profession than reaction engineering," says Mayuresh Kothare, chair of chemical and biomolecular engineering at Lehigh. "Witnessing Israel win the Wilhelm Award is, therefore, a very special moment for our department, and a fitting way to celebrate Israel's 30 years of pioneering accomplishments in this core area of our discipline."

In particular, Dr. Wachs was recognized for "seminal contributions towards development of innovative concepts for molecular chemical reaction engineering of mixed oxide catalyzed reactions by establishing fundamental catalyst molecular structure-activity kinetic relationships."

Earlier in the year, Wachs' contribution to research and education was recognized by the American Chemical Society at its Annual Meeting, which organized a symposium celebrating his three decades in academia.

According to Miguel A. Bañares, research professor at the Institute for Catalysis in Madrid, symposium contributions were provided by students, postdocs and colleagues to express gratitude for the positive impact that training and collaborating with Professor Wachs has had upon their lives.

Making the most of clean energy

Paving the way toward a "sharing economy" in renewable electric power

Recent years have witnessed the rise of an economic revolution of sorts—the advent of the so-called sharing economy. Businesses such as Uber, Lyft, and Airbnb have created a new kind of marketplace, in essence, by relying on the investments of others.

Could the electricity marketplace be next?

Boris Defourny, assistant professor of industrial and systems engineering, seeks to understand how this could take shape. He's recently won a National Science Foundation grant to analyze associated market models and develop theory and algorithmic strategies that will help integrate renewable energy so it can be used effectively across the power grid.

Defourny believes the distributed nature of renewable energy capture, which can reasonably be undertaken by everyone from individual households to major corporations and government agencies, makes it ripe for a similar economic disruption.

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"Renewables are on the rise," he says. "Yet in terms of instantaneous production levels, wind and solar are inherently volatile, and as such cannot be relied upon and fully utilized. A better coordination of these smaller, diverse, distributed power sources, coupled with an expansion of distributed energy storage resources, would allow for greater overall utilization of clean, renewable energy."

Defourny seeks to incentivize small energy producers and residential consumers to become suppliers of clean energy. Load aggregators and utility firms would leverage that clean power for other customers in real-time, even as its supply, and overall demand, fluctuates.

"At the moment," he says, "contractual and operational issues stand in the way. Yet the ability to seamlessly integrate more clean energy into the grid would, by definition, drastically reduce reliance on fossil fuels as well as associated environmental impact."

Defourny is developing business and technology models that would create mutually agreeable conditions for both the consumer/supplier and the utility firms, and studying the control mechanisms, contracts, and transaction environments for optimal pooling of clean energy. "It is a classic network effect," he says. "Greater participation yields greater individual and societal benefit. It needs a critical mass to really take off, and hopefully we can build some tools to help move the market in that direction."

International leadership and recognition

Dan M. Frangopol, the Fazlur R. Khan Endowed Chair of Structural Engineering and Architecture at Lehigh, has been elected to the Royal Academy of Belgium for Science and the Arts as a foreign member. He will participate in and contribute to the class of Technical Sciences.

The Academy was founded in 1772 by Holy Roman Empress Maria Theresa—the mother of Marie Antoinette—as the Imperial and Royal Academy of Sciences and Letters of Brussels. Its mission is to promote sciences and arts in Belgium through scientific and cultural activities and cooperation between universities in Belgium and between Belgium and the larger international academic community.

Frangopol studied for his Ph.D. at the University of Liège in Belgium for three years (1974-76) and worked in Brussels for three and a half more years (1979-83) as a design engineer before joining the University of Colorado at Boulder. In 2008, Frangopol was awarded an Honorary Doctorate (Doctor Honoris Causa) by the University of Liège.

His election to the Royal Academy of Belgium extends the Technical Sciences class into the areas of sustainability and resilience of infrastructure—topics in which Frangopol's research and expertise are internationally recognized.

Last year, Frangopol was elected to the prestigious Academia Europaea as one of only four foreign members in the Physics and Engineering Sciences section. The goals of the Academia include promoting a wider appreciation of the value of European scholarship and research, as well as making recommendations to national governments and international agencies concerning matters affecting science, scholarship, and academic life.

In late 2016, Frangopol was also named the inaugural recipient of the Alfredo Ang Award for Risk Analysis and Management of Civil Infrastructure from the American Society of Civil Engineers (ASCE). According to ASCE, Frangopol received the award "for exceptional efforts in advancing, advocating, and persistently promoting the life-cycle cost analysis of structures and structural systems, and their integration into reliability-based structural analysis and design."

Earlier in the year, Frangopol was awarded the ASCE's prestigious Outstanding Projects and Leaders (OPAL) award for lifetime achievement in civil engineering education. Recipients of this award must be professors or deans who have demonstrated excellence and have directed or changed the course of engineering education.

Mapping the brain—with noninvasive light

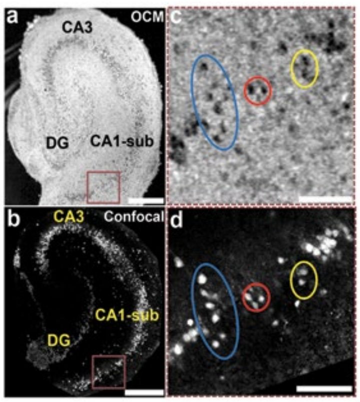
Chao Zhou likens our current brain-mapping ability to a Global Positioning System (GPS) that can help a user locate a city, but cannot offer a street-level view. Without such a map, says the assistant professor of electrical and computer engineering, medicine remains in the dark about the most effective ways to treat, prevent, and cure such disorders as Alzheimer's, schizophrenia, autism, epilepsy, and traumatic brain injury.

Current neural recording techniques use electrodes, or require the labeling of neurons with a genetic or chemical probe. These methods have significant downsides, according to Yevgeny Berdichevsky, also an assistant professor of electrical and computer engineering.

"Electrodes are quite invasive, and it is not clear that they pick up activity in every neuron," he says. "Chemical markers can be toxic, and slow to pick up all the action potentials. And genetic probing isn't approved for use in humans due to safety concerns."

Core researchers in Lehigh's Bioengineering program, Zhou and Berdichevsky are exploring the use of a breakthrough technology developed in Zhou's lab. Known as "space-division multiplexing optical coherence tomography," it is a noninvasive, ultrahigh speed imaging system that enables faster, more sensitive eye exams at ten times the speed of current technology, and at a drastically reduced cost.

The team also believes that SDM-OCT could map the brain using light—without requiring neuron labeling. The National Institutes of Health has awarded them a grant to explore the adaptation of this technology to achieve large-scale imaging of neural activity at the single-cell level.



A comparison of OCM and confocal 3D images obtained from the same sample.

OCT works by capturing light as it reflects from the surface of living tissue; more than 30 million people have their eyes examined each year with this noninvasive system that uses light waves to take cross-section pictures of the retina.

Zhou and Berdichevsky have previously demonstrated the ability to provide parallel and synchronized imaging from hundreds of neurons simultaneously, in a study they conducted of neuronal changes as a result of epilepsy.

"Once we were successful at using the technique to analyze epileptic tissue," says Berdichevsky, "we began to think about how it could be used to pick up signals from networks of neurons—something no one has done before."

Says Zhou: "SDM-OCT could provide the 'street-level' view that medical researchers need to advance the understanding of brain function."

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Besting the owl's aeroacoustics

Feather-inspired design cuts wind turbine noise

Many species of owl are able to hunt in effective silence by suppressing their noise at sound frequencies above 1.6 kilohertz (kHz)—which includes the range where human hearing is most sensitive.

A team of researchers studying the acoustics of owl flight is working to pinpoint the mechanisms that accomplish this virtual silence to improve man-made aerodynamic and aeroacoustic design of wind turbines, aircraft, underwater vehicles, and automobiles.

Through physical experiments and theoretical modeling, the team has developed a 3D-printed wing attachment that reduces wind turbine noise by a remarkable 10 decibels, using the downy canopy of owl feathers as inspiration—without negatively impacting aerodynamics.

"We have investigated how such a design can reduce roughness and trailing-edge noise," says Justin Jaworski, assistant professor of mechanical engineering and mechanics. "In particular, trailing-edge noise is prevalent in low-speed applications and sets the minimum noise level. The ability to reduce wing noise has implications beyond wind turbines, as it could be applied to other aerodynamic situations such as the noise created by air flowing past automobile sideview mirrors and sunroofs."

Jaworski began studying owl wings in 2011 with Nigel Peake, a professor of applied mathematics at the University of Cambridge, where Jaworski was a National Science Foundation international research fellow.

Three features, says Jaworski, seem to account for the owl's stealthy flight.

He holds up a long, brown and elegant owl wing and offers an explanation. The wing's leading edge, the part closest to the owl's head, he points out, is made of stiff, evenly spaced, mostly aerodynamic fibers that reduce noise.

The fluffy upper surface of the wing is made of a down feather material that is similar in texture to commercial velvet. When examined under a microscope, says Jaworski, this structure looks like vertical strings with interlocking barbs at their tops. This mesh creates a buffer layer that also stifles sound.

Arguably the most important feature of the wing is its porous and compliant trailing edge. This edge is usually where the most noise is generated. In contrast to the feathers on the trailing edge of a duck or eagle wing, which are very stiff, the trailing edge feathers on a large owl's wing are flexible and provide significant noise reduction.

"The trailing back edge is the predominant noise source for any blade that passes through the air—not only the owl, but also aircraft wings and wind turbines," says Jaworski. "If you can suppress the noise there, you can create a lot of benefits."

Cleared for takeoff

The team's findings have been published in two recent papers: "Bio-inspired trailing edge noise control" in the *American Institute of Aeronautics and Astronautics Journal* and "Bio-inspired canopies for the reduction of roughness noise" in the *Journal of Sound and Vibration*.

The research team—from Lehigh, Virginia Tech, Florida Atlantic University and University of Cambridge—specifically looked at the velvety down that makes up the upper wing surface of many large owls. This unique physical attribute, even among birds, contributes significantly to owls' noiseless flight. As seen under a microscope, the down consists of hairs that form a structure similar to that of a forest. The hairs initially rise almost perpendicular to the feather surface but then bend over in the flow direction to form a canopy with interlocking barbs at the tops—cross fibers.

The team has created a 3D-printed plastic attachment consisting of small "finlets" that can be attached to an airfoil or wing. The finlet invention may be retrofitted to an existing wing design and used in conjunction with other noise-reduction strategies to achieve even greater noise suppression.

In their experiments, the researchers simulated air flows using the Virginia Tech Stability Wind Tunnel.

"The most effective of our designs mimics the downy fibers of an owl's wing, but with the cross fibers removed," says Jaworski. "The canopy of the owl wing surface pushes off the noisy flow. Our design mimics that but without the cross fibers, creating a unidirectional fence—essentially going one better than the owl."

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Justin Jaworski studies owl feathers to improve aeroacoustic designs; experimental 3D-printed 'finlets' (left) designed by the team.

RESEARCH PHOTOGRAPHY BY PROF. NATHAN ALEXANDER (VIRGINIA TECH)

A spectrum of potential

A sharper focus for quantum cascade lasers

Once the preferred weapon of B-movie madmen and space-fantasy heroes alike, the laser—a device that generates an intense beam of coherent electromagnetic radiation by stimulating the emission of photons from excited atoms or molecules—has grown a bit domesticated of late.

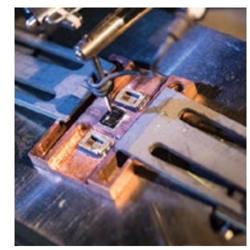
Known for document printing and home theaters, here and there it pops up in medical journals and military news, but it's basically been reduced to reading barcodes at the grocery checkout: a technology that's lost its mojo.

But lasers are still cool, insists Sushil Kumar of Lehigh University, with vast potential for innovation we've just begun to tap. And with support from the National Science Foundation, he's on a mission to prove it.

Sushil Kumar (above) seeks to develop terahertz lasers with vastly improved optical intensity.

Kumar, an associate professor of electrical and computer engineering, focuses specifically on lasers that arise from a relatively unexploited region in the electromagnetic spectrum, the terahertz (THz), or far infrared, frequency. A researcher at the forefront of THz semiconductor 'quantum-cascade' laser technology, he and his colleagues have posted world-record results for high-temperature operation and other important performance characteristics of such lasers.

His goal is to develop devices that open up a wide array of possible applications: chemical and biological sensing, spectroscopy, detection of explosives and other contraband materials, disease diagnosis, quality control in pharmaceuticals, and even remote-sensing in astronomy to understand star and galaxy formation, just to name a few.



Yet despite the known benefits, Kumar says that terahertz lasers have been underutilized and underexplored; high cost and functional limitations have stymied the innovation that would lead to such usage.

Focusing on a solution

Kumar believes he's on track to truly unleash the power of THz laser technology; he recently received a grant from the NSF, "Phase-locked arrays of high-power terahertz lasers with ultra-narrow beams," with a goal of creating THz lasers that produce vastly greater optical intensities than currently possible—and potentially removing barriers to widescale research and commercial adoption.

"The terahertz region of the electromagnetic spectrum is significantly underdeveloped due to lack of high-power sources of radiation," he explains. "Existing sources feature low output power and other undesired spectral characteristics, which makes them unsuitable for serious application."

His current project aims to develop terahertz semiconductor lasers with precise emission frequency of up to 100 milliwatts of average optical power—an improvement of two orders of magnitude over current technology—in a narrow beam with significantly less than five degrees of angular divergence.

Kumar works with quantum cascade lasers (QCLs). These devices were originally invented for emission of mid-infrared radiation. They have only recently begun to make a mark at THz frequencies, and in that range they suffer from several additional challenges. In this cutting-edge environment, Kumar's group is among a select few in the world making progress toward viable and low-cost production of these lasers.

Kumar's intended approach will significantly improve power output and beam quality from QCLs. A portable, electrically operated cryocooler will provide the required temperature cooling for the semiconductor laser chips; these will contain phase-locked QCL arrays emitting at a range of discrete terahertz frequencies determined by the desired application.

In previous work, Kumar and his group showed that THz lasers (emitting at a wavelength of approximately 100 microns) could emit a focused beam of light by utilizing a technique called distributed feedback. The light energy in their laser is confined inside a cavity sandwiched between two metallic plates separated by a distance of 10 microns. Using a box-shaped cavity measuring 10 microns by 100 microns by 1,400 microns (1.4 millimeters), the group produced a terahertz laser with a beam divergence angle of just 4 degrees by 4 degrees, the narrowest divergence yet achieved for such terahertz lasers from a single laser cavity.

Kumar believes most companies that currently employ mid-infrared lasers would be interested in powerful, affordable terahertz QCLs, and that the technology itself will spawn new solutions.

"The iPhone needed to exist before developers could write the 'killer apps' that made it a household product," he says. "In the same way, we are working toward a technology that could allow future researchers to change the world in ways that have yet to even be considered."

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A quantum leap for LEDs

Moving toward ultra-efficient solid-state lighting

There are obvious reasons why consumers increasingly turn to LED-based lighting, says Jonathan Wierer, associate professor of electrical and computer engineering. LED light bulbs consume 85 percent less energy than incandescent bulbs and 25-35 percent less than compact fluorescent light (CFL) bulbs. LEDs last for decades—and can be engineered in ways that just aren't possible with their rivals.

Wierer believes that LEDs can be made even more energy-efficient—perhaps twice as much—with better engineering of their active, or light-producing, regions. Working with Lehigh professor Nelson Tansu and colleagues from Sandia National Laboratories, Wierer has proposed the use of quantum dots (QDs) to produce LED light, in place of the "quantum well" technology currently used by manufacturers.

Quantum wells confine electrons and other particles in one-dimensional, rather than three-dimensional spaces, in ultra-thin layers of sandwiched materials. Carriers—electrons and electron holes—are injected into these layers at different energy states, and they recombine to produce the photons that give light. However, a phenomenon known as Auger recombination can cause what Wierer describes as an "efficiency droop" in LED performance.

QDs, on the other hand, emit light at specific frequencies when an electric current is applied. By changing their size, shape and material composition, engineers can tune these frequencies for efficiency and other key applications.

According to the researchers, if properly constructed, LEDs with QD active regions have the potential to outperform quantum well LEDs. The team's recent article in *Laser and Photonics Reviews* was based on a theoretical study conducted with computer numerical simulations. The group has begun to conduct experimental studies using etching and growth techniques to fabricate quantum dots. Their goal is to make smaller QDs, only 4 nanometers in size, of a uniform dimension and even distribution.

"If our theoretical work can be realized," says Wierer, "among other benefits, this could lead to ultra-efficient solid-state lighting sources with huge potential for energy savings."

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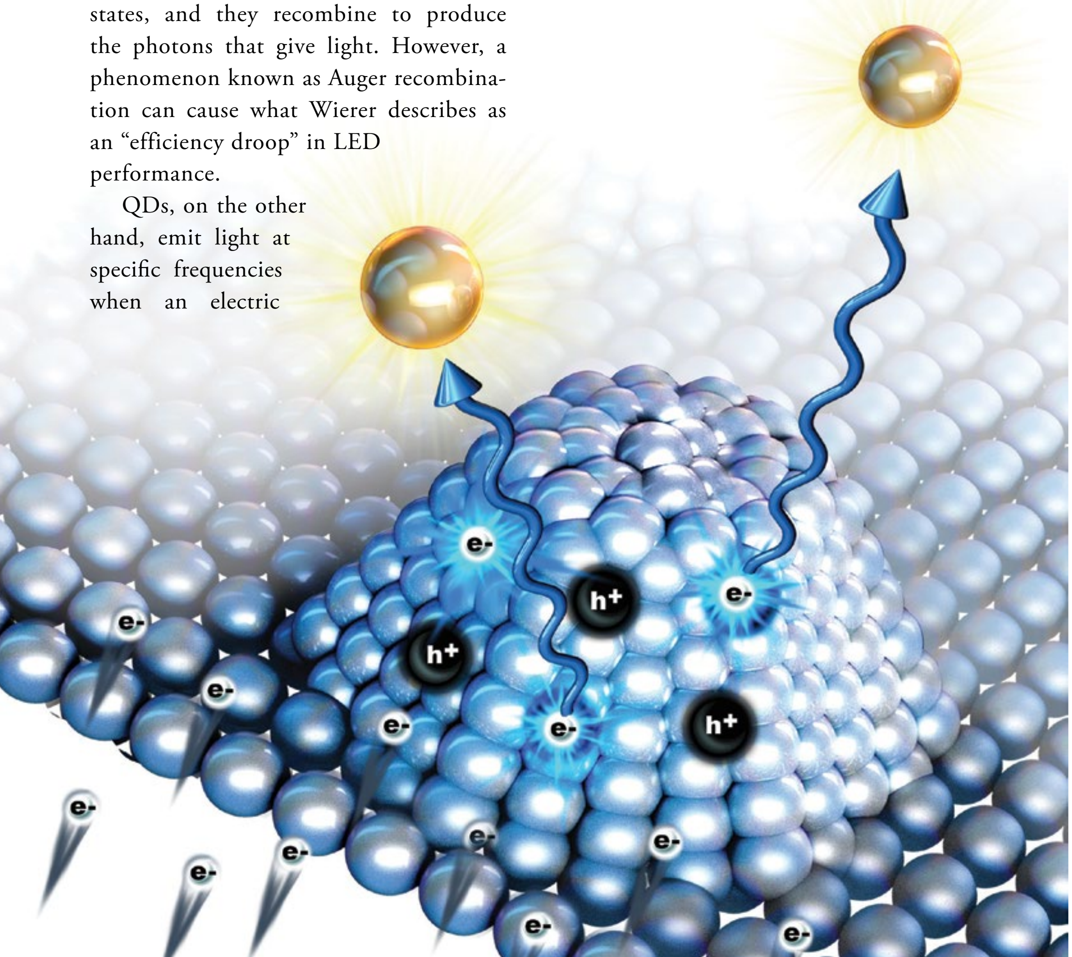


The spirit of innovation

RESEARCH RECOGNITION

In December, Professor Nelson Tansu was named as a 2016 Fellow of the National Academy of Inventors (NAI).

Election to NAI Fellow status is considered to be "the highest professional distinction accorded to academic inventors who have demonstrated a prolific spirit of innovation in creating or facilitating outstanding inventions that have made a tangible impact on quality of life, economic development, and the welfare of society."

Tansu, Lehigh's Daniel E. '39 and Patricia M. Smith Endowed Chair Professor in Photonics and Nanoelectronics, is widely regarded as one of the world's leading researchers and inventors in the field of semiconductor optoelectronics materials and devices.

As founding director of Lehigh's Center for Photonics and Nanoelectronics (CPN), Tansu leads a multidisciplinary research team encompassing electrical engineers, material scientists, applied scientists, and physicists that develops material devices and device architecture.

"Lehigh's research environment is purpose-built to foster interdisciplinary team science," says Tansu. "Innovation is often found where disciplines intersect—as are the really fascinating research problems. This is exactly what CPN researchers aspire to explore. We build integrated teams that address larger, more complex problems in a manner that allows us to develop more impactful solutions."

Tansu says his proudest accomplishments thus far are not necessarily patentable.

"The product of an academic research lab is not just technology," he says. "Much more impactful are the students who engage in our work and come out the other side ready to identify and explore their own ways to change the world."

Ph.D.s minted in Tansu's lab have gone on to technical leadership roles at places like Philips, Apple, Intel, Cree, and Veeco, while other graduates have found success in faculty roles at schools such as Case Western Reserve University, University of Tulsa, Rochester Institute of Technology, Clarkson University, and KAUST (Saudi Arabia).

 INTERVIEW BY WILLIAM TAVANI PHOTOS BY DEAN RIGGOTT

OPERATING WITH INTEGRITY

LEHIGH ALUMNUS AND NATIONAL ACADEMY MEMBER ON THE FRONTIER OF BIOMEDICINE

Dr. Michael J. Yaszemski ’77 ’78G, an orthopedic surgeon at Mayo Clinic in Minnesota, is renowned for his groundbreaking treatments of patients with skeletal defects requiring reconstruction. He performs spinal surgery and oncologic surgery of the spine, sacrum and pelvis. Yaszemski also directs Mayo’s Tissue Engineering and Biomaterials Laboratory, where he builds biodegradable scaffold polymers and uses tissue engineering strategies to promote bone and spinal cord regeneration. Yaszemski holds an M.D. from Georgetown University School of Medicine, as well as B.S/M.S. (Lehigh) and Ph.D. (M.I.T.) degrees in chemical engineering. A retired U.S. Air Force brigadier general, he served in Afghanistan and Iraq. In 2016, Yaszemski was elected to the National Academy of Medicine.

Q: ***Beyond scientific and mathematical intelligence, what are the fundamental qualities necessary to be a good researcher?***

A: Integrity is highest. You have to be honest in everything you do. Curiosity is incredibly important. And persistence. In surgery, we want to be prepared for every aspect of an operation, and we expect it will go as planned 100 percent of the time. In the lab, we expect mostly failures. If we have a success one out of 100 times, we’re ecstatic. With persistence, we learn from failures and eventually succeed.

Q: ***To what extent is your research informed and improved by the surgeries you perform?***

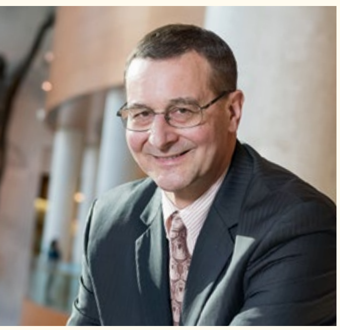
A: Everything we do in our lab is based on a research question formulated from an unmet clinical need. We start from where we as clinicians fail, we bring it to the lab, translate the clinical failure into a research question, try to get an answer and then take it back to the clinic.

Q: ***What types of tissue engineering strategies do you employ to promote spinal cord regeneration?***

A: We synthesize novel polymers. We do 3D fabrication of those polymers into scaffolds. We use a variety of 3D printing techniques. Most cells that regenerate tissue are anchorage-dependent; they have to find a surface they like and will attach to in order for them to make the tissue of interest. The scaffold serves as an anchorage for cells and as a temporary structural entity to provide guidance to the newly forming spinal cord axons. We haven’t yet enabled paralyzed animals to walk. But we have made new nerves grow across a scaffold in an injured spinal cord.

Q: ***What kind of biodegradable polymers do you work with in bone scaffolds?***

A: The one we use for bone is polypropylene fumarate. Prior to implanting the scaffold in the body, we have to keep it in a water-free environment. But in the body, it encounters the water that is a component of all our tissues, and it begins to move toward its equilibrium, which is a state of shorter and shorter polymer chains. That’s how it degrades. The design of the synthesis of the material for this was the subject of my Ph.D. thesis. It worked out well, and we’re still using it 20-some years later.



Michael J. Yaszemski, a retired U.S. Air Force brigadier general who served in Afghanistan and Iraq, is currently an endowed professor of orthopedic surgery and biomedical engineering at the Mayo Clinic College of Medicine, and deputy director of the Clinic's Center for Regenerative Medicine.

Q How does an engineering education prepare one to become a medical researcher or a physician?

Engineering teaches problem-solving. That's what we do in medicine. We're given problems and we have to sort out a plan to solve them. Engineering also gives us quantitative technical skills to measure the quality of our work. To be a researcher, those same things are important. I received a great education at Lehigh, and that has had a lot to do with my being able to do this job.

Q: ***How do you engineer these polymers to function in these scaffolds?***

A: We engineer the rate of scaffold degradation so that it is slower than the rate of bone regeneration. Bones heal at different rates. A small finger bone can heal in several weeks; a thigh bone (femur) can take up to a year to heal and then complete its remodeling process. If you put a scaffold in a thigh bone, it can't go away before the newly regenerated bone is ready to bear the loads that it experiences during activities of daily living. We also engineer the surfaces to be friendly for the anchorage of cells. Cells will anchor, or not, depending on several surface properties, like roughness and chemical composition.

Q: ***What kind of composite materials do you work with and how effective are they at regenerating bone?***

A: We use metals, ceramics and polymers. Our group's core competence is polymers, and they are what we use most. To make the composite material mimic the specialized bone-tendon junctions of the body, called entheses, we use a composite scaffold. Composite tissue scaffolds have interdigitating sections that will each support the formation of a specific tissue type. In this application, the two different scaffold sections represent the normal bone-tendon anatomy of the enthesis.

Q: ***How do polymers reconnect segmental nerve defects?***

A: A nerve scaffold is a tube. When a nerve injury results in a missing segment of nerve tissue, a new nerve has to grow through this tube to reach the nerve-muscle junction. The tube channels need protected space to keep scar tissue out so that new nerve fibers can grow through it. When the injured part of a nerve crosses a joint, the tube-shaped scaffold must bend as the joint bends, and the tube must maintain a circular cross-section as it bends. We changed the tube synthesis and fabrication parameters until we arrived at a manufacturing process that produced a tube that can bend 130 degrees before it flattens at the apex of the bend. That's enough for most joints.

Q: ***Your colleagues say you are exceptionally dedicated to your patients. What inspires this devotion?***

A: One of my mentors said we should take care of every patient according to the F2 rule: treat them like friends and family. I think most of us here take that to heart. It's what I would want of someone taking care of my family and friends.

Q: ***How has medicine improved the lives of persons with spinal cord injuries or diseases? How much more improvement do you foresee 10 years from now?***

A: In the past 10-15 years, we've made good progress in methods to decrease the secondary injury that occurs after a spinal cord injury, and in the rehabilitation of spinal cord injury patients, but not in the ability to get a spinal cord that's not working to start working again. The secondary injury is the response to the primary injury: the swelling and inflammation of the tissues in the vicinity of the primary injury site. I will stop short of predicting the future, but I hope that cell-based, stem-cell-based, molecule-based and regenerative medicine technologies let us see some improvement in the healing of an injured spinal cord.

Q: ***Mayo has a successful partnership with Lehigh's Healthcare Systems Engineering program. What role can systems engineers play in healthcare delivery?***

A: Under the Affordable Care Act, physicians are moving from being compensated for how much of something we do to being compensated for the quality we deliver. We have to measure that, and it has to be a quantitative measure. Systems engineering can play an important role to ensure that we don't duplicate things and that we optimize resources and processes in the operating room and clinic.

At Mayo, we have transitioned our Rochester campus and our surrounding healthcare system, which has more than 70 practices in the upper Midwest, into a single operating company. Some of the patients from these regional practices come to Rochester for consultations and/or surgical procedures, then go back home to receive support from family, friends, and their local physicians. A systems engineering approach can help optimize that process.

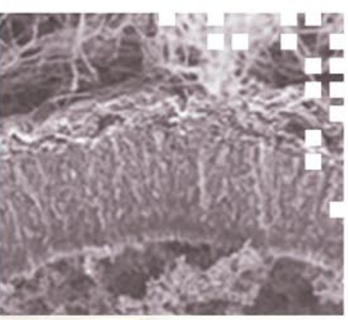
Q: ***You give much credit for your success to the teams you work with at Mayo. How does the leader of a team instill a spirit of teamwork?***

A: First is integrity, then trust. A leader who has earned trust has done so because his or her team members believes that she/he behaves with integrity. People must believe the leader wants the team to succeed and values their contributions. You have to leave your ego at the door and choose the right person to do the job. Look for discrete and early wins. Make goals reasonable. Accept failure in all team members, including yourself. No one will ever try something new again if you punish them for failing. If they have prepared, planned, considered the risks and given their best—but fail, thank them, and ask what we've learned and where we're going.


Health Research

STORY BY **CHRIS QUIRK**

DISSOLVING BOUNDARIES



ADVANCING MATERIALS FOR HEALTH, WHERE DISCIPLINES MERGE

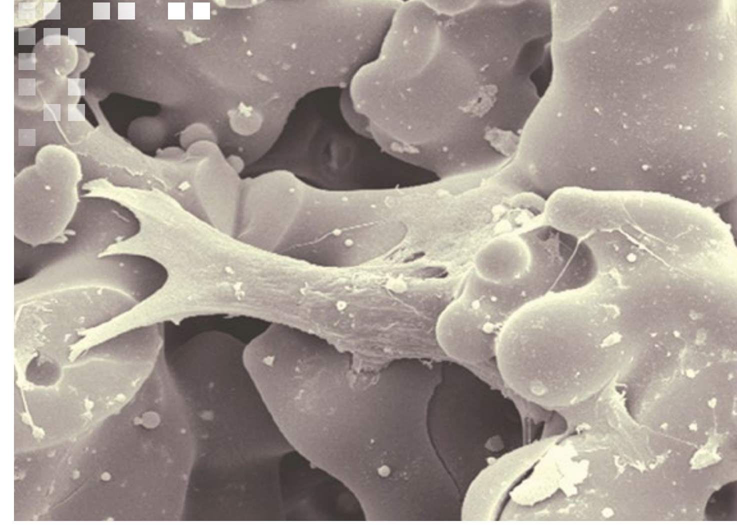
YALING LIU RECALLS THE MOMENT HE TRANSFORMED FROM A MECHANICAL ENGINEER INTO A CANCER WARRIOR.

"I was in Washington, DC, in August of 2011, preparing to participate in a panel discussion," says the associate professor and member of Lehigh's Bioengineering program. "I had a free morning before my meeting, and decided I'd spend it in a National Institutes of Health conference that happened to be taking place at a nearby hotel."

The conference he'd stumbled upon was focused on health technology in the developing world. Yaling, seeking nothing more than to satisfy personal curiosity, had taken a seat in a session highlighting a low-cost, mobile device for cancer screening.

"The talk was being led by public health experts and clinicians," he says. "With my background in fluid mechanics and engineering, I couldn't help but realize there were fundamental techniques that could be employed to improve upon an already-impressive design."

Yaling spent his first few moments as a cancer researcher in the back of a crowded conference room, scribbling out computations on the back of a hotel envelope: an inauspicious beginning for what has developed into a promising and amazingly inexpensive technique for isolating and detecting tumor cells in the bloodstream.



ENGINEERING AFFORDABLE, ACCESSIBLE HEALTH

Targeted nanotherapies that pinpoint and destroy pathogens while leaving healthy tissue unscathed. Metal foams and synthetic lattices that reinforce vulnerable body parts and promote healing. Wireless diagnostic tools implanted in the body that alert wearers to potential problems.

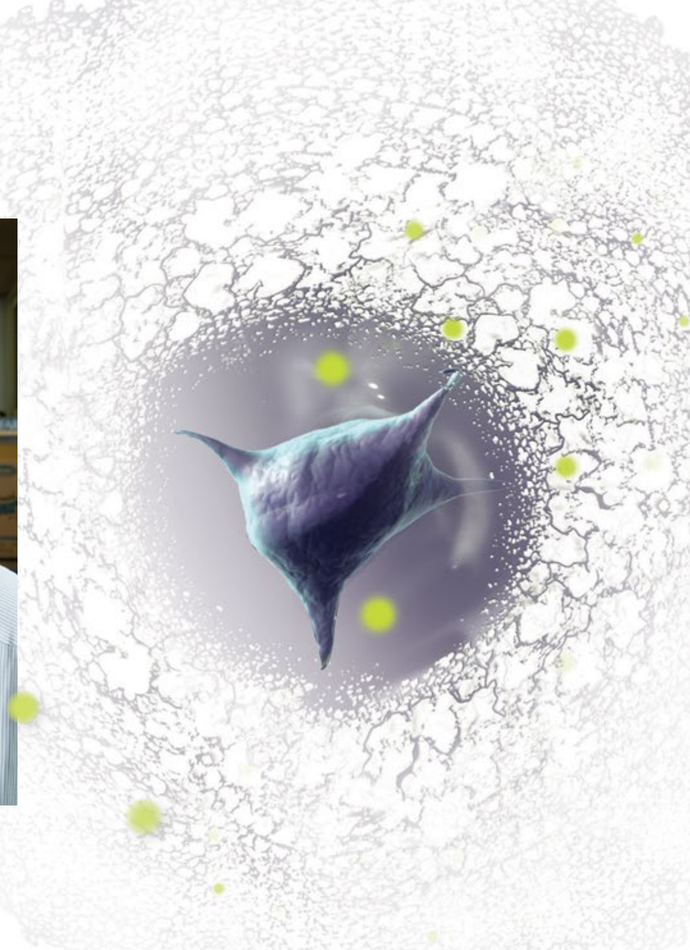
Wojciech Misiolek says that such 'miracles'—as well as other innovative recent advances in health technology—are brought about through the creative incorporation of expertise from across a spectrum of fields related to science, technology, engineering, math, and design. "At Lehigh, multidisciplinary is in our proverbial DNA," says Misiolek, chair of materials science and engineering and director of the Loewy Institute at Lehigh. "We actively seek out and foster expertise at the intersection of disciplines. So engineers here are 'genetically predisposed' to contributing to this emerging field, and our tradition of leadership in materials and mechanics serves as a powerful foundation for innovation."

"We have a long history of interdisciplinary work here at Lehigh," continues Gary Harlow, professor and chair of mechanical engineering and mechanics. "Collaboration that exploits multiple technologies is liable to push a researcher out of a typical comfort zone, so we attract people who are OK with that."

"The development of technology for medical usage brings added layers of complexity to traditional areas such as electrical, materials and mechanical engineering," explains Anand Jagota, a professor of chemical and biomolecular engineering and director of Lehigh's Bioengineering program. "For example, if you are going to grow a tissue or design an implant for the human body, you must understand the tissues that will absorb it. Your implant needs to have the mechanical or electrical capability to safely complete its task, and have the correct size, shape, and distribution of pores to accommodate the movement of nutrients and cells. Plus, if you want the implant to degrade at a specific rate, you must also understand how its location and usage in the body impacts its effectiveness and the healing of the tissues surrounding it.

"A solution that handles all of the necessary considerations couldn't possibly derive from a single perspective."

"The most interesting science in our era will be done at the borders between disciplines and by exploring the features of these largely unmapped regions," says John Coulter, professor and associate dean for research and operations. "In this biomedical materials field, five years from now the scenery will be entirely different than it is today, which is entirely different than it was five years ago. So, we develop people who will be able to figure out how to make contributions in an ever-evolving space."



Clockwise from top: A biocompatible glass scaffold for bone regeneration; Sabrina Jedlicka (far right) advises a growing number of undergraduate and graduate students in her lab; Hannah Dailey and Lesley Chow collaborate on 'tunable tissue engineering'; Anand Jagota (right) and Suresh Manohar '10Ph.D., now a postdoctoral researcher at Northwestern, explore the interaction between DNA and carbon nanotubes.

"This project allows us to share our expertise, bring out the best in our work and look to the future. It's one of the benefits of being here at Lehigh."

—Lesley Chow

"It's a misconception that an engineering degree 'locks you in' on a specific career path," he says. "Once you graduate or earn that Ph.D., the specific field tends to get less important. People will want to know: What are you doing *now*? How are you leveraging your skills to make a difference?

"The idea of coming to Lehigh and staying in a silo for an entire career isn't an option," he continues. "Here, it's a requirement to blend groups across disciplines, and that's especially evident in our bioengineering and health initiatives. We rely on that approach in all we do, and at the end of the day that mentality creates a wonderful benefit for our faculty and students."

A PERFECT COLLABORATION

Spend some time with Lesley Chow and Hannah Dailey '02 '06G '09Ph.D., and it will soon be abundantly clear that they make a great team. Chow, an assistant professor of materials science and engineering affiliated with Lehigh's Bioengineering program, and Dailey, an assistant professor of mechanical engineering, are both new members of Lehigh's faculty. They met at a new-hire orientation session—serendipity borne of Human Resources procedure—and now work together, and with a local hospital network, designing bioactive tissue scaffolds that can biodegrade as new tissue regenerates.

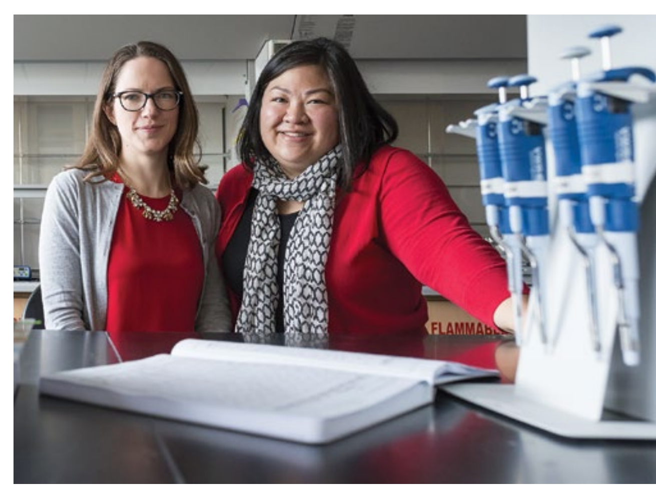
"Lesley and I are the perfect example of a Lehigh collaboration," says Dailey. "What we are working on is really exciting because it touches on everything from the design of materials to execution, physiological loading, mechanical design, and surgical implementation. Lehigh is really committed to investing in these areas and bringing together skill sets."

Their tunable tissue engineering project leverages Dailey's experience with orthopedic devices and Chow's knowledge of biomaterials. In their lab, they are building customizable lattices with bioactive surfaces, using a computerized robot that was customized into a specialized 3D printer. When the lattices are inserted in the body, the polymer scaffolding provides structural integrity, while bioactive functional groups attached on the surface attract the types of cells needed to promote the desired healing activity.

The lattices can be custom built for size and for a desired rate of biodegradation, depending on the polymer used. Varying biochemistry can also be presented on the lattices, depending on the physiological process needed.

"The benefit of our technique is that it's universal," says Chow. "We can look for segments of proteins to find the biological cues we need, and put them on the polymers before we print the lattice. The implant then presents these cues to the body in a biologically appealing way. And if we find out a particular molecule isn't working, we can change the chemical cue to foster the result we want."

One way of imagining the project is like 3D printing, with a twist. "Right now, 3D printing is a buzzword," Chow says. "We are riding that wave, but taking a slightly different approach by looking at the research from all angles. The processing affects materials, and vice versa, and this has an impact upon the cells themselves. So, we are getting down to the nitty-gritty and finding out what that cell will feel when it encounters our scaffold."

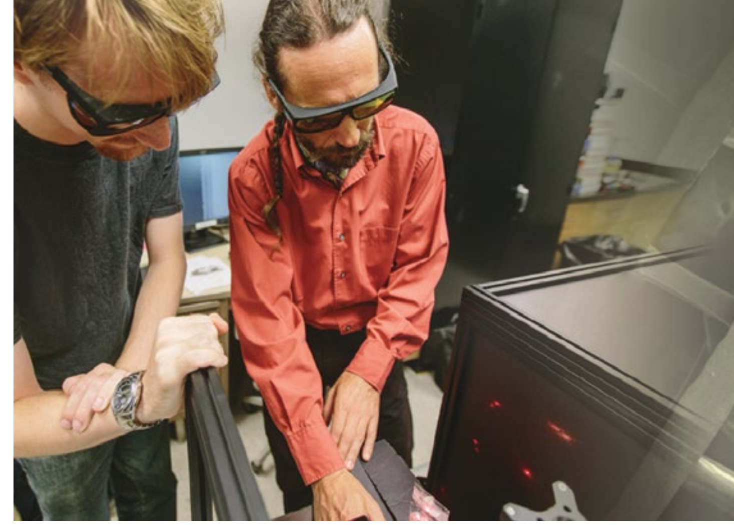


At present, Chow and Dailey are working toward clinical applications that include tendon, ligament and cartilage repair, but their ambitions reach higher.

"The platform we're developing can build polymeric structures that induce regeneration of tissue, and we will be able to tweak its parameters and apply it to lots of different clinical therapeutic areas," says Dailey. "Medical treatment for orthopedic injuries and degenerative joint disease can be incredibly difficult for patients, and places a tremendously expensive burden upon the U.S. healthcare system. We think our technology can make a real difference."

The team has received a Collaborative Research Opportunity grant from Lehigh and are partnering with the Department of Orthopaedic Surgery at St. Luke's University Health Network in Bethlehem.

"This project allows us to share our expertise, bring out the best in our work and look to the future," says Chow. "It's one of the benefits of being here at Lehigh."



UNLOCKING MYSTERIES ON A BREATHTAKING SCALE

Clockwise from above right: graduate student Michael Blades '12 and Slava V. Rotkin inspect a diffraction optics setup; a biodegradable 3D-printed scaffold made in the Chow Lab, as captured by scanning electron microscope; students working in Lehigh's Health Research Hub; (inset) a prototype of Yaling Liu's cancer detection device; (below) an artist's rendering of a carbon nanotube, wrapped in DNA, being introduced into a stem cell.

Faculty researchers Sabrina Jedlicka and Slava V. Rotkin began collaborating at the instigation of a student of Rotkin's seeking greater academic exposure to biophysics and materials engineering.

Rotkin, a professor of physics in the College of Arts and Sciences with a joint appointment in materials science, turned to Jedlicka, an associate professor of materials science and core member of the University's Bioengineering program, for help.

"I think we had talked to each other three times before that," notes Jedlicka, laughing, whose work studies the fundamental interactions between cells and substrates, with a specific focus in neurobiology.

The student's interest bloomed into an ongoing faculty-led exploration into the dynamics of nanotubes wrapped in DNA, and the fundamental physics and behavior of this hybrid material within cells.

"When nanotubes wrapped in DNA are introduced into a stem cell, the differentiation rate for that cell increases tenfold," Jedlicka reports. "The rate of differentiation from stem cells to neurons was remarkable, and encouraged us to further pursue therapeutic possibilities."

"The brain is the last frontier," she continues. "I've worked a lot with neuronal differentiation, taking a stem cell and changing it into something more mature. There are so many people suffering from brain diseases, and we need to think about alternative therapies that will improve the quality of life for people suffering from these ailments."

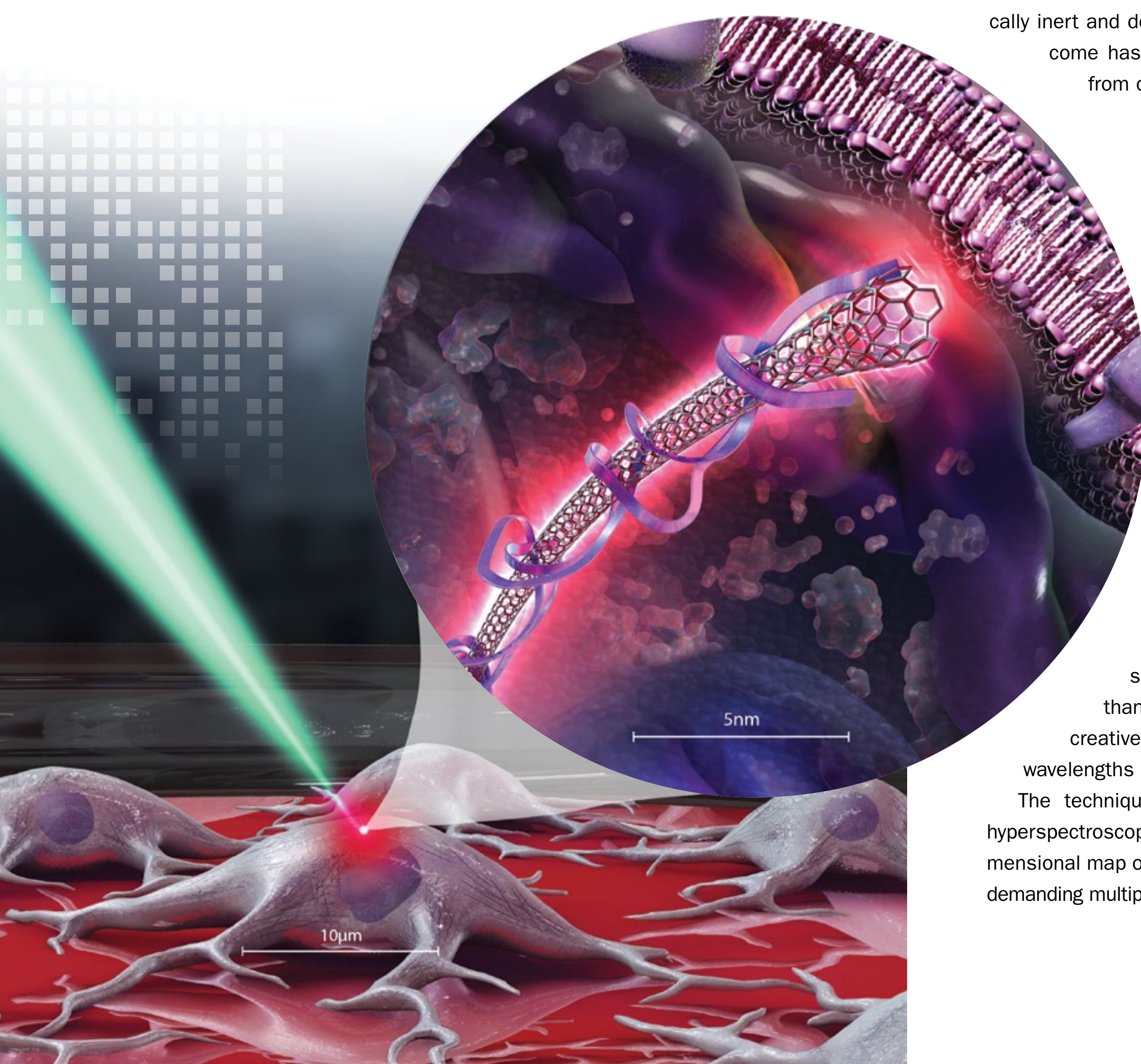
Her project with Rotkin combines nanoscale materials science and bioengineering in ways that have broad possibilities for biomedical therapies.

"We are not using active DNA," says Jedlicka. "It is biologically inert and doesn't encode for anything; we believe the outcome has more to do with DNA keeping the nanotubes from clustering and thus clogging inside the cells."

Interestingly, the project is one of the first to examine nanotubes within cells in pharmacologically relevant doses. Much of the prior research has used massive doses that are toxic to cells—for the simple reason that it made the nanotubes easier to find. "The approach is understandable from a materials research perspective," says Jedlicka, "but the medical requirement to 'first do no harm' is paramount. So we had to find a different way."

A cell is about 10,000 times larger than a nanotube, and thus one of the challenges to their research is getting a look at the interaction. Rotkin has vast experience in nanocharacterization, a field devoted to finding ways to, literally, make the invisible visible. "This is a big problem," says Rotkin. "At this scale, your tools are bigger than the thing you are looking at. You have to be creative and find ways to beat the limits of nature—the wavelengths of light are bigger than what we are seeking!"

The technique Rotkin employs, Raman microscopy, uses hyperspectroscopic measurements to build a kind of multidimensional map of areas in the cell. It is a slow, tedious process, demanding multiple passes to generate each image point by point.



But it has been successful, and they believe they have captured clear images of single nanotubes inside of cells.

Rotkin and Jedlicka have received seed funding from Lehigh to support this research, which has proved critical to laying the groundwork for further study on nanomaterial-cell interactions.

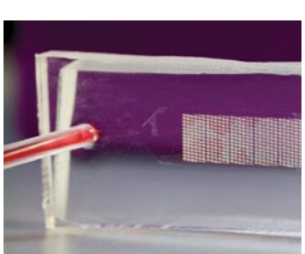
"That is very important," he says, "and for cross-disciplinary science the importance is squared or cubed. There is interesting physics and biology here, precisely *because* we are pushing the boundaries in this way. We've now been able to build some preliminary, supportive evidence that tells a much stronger story to potential funding and research partners."

CANCER DETECTION FOR LESS THAN LATTE

Yaling Liu, a specialist in nanomechanics who serves as associate professor of mechanical engineering, has developed technology to detect cancer long before a tumor would be noticed by MRI or other existing techniques. It could also be used to monitor the effectiveness of cancer treatment.

The material cost for the device is under a dollar, and Liu anticipates a complete device in the $5 range. Its low cost raises the potential that it could be used for home testing or deployed in the developing world.

Liu's foray into the materials for medicine occurred when he attended a conference on affordable medical devices several years ago. In simple terms, Liu applied his expertise in computational fluid mechanics and nanofabrication to come up with a chip that can detect certain tumor cells in the blood. The 'lab-on-a-chip' his team has developed works by running a fluid sample across a specially formulated surface where pathogens, such as circulating tumor cells, or CTCs, are trapped and identified. The chips are made with transparent polymers, and the polymer surface is structured so that it can be populated with antibodies able to capture the tumor cells.



"The most interesting science in our era will be done at the borders between disciplines and by exploring the features of these largely unmapped regions."

—John Coulter, *professor and associate dean for research and operations*

"The unique thing is the design of the capture bed on the surface of the chip," says Liu. "The capture bed is in the substrate, and has both microscale and nanoscale features that are engineered to enhance capture efficiency. Cells have protruding patterns, so we have tried to create patterns on the capture pad that are complementary to the patterns on CTCs. The herringbone surface we employ generates a passive vortex that mixes the cells, and increases the chance that CTCs will collide with the capture pad. We're also adding some other nanoscale features like pillars or nanospheres that are complementary to the surface components of those tumor cells."

Much of Liu's current research interests involve mimicking animal or human tissue function to develop new testing and diagnostic tools. In that vein, Liu is creating a technique to speed and enhance pharmacological testing with a device that mimics blood vessels and blood flow.

"There is established, detailed data on ranges of blood flow," he says. "We culture different types of tissues together to recreate blood vessels, and then we can inject a very low quantity of a drug and track the response. We'll also be able to culture human cells in 3D, rather than in a two-dimensional culture dish."

Current animal or human drug testing does so one condition at a time; a device as envisioned by Liu would allow for high-speed concurrent testing for hundreds of different conditions.

"My original training is mostly in mechanical engineering," says Liu, "and personally I feel like the medical field is an often-overlooked application area of my home discipline. The tools I generally use hail from the world of mechanical engineering and mechanics, but have impact in ways they've never had before."

STRONGER STRUCTURES FROM THE GROUND UP

Professors Muhannad Suleiman, Bryan Berger, and Derick Brown (clockwise from left) recently received an 18-month grant from the National Science Foundation to explore silicatein's potential as a soil strengthening agent.

STORY BY **KURT PFITZER** • PHOTOGRAPHY BY **JOHN KISH**

A SEA SPONGE ENZYME COULD PROVIDE **GREENER, FIRMER SOIL FOUNDATIONS**

Liquefaction is hardly a household word, but the phenomenon is all too familiar to the residents of Christchurch, New Zealand.

Between 2010 and 2016, Christchurch experienced five major earthquakes. The largest in magnitude struck in February 2011, killed 185 people and destroyed much of the city's infrastructure. It was the third-worst natural disaster in New Zealand's history.

Much of the destruction was the result of liquefaction, which occurs when water-saturated, loose, sandy soils are subjected to earthquake loading. Soil starts to behave like a liquid and loses the ability to support structures, or it shifts or slides down even a gentle slope.

During the February 2011 earthquake and its aftershocks, wrote *The Press*, Christchurch's largest newspaper, liquefaction became the "scourge of Christchurch," causing thousands of tons of grey sandy silt to bubble out of the ground.

Liquefaction during the 2011 Christchurch Earthquake in New Zealand pushed up road surfaces and caused sand boils to appear.

The Christchurch example, and the damage from liquefaction during the 1964 earthquakes in Japan and Alaska, says Muhannad Suleiman, shows that a structure is only as strong as the soil on which it stands. A bridge or skyscraper can be built with the best materials and construction techniques, but it can't withstand earthquakes or other natural hazards if it rests on weak soils.

Suleiman, an associate professor of geotechnical engineering, leads an interdisciplinary team of researchers who are enlisting the aid of an enzyme found in deep sea sponges to provide buildings, bridges and other structures with a firmer, more environmentally friendly soil foundation.

The enzyme, called silicatein, has shown promise in precipitating the formation of flexible calcite (calcium carbonate) in soils. The calcite acts as a cementing agent and strengthens soil by causing its particles to bond together.

Suleiman and two other associate professors, Bryan Berger of chemical and biomolecular engineering and Derick Brown of civil and environmental engineering, have received a grant from the National Science Foundation to synthesize silicatein in the lab and explore its potential as a soil-strengthening agent. The group also has a Faculty Innovation Grant from Lehigh. They are the first to test the enzyme for this application.

Silicatein shapes up

Engineers have traditionally strengthened weak or loose soil by compaction or by cement-based grouting, says Suleiman. This helps soil resist the loading imposed by natural hazards. But these two traditional methods are energy-intensive, and the production of cement generates significant carbon dioxide.

More recently, Suleiman and other researchers have had success using microbes, or bacteria, that occur naturally in soil to precipitate calcium carbonate (one of its forms of precipitation is calcite). The process is called microbial induced carbonate precipitation, or MICP; Suleiman is collaborating with a biologist in Qatar to use MICP to improve soil's performance under sand storm conditions. But MICP has limitations. It yields a brittle bond between soil particles and also produces ammonia, a hazardous material. And the microbes, which measure 1 to 2 microns across, are too large to penetrate the very small pores that are typical of silty and clayey soils.

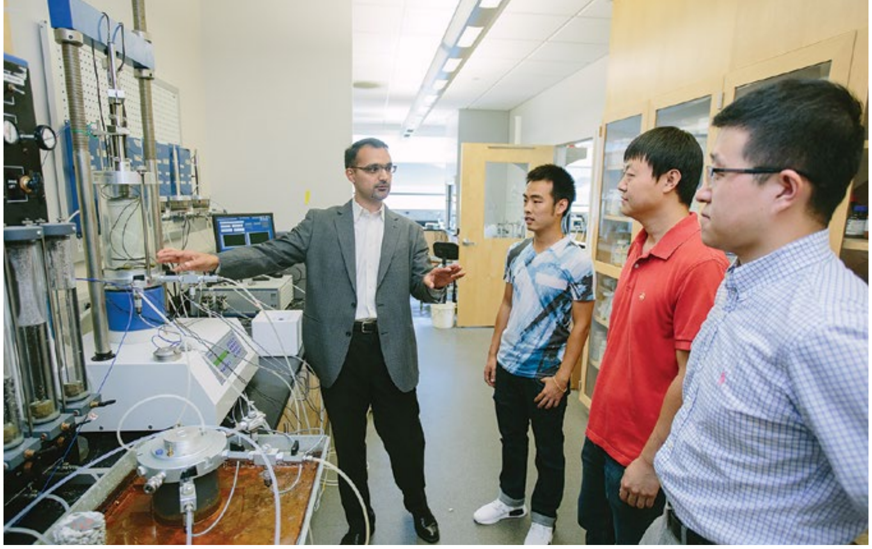
These drawbacks, says Suleiman, limit the types of soil to which MICP can be applied and the ability of soil to withstand large strains such as those generated during earthquakes. They also limit the potential for MICP to be used in supporting structural foundations and in mitigating liquefaction.

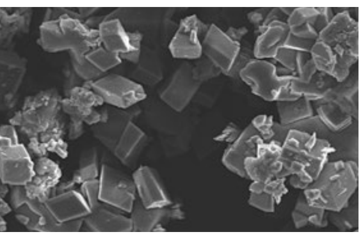
PRE-CONDITIONS OF LIQUEFACTION

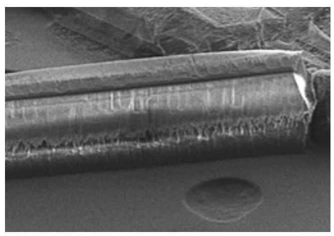
SANDY SOIL

SEVERE SHAKING

EXCESSIVE WATER PRESSURE IN SOIL







Above: Muhannad Suleiman with graduate students Kewei Gao, Yue Jia, and Hai Lin (left to right); scanning electron microscopy images show different forms of precipitated calcium carbonate that could improve the properties of soils when subjected to shearing.

By contrast, says Suleiman, silicatein promises to produce a stronger, more flexible bonding of soil particles. Because the enzyme is much smaller than a microbe, it can be potentially used in much finer soils. And silicatein has two additional assets.

"Sustainability and environmental friendliness are the main advantages of our method," says Suleiman. "We're working with a natural material."

One key to silicatein's success, says Suleiman, is that it precipitates the formation of rod- or needle-shaped calcite crystals. Their elongated structures enable the crystals to form stronger and more flexible bonds between particles of soil.

"Based on research by our group and others, silicatein causes a specific formation of calcium carbonate. Instead of precipitating calcite crystals that are cubic in shape, silicatein changes the crystallization into a needle shape."

The typically cube-shaped calcite crystals, says Suleiman, "produce brittle bonds that break at small strain. By contrast, calcite precipitated with silicatein, because of its rod-shaped crystal, forms strong, flexible bonds that can withstand large strains without breaking."

Less cost, more precision

To achieve the optimal shape of the calcite crystals, Berger modified an existing method of synthesizing the silicatein enzyme.

"We read reports from other researchers that said the enzyme could be added to a solution of calcium to template the growth of needle-shaped crystals. We make a high-concentration solution of the chemicals that form calcite. Then, when the solution begins to crystallize, we add the enzyme.

"The enzyme causes the calcite to crystallize into the structure and shape that we want, which the calcium solution will not do naturally on its own."

Suleiman decided to test silicatein's soil-strengthening potential in 2015, when he and his group came across an article published by researchers from Johannes Gutenberg University and the Max Planck Institute in Germany. Writing in *Science*, the group reported the creation of a new synthetic material made of silicatein and calcite, characterized by a "rubber-like flexibility" and inspired by the spicule, a structural element of the sea sponge.

Suleiman spoke with Brown after reading the *Science* article. Brown urged him to contact Berger, who was working on a project that employs silicatein to synthesize the metal oxide nanoparticles that are used in catalysts, separations and other applications.

This came as a welcome surprise to Suleiman.

"I honestly did not even know that someone at Lehigh was working with this enzyme," he says.

Berger and three other faculty members—Steve McIntosh and Mark Snyder of chemical and biomolecular engineering and Chris Kiely of materials science and engineering—have an Accelerator Grant from Lehigh to scale up the biomanufacturing of functional, nanostructured materials.

The current methods of synthesizing many metal oxides, says Berger, require heat, high pressure and chemical solvents that are expensive and toxic. Silicatein overcomes these drawbacks.

"The skeleton of the sponge that produces silicatein is composed of mineralized silica. The sponge utilizes the silicatein enzyme to mineralize sand to form its skeleton. So it has a natural ability to convert metal to metal oxides. We modify the silicatein to mineralize metal precursors into crystalline metal oxides at room temperature and pressure and using only water.

"It's a much cheaper and more environmentally friendly method than the current chemical methods."

Silicatein also makes it possible to synthesize nanoparticles and other products with greater precision than conventional chemical methods, says Berger.

"Chemical synthesis is homogeneous. Combined with the high temperature and pressure that are required to convert metals into metal oxides, this makes it difficult to control the synthesis and direct the oxide nanoparticles where you want them to be. With our method we can control the deposition of the enzyme and more easily fabricate materials."

Fate and transport

Working with McIntosh, Snyder and Kiely, Berger has achieved some success in scaling up the production of silicatein, which has benefited his work with Suleiman and Brown.

"Without the ability to make large quantities of the enzyme, it's difficult to translate this into a useful technology for industries," says Berger. "I learned how to do this through a trial-and-error process while I was working with Steve, Mark and Chris, and it was a contribution that we were able to make early to Muhannad and Derick's project."

Suleiman, Berger and Brown are also attempting to engineer silicatein so it provides the optimal bond properties between soil particles, enabling the soil to remain stable when subjected to natural hazards.

"We have looked at different percentages of silicatein and how they affect the shape and the form of precipitated crystals," says Suleiman. "Based on preliminary results, we have found that, generally, 5 to 10 percent of silicatein gives us the optimal crystal shape. Once we go beyond that percentage, we don't see a lot of rod-shaped precipitations."

This spring, the researchers plan to test the silicatein-precipitated calcite crystals in soil.

"Because it's an enzyme, we need to look at the sorption of silicatein onto the sand and ultimately onto soil," says Brown, whose expertise lies in soil chemistry and in the fate and transport of bacteria through soils. "That will affect how far we can transport it. We are concerned with the transport of the enzyme and of any other constituents. We want to see how far out this cementation would extend."

The partnership has been an education for Suleiman, Berger and Brown.

"I am not an expert in the geotechnical side or in enzyme production," says Brown. "And Muhannad's and Bryan's backgrounds are not in soil chemistry and sorption at the soil surface as mine is. So we've taught each other."

"It's been a mutual learning experience for all of us," says Suleiman. "We meet and try to get to the point where we speak the same language. Similar words could mean different things in different fields. But we now understand roughly what each other is doing."

"This latest project allows me to apply my work to environmental problems. I didn't realize there were so many opportunities."

— Bryan Berger, *bioengineering*

"Working with soil and foundation engineers is totally new to me," says Berger. "It's been fascinating. Previously, I've been able to apply what I do—engineering biological systems—to the solution of medical problems or the manufacturing of materials.

"This latest project allows me to apply my work to environmental problems. I didn't realize there were so many opportunities."

3D PRINTING FOR STRUCTURES

Precast concrete is a product that is fabricated in a controlled environment in advance of a construction project and transported to the site when appropriate. It differs from the more traditional method of pouring concrete on site—"cast-in-place" concrete—in that it makes the creation of multiple identical structural members easier and more reliable. The downside: Less freedom to create unique members.

Clay Naito, professor of structural engineering, was at a conference at the Precast Concrete Institute when he had an idea: Use 3D printing technologies to enhance what you can do with precast concrete.

"The current method of printing concrete is to build your structure by pumping it out on site like icing in a cake funnel," Naito says. "You can do it quickly, but you can see the layers on the finished product. What I wanted to do was more refined, to get nice details on the surface of the components."

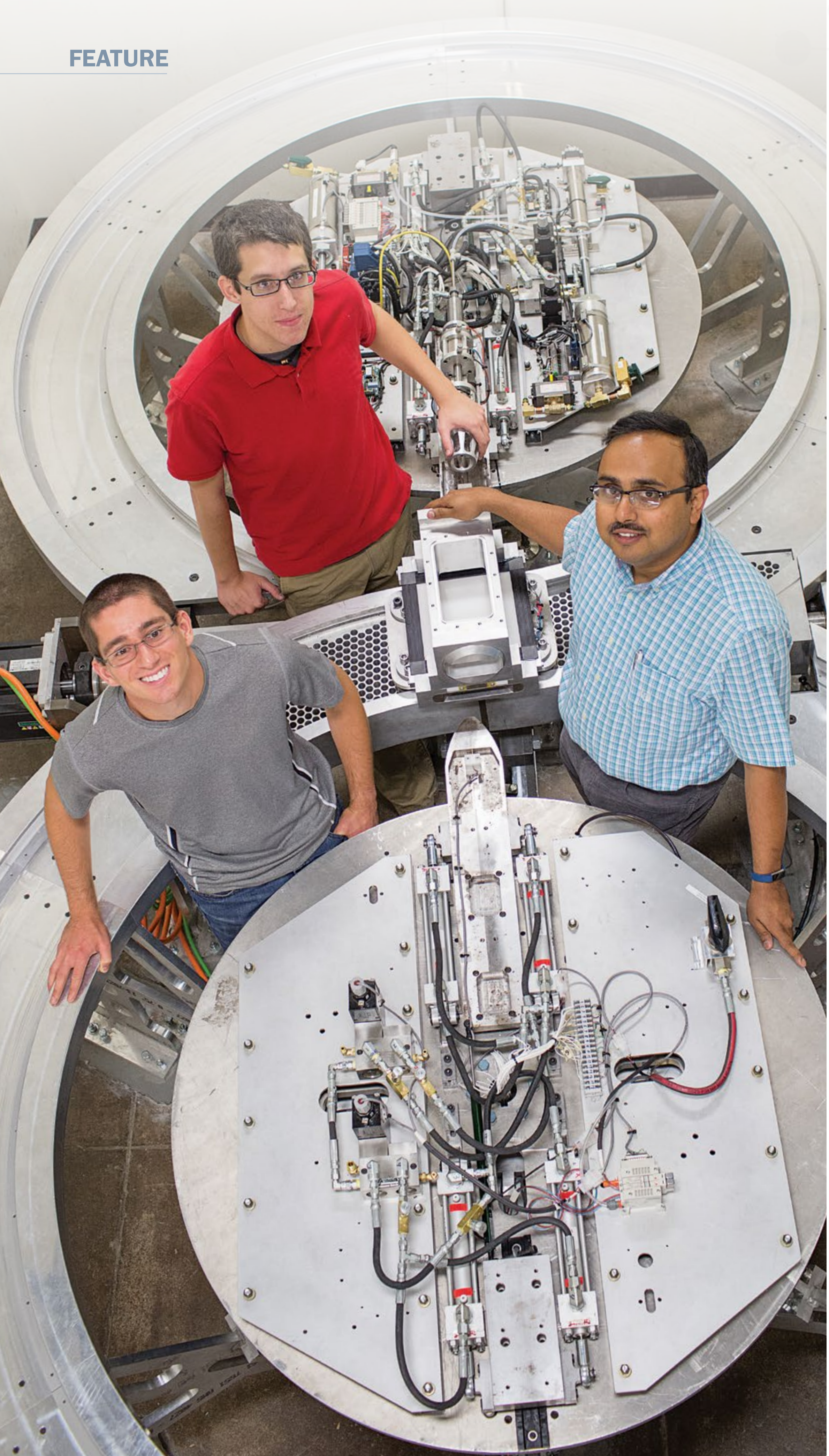
Naito has been using 3D printing as part of his Civil Engineering Materials class, so he knew the technology was available on campus. What surprised him was the amount of interdisciplinary cooperation he was able to find.

He recruited a team of students to begin work through Lehigh's Mountaintop Initiative. "The academic diversity has been amazing to see. The team is made up of students from civil engineering, mechanical engineering, materials science, chemical engineering, chemistry, architecture, and art," Naito says.

John Fox, assistant professor of environmental engineering, supported the effort based on his experience with binder jet printing, an offshoot of 3D printing. Nik Nikolov, assistant professor of art and architecture, supported the team with optimization of structural shapes.

"Binder-jet is being used industrially right now with sand," says Naito. "They're creating large complex sand molds for things like propeller blades and engine parts by forming a thin layer of sand, printing a binding agent at the desired location and repeating," Naito says. "When it's done, the sand and binder creates a rigid matrix. You blow away the unbound sand, and you have your mold. We're trying to do the same with concrete."

The group ultimately discovered several viable mixes, and they were able to print, but there's more work to do. "We're hoping to team with Paolo Bocchini [Frank Hook Assistant Professor of Structural Engineering] to look at the life cycle of some of the structural members we create," Naito says.



Serious discussion on the future of energy use, says Arindam Banerjee, is turning more and more to nuclear fusion, a potential power source that not long ago was considered a distant dream.

Fusion is the process by which the sun generates heat and light. It occurs when two isotopes of hydrogen—deuterium and tritium—collide at great speeds under extreme heat and pressure and fuse to form helium, losing a small amount of mass and releasing huge quantities of energy.

Unlike fossil fuel-fired power plants, fusion reactors emit no greenhouse gases such as carbon dioxide or toxic pollutants such as mercury or sulfur dioxide. They produce no long-lasting radioactive waste, and the process itself is highly efficient.

BRINGING

Banerjee, an associate professor of mechanical engineering and mechanics, says advances in supercomputing and the development of novel experimental techniques may hasten fusion's progress as a viable, cost-effective energy source.

"In the last decade," he says, "advances in supercomputers have given us enormous power to numerically model complex phenomena like nuclear fusion. This has resulted in quite a leap in understanding the fusion process."

Half a dozen processes occur simultaneously inside a nuclear fusion reactor, says Banerjee. They include nuclear reactions, combustion, radiative heat and shock waves. Each process interacts with and influences the others. For fusion research to advance, all the processes and interactions must be numerically modeled and understood—a task for which today's supercomputers are ideally suited.

"The new tools enable us to do large-scale simulations. How large? Ten years ago, I would have needed a supercomputer to run simulations that I can now run on my laptop. And today, the largest supercomputer can model the entire nuclear

FUSION INTO FOCUS

fusion process, including the equations that represent the underlying coupling of physical phenomena."

A second reason for Banerjee's optimism is a unique experiment that he and his students are conducting on a two-wheel, high-acceleration facility developed in their lab. The system replicates the turbulence inside the fusion reactor and sheds light on hydrodynamic instabilities that limit the reactor's efficiency.

INSIDE THE FUSION REACTOR

The simultaneous phenomena that make nuclear fusion so complex occur inside the fusion reactor under extremely high pressure with temperatures reaching tens of millions of degrees Celsius. The heat sustains the fusion reaction, while the pressure confines the hydrogen isotopes, allowing them to fuse.

Researchers today are testing two different approaches to achieve fusion—magnetic confinement and inertial confinement. Banerjee studies the second method, in which high-powered x-rays and lasers heat metal shells containing hydrogen isotopes as they pass through the reactor. The goal is for the isotopes to fuse and release energy before the heat from the lasers and x-rays melts the shells.

During this process, says Banerjee, a multifluid surface forms between the melting metal and the hydrogen gas, creating a phenomenon called Rayleigh-Taylor Instability, which occurs at the interface of two fluids of differing densities.

"Rayleigh-Taylor Instability causes the metal shell to rupture and the gas inside to escape," says Banerjee. "This reduces the yield of inertial confinement fusion."

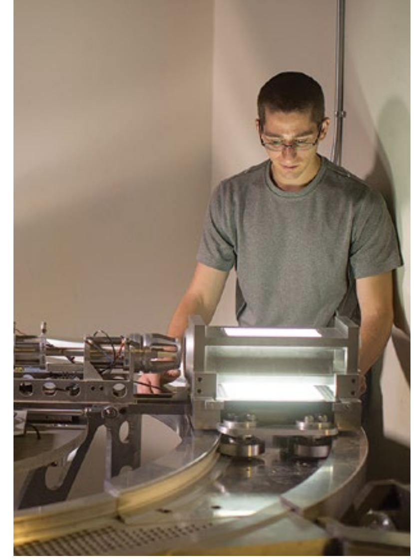
Banerjee and his students want to learn how Rayleigh-Taylor Instability evolves over time inside the inertial confinement capsule and how it can be suppressed or mitigated. They contribute their results to the "larger picture" being developed by physicists at Los Alamos National Laboratories in New Mexico.

"Our goal at Lehigh is to better understand the hydrodynamic instability of the mixing of the hydrogen gas with the molten metal. But hydrodynamics is just one feature of what is happening inside the fusion reactor. So we provide Los Alamos with data from our model that helps their physicists, who are developing more elaborate and detailed models of all the phenomena occurring inside the reactor."

Banerjee's group is carrying out several sets of tests. In one, they are using two real-world fluids—mayonnaise and air—to mimic the behavior and interactions of the molten metal and hydrogen inside the fusion reactor.

"We use mayonnaise to represent the molten metal," says Banerjee, "because it has properties that, like molten metal, are rate-dependent. If you change the shear or strain rate, the properties of the mayonnaise change too. This mimics what you have in an inertial confinement fusion capsule, in which one of the two fluids—the molten metal—has rate-dependent behavior."

A second experiment is conducted on the two-wheel, high-acceleration testing facility. Banerjee and his students fill a container with two fluids of different densities, place it on the track of one of the two wheels of the test facility and turn on the track so the container circles it at a predetermined speed. When the track is "flipped," the container switches from one wheel to the other, changing its direction of gravity in the process.



Opposite page, counterclockwise: Ph.D. students Zachary Farley and Andrew Bergey with Arindam Banerjee in the group's hydrodynamic testing facility. Left: Farley observes the two-wheel facility in action.

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"On one wheel of the track," says Banerjee, "the container is on a stable stratification. When it flips to the other side, it becomes unstable. It rotates like a centrifuge so the heavy fluid is outside and the lighter fluid is inside. The moment the track is flipped, the stratification of the container is reversed, causing the lighter fluid to move to the outside and the heavier fluid to the inside."

The change in orientation of the two fluids, says Banerjee, causes mixing, which is an undesired outcome inside the fusion reactor as it allows hydrogen isotopes to escape from the inertial confinement capsule before fusing.

The purpose of this experiment, says Banerjee, is to determine the Reynolds threshold number at which mixing occurs and then go a step further.

"The challenge is that no one has been able to run experiments beyond that threshold number. The facility we've built actually allows us to run experiments at Reynolds numbers beyond that threshold number. Beyond that number, mixing becomes universal."

The two-wheel, high-acceleration facility, says Banerjee, is the only one of its kind in the world. "We are, in terms of Reynolds capability, several orders of magnitude improved over what any other experiment can do right now."

Banerjee has conducted fusion-related research for 12 years. His work is supported by a CAREER Award from the National Science Foundation and by successive grants from the U.S. Department of Energy. He has published his results in the top journals in his field, including the *Journal of Fluid Mechanics* and *Physical Review E*.

STORY BY **CHRIS QUIRK**

LEARNING IN THE AGE OF KEEN

A revolutionary approach to curriculum design puts students in the driver's seat

THROUGH KEEN, THE KERN FAMILY FOUNDATION SUPPORTS A NETWORK OF UNIVERSITIES, FACULTY, AND STUDENTS IN INSTILLING AN 'ENTREPRENEURIAL MINDSET' AMONG THE NEXT GENERATION OF ENGINEERS.

Ed Webb, an associate professor of mechanical engineering and mechanics at Lehigh, was dismayed as he reviewed the student reactions to the first project in his Strength of Materials class in 2015.

"One student said 'I felt I learned little except how to be frustrated over a computer code.' They hated it."

Soon after, Webb attended a workshop on "Integrating the Curriculum with Entrepreneurial Mindset," hosted by Lawrence Technological University through the Kern Entrepreneurial Engineering Network (KEEN). Inspired to find ways to spark his students' creativity and engagement, he challenged the next semester's class with an open-ended project: design a treehouse for a charmingly eccentric 'Aunt Ada.'

KEEN, an initiative of The Kern Family Foundation, is a collaboration of colleges and universities dedicated to developing an entrepreneurial mindset in engineering students. In Webb's class, the real-world approach he built into the assignment yielded, along with plans for a fully functioning treehouse, a design for an elevator within a hollow trunk, ways to use locally sourced materials to meet sustainability goals, information on the average heights of trees commonly found in the Poconos so the treehouse wouldn't tower above the forest, and a walk-out porch placed with the detonation heights for various classes of fireworks in mind, so Aunt Ada could see a nearby fireworks display every July 4th.

"They blew the project out of the water," recalls Webb. "One student said they wished every professor at Lehigh would adopt this approach."

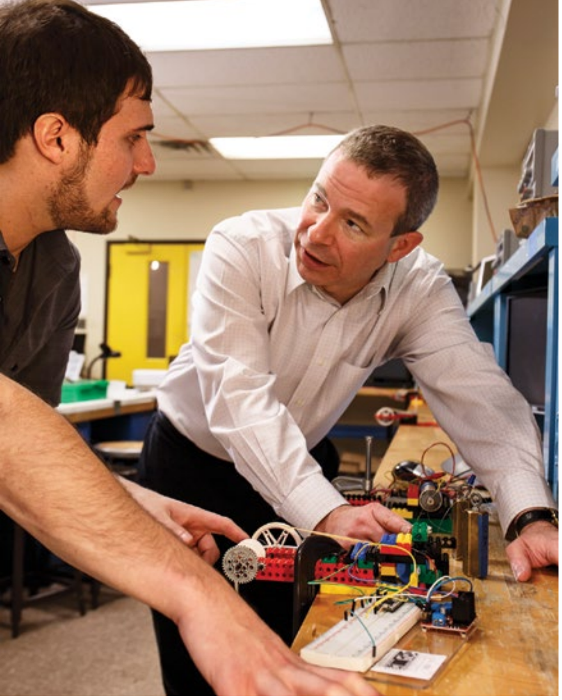
The root of the entrepreneurial mindset that KEEN seeks to instill in engineers is summed up by KEEN's "3C's," curiosity, connections and creating value. The idea is to encourage engineers to adopt holistic thinking that challenges conventional ideas and integrates fresh ones. By taking ownership and thinking broadly and creatively about every aspect of projects they work on, engineers have a chance to enrich the lives of the people that their work touches.

29
KEEN PARTNER UNIVERSITIES

"Entrepreneurial engineering takes engineering to the next level," says Thor Misko, program director and team leader of the Entrepreneurial Engineering Program at The Kern Family Foundation. "We want to combine the entrepreneurial mindset with the engineering skill set. It's not just about design, we want to empower engineers to identify new opportunities and make an impact."

John Ochs is working to implement the KEEN tenets throughout Lehigh's engineering program. Ochs, a professor of mechanical engineering and mechanics and director of the university's Technical Entrepreneurship capstone course, was at the table to help shape KEEN's mission when it was launched just over a decade ago. He serves as the point person on campus now that Lehigh has joined the network of participating schools.

"We're leveraging KEEN training to influence the way faculty create their curriculum," he says. "All undergraduate engineering students should be exposed to KEEN's entrepreneurial minded learning (EML) techniques and have the chance to incorporate them into their educations and careers. So, we intend to infuse EML in some way into all core courses across every major. At present, some 45 engineering faculty who teach those core courses are employing KEEN principles to develop their own EML modules, and we plan to host further training to grow this over time."



"We are very broad about how we want this mindset change to occur," he says. "We are providing a roadmap, and cultivating a community of like-minded faculty who will integrate EML across Lehigh's engineering landscape."

Sue Perry, a professor of practice in chemical engineering associated with Lehigh's Bioengineering program, has been working with faculty on implementing KEEN principles within the program's undergraduate studies, examining current courses to identify overlap in specific topics between early and advanced undergrad courses.

"We intend to create a learning continuum so students retain fundamental principles and have context to strengthen their knowledge as they progress," says Perry. "We are developing modules through which faculty can create context connections in earlier courses, and give students the tools to think progressively about topics as they follow the curriculum."

3,019
KEEN ENGINEERING FACULTY

"For example," she says, "we are using the human cardiovascular system as a way to create context across the portion of our curriculum dedicated to fluid dynamics. In sophomore level classes, we'll be introducing the concepts of biomaterials and biomechanics by having students design and 3D print artificial heart valves in one class, then test them for function and output in the next. Our Junior year fluids course examines the principles of fluid dynamics of the cardiovascular system—and by that point, students will have context for the theory we're presenting, and will be prepared to think more deeply about how they can *apply* their knowledge."

"If we can use active, project-based learning to create connections," she continues, "we also create a greater depth of understanding from start to finish in the curriculum."

"The KEEN program is transformational to the entire college and its curriculum," says Greg Tonkay, associate dean of academics affairs and associate professor of industrial and systems engineering. "It's empowering our students and supporting faculty teams that are making things happen."

The new principles flip traditional pedagogical goals, and how those goals will eventually be measured. "We are moving from assessing faculty teaching to assessing student learning," says Ochs. "And when you get students involved in this active, collaborative learning, the whole classroom comes alive. You have to see it happen, and when you do, it makes a believer out of you."

In an important sense, the KEEN principles go to the root of what an engineering education is all about: What constitutes a fulfilling life? "The underlying tone of KEEN is about human flourishing. Our mission is to create personal and societal value through a lifetime of meaningful work," says Misko.

One innovation of the KEEN implementation at Lehigh has been teaming up faculty and students to work together in developing programs and activities. "Lehigh is one of the few schools in KEEN to use a co-development model, and we are encouraging others in the Network to try it because student insight is so valuable," Tonkay reports. "We have also included facets of the KEEN experience into our PreLUsion program for women engineers, a pre-first-semester initiative that allows students to get a jumpstart on their first year at Lehigh."

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KEEN UNDERGRADUATE ENGINEERS

Clockwise from left: Professor John Ochs; Matt Bilsky and Ed Webb (l to r) discuss the MechE senior lab; all smiles with the PreLUsion pre-semester program for incoming first-year women engineers.

Matt Bilsky '12 '14G '17Ph.D., a postdoctoral researcher and adjunct professor at Lehigh, modified the KEEN-inspired curricula he developed for a mechanical engineering lab course for use with the PreLUsion program.

"I talk to a lot of students about the Lehigh style, and how it is both real world and adaptable," he reports. "It's about how to learn. This is the true value of a Lehigh education, and KEEN enhances it. I would love to be an undergraduate now."

"And that," replies Ochs, "is precisely how we want every one of our faculty members to feel."

Brandon Krick (above, below with student Mark Sidebottom) studies the science of wear and friction.

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A tribologist's quest

Brandon Krick explores the interdisciplinary science of surface interaction

Brandon Krick says he's had the good fortune to research space and dinosaurs—"all the things you want to explore as a kid," he says. But his real passion is the science of tribology, "which few people have ever heard of," he admits.

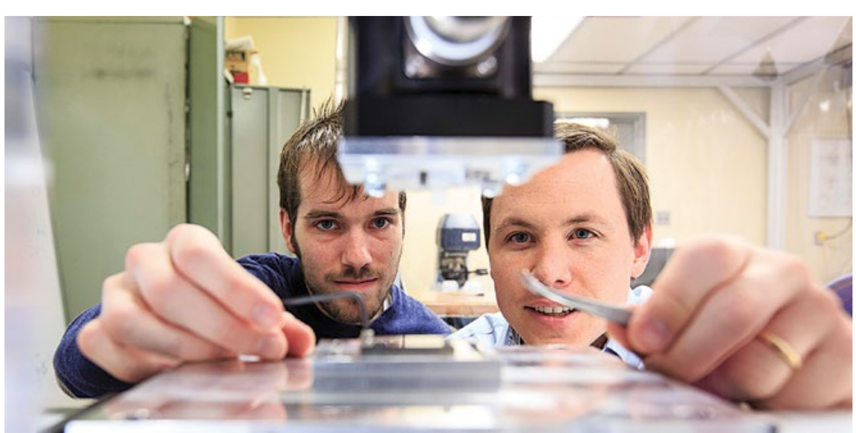
For Krick, assistant professor of mechanical engineering and mechanics, tribology—the study of friction, wear, and lubrication—has long been as fascinating as any sci-fi-movie mainstay. Derived from the Greek *tribos*, meaning "to rub," tribology is the study of interactive surfaces in motion. Its foundations as a distinct scientific discipline are relatively recent. But uses for tribology are simultaneously at the leading edge of materials science and older than technology itself. Grinding a stone ax to a sharp edge involves tribology. So does developing materials that allow an instrument array on a satellite to slide open in low-earth orbit—and so does discovering prehistoric teeth that can slice and grind at the same time.

He points to the namesake product of WD-40 Company as an example of his fascination with tribology. "WD-40 was developed 60 years ago as a corrosion inhibitor for the rocket industry and is now a spray lubricant in everyone's garage," Krick says. "Yet it hasn't been clear how the ingredients in WD-40 interact to produce its performance." Krick, with students Mike Goldstein and Jacob Smith, is working with the company to analyze how the elements in this compound come together to produce its properties, in hopes of enhancing the formulation.

Understanding the fundamental science of friction and wear has vastly more significance than silencing a squeaky door hinge. Developed countries lose an estimated 2 to 7 percent of GDP to costs associated with friction and wear, including energy loss and replacement of worn-out machinery. "The toll is approaching a trillion dollars in the U.S. alone," Krick says. "You need friction or you wouldn't have any grip or be able to react to force. But we need to be able to predict, control and in many cases reduce friction and wear, and that will lead to new materials and devices."

Doing so is inherently interdisciplinary. "The frontiers of tribology research involve interfaces of disciplines as well as materials," Krick says. "You have to think about chemistry, physics and mechanics all being involved. It's a very collaborative field."

Interdisciplinary collaboration helped launch Krick's research career as a graduate student at the University of Florida. Together with his Ph.D. advisor Greg Sawyer and Florida State paleobiologist Gregory Erickson, Krick discovered that plant-eating, duck-billed hadrosaurs had complex dental batteries consisting of multiple materials with different wear rates—a versatile system different from that of humans and animals. Krick and his team have continued working with fossils at Lehigh University, demonstrating that the three-horned triceratops had complex dentition with additional features more complex than any reptile or mammal now alive.



Implications go beyond understanding what animals ate during the late Cretaceous period. Krick and his students Tomas Grejtak and Mark Sidebottom, working with Natasha Vermaak, Lehigh assistant professor of mechanical engineering and mechanics, and her student Xiu Jia, are using the computational model Krick developed to explain—and reveal—tissue structure in prehistoric animals in order to optimize modern composite materials.

"If you understand how material properties affect global properties of a system, you can design something that has a low wear rate or lower frictional force or electrical conductivity and optimize for multiple properties simultaneously," Krick says. As with dinosaurs, "composites allow you to take material A that's good at one thing and material B that's good at another and put them together to make a material that's good at both." The National Science Foundation has awarded a three-year grant for the team's work on topology optimization for wear of composite materials.

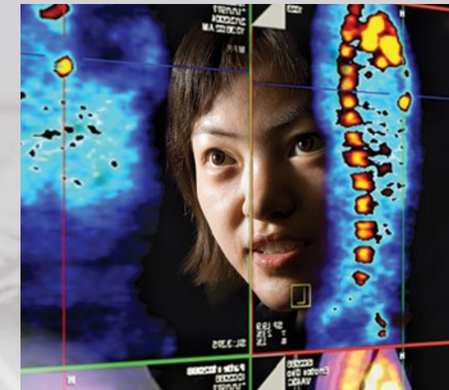
Working with Professor Nelson Tansu and Ph.D. student Guosong Zeng in Lehigh's Center for Photonics and Nanoelectronics, Krick has discovered that gallium nitride—well known for its electronic and optical properties—also has ultralow-wear properties akin to diamonds. "This will have huge ramifications for device design," Krick says.

Yet the tribology of soft materials can be just as important as that of hard ones, especially in biological and biomedical research. "With the exception of teeth, tissues in contact with each other throughout the body tend to be soft," Krick says. "The importance of surfaces interacting at the cellular level makes biomedical research a promising field for tribologists."

Lehigh is well suited for this interdisciplinary range of projects, says Krick, who previously worked with large state universities where collaboration between departments was more challenging. "We have unique facilities, curious and engaged students, and a very favorable size in that we're both large and small enough that we can easily interact across departments," he says. "There are very low barriers to collaboration."

HEALTH RESEARCH AT LEHIGH

Lehigh has recently announced the formation of a new college devoted to research and education in health. A variety of engineering faculty are already engaged in projects related to healthcare and medicine. Here are a few examples:



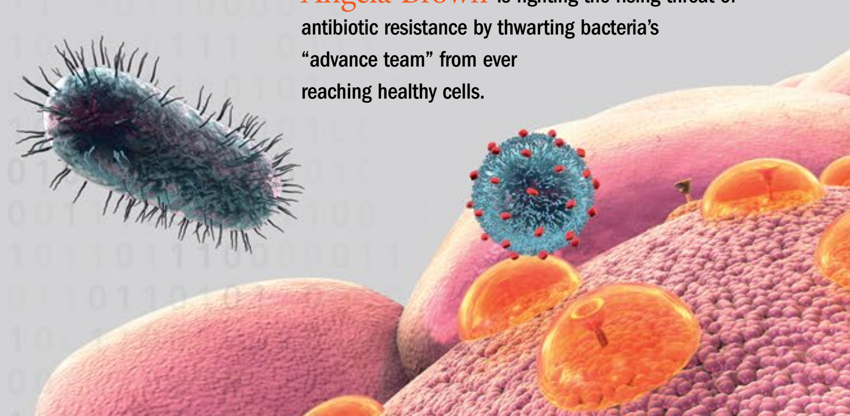
Xiaolei Huang builds image analysis systems that solve computational problems in biomedicine, perception, and cognition.

Javier Buceta and Paolo Bocchini develop probabilistic models that aid in resource allocation and other decisions related to the global fight against Ebola.

Xuanhong Cheng has developed a hand-held, portable device that allows healthcare workers to monitor the spread of the HIV virus in rural and developing areas, a major advance over costly, lab-bound systems.

Brian Chen computationally models molecules in 3D, and writes algorithms that allow medical researchers to compare these features to real-world medical issues.

Angela Brown is fighting the rising threat of antibiotic resistance by thwarting bacteria's "advance team" from ever reaching healthy cells.



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OPERATING WITH INTEGRITY

Integrity, curiosity, and persistence, says Lehigh University alumnus and Trustee Dr. Michael J. Yaszemski '77 '78G, are the keys to successful research. Currently a professor of orthopedic surgery and biomedical engineering at the Mayo Clinic's College of Medicine and deputy director of its Center for Regenerative Medicine, Yaszemski is a 2016 electee to the National Academy of Medicine.

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