LIGHTER LIFELINE FOR COPD USERS

A more compact medical oxygen device supplies steadier air flow.

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THE BENEFITS OF FELLOWSHIP

Rossin programs help newcomers chart career and research paths.

See page 22

resolve®

A FOCUS ON LEHIGH ENGINEERING • VOLUME 1, 2015

MOVING AT *WARP SPEED*

FEW LIMITS ARE IN SIGHT FOR MANUFACTURING'S NEW INNOVATORS.

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

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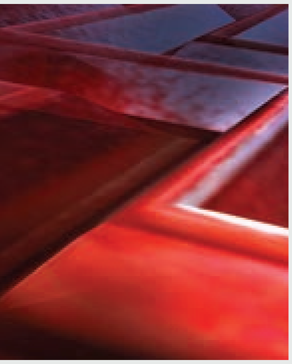

ON THE COVER

A chip designed to detect tumor cells circulating in blood demonstrates engineering's role in medicine and in advanced manufacturing. *See page 18.*

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A FOCUS ON LEHIGH ENGINEERING
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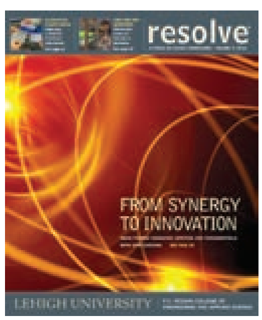
LEHIGH UNIVERSITY

A new season for manufacturing

Welcome to the 17th 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.

Manufacturing has long been a major strength at Lehigh. Beginning with our historical ties to Bethlehem Steel, generations of engineering graduates have taken positions of industrial and academic leadership in manufacturing, often as an outgrowth of collaborative research projects involving faculty members and industrial partners.

Our students benefit from these partnerships. Through our Integrated Product Development, Integrated Business and Engineering and similar programs, engineering students have teamed with students in business and the arts to design and make products for industry sponsors. They have also collaborated on manufacturing projects with students from local middle schools.



This issue of *Resolve* takes a look at more recent developments in manufacturing—the advanced systems, processes and materials that are helping to support a 21st-century rebirth of the science and the technology of making things.

The article "Moving at Warp Speed," on pages 10-15, gives an overview of some of our advanced manufacturing activities. These endeavors include metal forming, welding, injection molding and additive manufacturing, or 3D printing as it is popularly known, and they utilize polymers, nanocomposites, metals and other materials.

Much of the progress in advanced manufacturing has been made possible by research at the microscale and the nanoscale that gives us unprecedented control over deposition and other fabrication techniques and over the composition and properties of materials as well.

The applications of advanced manufacturing at Lehigh are coming in a variety of areas, from biodegradable scaffolds and kidney dialysis filters to LEDs, solar cells and lighter-weight car structures.

On pages 18-21, an article titled "In Pursuit of the Deadly Tumor Cell" explores a specific advanced manufacturing project with critical medical significance. Yaling Liu, assistant professor of mechanical engineering and mechanics, and his students are working with researchers at the University of Pennsylvania and the Max Planck Institute to build and test a "lab-on-a-chip" that can detect the presence of a relative handful of tumor cells in a milliliter of blood.

Liu has patterned the "capture pad" of his device with biomimetic nanoscale features to improve its efficiency and selectivity for targeting cancer cells.

Another project with a much-needed medical application is the subject of the article "Taking the Pulse of the Market" on pages 16-17. This piece chronicles the efforts by two of our senior faculty members in chemical and biomolecular engineering, Mayuresh Kothare and Shivaji Sircar, to commercialize a smaller and more efficient medical oxygen concentrator for persons with chronic obstructive pulmonary disease.

The Q and A in this issue, on pages 8-9, features John D. Simon, who will become Lehigh's 14th president on July 1. Simon, currently the provost at the University of Virginia, has gained international renown for his educational leadership at UVA, Duke University and the University of California at San Diego and for his pioneering research in several fields of chemistry, including melanin and ultrafast chemistry.

Pages 22 and 23 are devoted to our Rossin Fellowship Programs. These programs, which are supported by the endowment of the engineering college by the late Peter C. Rossin '48 and his wife, Ada, help new students and faculty members thrive at Lehigh while charting their futures.

I hope you enjoy this issue of *Resolve*. Please drop me a line with your thoughts and comments.

"Applications of advanced manufacturing at Lehigh include biodegradable scaffolds, dialysis filters, LEDs, solar cells and lighter-weight car structures." —Daniel Lopresti

Daniel Lopresti

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Helping sulfur reach its potential

A chemical engineer seeks to enhance fertilizers and boost food production.

Alongside the world's major oil and natural gas refineries, says Jonas Baltrusaitis, deposits of sulfur are growing larger and larger each year. One mountain of sulfur in Kazakhstan, he says, has even been photographed from space shuttles orbiting the earth.

"Soil needs sulfur to uptake nitrogen. Without sulfur, nitrogen is not taken up but dissolved in water and washed away. Everything ties together."

—Jonas Baltrusaitis

Elemental sulfur today occurs chiefly as a by-product of the refining of petroleum and natural gas. Sulfur is nonreactive, but as part of the compound sulfuric acid (H_2SO_4), it is a critical ingredient in nitrogen-based phosphate fertilizers that enrich the soil and enhance crop growth.

Baltrusaitis, an assistant professor of chemical and biomolecular engineering, wants to develop a sustainable method of processing sulfur into sulfuric acid that would "bridge the gap" between the unused mounds of sulfur and the demand for H_2SO_4 in fertilizers.

He is seeking to determine the optimal proportions of urea, sulfuric acid and water in fertilizers while achieving the nitrogen-to-sulfur ratio at which fertilizers work most efficiently. Urea is a nitrogen-based, water-soluble compound.

Fertilizers with lower crystallization temperatures work better in cold climates, while those that crystallize at higher temperatures are more suited for warmer climates. Baltrusaitis measures the temperatures at which phase changes from liquid to solid occur in various types of fertilizer.

His eventual hope is to develop and test fertilizers that improve crop yields and help meet global food demands, which he says are projected to rise 40 percent by 2030.

Baltrusaitis recently reported his research in the American Chemical Society's *Journal of Sustainable Chemistry and Engineering* in an article coauthored with A.M. Sviklas and J. Galeckiene of the Kaunas University of Technology in Lithuania.

For several reasons, he says, the amount of sulfur in soils worldwide is falling. Oceanic emissions of dimethyl sulfate—which eventually fall on land—are decreasing due to climate change and to acidification caused by the oceans' uptake of greater amounts of man-made CO_2 emissions. And in an effort to curb acid rain, many countries have limited sulfur content in gasoline and other fuels—thus decreasing its presence in rain.

Meanwhile, an estimated 60 million tons of elemental sulfur pile up each year next to petroleum and natural gas refineries as humans gradually exhaust deposits of low-sulfur-content oil and gas and tap resources with higher amounts of sulfur.

Baltrusaitis wants to process elemental sulfur into sulfuric acid that can be incorporated into nitrogen-based phosphate fertilizers that work in both cold and warm climates.

"My goal is to return sulfur to the environment in its reactive form, as sulfuric acid, so it can be absorbed by plants and increase the efficiency of soil in uptaking nutrients. The more efficient we can make this uptake process, the greater the crop yields we will have."

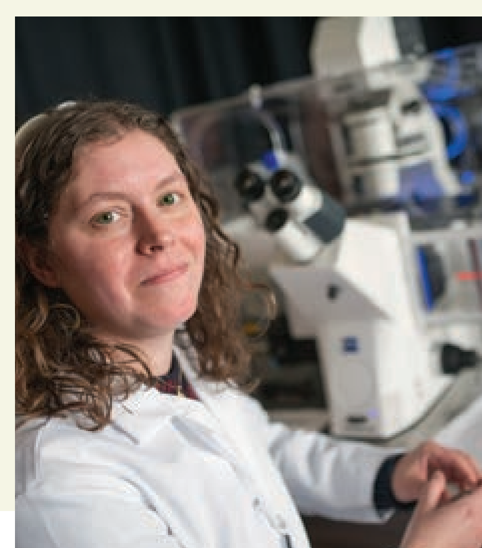
The results achieved by Baltrusaitis's group promise to benefit the environment as well as crop yields.

Soil that contains insufficient amounts of sulfur, he says, loses its ability to absorb nitrogen and other nutrients. As a result, crops receive less than optimum nutrition, while nitrates wash away and end up polluting streams and rivers.

"Soil needs sulfur to uptake nitrogen," says Baltrusaitis. "Without sulfur, nitrogen is not taken up but dissolved in water and washed away. The results are algae blooms in water bodies, fish dying because of the lack of oxygen, and the eutrophication of the environment.

"Everything ties together."

FINDING NEW USES FOR THE VERSATILE POLYMERIC GEL



Microfluidics for accelerated drug assays

An electrical engineer seeks to streamline discovery of epilepsy medications.

Approximately 125,000 Americans each year develop epilepsy, a brain disease marked by recurring seizures that are sudden and unpredictable and can have dangerous and even fatal consequences. There is no known cure for epilepsy, but medications can control seizures.

Some 30 percent of epilepsy patients, however, suffer seizures that do not respond to existing medications, says Yevgeny Berdichevsky. And the gradual onset and slow progression of the disease complicate efforts to identify and test new anticonvulsant drugs quickly.

Berdichevsky, an assistant professor of electrical and computer engineering, recently received a grant from the National Institutes of Health (NIH) to help speed the process of drug discovery by testing multiple potential epilepsy medications simultaneously.

By performing drug assays on 1-inch-square chips imprinted with microwells, he reduces the area required to grow individual epilepsy cultures, or tissue samples, and makes it possible to test as many as 18 drug candidates at one time. The samples, taken from the brain's hippocampus, where epilepsy frequently occurs, have the thickness of several human hairs.

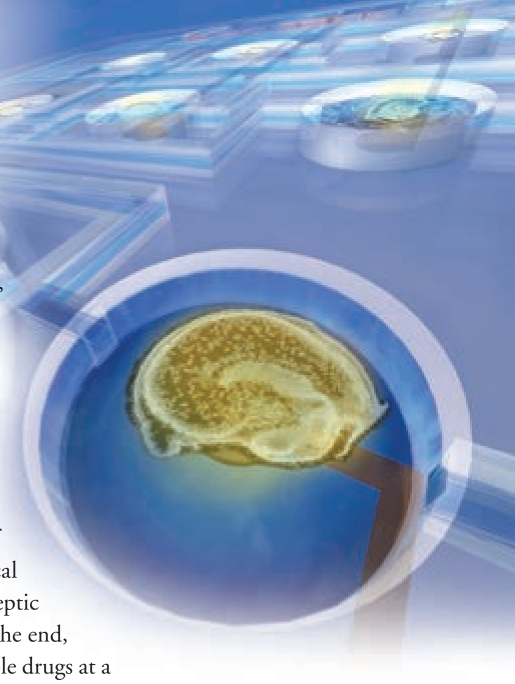
A network of microfluidic channels divides the samples into experimental groups while enabling the "feeding" of the samples, which require large amounts of glucose and amino acids. The channels, which Berdichevsky is developing with help from Jing Liu, a Ph.D. candidate in electrical engineering, also facilitate the application of drugs, inhibitors and other molecules.

The chip is also imprinted with multiple arrays of electrodes, each the size of a period, which detect the electrical activity in tissue samples that signifies epilepsy. This activity can take up to two weeks to develop and can be difficult to measure in a timely fashion because of the need to precisely control humidity, carbon dioxide levels and other environmental parameters.

The research techniques Berdichevsky employs—imprinting electrodes on a chip and patterning the chip surface with microfluidics—are well-established. What makes his approach novel, he says, is combining the two techniques to perform experimental tests on 3D tissue samples.

"To do faster drug screening," he says, "we need to monitor the activity of many slices of tissue simultaneously, from the time current is applied through the electrodes to about 14 days later, when epileptic activity is present.

"Our goal is to increase the rate of drug development by significantly improving the scalability of long-term electrical monitoring of epileptic activity in vitro. In the end, the testing of multiple drugs at a time is an engineering problem."



Multiple microwells on Berdichevsky's assay chips make it possible to test up to 18 drug candidates at a time.

Berdichevsky hopes to scale up his testing platform so that it can screen small-molecule inhibitor candidates in drug libraries. "What we're doing is early-stage drug target discovery. If we find that a molecule inhibits epileptic activity, that tells us what protein is causing epileptic activity and would be a good target for a drug. Once we find a target, we can let the pharmacological companies test drugs."

Berdichevsky, a faculty member in Lehigh's bioengineering program, began studying epilepsy five years ago at Massachusetts General Hospital, where he came up with the idea of testing multiple slices of the hippocampus.

Substances with a complex microstructure, from blood to polymeric liquids, exhibit changes in behavior when they are subjected to external forces. They may deform elastically or break apart. When combined with liquids and malleable solids, these substances change their properties in ways that researchers can exploit for practical uses.

Kelly Schultz, assistant professor of chemical and biomolecular engineering, is an expert in rheology, the study of minute changes, or deformation, in matter when a force is applied.

In one project, Schultz is investigating how synthetic hydrogel materials interact with human cells to build matrices for tissue regeneration. In another, she is studying chemically cross-linked gels. Schultz also studies the behavior of colloidal gels used in home care products and cosmetics.

Schultz recently won awards from TA Instruments, the leading manufacturer of rheological instruments, and the American Chemical Society's (ACS) Petroleum Research Fund.

TA Instruments named Schultz a Distinguished Young Rheologist and provided her with an AR-G2 Rheometer, which enables researchers to push, pull or tear fluid materials and measure the resulting effect, such as changes in stiffness or viscosity.

The new instrument will help Schultz develop polymeric hydrogel materials for wound healing, tissue regeneration and other medical applications. She and her graduate students are also developing microrheological techniques that measure how synthetic hydrogel scaffolds affect and interact with human mesenchymal stem cells.

"If we can better understand that process," she says, "we can make better materials that can manipulate cells and get them to do what we want."

ACS's Petroleum Research Fund awarded Schultz a $110,000 Doctoral New Investigator Grant for her studies of the material properties of chemically cross-linked polymeric gels, which are used in enhanced oil recovery and petroleum research. Her group is using rheology to try to gain a deeper understanding of the gelation process and to adjust it for the specific properties needed in this application.

Current methods of extracting crude oil involve fracturing minerals in the ground and using harmful chemicals to prevent water from entering those fractures.

"The gel would be inserted into the fracture to create a barrier against the water," she says. "We made it photo-polymerizable, which means it goes in as a liquid and becomes a gel when you shine light on it. This gel would provide a more environmentally friendly solution."

An unexplained attraction

Simulations illuminate the affinity between carbon nanotubes and DNA.

Carbon nanotubes (CNTs), hexagonal lattices of carbon atoms rolled into tubular shapes, are useful in a variety of applications. Different types of CNTs can be distinguished by their chirality, or the orientation of their atomic lattices. Chirality, in turn, determines a nanotube's properties.

"Our ability to use carbon nanotubes boils down to their chirality, but it's very difficult to synthesize a specific kind of nanotube," says Jeetain Mittal, assistant professor of chemical and biomolecular engineering. The typical production method—chemically synthesizing CNTs in an aqueous solution—results in a grab-bag of nanotubes having different chiralities.

Mittal's group is trying to develop a rational computational design method of sorting CNTs that could lead to high-purity, high-yield nanotube production.

Scientists know that short, single-strand DNA sequences are attracted to CNTs in solution, and that a particular DNA sequence adheres to a nanotube counterpart of specific chirality. The reason for the attraction is not understood, says Mittal, but the behavior has been used to isolate individual types of nanotubes.

"If you said, 'I would like this type of nanotube. Can you tell me which DNA sequence to use to isolate it?'—we can't do that without a lot of trial and error."

Mittal's group is trying to determine which possible structures DNA molecules take when they attach to nanotubes, and which structural motifs help explain that behavior. Because the structure of biological molecules defines their functions, the group hypothesizes that the function of DNA sequences around CNTs is also related to the structure of the DNA sequences.

The answer to this question could help solve the sorting problem and also make it possible to design DNA-CNT hybrids for cell imaging, chemical detection and other applications.

Mittal's group has conducted controlled experiments to examine how different DNA configurations behave around different types of nanotubes. They have found a range of behaviors that provide useful information on how certain DNA sequences work. They have employed computer models whose simulations provide information that is not accessible when using experimental techniques.

The group is now developing simpler, coarse-grained computational models. These are more efficient because they remove the representation of water molecules from the aqueous solution, and they represent large groups of DNA atoms with single beads.

"To get to the point where we can predict which DNA sequence will distinguish a specific CNT," says Mittal, "we need a simpler model. This will help us get to the relevant data much more quickly than a complicated model that takes a long time to run."

TAKING AIM AT ACID GASES

An "army of collaborators" receives a competitive DOE grant.

A coalition of seven research institutions has received an $11.2 million grant to streamline the removal of acid gases from large-scale energy applications.

The four-year award from the U.S. Department of Energy will be shared by the Georgia Institute of Technology, Washington University in St. Louis and the Universities of Alabama, Florida and Wisconsin, as well as Lehigh and Oak Ridge National Laboratories. The institutions have formed an Energy Frontier Research Center (EFRC) for Understanding and Control of Acid Gas-induced Evolution of Materials for Energy (UNCAGE-ME).

Georgia Tech is lead university for the project. Israel E. Wachs, director of Lehigh's Operando Molecular Spectroscopy and Catalysis Research Lab, is Lehigh's lead researcher.

Acid gases, including CO_2, sulfur oxides (SO_2), nitrogen oxides (NO_2) and hydrogen sulfide (H_2S), are generated by automobiles, fossil-fuel power plants, natural gas extraction, refineries, chemical manufacturing and other activities. Acid gases harm people, trees and crops. CO_2 and NO_2 are also greenhouse gases.

Scientists use membranes and sorbents to separate and concentrate CO_2 for carbon sequestration. Reactive catalysts convert acid gases to less harmful compounds. The performance and durability of these agents can be undermined by the degrading effects of acid gases. The researchers hope to prolong the lifetimes of the agents by better understanding how acid gases interact with them.

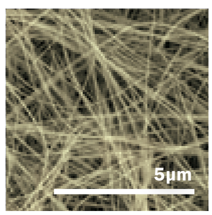
The researchers are performing molecular spectroscopic studies of the surface functionalities and bulk structures of membranes, sorbents and catalysts and combining these studies with multiscale computational and theoretical modeling of the agents' interactions with acid gases.

The project has four thrust areas—the interaction of acid gases with nonporous oxide-based solids, with disordered porous solids and with the external surfaces of porous materials; and the effect of defects and

Nanofiber processing becomes serendipitously easier

Animesh Kundu was doing research for his Ph.D. thesis when he inadvertently came upon a new and more efficient method of growing titanium oxide-based nanofibers.

In an effort to develop new strategies for processing ferroelectric thin films, Kundu added organic salts to stabilize the material. What he ended up with, however, were long (a few hundred microns) and ultrathin (less than 100 nm) fibers with a unique rectangular cross-section, as opposed to the circular cross-section typical of nanofibers.



"I realized these were oxide nanofibers, and that they represented an entire field of their own to explore," says Kundu, now a research scientist at the Center for Advanced Materials and Nanotechnology.

Current methods of processing titanate nanofibers require multiple steps and take 50 to 120 hours. Kundu's method requires a single step and a mere two to eight hours.

"I stumbled onto this," he says. "It was a complete accident, and really serendipitous."

With help from Lehigh's Office of Technology Transfer, Kundu patented the technology. The invention earned a National Innovation Award at the 2014 TechConnect World Conference and Expo in Washington, D.C.

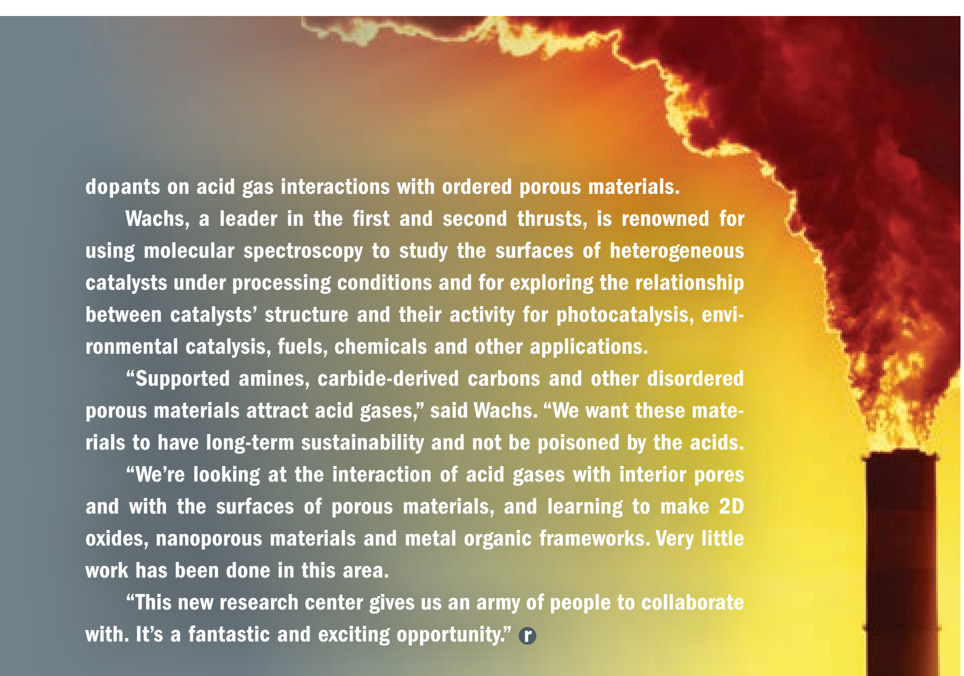
Titanate- and other oxide-based nanofibers have applications in solar cells and lithium ion batteries, as antimicrobial agents, and more.

Kundu grows the titanate nanofibers in water pressure-heated to 120 to 150 degrees centigrade. "The growth of the nanofibers is similar to the way minerals underwater are formed in hydrothermal conditions," he says.

The nanofibers contain titanium oxide powder, sodium hydroxide and other agents. Their composition can be tuned for specific applications.

At the TechConnect conference, a Nike representative suggested that Kundu weave the titanate nanofibers into antimicrobial fabrics. It's a promising idea, he says.

"I'm hoping to develop an application to bring more value to the nanofibers beyond lithium ion batteries. I have to find my own niche for this material."



dopants on acid gas interactions with ordered porous materials.

Wachs, a leader in the first and second thrusts, is renowned for using molecular spectroscopy to study the surfaces of heterogeneous catalysts under processing conditions and for exploring the relationship between catalysts' structure and their activity for photocatalysis, environmental catalysis, fuels, chemicals and other applications.

"Supported amines, carbide-derived carbons and other disordered porous materials attract acid gases," said Wachs. "We want these materials to have long-term sustainability and not be poisoned by the acids.

"We're looking at the interaction of acid gases with interior pores and with the surfaces of porous materials, and learning to make 2D oxides, nanoporous materials and metal organic frameworks. Very little work has been done in this area.

"This new research center gives us an army of people to collaborate with. It's a fantastic and exciting opportunity."

MAKING A MARK WITH MATERIALS

MRS Fellow tapped to help lead online* Science *journal.

Zakya Kafafi, adjunct professor of electrical and computer engineering, was recently named deputy editor for chemical, physical and materials sciences, and engineering of *Science Advances*, an online, open-access offshoot of *Science* magazine that will post original papers and review articles weekly.

"*Science Advances* will publish the crème-de-la-crème as far as scientific quality goes," says Kafafi, who is also a core faculty member of Lehigh's Center for Photonics and Nanoelectronics.

"One of our goals is to include papers that are really interdisciplinary in nature. We also want to create some excitement among new scientists, and give them a vision of what they can do to change the world."

Kafafi, author of 235 journal articles and several book chapters, has done pioneering work in organic optoelectronic materials and devices, leading to applications in flat panel displays and solid state lighting. She has earned an Edison Patent Award from the Naval Research Laboratory for inventing a method of patterning electrically conductive polymers and an R&D 100 Award for inventing a cryogenic link that moves vertically and rotates in a vacuum at very low temperatures.

In a collaboration with Filbert Bartoli, department chair of electrical and computer engineering; Ph.D. candidate Beibei Zheng; and Qiaoqiang Gan '10 Ph.D., assistant professor of electrical engineering at SUNY-Buffalo, Kafafi is studying metallic plasmonic nanostructures that are integrated within organic solar cells to improve their efficiencies.

Kafafi, a Fellow of the Materials Research Society, began her career doing research in low-temperature spectroscopy and then organic electroactive materials and organic light-emitting diodes.

"In the 1990s," she says, "there were no flat panel displays or smartphones. It has been very rewarding to see the impact of the science and research I was working on."

At the Naval Research Lab, where she worked for more than 20 years, Kafafi founded and directed the Organic Optoelectronics section. From 2007 to 2010, she served as head of NSF's Division of Materials Research.

"NSF has a policy that allows you to devote one day a week to research," says Kafafi. "That's 52 days a year, and if you add in weekends, you can get some serious work done."

A dose of optimization for rising healthcare costs

A model examines the critical roles of reinsurance and expenditure allocations.

The growing costs of healthcare and health insurance, says Aurélie Thiele, have opened up opportunities for engineers who are well-versed in the art of optimization.

Thiele, associate professor of industrial and systems engineering, is responding to the challenge by developing models that optimize the relationships among costs, risks and the options offered in employer insurance plans.

Despite vaults full of data and decades of experience processing claims, she says, the health insurance industry has done relatively little to optimize data to control costs.

"Human resource analysts develop plans that are relevant to their patient populations," says Thiele, "but without state-of-the-art quantitative tools there has been a lot of guessing."

Thiele is on sabbatical at MIT working with Dimitris Bertsimas, the Boeing Professor of Operations Research at the Sloan School of Management, to optimize the design of health insurance and reinsurance policies from the perspective of employers offering a menu of insurance policies for workers to choose from.

Based on previous claims data and the number of plans an employer wishes to offer, the researchers are developing a mathematical model that assesses parameters such as deductible size and coinsurance. They are examining whether reinsurance, in which an employer shifts the risk of inordinately large claims to a reinsurance company for a fee, can help decrease the premiums paid by employees.

Their goal is to help companies control costs, maintain fairness for lower-paid workers and protect against rare but expensive medical conditions.

Optimization uses big data and computational finesse to look at problems with many variables and achieve the best possible outcome, says Thiele, who co-directs Lehigh's M.S. program in analytical finance.

Choosing a healthcare plan can be daunting. Employers can select from as many plans as they want but usually offer workers only a handful of options to choose from. Some public health exchanges, on the other hand, make as many as 80 plans available.

"The literature says that too many choices paralyze customers," Thiele says. "There is a moment when it becomes too much information for the average person."

"It turns out that deductibles and reinsurance are the most important policy parameters."

—Aurélie Thiele

The proof-of-concept model that Thiele and Bertsimas are developing slices through data to address key questions: What options can be offered given the expenditures made by employers? What expensive conditions affecting only a few patients can be reinsured to spread risk over larger pools?

These questions involve large amounts of nonlinear data and are well-suited to optimization techniques, Thiele says.

Thiele and Bertsimas's preliminary findings show that companies' allocation of expenditures—between preventive and sick care, or pharmaceutical and surgical intervention—is critical.

"High-level decision-making is more important than the precise values of policy parameters," she says, "because it drives employee behavior." For example, helping employees feel secure seeking preventive care can reduce sick days, costlier treatments or hospitalization down the line.

"It turns out that deductibles and reinsurance are the most important policy parameters," Thiele says. If deductibles are too low, employees don't have enough of a personal investment. Maximum out-of-pocket limits, however, while reached by only a few, make a real difference in the lives of patients who are already sick.

Thiele's model also helps employers determine how much to reinsure against expensive cases that rarely occur. Reinsurance spreads these low-probability risks over a larger pool, she says, and evidence shows that it keeps premiums down for everyone in a group.

So far, Thiele and Bertsimas are working with data from known care and cost trends. Their model is open, allowing companies to understand how it will use their sensitive data. The researchers are also breaking their model into small parts so that practitioners with different experience in insurance, surgery or family practice can see how it is relevant to them.

This approach is new for Thiele's branch of engineering. "A lot of industrial engineers look at healthcare as if patients were products in a warehouse," she says, "because they understand those flows very well."

Addressing the nation's health insurance challenges, however, requires more than a simple application of existing technology.

"Optimization improves what we are able to do by a significant factor. We have to create new models and frameworks to be able to help the health insurance industry and patients."

Automation for greater software security

Computer scientists design an interactive scheme with multiple layers.

As information technology connects people in ever more elaborate ways, says Gang Tan, the variety, and the backlog, of software programs that require protection from hackers, bugs and coding errors is growing rapidly.

Tan, an assistant professor of computer science and engineering, and his collaborators are designing a system that will retrofit existing software to provide "defense-in-depth" protection.

The group, which also includes researchers from Penn State and Rutgers universities and the University of Vermont, recently received a four-year grant from NSF.

The group is designing a system that helps operators determine what data in a software system needs protection, and which entities should have access to that data. Then it inserts security checks to perform authorization and to authenticate users for privileges.

"As long as the security policy for software stays the same during an upgrade or when features are added," says Tan, "our system can produce security checks to enforce the policy. At every point on the way, from the creation of an app to an add-on or upgrade, our system can add these checks according to an existing policy."

Typically, says Tan, software developers write security codes to prevent unauthorized access to critical data. This is usually done manually, and the process is error-prone, time-consuming and not scalable. As a result, unauthorized users can gain access to restricted data. And the security checks need to be updated each time the operating system or critical software on a device is upgraded or adds a new functionality or feature.

Tan's group wants to automate this process by adding three layers of defense-in-depth to software: authorization to restrict access to sensitive data to authenticated users; containment to limit damage from security breaches; and auditing to monitor software as it is operating so developers can be informed of the need for additional defenses.

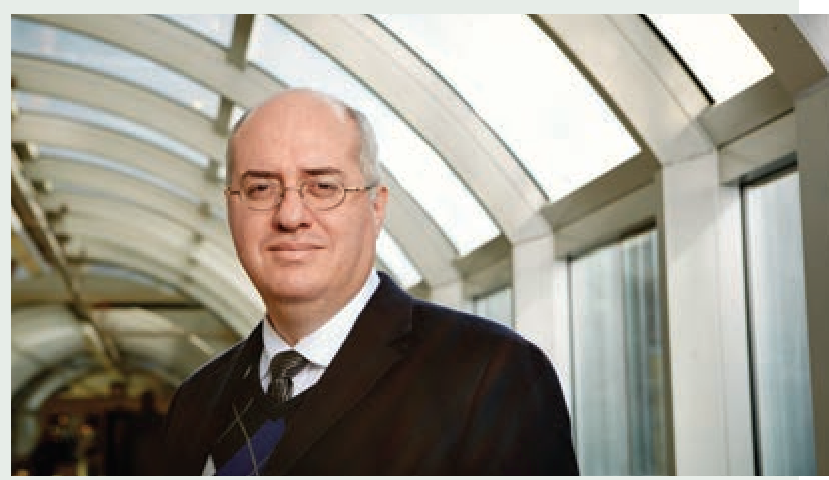
The group is creating synergies among the three layers of protection and designing its system to add security checks automatically to the security policies of existing software.

"Our system can add multiple layers of protection according to a security policy," Tan says. "It can handle upgrades without user involvement, and it will explore the interaction among these layers to achieve greater efficiency and security."

Using a technique called the principle of least privilege, the system assigns separate security checks to separate components of the system so that if one component of the software has been compromised, other components can continue to function.

AI EXPERT NAMED NSF PROGRAM DIRECTOR

Hector Muñoz-Avila has begun a two-year rotation.



Hector Muñoz-Avila, associate professor of computer science and engineering, has applied his expertise in artificial intelligence (AI) to a broad variety of endeavors in the last few years.

Using AI and sensors, Muñoz-Avila is helping structural engineers predict when bridges will fail. Using the principles of goal-driven autonomy, a field in which he is a pioneer, he is helping electrical engineers orchestrate the components needed to generate energy from ocean waves.

In a collaboration with psychologists, Muñoz-Avila is developing computational models based on neural networks to represent semantic interference and other phenomena that occur inside the brain.

Recently, Muñoz-Avila was asked by NSF to serve as a program director in its Directorate for Computer and Information Science and Engineering in Arlington, Va. Last fall, he began a two-year rotation in the Robust Intelligence Cluster of the directorate's Division of Information and Intelligent Systems (IIS).

NSF program directors make recommendations about proposal funding. They help shape the nation's direction in science, engineering and education and in the defining of new funding opportunities.

The NSF appointment comes on the heels of a sabbatical Muñoz-Avila spent at the Norwegian University of Science and Technology (NTNU) in Trondheim, where he studied the application of AI to deep-sea oil-drilling rigs. The goal of the project is to avoid expensive shutdowns by predicting when physical systems might fail.

One common theme to his varied research activities is the application of case-based reasoning and other AI techniques to intelligent systems, or agents, that have the ability to sift through thousands of stimuli and data points, and to pinpoint and correct unusual patterns or anomalies. These agents can be robots, automated computer game players or systems that monitor an electrical grid. Their ability to learn from their experiences and mistakes and to take corrective action without human intervention is part of the new field of goal-driven autonomy.

In 2012, Muñoz-Avila received a three-year research grant from NSF to develop autonomous agents that dynamically identify and self-select their goals, and to test these agents in computer games.

INTERVIEW BY **KURT PFITZER AND CHRIS LARKIN** PHOTOGRAPHY BY **CHRISTA NEU**

A SUPPORT STRUCTURE FOR INTEGRATED SCIENCE

PERIODIC REINVENTION, SAYS LEHIGH'S NEW PRESIDENT, REJUVENATES RESEARCH.

John D. Simon, executive vice president and provost at the University of Virginia (UVA), will become Lehigh's 14th president on July 1. Simon's research interests span the structure and function of melanin, ultrafast chemistry, atmospheric chemistry and the interactions between proteins and functionalized nanospheres. At UVA, Simon helped launch the Data Science Institute and Advanced Research Institute while establishing a Center for Global Inquiry and Innovation, a major in global studies and a physical presence in Asia. Previously, he was vice provost for academic affairs and chair of chemistry at Duke University and professor at the University of California at San Diego. Simon holds a Ph.D. from Harvard University.

Q: ***How did you come to be interested in the structure and function of melanin?***

A: When I was at Duke, I had a postdoctoral fellow, Susan Forest, who was interested in Seasonal Affective Disorder and wondered if it was tied to photoreceptors in the skin. The dominant photoreceptor in the skin is melanin. We started reading as much as we could about melanin. There were hundreds of relevant papers at the time, but we quickly realized that no one knew much about melanin's chemical structure. So we decided to see what we could learn about the molecular structure and relationships between structure and function. We ended up studying intact organelles from squid, and human brains and eyes.

Along the way, we learned that a tremendous amount of calcium is bound by melanins, and there were conjectures that melanin might play a role in calcium regulation. We determined the first association constants between intact pigment granules and calcium. We did spend a lot of time trying to elucidate the molecular structure of melanin, but never figured it out. You can put that particular project in my failure column. My standard line now is that the structure of melanin will be figured out when the right chemist tackles the problem.

Q: ***What did you learn from this project?***

A: We learned that projects like this require interdisciplinary teams to tackle and make advances. In one area of our research—the changes in retinal melanosomes that occur with aging—we worked with researchers around the world, each of whom brought a different expertise to the problem. Together we were able to provide new and important insights into changes in the melanosome that account for functional changes of the pigment. There's certainly a role for chemists to play, but we learned that to have an impact, this is not a problem that can be addressed solely by chemistry.

I believe that the best science I've ever been involved in is our work on melanin—but I never would have gotten tenure in a traditional chemistry department for doing it. My colleagues would not know how to judge the work. And yet I think this work exemplifies where scientific research is going: In more and more complex problems, people will work in teams, each person contributing a piece to the puzzle that results in a larger impact. This is the nature of interdisciplinary work.

Q: ***Your study of a squid ink sac preserved from the Jurassic Period was published in the* Journal of the Proceedings of the National Academy of Sciences. *How did this project begin?***

A: This project has been a blast. One of my collaborators on the project, Philip Wilby, a geologist with the British Geological Survey, was reading the records of the construction of a railway from London to Wales. The record described a squid kill the crew had stumbled on while digging the railway. With an estimated location for the site, an excavation was done and Wilby found an intact squid ink sac from the Jurassic Period—the only fully intact one ever recorded.

Wondering whether the pigment in the ink sac differed from the pigment in modern squid ink sacs, Wilby approached Shosuke Ito, a Japanese chemist who is a guru in melanin chemistry and one of my closest collaborators. In the end, researchers from Japan, the U.S., India, England and Poland looked at this from a variety of angles. We couldn't detect any differences between the Jurassic sample and modern-day melanin, indicating there's been essentially no evolution in the structure of the pigment or the morphology of the granules, etc., in squid for over 200 million years.

Q: ***You have explored a wide range of research interests.***

A: I think the days are over when a researcher starts in a particular field of study and stays there for an entire career. You have to reinvent yourself periodically because the problems of interest in the scientific community change. You have to have a more open view about what you can get passionate about, what you can do yourself, what you can do in teams. I think a research university today has to structure itself to support this.

Q: ***As president, do you hope to build on Lehigh's strengths in interdisciplinary programs?***

A: Yes. I'm hoping faculty and employers will provide guidance. If we educate students in interdisciplinary spaces, we need to make sure there are career opportunities after graduation. A lot of institutions struggle with balance—giving students breadth in coursework as well as the skills they need for today's workforce. I think Lehigh's interdisciplinary programs do both.

Q: ***How well are we preparing K-12 students to pursue STEM careers?***

A: I have a high school senior and a high school junior. One is interested in engineering, one in biology. I don't think their high school experience has truly exposed them to the excitement of science. They have a lot of homework problems to solve, but they don't know what problems scientists are tackling today. Exposing students to what's happening in the world of scientific research today could create the passion to become a scientist and contribute to advancing our quality of life.

We aren't educating our teachers to teach that way. The STEM dropout rate is a serious national issue. And I always get pushback when I raise the issue of whether we should be teaching integrated science or individual disciplines in high school. If you ask average high school graduates whether photosynthesis is a problem in biology, chemistry or physics, I think very few would say all three.

I had a colleague at Duke, David Needham, an engineering professor, who framed a course around the question of "How did Nature solve the x problem?" You ask why something works—how proteins replicate DNA, for example—and you find out this is a very interdisciplinary question with biological, chemical, mathematical and physical components and that proteins are one of the beauties of true engineering. Students are much more motivated when they're trying to understand why something works than when they're memorizing a set of rules.

Q: ***How soon should undergraduates start doing research?***

A: Immediately. I used to take freshmen from our introductory courses at UCSD and Duke, put them in the lab and cross my fingers. If they stayed interested, by their senior year they were as motivated as any graduate student. Undergraduates are so hungry for the opportunity to be part of the discovery process that you never know what idea they might come up with. They're unencumbered by everything you think you know. I've written a lot of papers with undergraduates, many on topics that were unplanned.

Q How does this need for balance pertain to modern engineering education?

Engineers today need skills that go beyond mastering their field of engineering. They need to understand the world they aspire to impact with their inventions. You can design a product for delivering clean water in sub-Saharan Africa, but if it is culturally something that the population won't use, you're not going to have any impact. So I think engineers need to understand culture, politics and history, finance and entrepreneurship, to place their solutions—based on science and technology—in the context of the populations that are to use them. All this also requires good communication skills.

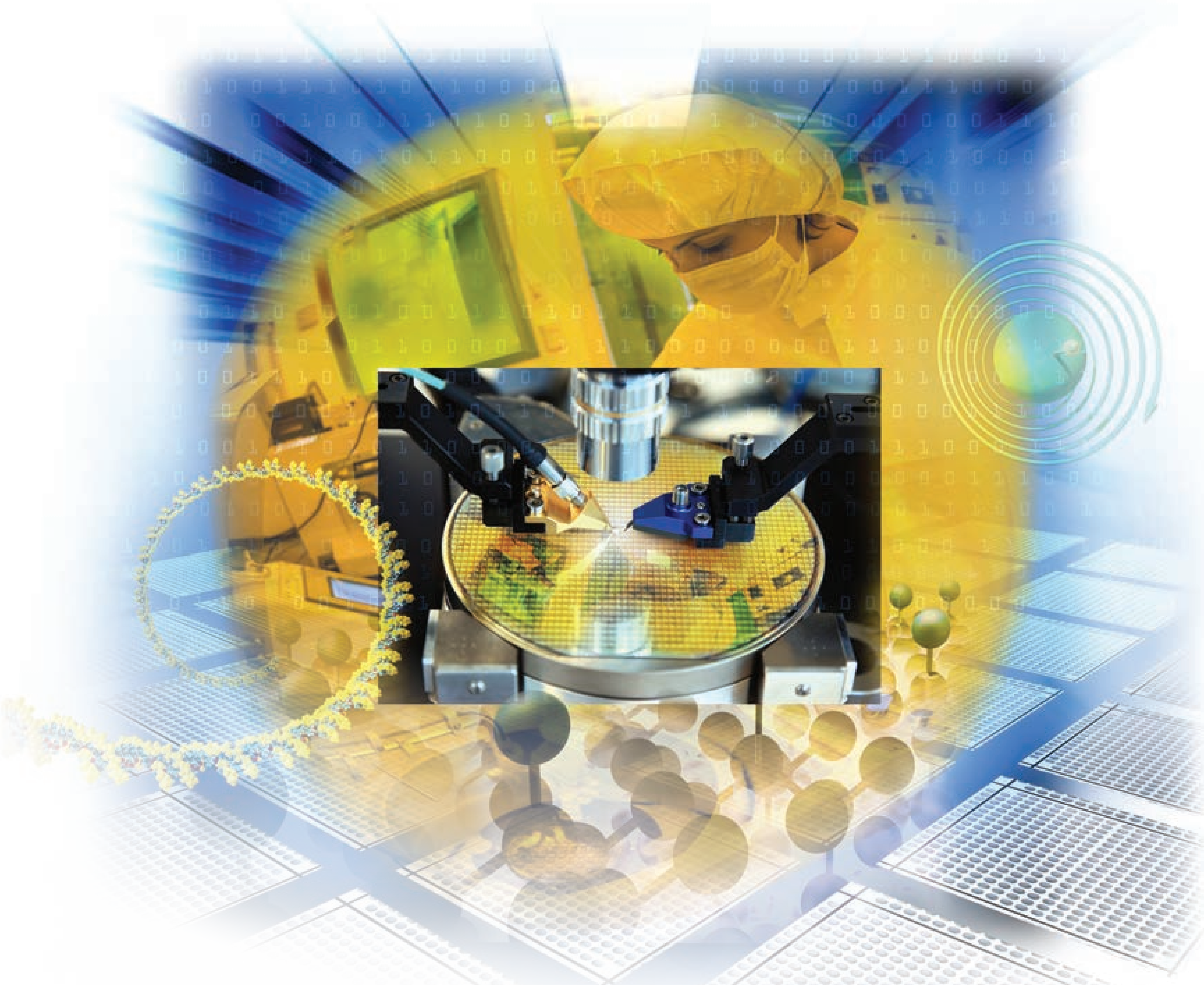
Q: ***How can universities increase the participation of women and underrepresented groups in engineering?***

A: In regard to underrepresented groups, I think students enroll with the same level of intelligence and motivation but with different backgrounds and different levels of access to college preparation. The question then is, "What are we doing institutionally to support these students and ensure that they have the right tools to succeed?" They may doubt whether this is the profession for them, because they see few people with like backgrounds.

In regard to attracting and retaining more women faculty, at Virginia, we've looked at a lot of things—how offices and lab space are assigned, committee loads, whether or not we have any unintended bias. As provost, I've felt that you must be vigilant about developing diverse candidate pools and making an effort to reach out to candidates.

Q: ***What is your most memorable accomplishment?***

A: In my junior year of college, I obtained my first piece of research data; I was using spectroscopy to probe the complex formed between trivalent europium ions and crown ethers. It was the first time I knew something that no one else in the world knew. I remember this moment because I was really excited, and I wanted to share it with friends who frankly couldn't care less. The sense of discovery was motivating to me. I knew at that moment, that if I could make it, I was going to be a scientist. I remember that day as if it was yesterday. It changed my life.



MOVING AT WARP SPEED

STORY BY **RICHARD LALIBERTE** ILLUSTRATION BY **LINDA NYE**

ADVANCED TECHNOLOGIES ADD UP TO INNOVATION IN MANUFACTURING

Every block of stone, Michelangelo once said, contains a statue inside. It is the task of the sculptor to discover that statue and to reveal it by scraping away every superfluous layer of stone until its final form takes shape.

Many traditional manufacturing processes—trimming wood on a lathe, cutting sheet metal to form a car body—work in a similar way: by removing material. But in recent years, another concept has gained momentum in industry and in home workshops: additive manufacturing, or what the general public often thinks of as 3D printing.

"Additive manufacturing is the complete opposite of traditional manufacturing," says Brian Slocum, who directs the Wilbur Powerhouse and Design Labs, the hub for manufacturing innovation at Lehigh. "You add material to get a part where nothing existed before."

Additive manufacturing falls under the broader umbrella of advanced manufacturing, which describes the application of new technology—often at the nanoscale—to make better products, more efficiently, with improved materials and processes.

The potential for innovation in advanced and additive manufacturing is enormous, say Lehigh researchers.

"You can make materials that are hard, soft, biological, conductive, biodegradable, or with a variety of combined properties," says James Gilchrist, the Class of 1961 Professor of Chemical and Biomolecular Engineering. "The sky is the limit, but the science still has a lot of open questions."

A NATURAL EXTENSION

3D printing burst into the public imagination in recent years as inexpensive machines like MakerBots became available at prices lower than some home computers. But the technology to create objects by depositing successive layers of material—once known as rapid prototyping or rapid tooling—has been used for years in automotive design and other industrial applications.

Additive and advanced manufacturing are built on foundations that are longstanding Lehigh strengths, one of which is the science of joining materials, or welding.

"A lot of additive manufacturing is based on welding processes," says John DuPont, the R.D. Stout Professor of Materials Science and Engineering. "When a welder deposits weld metal onto a surface, that's similar to a printer depositing material onto a surface."

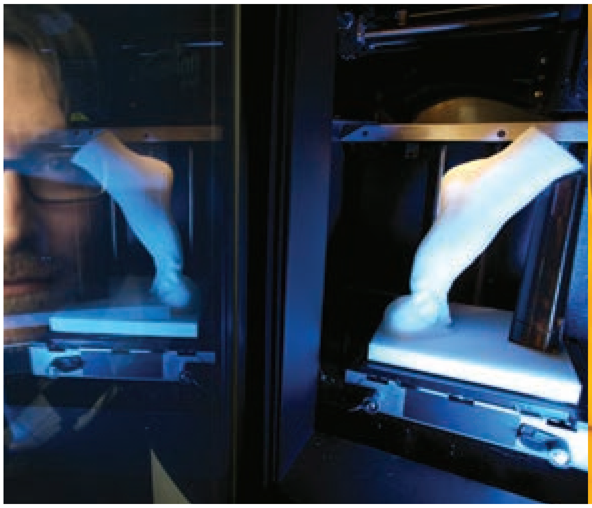
In advanced manufacturing, says DuPont, new alloys and new parts are welded together to make products. The materials are subjected to entirely different thermal conditions—wide-ranging temperatures, fast or slow heating and cooling—from the conditions used during a part's manufacture.

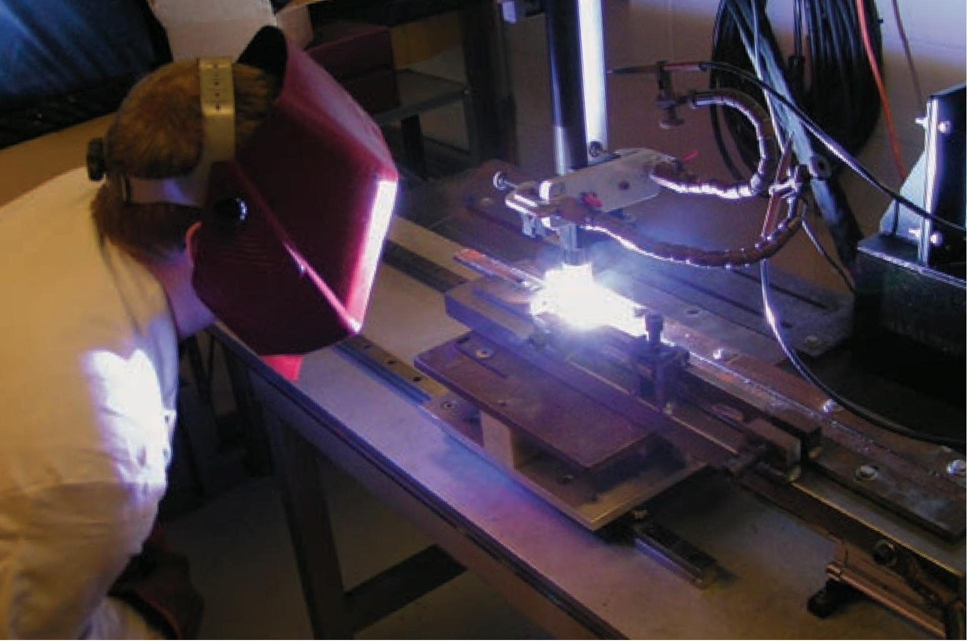
"The atomic characteristics and microstructure—which are carefully controlled by the alloy producer—change considerably," DuPont says.

These changes can cause parts to fail, especially during applications involving extreme conditions. DuPont and his students are working with alloy manufacturer Special Metals to determine why welding causes a high-performance nickel alloy—used in advanced, ultra-supercritical coal-fired power plants—to lose 30 percent of its strength.

This collaboration is funded by industry and the NSF as an Industry-University Cooperative Research Center that includes four universities (Lehigh, Ohio State, Wisconsin-Madison and the Colorado School of Mines) and 32 supporting members from industry and national laboratories (Los Alamos and Oak Ridge).

"YOU CAN MAKE MATERIALS THAT ARE HARD, SOFT, BIOLOGICAL, CONDUCTIVE, BIODEGRADABLE, OR WITH A VARIETY OF COMBINED PROPERTIES. THE SKY IS THE LIMIT." —James Gilchrist





By observing nanoscale changes to weld structure, DuPont's group determined why a high-performance nickel alloy was losing strength during welding.

The partnership, called the Center for Integrative Materials Joining Science for Energy Applications, has doubled from 16 to 32 industrial partners in its first five years, says DuPont, who directs the center's Lehigh site.

DuPont's group, led by Ph.D. candidate Dan Bechetti, is investigating the nickel alloy welding problem, utilizing Lehigh's state-of-the-art electron microscopy and welding labs to understand changes to weld structure at the micro- and nanoscales.

"Five or six theories could have explained what was happening to the alloy," DuPont says. "Dan had to figure out which one was right. Now that we know, we can work on solutions." The group published its findings in two articles in the journal *Metallurgical and Materials Transactions*.

RUNNERS, AND A FOURTH DIMENSION

Much of additive and advanced manufacturing involves flowing polymers. Polymer flows form the basis for manufacturing via injection molding, but engineers do not yet fully understand what happens to molten material as it flows through conduits called runners, nor what the final properties of materials are once they form products.

Industry typically hasn't placed great importance on the runners, says John Coulter, professor of mechanical engineering and mechanics and associate dean for graduate studies and research.

"The mindset has been that you just take circular tubes and push hard so material comes out the other end," he says. "Until recently, no one considered what was happening inside the runners. But what goes in is not the same as what comes out."

With NSF funding, Coulter and his students have explored a technique called melt rotation, which modifies shear strain rate patterns inside runners so that polymers flow more consistently and parts form with more uniform properties. The group is also researching hot runners, which keep material molten until it reaches product cavities in order to help reduce waste and boost efficiency.

"That's difficult to do with some materials," he says. "We're trying to advance the utilization of hot runner systems further by understanding the process better."

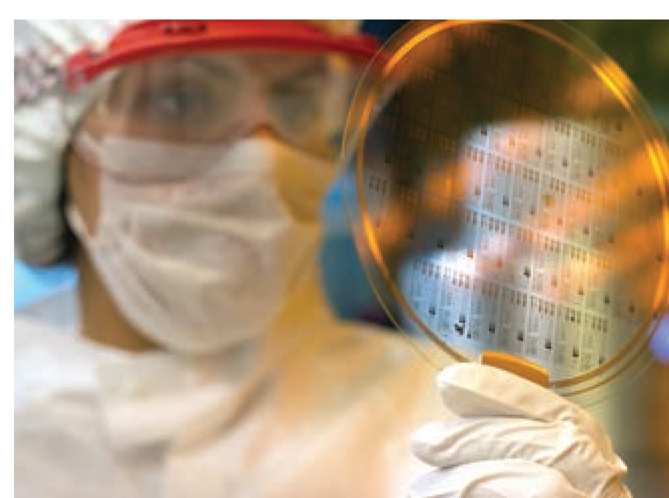
Once a part is formed, its properties can vary according to how the material's molecules are oriented. A process called melt manipulation, which Coulter has explored with NSF funding, can control this orientation and influence a variety of parameters such as optical and mechanical properties, biodegradation and strength.

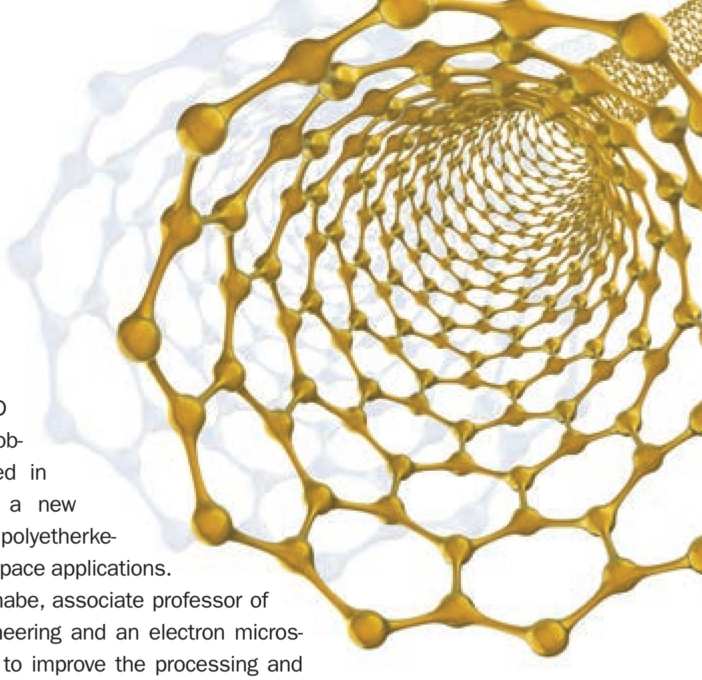
"Two parts can look identical, but one—and we've seen this at Lehigh—can be 60 percent stronger if you manipulate its internal molecular orientation distribution, even though both parts are made of the same material," Coulter says. This can be expanded to advanced additive manufacturing, which, he adds, can be thought of as 4D printing—with greater control over material properties being the fourth dimension.

Coulter and Sabrina Jedlicka, assistant professor of materials science and engineering, are using these material variations to develop biodegradable scaffolds for growing tissue—a promising application for additive manufacturing. They're also working with Xuanhong Cheng, associate professor of materials science and engineering, to develop plastic products with carefully designed micro- and nanoscale surfaces that could be used in medical devices such as virus-separation products and "smart" petri dishes tailored to grow specific cells and viruses. The scale-up of the nanomanufacturing is being addressed

"TWO PARTS CAN LOOK IDENTICAL, BUT ONE CAN BE 60 PERCENT STRONGER IF YOU MANIPULATE ITS INTERNAL MOLECULAR ORIENTATION DISTRIBUTION."

—John Coulter





with partners at the Georgia Institute of Technology and the University of Puerto Rico at Mayagüez. The group is pursuing initial commercialization with NSF funding.

In a similar project, Yaling Liu, who directs Lehigh's Bio-Nanomechanics Lab, is working with researchers from the University of Pennsylvania to create a chip etched with micro- and nanogrooves that selectively trap circulating tumor cells (see page 18).

MULTIPLE ROLES FOR NANOCOMPOSITES

Ray Pearson, professor of materials science and engineering, has been pursuing applications for polymer nanocomposites for 10 years with funding from NASA and the Semiconductor Research Corporation (SRC). NASA hopes nanocomposites can toughen fiber-reinforced composites in aerospace applications. SRC hopes they can toughen polymers in microelectronic packaging.

"Nanoparticles can be effective toughening agents," says Pearson, "but they often impart a significant increase in melt viscosity, which can be a show stopper in many applications."

Pearson directs Lehigh's Center for Polymer Science and Engineering, which hosted its ninth annual SPE Polymer Nanocomposites Conference in October and included a session on nanocomposites for 3D printing. His introduction to additive manufacturing came in 2013 when Martin Harmer, professor of materials science and engineering, asked him to collaborate with 3D Systems in Langhorne, Pa., on a polyamide 12-based selective laser sintering (SLS) project.

"SLS is a perfect match for polymer nanocomposites," he says, "because the process doesn't involve long flow lengths—the particles simply fuse together. The trick is how to treat SLS powder with inorganic nanoparticles. This was the focus of a research project funded by RAMP [Research for Advanced Manufacturing in Pennsylvania] and continues to be an area of interest in RAMP2 [Research for Additive Manufacturing in Pennsylvania]."

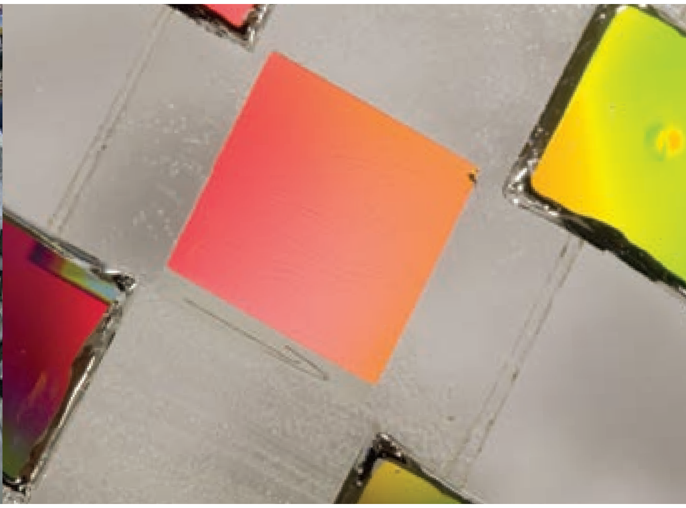
In his RAMP2 project, Pearson is working with 3D Systems and Arkema, a global materials company based in France that is developing a new high-temperature polymer, polyetherketoneketone (PEKK), for aerospace applications. Pearson and Masashi Watanabe, associate professor of materials science and engineering and an electron microscopy expert, are attempting to improve the processing and mechanical properties of PEKK-based nanocomposites. Graduate students Binay Patel, Samantha Tumolo and Yuanyuan Wang and undergrads Christina DiNapoli and Chris Watson are working on the project. America Makes and the Pennsylvania Department of Community and Economic Development are providing funding.

DIES, DIALYSIS AND MAGNESIUM

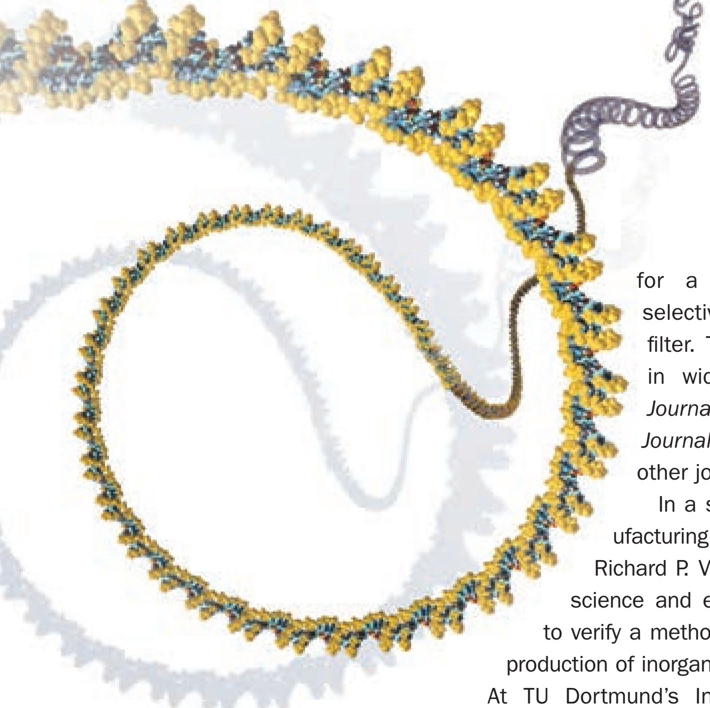
Wojciech Misiolek, director of Lehigh's Institute for Metal Forming, has worked two decades in rapid prototyping and rapid tooling. With Stephen Rock, his former Ph.D. student at Rensselaer Polytechnic Institute, where Misiolek worked before joining Lehigh's faculty in 1997, he's published papers on freeform powder molding, a patented rapid prototyping technology.

In the past decade, Misiolek has turned his attention to advanced manufacturing, using Lehigh's scanning and transmission electron microscopes to gain an atomic-level understanding of the behavior of metals and alloys used in medical, energy and automotive applications.

In one study, Misiolek and his students tested heat-treated anodic aluminum oxide as a possible material



Graduate student Forough Mahmoudabadi (left) examines a thin-film transistor made of indium gallium zinc oxide; (below) nano-molded optical diffraction gratings fabricated in Coulter's lab.



for a nanoporous and more-selective ceramic kidney dialysis filter. They reported their results in widely cited papers in the *Journal of Membrane Science,* the *Journal of Materials Science* and other journals.

In a study utilizing additive manufacturing technology, Misiolek and Richard P. Vinci, professor of materials science and engineering, are attempting to verify a method for the customized mass production of inorganic medical implants.

At TU Dortmund's Institute for Forming Technologies and Lightweight Construction in Germany, where he has been Mercator Visiting Professor for four years, Misiolek has investigated new methods of recycling aluminum chips to improve aluminum recovery. His group found that special extrusion dies improved the metal's mechanical properties by allowing more strain and shearing during metal flow. Misiolek has advised four TU Dortmund students, three of whom have received Ph.D.s.

Misiolek has also worked with researchers in Colombia, Brazil, Norway, Australia and New Zealand. In a study for a consortium comprised of the U.S. Department of Energy and U.S. automakers Ford, Fiat-Chrysler and GM, his group determined the optimal concentrations of cesium and zinc in a magnesium alloy proposed for use in lighter-weight (than aluminum) front-end car structures. The alloy improved magnesium's ability to deform without compromising its strength or its ability to bear loads, a critical property for the geometrically complex shapes of auto parts.

Currently, Misiolek's group is working with TE Connectivity to determine if direct laser sintering/melting (DLS/M) processing techniques can complement or replace existing methods of fabricating copper conductors. Misiolek and Watanabe are co-principal investigators on the project, which is supported by RAMP and includes Ph.D. candidates Anthony Ventura and Austin Wade.

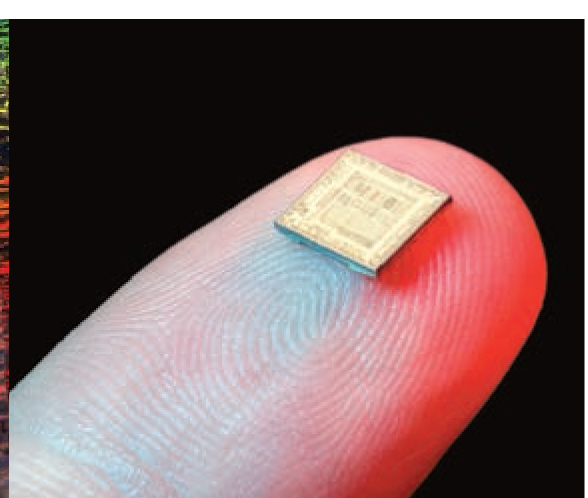
Lehigh is acquiring a DLS/M unit that uses computer-controlled high-powered laser energy to heat metal or ceramic powders and layer them progressively to create solid forms along multiple axes. Principal investigators for the project are Misiolek; Harmer, a ceramics expert; and Sudhakar Neti, professor of mechanical engineering and mechanics and a heat-transfer expert.

"DLS/M processing techniques cause most materials to exhibit different properties in the X, Y and especially Z axes," says Misiolek, who is also the Loewy Professor of Materials Forming and Processing. "One of our challenges is to understand how properties can change, especially if you alter the parameters of a deposition process."

Funding from the Loewy Family Foundation allows Lehigh to host one or two visiting professors each year.

"BECAUSE OUR STUDENTS HAVE ACCESS TO A VARIETY OF ADDITIVE TECHNOLOGY TOOLS, THEY WILL BE BETTER SUITED TO UNDERSTAND ALL THE NEW TECHNOLOGIES, NOT JUST A FEW."

— Brian Slocum



TINY, POWERFUL COATINGS

It's one thing to learn how things work at the nanoscale in the lab and another to apply that knowledge on an industrial scale. "An iPhone is cool," says Gilchrist, who directs the Laboratory for Particle Mixing and Self-Organization. "The process of making a million iPhones is cooler. That's manufacturing—the idea that you can scale up amazing technology."

Scaling up is also critical to coating technology, says Gilchrist. A product or part's properties can be altered simply by coating it with microscopic layers of particles. Gilchrist's group is working with Nelson Tansu, the Smith Family Endowed Director of the Center for Photonics and Nanoelectronics, to coat LED lights with particles that behave like tiny lenses.

"The light efficiency of the LEDs more than doubled," says Gilchrist, "without changing anything about the process except putting a nanoscale layer on top."

One method of applying particles to a coating is to dip the material that is being coated through an interface that deposits particles on a substrate.

"There's a well-known process for this called Langmuir-Blodgett deposition," Gilchrist says. "The problem is, it's not scalable."

But what if the deposition could be done on a roll of material resembling the rolls of newsprint being inked at a printing plant? That's the idea behind Gilchrist's recent acquisition of an automated Langmuir-Blodgett apparatus. The device, one of only a few of its kind in the world, uses fluid mechanics to carry particles that self-organize on a moving carrier fluid like a conveyer belt. It has enabled Gilchrist's group to deposit particles on coatings 100 to 1,000 times faster than would be possible using the dipping method.

"This is a big deal," Gilchrist says. "Every time I show the apparatus to industry or academia, they ask if they can use different particles, use different fluid or make it go faster. We're working on all three.

"Making layered structures to form a nanocomposite is not unlike additive manufacturing. We're thinking about how to extend this so we can coat 3D objects that are more complex than a flat substrate."

A HUB FOR INNOVATION

The Wilbur Powerhouse, which will house the DLS/M unit, has become Lehigh's additive manufacturing center. Students from any academic department may use a range of tools, including eight MakerBot machines and eight similar new Ultimaker 2s.

"Students use the printers 24-7," Slocum says. "It's insane how much they get used."

At first, Slocum was skeptical about providing a 3D printer to any student who wanted to use it.

"I thought they'd be printing key chains and trivial things," he says. The first MakerBot went into the Powerhouse lab with no fanfare or advertisement—only the machine and a sign saying it was available.

"Within a week, just by word of mouth, there were lines to use it," Slocum says—not for key chains, but for tests, prototypes and products for design and engineering classes. The same thing happened when he added a second machine.

"The uses were so well-aligned with Lehigh's education mission that we quickly developed a bank of 16 printers."

Wilbur Powerhouse also stocks a professional-grade FDM (fused deposition modeling) machine, a photopolymer deposition machine that makes stronger parts by curing high-resolution printed resins with ultraviolet light, and a full-color 3D printer that can produce multiple colors in a single object.

Professors incorporate the machines into their classes. In Mechanical Behavior of Materials, taught by Vinci, students produce an imaginary replacement part for a Mars rover. They compete to find the strongest and most efficient design and to determine which printer technology and materials would prove most useful to astronauts on a repair mission.

"On the last day, there's a competition that tests parts to failure," says Slocum. "The lightest, strongest part wins a prize—which we also print, of course."

"MAKING LAYERED STRUCTURES TO FORM A NANOCOMPOSITE IS NOT UNLIKE ADDITIVE MANUFACTURING." —James Gilchrist

Additive manufacturing technology, says Slocum, removes the technical roadblocks to innovation.

"Prototyping used to intimidate students. To take a virtual model and actually fabricate something required a huge knowledge base that many students didn't have, along with 12 to 14 tools and at least a week and a half of time."

If a product didn't turn out, students had to start the difficult fabrication process from scratch. Months could pass before a design became a finished prototype.

"Now," says Slocum, "students hit 'print' and have their part. If they need a new version, they adjust the software and print one in 20 minutes. The barrier between virtual and physical worlds doesn't exist anymore."

In Manufacturing, a class taught by Dr. David Angstadt of mechanical engineering and mechanics, students use 3D printing to make tooling for injection molds that produce small metal racecars.

"The mold wasn't as strong as one traditionally made from aluminum or steel, but getting to an actual part was much faster and cheaper," Slocum says. A YouTube video showing the result has generated calls from all over the country asking for more information.

Thanks to the Powerhouse and to Lehigh's numerous collaborations with industry, students gain the real-world experience and hard-to-find technical knowledge and skills that employers are increasingly seeking, says Slocum.

"Because our students have access to a variety of additive technology tools, they will be better suited to understand all the new technologies, not just a few.

"Additive manufacturing is moving at warp speed and there's a lot of room to grow."

Students work to improve the light-extraction efficiency of LEDs (near left) in the Center for Photonics and Nanoelectronics; silica particles coating a silicon wafer (far left) generate a rainbow of colors.

TAKING THE PULSE OF THE MARKET

STORY BY **KURT PFITZER**
PHOTOGRAPHY BY **RYAN HULVAT**

Engineers seek to commercialize a compact breathing device.

Kothare and Sircar believe their technology will reduce MOC weight while supplying more oxygen.

If you've seen the growing number of TV ads for breathing devices, it won't surprise you that the National Institutes of Health ranks chronic obstructive pulmonary disease (COPD) as the third-leading cause of death in the United States.

COPD includes a suite of progressive and incurable illnesses, led by emphysema, which reduce the quantity of air flowing into the lungs. This occurs when the tiny airways in the lung lose their elasticity, fill with mucus or become inflamed, or when the walls between airways are destroyed.

To get the oxygen they need, COPD patients were once confined to their beds and connected by breathing tubes to machines filled with compressed oxygen. To leave their homes, they had to carry a cylinder of oxygen or haul a tank on a dolly.

In the past two decades, portable, battery-operated medical oxygen concentrators (MOCs) have enabled many COPD patients to carry on daily activities and even travel.

Mayuresh Kothare, Shivaji Sircar and their students have developed a bench-scale model of an MOC that they believe will significantly exceed the performance of commercial MOCs and improve quality of life for COPD patients.

Kothare, department chair of chemical and biomolecular engineering, and Sircar, adjunct professor, have worked five years on the project. Kothare specializes in constrained and optimal predictive control theory. Sircar, an expert in adsorption science and technology for gas separation, has many years of industrial experience.

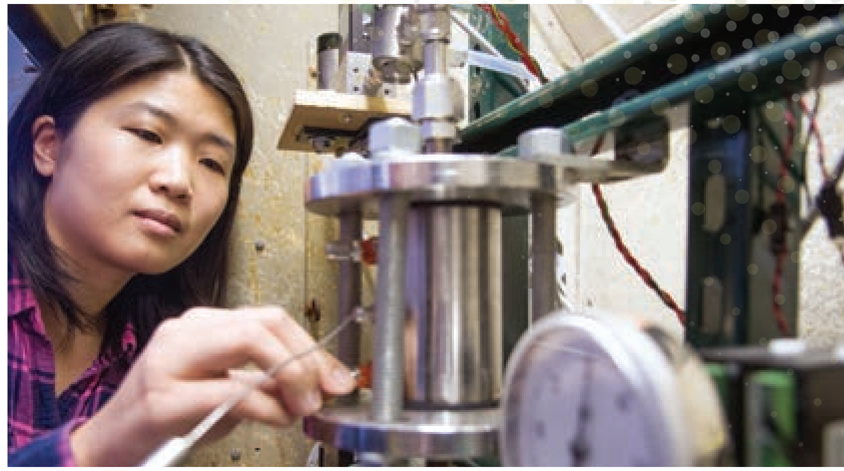
The researchers have one patent with a second pending on a technology that would reduce an MOC's weight while increasing its ability to recover oxygen from the air. They have received funding from the University Science Center in Philadelphia and grants through NSF's Innovation Corps (I-Corps) and Partnership for Innovation: Accelerating Innovation Research-Technology Translation (PFI:AIR-TT) programs. The support has helped the group gain entrepreneurial skills.

Smaller, lighter, faster

The bench-scale MOC developed by the Lehigh group improves on current technology in several critical parameters.

Like most commercial MOCs, the Lehigh MOC can be plugged into a wall socket or operated with batteries. It uses a rapid pressure swing adsorption process (RPSA) to generate roughly 90-percent-pure oxygen (O_2) from compressed ambient air that contains only about 21 percent O_2.

The Lehigh group has reduced device size by employing a single column of adsorbent to separate nitrogen (N_2) from O_2, as opposed to the two or more columns found in conventional MOCs. This scheme allows the use of a simpler process control system employing fewer switching valves and related hardware. The Lehigh MOC has also demonstrated the ability to produce 1 to 3 liters per minute or more of 90-percent-pure O_2 from compressed ambient air with process cycle times of 3 to 6 seconds. This



Ph.D. candidate Chin-Wen Wu has helped validate the design of the MOC.

Vemula Rama Rao (below, left) demonstrates the bench-scale model during a presentation at the University of California at Berkeley.

cycling frequency is three to five times faster than that of commercial portable MOCs.

The Lehigh design uses only a third of the adsorbent inventory (pellets of a type of zeolite, a microporous, aluminosilicate mineral) required by commercial MOCs. This reduces unit weight and size. The design also allows for a continuous rather than a pulsed flow of oxygen, and its size and flow rate can be easily scaled up or down. A "snap on" concept allows the MOC to be hooked to an existing compressed air line for O_2 production. This eliminates the need for a dedicated compressor, thus reducing weight while adding to portability. Compressed air lines are available in hospitals, cruise ships and commercial airplanes.

Thus, while current FDA-approved MOCs for ambulatory patients weigh 7-8 pounds and supply about 1 liter per minute of O_2, the Lehigh group hopes to reduce MOC weight to 4-5 pounds while increasing continuous oxygen supply to 2-4 liters per minute or more.

And while the batteries in commercial MOCs need recharging after 4 hours, the Lehigh group hopes to increase this duration by about 25 percent.

The group recently reported in *AIChE Journal* that its results "indicate that the adsorbent inventory of an MOC can be potentially reduced by a factor of three while offering a 10 to 20 percent higher O_2 recovery compared to a typical commercial unit."

The bridge to the market

The I-Corps and PFI:AIR-TT grants have helped the Lehigh group take steps toward commercial deployment of its device. In the I-Corps program, researchers learn the needs of the customer and the market by interviewing consumers. The PFI:AIR-TT grant helps groups develop "proof-of-invention" prototypes. The goal is for researchers to market new products by starting a company or by licensing inventions to existing companies.

Will weigh **4-5 POUNDS VS. 7-8** for current devices

Will supply **2-4 LITERS VS. 1 LITER** of O_2 per minute

Will employ **1, NOT 2,** columns of adsorbent

Will use **⅔ less** adsorbent inventory

Will **GENERATE CONTINUOUS O_2** rather than pulsed flow

Will increase battery life **BY 25%**

COURTESY OF VEMULA RAMA RAO

Kothare and research scientist Vemula Rama Rao studied supply chain management, marketing and business model canvassing in I-Corps workshops at the University of California at Berkeley. Their textbook was *The Startup Owner's Manual: The Step-By-Step Guide for Building a Great Company* by Steve Blank and Bob Dorf. In the course, the researchers explained their technology in presentations to other research teams, to other I-Corps groups and to Berkeley business faculty members.

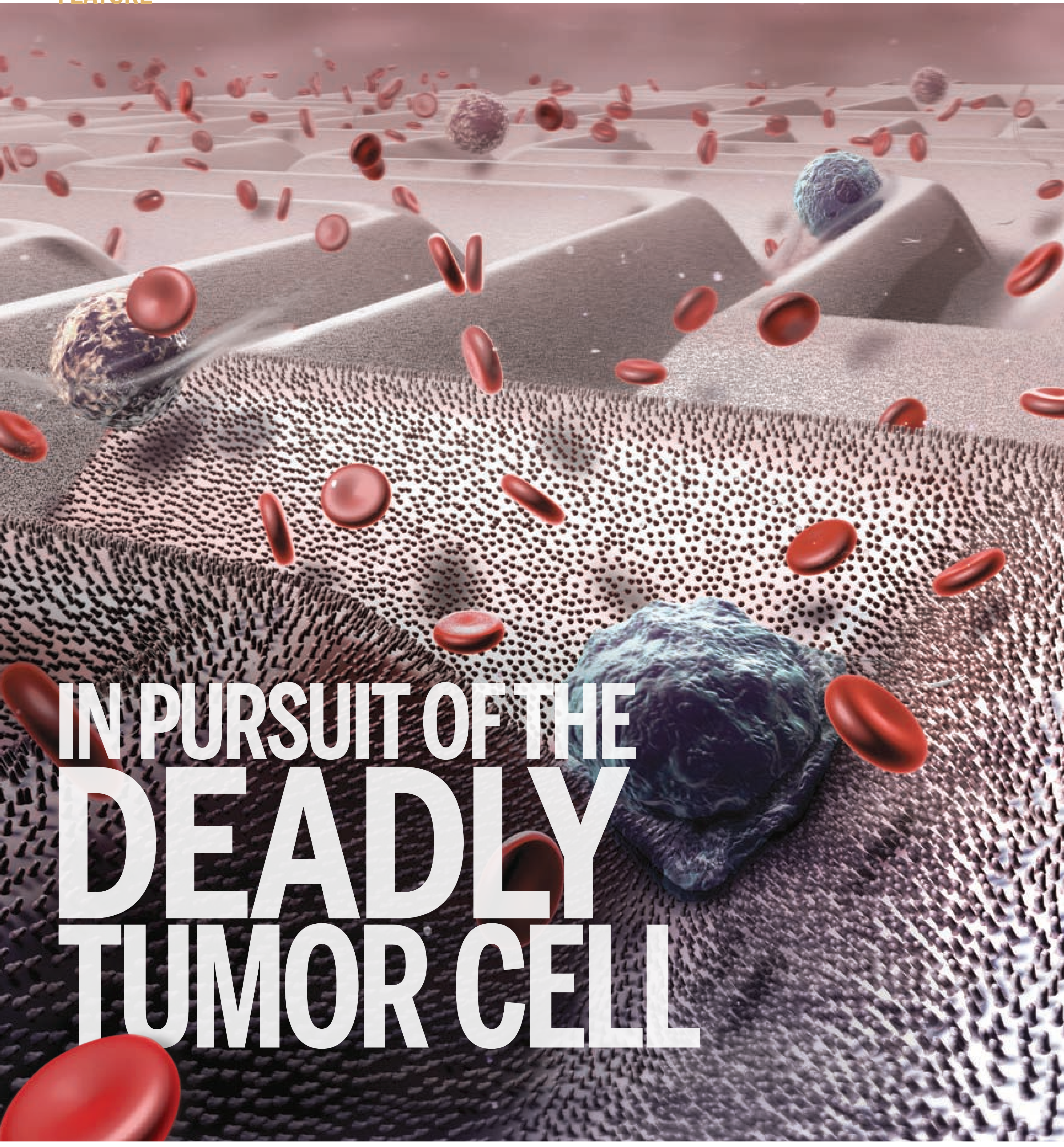
Kothare and Rao also interviewed potential consumers of their product, including doctors, patients, medical device and valve manufacturers, and companies that fabricate zeolite. By phone, by Skype and in person, the researchers talked to 100 people. They visited MOC equipment suppliers and hospitals and even went to an oxygen bar in San Francisco where patrons breathe flavored oxygen and chat and watch TV.

The Lehigh group is now building a prototype and talking with potential partners, including medical device companies. Technical hurdles remain. The bench-scale model must be reduced in size to the dimensions of a book. This means smaller valves, compressors and interior hardware. The MOC design, which the group has validated at the bench scale, must now be confirmed at actual commercial size.

The researchers have published 12 papers in journals and conference proceedings. Recently they received a Business Opportunity Validation Grant from the Life Sciences Greenhouse of Central Pennsylvania.

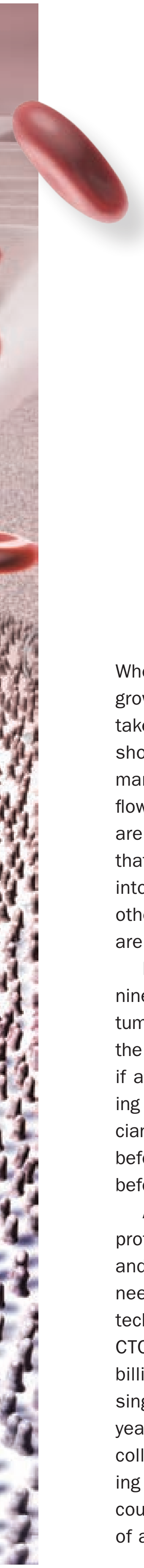
"The commercialization of a new product is a long process," says Yatin Karpe, associate director of Lehigh's Office of Technology Transfer. "No one is going to jump on your product because it sounds good—it has to look good, feel good and work well.

"Above all, it has to fit the needs of the customer and the market."



IN PURSUIT OF THE DEADLY TUMOR CELL

STORY BY **ROBERT W. FISHER '79** ILLUSTRATION BY **NICOLLE FULLER**



OPTIMIZING NANOPILLARS AND MICROFLUIDICS, A GROUP SEEKS EARLIER CANCER DETECTION.

When a malignant tumor begins to grow somewhere in the body, it can take time—too much time—before it shows up on released biochemical markers in the blood. The increased flow of blood around tumors, which are highly vascularized, makes it likely that some tumor cells will split off into the bloodstream and spread to other areas of the body before they are detected.

Metastatic cancer accounts for nine of every ten deaths from solid tumors, but the survival rate is high if the cancer is detected early. But what if a simple test could identify circulating tumor cells (CTCs) and alert physicians to the presence of the cancer before a mass shows up on a scan or before symptoms present?

A team led by Yaling Liu, associate professor of mechanical engineering and mechanics and also of bioengineering, has developed a promising technique for isolating the handful of CTCs that might be circulating among billions of normal blood cells in a single milliliter of blood. With a three-year grant from the NSF, Liu and his collaborators are designing and testing a tiny "lab-on-a-chip" device that could make screening for CTCs part of a normal blood test.

"Early cancer detection has become a major focus of translational cancer research," Liu says. And with good reason: Cancer is the second-leading cause of death in the U.S., claiming more than 575,000 lives each year, almost as many as cardiovascular disease and four times more than lower respiratory disease, the third affliction on the list.

Many cancers are survivable if caught in time, but the Centers for Disease Control and Prevention says that nearly half of colorectal and cervical cancers and one in three cases of breast cancer go undetected until they are at an advanced stage.

CTCs could play a critical role in the quest by researchers to develop new techniques for early cancer detection. Many cancers express unique protein markers, such as CA 15-3, which indicates breast cancer, or prostate specific antigen (PSA), for which men are screened to detect prostate cancer. But blood contains millions of proteins, making it difficult to detect protein cancer markers. By contrast, blood contains only a few types of cells.

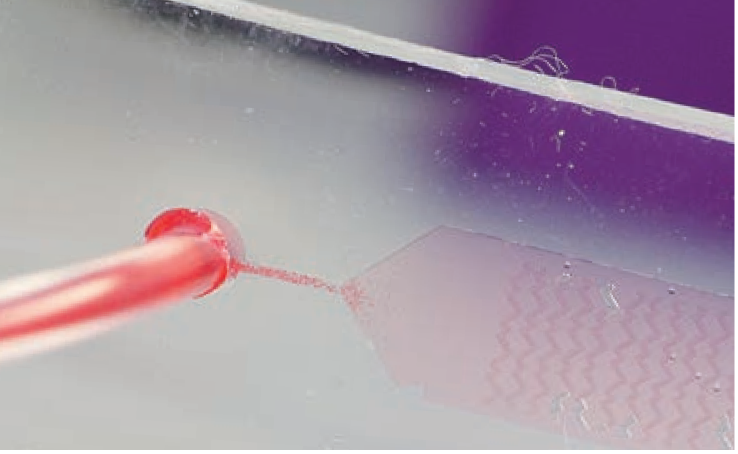
"It is relatively easier to detect a particular cell type," says Liu, "and the results are more stable, too."

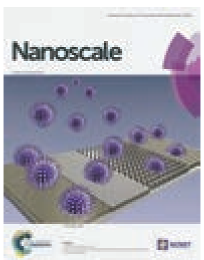
A lab-on-a-chip performs tests on a microfluidic device smaller than a few square centimeters using as little as a few milliliters of fluid. Liu's rectangular chip, made of the polymer PDMS, is about the length of two quarter coins. Its key feature is a tiny flow channel based on a hierarchically designed pad that is optimized to capture tumor cells from the blood flowing across it.

"Cells have protruding patterns," says Liu. "We have tried to create patterns on the capture pad that are complementary with the patterns on CTCs."

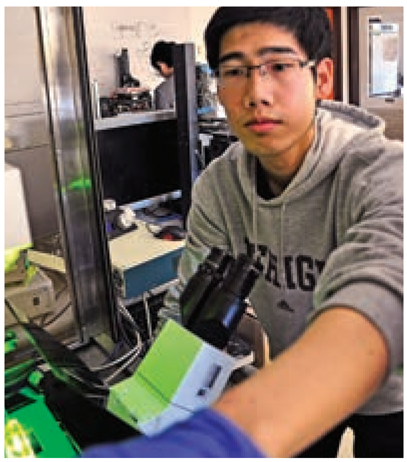
The low cost of Liu's device—"You could build one for ten bucks," he says—raises the potential that the device could be used for home tests or deployed in the developing world.

Liu (right) and Ph.D. candidate Wentao Shi examine a photo-curable biomaterial. The biomimetic features on the capture pad of Liu's chip (opposite) are designed to adhere to tumor cells while allowing normal blood cells to flow past.





Wang coats the nanopillars on the capture pad with an antibody that has an affinity with a chemical expressed by tumor cells and forms a strong bond with the cells' microvilli.



A FOCUS ON CELL SIZE AND FEATURES

To isolate CTCs, Liu's group is trying to improve the capture efficiency and selectivity of the capture pad on their device. Capture efficiency refers to the percentage of CTCs that the device collects. Selectivity measures how well it rejects unwanted cells, such as red and white blood cells.

To achieve those two goals, the group has designed the capture pad to mimic the biological features of the CTCs. Tumor cells have both nano- and microscale features. The cells are 15 to 30 microns in diameter. They bind to other cells—and to optimally designed diagnostic devices—with protrusions called microvilli that are less than 2 microns long, and less than 200 nanometers in diameter.

Using microfluidic design principles, Liu's group engineered vortices on their device to increase the chance that tumor cells will collide with the surface of the flow channel. The group also arranged ripples in a herringbone pattern lining the bottom of the capture pad.

"The herringbone surface generates a passive vortex that mixes the cells," he says, "and increases the chance that they will collide with the capture pad. It's a bio-transport process." All the cells in a sample are flipped around by the vortices—red and white blood cells as well as tumor cells. Unlike similar devices described in the literature, the Lehigh device avoids sharp corners to prevent unwanted cells from being trapped, opting instead for smooth curves that reduce damage to passing cells.

After cells collide with the capture pad, the goal is to make CTCs adhere while normal blood cells flow past. To accomplish this, the group coats the pad with a layer of anti-epithelial cell adhesion molecules (anti-EpCAM) which bond with CTCs but not with normal cells. The group also attaches arrays of nanopillars to the pad to snag tumor cells and discourage regular cells from attaching. The pillars and herringbone ripples are fabricated on the bottom of the tiny flow chamber. Blood flows through an inlet, across the microfluidic surface, and out the other end of the device, leaving behind a high percentage of the CTCs and relatively few regular blood cells.

FINDING IDEAL HEIGHT, SIZE AND SPACING

The next challenge, says Liu, was a geometry optimization problem—to find the most effective combination of ripple pattern and pillar dimensions (size and spacing). Shunqiang Wang, a Ph.D. student in Liu's lab, says the group has tested ripples with wavelengths from 30 to 160 microns and whose spacing ranges from sparse to dense.

Wang built a geometry matrix matching capture pads with combinations of ripple amplitude, wavelength, pillar height, size and spacing against the known dimensions of tumor cell size and microvilli to determine which options would achieve the best capture efficiency and selectivity. These prescribed nanopillar candidates were then fabricated using metal-assisted chemical etching in the lab of Liu's collaborator at the Max Planck Institute in Germany.

The group uses another weapon to

> *"The herringbone surface generates a passive vortex that mixes the cells and increases the chance that they will collide with the capture pad. It's a bio-transport process."*
>
> —Yaling Liu

isolate CTCs, a process known as "immunoaffinity-based capture." The tumor cells that form most common cancers, including breast, colorectal and prostate cancers, have a shared signature, says Wang. They express a chemical called EpCAM that acts like a "glue" and binds tumors together. EpCAM can also be cleaved to formulate a complex that binds with DNA and stimulates production of the molecules that promote tumor growth. Because EpCAM is expressed by a range of cancer cells and by some stem and epithelial cells, but not by other cell types, it is a good way to identify CTCs in the blood.

EpCAM molecules seek to bind with anti-EpCAM, an antibody. Other cells have no such affinity and are less likely to be captured, Wang says. Liu's group coats the surface of the nanopillars with anti-EpCAM. The microvilli of passing CTCs grab the pillars like interlocking fingers, forming a strong bond. Searching for tumor cells that are expressing EpCAM, says Liu, "can be used as a broad spectrum diagnostic device, because it works for a majority of cancers."

The group has conducted separate tests on each level of its design: the microfluidic flow over the wave-herringbone surface and the capture of CTCs by the antibody-coated nanopillars. As the NSF grant approaches its final year, the group is working with researchers at the University of Pennsylvania to fabricate a hierarchical structure with nanopillars embedded along the herringbone ripples. This hybrid surface, says Liu, is much more complicated to make than the individual components.

A SWEET SPOT, NOT A TRADEOFF

Some research groups have developed diagnostic techniques that achieve label-free detection based on the physical properties of the cell, including size, density and deformability, Liu says. Others use magnetic nanoparticles coated with anti-EpCAM to isolate CTCs. Most of these techniques, however, have a "significant tradeoff between capture efficiency and selectivity," he says. They capture 90 percent or more of the CTCs, but with greatly reduced selectivity. The resulting mixture has so many blood cells that it is difficult to isolate and count the CTCs.

Liu's results have been encouraging. His group has identified a number of design parameters that can improve the device's efficiency. They have shown at the microscale that ripples about six times as wide as a target cell's diameter work best at putting cells in contact with the surface of the capture pad. And they have found that increasing the depth of the ripples in the herringbone pattern improves CTC capture. The most promising device candidates have been fabricated in the lab of project collaborator Shu Yang, professor of materials science and engineering and of chemical and biomolecular engineering at UPenn.

At the nanoscale, the group has found that, although CTC capture decreases as the diameter of the pillars increases, there is a sweet spot in their spacing. If the pillars are too tightly packed, passing cells glide by as if they were flowing over a bare surface. If the pillars are too spread out, passing cells can be trapped between them, thus increasing nonspecific cell capture. "Spacing a little bit bigger than the diameter of the microvilli seems ideal," says Wang.

Developing a lab-on-a-chip to detect cancer is a cross-disciplinary effort involving mechanical engineers, biochemists, fluid dynamics experts and materials scientists. Liu's other collaborators include Xuanhong Cheng, associate professor of materials science and engineering, and Antony Thomas, a Ph.D. student in Liu's group. The researchers receive additional technical support from the Max Planck Institute and UPenn fabrication teams.

Liu's group is also working on other microfluidic devices; one project is funded by the National Institutes of Health. They have filed a patent for a biomimetic device that evaluates the efficacy of nanoparticle drug carriers. The tiny particles can be coated with ligands that bind with receptors at disease sites, allowing the manufacture of "nanorockets" that enable a drug to home in on specific disease cells. Liu's group has studied the shape of the drug molecule, blood flow and the geometry of a patient's vascular system and how their complex interactions affect drug delivery. They have coated a layer of endothelium cells on a microfluidic device to study how nanoparticles transport and bind in blood vessels. The researchers are working with Particle Sciences, a Bethlehem-based biotech firm, to validate the effectiveness of commercial drug delivery evaluation systems.

INSPIRING THE NEXT GENERATION

The group has attracted the involvement of younger researchers. When Wang explained the project last year during the Lehigh Valley Science Festival at Coca-Cola Park in Allentown, one teenager listened intently.

"Afterwards," says Roy Ghosh, who is now a ninth grader at Parkland High School, "I became engrossed in microfluidic devices and cancer cell capture, and I researched many reports to learn about circulating tumor cells and the engineering of these devices."

The encounter led Ghosh to take an internship in Liu's lab and explore a possible improvement to the project. Ghosh and Wang developed a model in which blood flows past an inclined wave pattern coated with E-selectin, a protein found on endothelial cells that binds more securely with white blood cells than with CTCs and does not interact with red blood cells. This binding process involves rapid bond formation and breakage kinetics, allowing white blood cells and CTCs both to roll adhesively along the surface but at different velocities. This, Ghosh theorized, would separate white blood cells and CTCs out to different rolling paths while nonadhering red blood cells follow the streamline and flow straight to the outlet.

The result, says Ghosh, would be "more than 90-percent separation efficiency. This creates a novel method for label-free, quick, inexpensive and efficient cancer cell separation and diagnosis."

MAKING CANCER IRRELEVANT

Lehigh University's Yaling Liu had a few hours to kill before an appointment at NSF's headquarters. His curiosity led him to a seminar on cancer detection in developing economies, and he soon realized his expertise could help make a quantum leap forward. Now, Liu and his team are testing a low-cost screening device that could pinpoint tumors before they appear on an MRI. The project illustrates engineering's relevance to modern medicine; see the video profile at www.lehigh.edu/liu or via the QR code.

STORY BY **CHRIS QUIRK**

PREPARED TO HIT THE GROUND RUNNING

Three programs help newcomers find their feet.

Rossin Junior Fellows have organized Canstruction® (left) and CHOICES (top, with Drescher at right) events for local students; (above), Berger.

It is uncommon to go from graduate school to a university teaching position without first working as a postdoctoral researcher or in industry.

Alexandra Coman, who joined the faculty of Ohio Northern University after earning a Ph.D. in computer science at Lehigh in 2013, gives much of the credit for her rapid rise to the Rossin Doctoral Fellowship program.

"This program was immensely beneficial for me," says Coman, "and for anyone considering applying for a faculty position after their Ph.D."

The fellowship is one of three Rossin programs that help students and faculty make transitions in their careers. Annually, Doctoral Fellowships are granted to two dozen Ph.D. candidates, Rossin Assistant Professorships are awarded to several new faculty members, and about 50 Rossin Junior Fellows are chosen from the ranks of Lehigh's sophomore, junior and senior engineering students. The programs were made possible by a gift from the late Peter C. Rossin '48.

Coman, who studies artificial intelligence and case-based reasoning, benefited from two courses taught to Rossin Doctoral Fellows by John Coulter, associate dean for graduate studies and research in the P.C. Rossin College of Engineering and Applied Science.

"There are some things I learned in those courses that I only fully appreciated once I myself began teaching," says Coman. "Professors came to our classes to tell us about their teaching methods, and we were given the chance to present and be critiqued. That helped me transition from thinking as a student to thinking as a faculty member."

The one-credit courses are called Teaching and Presentation Skills and Preparing for the Professoriate.

"When we developed these courses for doctoral students," says Coulter, "we asked ourselves: 'What do we wish we had known when we were Ph.D. students?' The students in the courses get hands-on teaching and presentation experience. We teach them how to prepare for lectures and classes, the positive and negative aspects of an academic career, and how to apply for an academic job, which is not a typical job search of the kind you see for positions in industry."

The Doctoral Fellowships program offers added advantages for international students.

"Some things in the American academic system were completely new to me; how it works, how the teaching process differs, what students expect," says Coman, who holds a B.S. from Romanian-American University in Bucharest.

Aykut Bulut, a Rossin Doctoral Fellow from Turkey, is helping new graduate students apply to Lehigh and get acclimated once they arrive.

"We help them apply to Lehigh from abroad," says Bulut, an industrial engineering major who studies discrete optimization. "We also work with people from other countries once they arrive. In addition, the fellowship funded the last conference I went to."

2014's Rossin Assistant Professors—chemical engineer Bryan Berger, mechanical engineer Arindam Banerjee and electrical engineer Yevgeny Berdichevsky (see story, page 3)—say the program helps students get professional recognition.

"One thing that's very beneficial is that we can use the support to take students to national meetings," says Berger, whose research focuses on quantum dots, membrane biology and biocompatible surfactants.

"This year, I'm taking two students, one graduate and one undergraduate, to the American Chemical Society meeting. They are presenting, and their visibility at these conferences is really helpful for them to compete with students at other top institutions."

Banerjee works in fluid dynamics, with applications in wave energy and inertial confinement fusion capsules. He is collaborating with scientists at the national laboratories in Livermore and Los Alamos.

"The Rossin Fellowship is an internal grant," he notes. "That's important because you can't pay for foreign travel with a federal grant. As a result, I can take a graduate student to France this summer for the European Wave Energy conference."

The Rossin funding also allows professors to place bets on promising research that might not pan out.

"It's so hard to get funding for any project," says Berger, "especially if you don't have preliminary data and support for an idea. This funding gives me the opportunity to hire a student for a semester and see what happens. That's key to finding new directions that can lead to major funding from NIH or NSF."

"This funding gives me the opportunity to hire a student for a semester and see what happens. That's key to finding new directions that can lead to major funding."

—Bryan Berger

Rossin Junior Fellows devote themselves to mentorship and service. They have run projects at neighboring Broughal Middle School and at Lehigh's annual CHOICES events for middle school girls.

"The Rossin Junior Fellows program," says chemical engineering major Nicolette Drescher '15, "is about giving back."

Junior Fellows also help freshmen navigate registration. "Many of us are here during orientation week," says mechanical engineering major Lauren Walker '15. "We assist them with adding and dropping classes, set up PINs, whatever they need."

Olivia Yang, a chemical engineering senior, remembers the guidance she received from Junior Fellows her first week at Lehigh. "I was floundering when I first got here. I had to change schedules, and do a lot of things that I had no idea about. The Junior Fellows shepherded me through that time."

Yang is now a Junior Fellow herself. "We've been through it all," she says, "so who better to help?"

THE ROSSIN FELLOWSHIP LEADERSHIP PROGRAM recognizes assistant professors, Ph.D. candidates and undergraduate students in engineering who excel academically and have contributed to Lehigh and the community. The program exemplifies the spirit of the late Peter C. Rossin '48, who with his wife, Ada, gave a $25 million gift to the engineering college in 1998.

Rossin Junior Fellows serve as peer mentors and tutors, conduct outreach activities, and give campus tours to high-performing incoming students. Doctoral Fellows receive special preparation for careers in academia and research. Rossin Professorships honor young faculty who show significant career potential and a proven ability to reach out to other disciplines. The Rossin Fellowship program boasts an active membership of 61 undergraduates, 58 doctoral candidates, and six junior faculty.

Faster algorithms, says Curtis, can achieve realistic, real-time solutions to complicated nonlinear problems when information is missing.

Finding the optimal balance in the face of uncertainty

A researcher models large-scale complexity as a series of finite-dimensional problems.

"The test of a first-rate intelligence," the American novelist F. Scott Fitzgerald wrote, "is the ability to hold two opposing ideas in mind at the same time and still retain the ability to function."

Psychologists call this juggling of contradictory beliefs cognitive dissonance, and they say it is likely to induce stress.

Their warning, however, has not gotten through to Frank E. Curtis, who makes his living by finding simple solutions to problems of great complexity.

In a world characterized by uncertainty and randomness, Curtis has learned not just to function but to thrive.

Curtis, the Frank Hook Assistant Professor of Industrial and Systems Engineering, writes algorithms that enable computers to solve large-scale continuous optimization problems. He is collaborating with researchers at Argonne National Laboratory through a five-year Early Career Award from the U.S. Department of Energy (DOE).

In a single-investigator project for the NSF, Curtis has developed algorithms that solve large-scale continuous optimization problems in less than a quarter of the time required by conventional methods.

The problems that interest Curtis contain countless variables and must be solved in real time. For the DOE, he and his students are seeking to achieve steady, efficient generation and distribution of electrical power while avoiding down time and allowing consumers to optimize the prices they pay. Each point of interest in a power network—from the power plants that generate electricity to the homes, schools and businesses that consume it—is represented as a node.

"At every node, there needs to be a balance; the input and output of electricity must be equal to each other. While the objectives differ between the consumption and generation nodes in a network, the principles everywhere are the same.

"Within a network, pricing must be set optimally and in real time for each consumption node. You have to manage supply and demand so that customers can optimize their use of energy. You also have to enable network administrators to provide a steady flow of energy without the fluctuations that cause instabilities."

Another continuous problem features an oncologist attempting to limit damage to healthy cells while destroying a tumor. The goal is to apply excessive heat to tumor cells while keeping the temperature below a lower threshold for noncancerous cells.

Curtis writes a partial differential equation that represents the temperature of every cell in and around the tumor while dealing with myriad variables: How will heat from radio or microwaves disperse across millions of cells? How will the temperatures of individual cells affect each other, and how will they in turn be affected by the amplitude and frequency of the radio or microwaves?

"We have to model for time and space," he says. "We do that by turning one large-scale problem into a series of finite-dimensional ones.

"The goal is to achieve realistic solutions to complicated problems that require making decisions under uncertainty, when we don't have all the information we want."

Tradeoffs are inevitable, says Curtis. A mathematical model's representation of reality gains accuracy in proportion to the numbers of variables and equations it involves. But the more complicated a model becomes, the more time a computer requires to generate a solution.

To enable computers to solve the challenges posed by continuous complex systems, Curtis says, algorithms must be fast, dynamic and scalable—yet simple.

"We try to find the right balance between modeling the real world while achieving a practical solution. In our mathematical models, everything is an approximation of reality. We want to represent the real world while making problems tangible to solve.

"With power flow, for example, we model direct current instead of alternating current (AC)—not because this is how power behaves but because our equation becomes linear and can be more easily solved."

His work, says Curtis, requires him to keep one foot in the real world of engineering and the other in the abstract world of applied mathematics.

"As a theoretician, you want to set up a mathematical model that's as close to reality as possible, but you have to appreciate that your model needs to be solvable in order to be useful.

"On the other hand, real-world practitioners should have an appreciation for theory because that gives them a solid foundation for their ideas, which is critical if they want to solve more complex problems."

Power networks and cancer treatment are two of the applications for the dynamic, scalable algorithms that Frank E. Curtis has developed.

Early Manufacturing Leadership

Although their inventions have been supplanted by new technologies and processes, these Lehigh engineers led breakthrough manufacturing innovation that improved industry and benefited society:

Jack Rathbone 1921

In 1975, Monroe "Jack" Rathbone was one of 19 men from two centuries of American life chosen by the editors of *Fortune* magazine for permanent membership in the Hall of Fame of Business Leadership. An exceptional organizational leader by any measure, Rathbone was also hailed for his technical prowess in the development of the fluid catalytic cracking process, which dramatically increased the efficiency of oil refining and manufacturing.

Daniel McFarlan Moore 1889

An early 20th-century inventor, entrepreneur and holder of more than 100 patents, Moore developed the Moore Lamp, the first commercially viable light source based on gas discharge instead of incandescence and the predecessor to contemporary neon and fluorescent lighting. Later in his career, he developed a miniature "glow lamp" that is still used by electronic and appliance displays, as well as vacuum tubes for early television. His early career with United Edison Manufacturing Company ended abruptly when the famed inventor asked the upstart engineer, "What's wrong with my lamp?" and Moore responded, "It's too small, too hot and too red."

Tsai Shengbai 1919

Tsai, a pioneering Chinese industrialist, was one of Lehigh's earliest and most successful international students. In 1914, the Chinese government sent him to the U.S. to receive an education in mining engineering—an education he used to lead the development of the country's modern silk industry during the country's 1930s-era industrial expansion. Under Tsai's helm, Mayar Silk Mills, a premier Shanghai silk manufacturer, built strong technological, marketing and management prowess to reach a dominant position, and Tsai became an icon in early Chinese industrial circles.

To learn more about the achievements of Lehigh engineers, visit ***lehigh.edu/engineering****.*

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THRIVING IN AN ERA OF CHANGE

John D. Simon, Lehigh's next president, says universities should help researchers "reinvent themselves" and "take a more open view of the problems they become passionate about."

See page 8