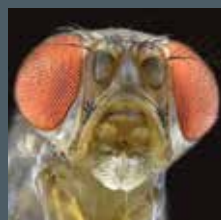




THE MEASURE OF THE MARKET

I-Corps encounters
prove valuable in
unexpected and
pivotal ways.

See page 16



KEEPING TIME WITH A FLY

Blue laser pulse
paces the heart
of *Drosophila* over
its lifetime.

See page 20

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A FOCUS ON LEHIGH ENGINEERING • VOLUME 1, 2016

THE BROADER IMPACT

RESILIENT INFRASTRUCTURE STRENGTHENS
THE FABRIC OF COMMUNITIES SEE PAGE 10

LEHIGH UNIVERSITY

P.C. ROSSIN COLLEGE OF
ENGINEERING AND APPLIED SCIENCE



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A FOCUS ON LEHIGH ENGINEERING

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Poised for a wider impact

Welcome to the 19th 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.

As I think about the future of Lehigh engineering, I am grateful for the recent establishment of the Charles '57 (industrial engineering) '15GP '19GP and Nan Strauch Endowed Deanship for our College.

Charles and Nan Strauch have given generously to education throughout their lives, supporting innovative programs at Lehigh, at other institutions of higher education, and at K-12 charter schools. Their latest gift of \$5.5 million will help support initiatives across the College. We greatly appreciate their vote of confidence in our mission.

The cover story starting on page 10 of this issue of *Resolve* explores cutting-edge research into resilient infrastructure. In addition to buildings, bridges and other structures, the term *infrastructure* today includes systems such as energy generation and distribution, communications and networking, transportation and water treatment.

Natural and manmade catastrophes in the past few years have shown that it is no longer sufficient for these structures and systems merely to withstand disasters and protect people's lives. Resilient infrastructure must also resume operating quickly following a disaster.

In our Q and A (page 8), Clifford C. Eby '73 explores resiliency in transportation systems and related issues. Cliff recently retired as president of the U.S. Transportation sector of WSP | Parsons Brinckerhoff, a global engineering and professional services giant.



In the article "A Win-Win-Win Situation" (page 16), we delve into a handful of projects supported by the National Science Foundation's I-Corps program. I-Corps fosters entrepreneurship in faculty research groups by guiding the commercialization of technology that was developed as a result of other NSF-funded projects. As a graduate of the I-Corps program, I can assure you that it enhances our effectiveness as educators in the classroom and as scholars leading use-inspired research endeavors.

"A Heart-Healthy Laser" (page 20) focuses on fascinating research by Chao Zhou and his students as they seek to create a light-based pacemaker. By integrating genetics and optics, the team has found

"The Strauchs' latest gift will help support initiatives across the College. We greatly appreciate their vote of confidence."

that it can shine a light that noninvasively controls the heart rate of a living fruit fly.

The final feature is devoted to another NSF-backed endeavor, the International Materials Institute for New Functionalities in Glass. In 2006, the IMI-NFG was featured in the very first cover story of *Resolve*. Now, one decade later, as our glass science researchers embark on new endeavors, we review the global impact of the IMI-NFG team's thoughtful balance of research, outreach and education.

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



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A \$5 fix for a nasty parasite

A team designs a biomimetic substrate to expand the scope of Cryptosporidium monitoring.

The parasite *Cryptosporidium* has long baffled medical doctors and utility operators. When ingested, the microscopic protozoan causes gastrointestinal illness that has no medical cure and can be fatal to persons with weak immune systems. *Crypto* is so small that it can pass through the filters of water-treatment plants, and it is resistant to chlorine, the most common water disinfectant.



Crypto spreads through fecal-oral transmission. When an animal drinks tainted water, the pathogen travels through its host's digestive system, is excreted into the environment and is carried by rain or runoff to a stream. The key to preventing *Crypto* from contaminating drinking water supplies, says Kristen Jellison, is to detect its source in watersheds and thus determine where limited utility budgets can most effectively be spent.

Jellison, an associate professor of civil and environmental engineering, has spent a decade studying *Crypto* in collaboration with the Philadelphia Water Department. With funding from an NSF CAREER Award, she has learned that the environmental form of *Crypto*, the oocyst, binds to biofilms on the surfaces of rocks and other inanimate objects in streams. These biofilms provide a protective haven for the pathogens.

The conventional method for detecting *Crypto*, says Jellison, is to remove and filter water from a suspected stream. But this “point in time” technique provides only a snapshot of stream conditions. Filters cost more than \$100 apiece. Due to high costs and limited budgets, utilities are forced to limit the number of sample locations they monitor as well as the frequency of sample collections.

Jellison and Sabrina Jedlicka, an assistant professor of materials science and engineering, have a three-year grant from NSF to develop a biomimetic surface, or a substrate that selectively attaches to *Crypto* oocysts. Roughly the size of a laboratory slide, the substrate will be physically and chemically engineered to bind only with oocysts and to remain in a stream as long as two weeks.

“Our goal,” says Jedlicka, “is to make a substrate based on the shape or surface chemistry of the *Crypto* oocysts so they attach to the substrate in a robust and predictable manner. This will enable us to




quantify the number of oocysts passing across the surfaces over a period of time in a specific location.”

“We think we can develop a surface that can be commercially produced for around \$5,” says Jellison. “This would allow utilities and water resource managers to better protect the public from exposure by sampling more locations with greater frequency and obtaining more reliable and comprehensive data about the sources of the parasite in the watershed.”

The two researchers and their students have identified the chemistry and mechanics that cause oocysts to bind to biofilms, and they have modeled the kinetics of the binding. Now they want to design a biomimetic surface such that oocysts bind consistently to the substrate regardless of water quality, time of year, amount of sunlight, presence of nutrients in the water, water temperature, velocity and flow rate of the water, and other conditions.

Ultimately, their device could be used to determine the concentration of oocysts, and their points of entry, in complex watersheds with multiple potential point sources.

“We need to monitor upstream and downstream of sewage discharge pipes, agricultural fields, recreational sites and wildlife gathering areas,” says Jellison. “These are places where oocysts are likely to enter a watershed. This kind of information would help utilities focus their efforts strategically within large complex watersheds to have the biggest impact on the protection of public health.” 

“Our goal is to make a substrate based on the shape or surface chemistry of the *Crypto* oocysts so they attach to the substrate in a robust and predictable manner.” —Sabrina Jedlicka





Why it matters how rivers behave

There's arguably nothing more important to the resiliency of a community than a river. Besides providing drinking water, allowing for the passage of floods, and meeting other societal needs, rivers and the wide range of species that inhabit them influence the overall stream ecology. And the interaction of a river's flow with the built environment, including bridge crossings and other types of infrastructure, affects traffic, commerce, emergency services and more.

In Lehigh's newly renovated ImbT Hydraulics Laboratory, Panos Diplas, the P.C. Rossin Professor and Chair of the civil and environmental engineering department, studies two river phenomena—scour and meandering—that have challenged engineers for centuries.

Scour typically occurs during major floods, when a river's flow rises, kicks up sediment on the riverbed and transports it downstream. It is by far the leading cause of bridge failure in the United States.

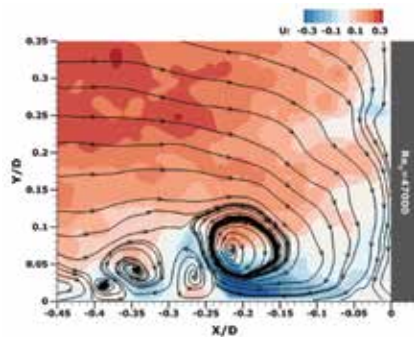
"When sediment in the vicinity of a structure is mobilized," Diplas says, "a scour hole forms where the structure meets the soil. This, in turn, can compromise the structure's integrity."

In an NSF project, Diplas and his group are studying the movement of sediment particles. With support from the National Cooperative Highway Research Program, they are attempting to determine the physical mechanisms responsible for scour development near structures. Their goal is to devise cost-effective scour mitigating measures that will allow bridges to withstand severe flow conditions.

Meandering occurs when rivers move and bend in seemingly random

ways. It is a natural, healthy process, but scientists have not yet determined why rivers meander instead of following a straight path.

When a river meanders far outside of projections, says Diplas, a bridge built over a river can be isolated on a floodplain. It no longer performs optimally and can be compromised by an extreme event, costing money, time and even lives.



The simultaneous presence of four vertical structures demonstrates the highly complicated nature of the flow.

Human responses to meandering can upset naturally occurring conditions that sustain fragile river ecosystems, says Diplas. Fish populations have shrunk rapidly when humans manufacture unnatural conditions to counteract the effects of meandering.

Diplas takes a big picture approach to solving river-related problems and encourages students to look at water resource problems at the systems level.

"We tend to treat the symptoms rather than the disease," he says. "If you try to fix a problem by simply putting a bandage on it, you can make it worse or create more problems in the future." 📺

The global ties that bind water, food and climate

Tara Troy, assistant professor of water resources engineering, takes a very macro-level approach to her field of study. "You can't think about water in isolation of climate or agriculture or energy," she says. "All of these systems are linked. That makes a hydrologist's job challenging, but it also means our research answers very societally relevant questions."

Among them: How are changes in international food consumption affecting groundwater resources at home? A recent paper published in the journal *Proceedings of the National Academy of Sciences* spoke to the growing globalization of food and water resources and why Troy's bird's eye view of this system is important to help optimize the use of finite resources.

The paper, which was coauthored by Troy and by Landon Marston, Megan Konar and Ximing Cai of the University of Illinois at Urbana-Champaign, examined the way droughts have forced many American farmers to look deep underground for a source of water for crop irrigation.

According to the paper, as much as 18 percent of American cereal crops—grains like corn, rice and wheat—depend on groundwater from three significant American aquifer systems: the Central Valley, High Plains, and Mississippi Embayment. Though trillions of gallons of water sit untapped beneath the surface of the earth, it will become increasingly costly to extract that water before it eventually runs out, and continued reliance on this water could have severe effects on the global food supply, as other nations—including Japan, Taiwan and Panama—buy their cereal grains from U.S. sources that rely on groundwater.

"Under an uncertain climate future, in which rain-fed agriculture is likely to experience more droughts and extreme climate events, groundwater resources may become more valuable," the paper says. Just how valuable? That's still to be determined, but this new knowledge of the virtual transfers of groundwater resources, combined with an increased understanding of local production withdrawals, will empower producers, consumers, water planners, and other decision makers to balance current food and water needs while keeping an eye on future consumption.

To answer these complex, large-scale problems, Troy is seeking to identify links between systems through modeling and data analysis.

"As we continue to acquire more measurements and learn more about the interconnected processes that lead to these problems," she says, "we'll be able to start developing smarter, more sustainable solutions." 📺



VIEW THE VIDEO ONLINE @ lehigh.edu/resolve



Scientists map the strain in a wonder material

With Raman spectroscopy and statistical analysis, group probes the properties of graphene.

Graphene is the thinnest material known to science, and one of the strongest as well. A 1-atom-thick sheet of carbon, graphene was the first 2D material ever discovered.



By weight, it is 150 to 200 times stronger than steel. It is also flexible, dense, virtually transparent and a superb conductor of heat and electricity.

An international research group has reported a breakthrough in the effort to characterize the properties of graphene noninvasively while acquiring information about its response to structural strain.

Using Raman spectroscopy and statistical analysis, the group took nanoscale

measurements of the strain present at each pixel on the material's surface and obtained a high-resolution view of the chemical properties of graphene's surface.

The results, says Slava V. Rotkin, could enable scientists to monitor levels of strain quickly and accurately as graphene is being fabricated. This in turn could help prevent the formation of defects that are caused by strain.

"Scientists already knew that Raman spectroscopy could obtain implicitly useful information about strain in graphene," says Rotkin, a professor of physics in Lehigh's College of Arts and Sciences with a dual appointment in the department of materials science and engineering. "We showed explicitly that you can map the strain and gather information about its effects."

"Moreover, using statistical analysis, we showed that it is possible to learn more about the distribution of strain inside each pixel, how quickly the levels of strain are changing, and the effect of this change on the electronic and elastic properties of the graphene."

"We showed explicitly that you can map the strain and gather information about its effects."

—Slava V. Rotkin

The group reported its results in *Nature Communications* in an article titled "Raman spectroscopy as probe of nanometer-scale strain variations in graphene." In addition to Rotkin, the article was authored by researchers from RWTH/Aachen University and the Jülich Research Centre in Germany, the Université Paris in France, Universidade Federal Fluminense in Brazil, and the National Institute for Materials Science in Japan.

Graphene has found its way into applications ranging from tennis rackets to smartphone touch screens. The 2013 market for graphene in the U.S., according to a 2014 article in *Nature*, was estimated at \$12 million.

Among the obstacles holding up further commercialization of graphene is the presence of defects that impose strain on graphene's lattice structure and adversely affect its electronic and optical properties. Related to this is the difficulty in producing high-quality graphene at low cost and in large quantities. **1**

The potential power of the nanocomposite

Ceramic-metal composites are widely used in microelectronic, automotive and aerospace applications. They have the potential to combine the hardness and high wear resistance of ceramics, and the toughness, ductility and good electrical and thermal conductivity of metals.

Helen Chan and Rick Vinci are investigating the microstructure development and mechanical behavior of novel ceramic-metal composites. They have experimented on oxides with two individual metal ions, such as barium titanate, whose metals have different affinities for bonding with oxygen.

As a result of this difference, says Vinci, who directs the Center for Advanced Materials and Nanotechnology, only one of the metal ion types stays bonded to the oxygen during reduction. This processing strategy is fundamentally different from conventional methods, in which metals and ceramics are mixed and consolidated.

The goal of the two researchers is to develop a new class of ceramic-metal nanocomposites, whose nanoscale features give rise to superior mechanical properties, as well as novel electrical and magnetic behavior. The project is funded by NSF.

Some oxide combinations appear better suited to the partial reduction process than others. Graduate student Michael Kracum has demonstrated interesting results

using a mixed oxide of copper and aluminum.

Using scanning and transmission electron microscopies, the researchers have found that on reduction of CuAlO_2 , the copper forms discrete nanoparticles embedded just nanometers apart in the oxide.

"This intimate arrangement of the copper and ceramic phases would be almost impossible to achieve by conventional processing," says Chan, who chairs the department of materials science and engineering.

Micromechanical tests, in which specimens of micron-sized dimensions are deformed inside a scanning electron microscope (SEM), are ongoing to characterize the composite material's mechanical behavior.

Chan and Vinci believe that many more mixed oxide pairings of interest exist, and this is being pursued by Kevin Anderson in his doctoral research. Ultimately, the goal is to tailor the arrangement and composition of the metal and ceramic components to achieve a nanocomposite with unique properties. **1**



Group enlists bacterium to produce greener, lower-cost quantum dots

Quantum dots (QDs)—man-made semi-conducting nanoparticles with unmatched optical and electronic properties—are used in medical imaging, LEDs, lasers, solar cells and optoelectronics.

But QDs are expensive and complicated to make, and current chemical synthesis methods require heat, high pressure and toxic solvents.

Three Lehigh researchers recently demonstrated the first precisely controlled, biological way of making QDs. Their green, one-step method harnesses bacterial cells to generate QDs without heat or chemicals.

In a cover article published last July by *Green Chemistry*, Bryan Berger, Steven McIntosh and Christopher Kiely and their students reported the successful production of cadmium sulfide (CdS) QDs using an engineered form of the bacterium *Stenotrophomonas maltophilia*. Berger and McIntosh are associate professors of chemical and biomolecular engineering. Kiely is a professor of materials science and chemical engineering.

Using a process called directed evolution, the group altered *S. maltophilia* so it selectively produced QDs. By confining the bacteria in a beaker containing water, cadmium and sulfur precursors, and minimal levels of

carbon and nitrogen, the group caused the bacteria cells to forgo most normal biological functions.

The cells built QDs by sequestering metal ions from their environment, generating a reactive sulfur source, and controlling the resultant structure to form a crystal. The researchers then used a centrifuge to pull the much larger cells away from the CdS nanocrystals in solution.

The three-year-old project is supported by a \$2 million grant from NSF's Division of Emerging Frontiers in Research and Innovation (EFRI). The group also received funding from Lehigh's Faculty Innovation Grant (FIG) and Collaborative Research Opportunity Grant (CORE) programs.

"The beauty of a biological approach is that it cuts down on production needs and time and on environmental burden," says Berger. Industrial processes require hours to grow QDs as well as additional processing and purifying. Biosynthesis can take just minutes to make QDs in water by an inherently "green" route that operates at ambient conditions and does not require post-processing.

The group's technique also enables QD particle size to be controlled to fractions of a nanometer, allowing the researchers to tune the QDs' optical and electronic properties.

The group used an aberration-corrected scanning transmission electron microscope (AC-STEM) to examine the structure and composition of each QD, which is composed of only tens to hundreds of atoms.

"Even with this new microscope, we're pushing the limits of what can be done," says Kiely. The AC-STEM scans an ultra-fine electron beam across a field of QDs. The QD atoms scatter the electrons in the beam, producing a shadow image on a fluorescent screen. A digital camera records the highly magnified atomic resolution image of the nanocrystal for analysis.

Figuring out how to separate the QDs from all the biological material surrounding them was a slow but crucial process, says Kiely.

"Once you get rid of the organic residues, you begin to see the true structure of the material. It took many months of frustration for our students (Zhou Yang, Leah Spangler,

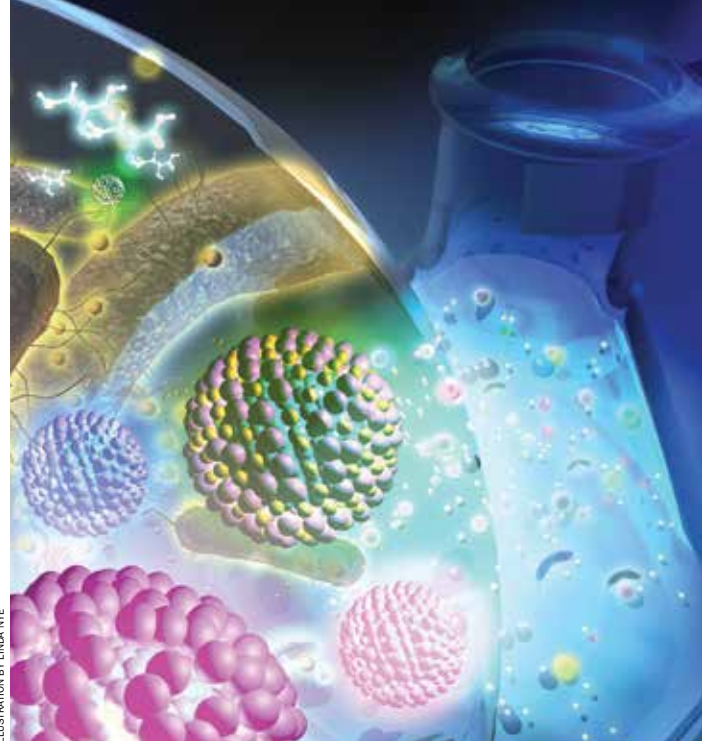


ILLUSTRATION BY LINDA NYE


Chris Curran, Robert Dunleavy and Li Lu) to determine exactly how to do this."

A single enzyme in the bacteria is responsible for QD generation, says Berger. The group believes QDs can be generated at low cost with the same enzyme synthesized from yeast or another easily manipulated bacterium.

The team is scaling up its process in hopes of establishing a company that makes inexpensive QDs in an eco-friendly manner. Conventional manufacturing costs for CdS QDs range from \$1,000 to \$10,000 per gram. Biomanufacturing could cut that price by a factor of 10, producing grams of QDs per liter of batch culture, says McIntosh.

Their production technique, the researchers say, could lead to QD applications ranging from greener manufacturing of methanol to efficient generation of electricity from sunlight. Water purification and metal recycling are two other possible uses, because the enzyme makes QDs by isolating heavy metals from water.

"We also want to create many different types of functional materials, large-scale as well as individual quantum dots," says McIntosh. He imagines developing a process by which QDs arrange themselves into macrostructures.

"If we can get to macroscale, make more of the material and control how it's structured while maintaining its core functionality, we could potentially get a solar cell to assemble itself with quantum dots. That would be incredible." 

The group can control QD particle size to within fractions of a nanometer while tuning the QDs' optical and electronic properties.

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Anderson (left), Chan (center) and Kracum perform tests inside an SEM to characterize the composite's mechanical properties.

Correcting errors with redundancy

Data transmitted through noisy and unstable environments is vulnerable to errors. The data flows we count on daily—streaming *Star Wars*, Skype-ing a child at college, saving a photo to disk—are protected by error correction protocols that add extra bits to data that can be used to recover the message at its destination.

Error correction has been part of communications for decades, says Zhiyuan Yan, associate professor of electrical and computer engineering. Today's wireless networks rely on methods introduced in the 1990s.

Yan is principal investigator on a \$300,000 National Science Foundation project to bring the error protection protocols of the next generation, known as polar codes, into the mainstream.

"Transmitting and receiving bits is not a perfect process," Yan says. Polar codes, first theorized in 2009, are a promising method to maximize channel bandwidths while reducing the computing resources required to decode on the fly.

"Polar codes are about the integrity and reliability of the data," he says. During our telephone interview, the analog sound waves of my voice were encoded by my cellphone into digital bits, which flowed through a cell tower to a wired network, to Lehigh's telephone system, and then were decoded back to sound in Yan's earpiece. A routine process, yet wavering wireless signals and network congestion can result in errors, Yan says.


Error correction introduces redundancy to correct errors. An elementary (and highly inefficient) method is to repeat data. A binary message, 1011, could be sent as 111-000-111-111. If interference scrambles it to 111-010-110-111, the method would understand the inconsistent triads 010 and 110 as 0 and 1, and the message would be received correctly.

Yan will work on "a multidimensional approach to the two big challenges in the field." He intends to harness the codes' efficiency on nearly infinite blocks of data to apply to smaller blocks sent in practice. He

will also focus on making hardware implementations of decoding algorithms faster and more reliable.

"A lot of applications require short delays in decoding," he says. "The mouth-to-ear delay in a phone conversation needs

to be less than a fraction of a second. Otherwise it destroys the rhythm of the conversation."

Other uses, like writing data to a drive, privilege reliability. "You won't mind if you wait an extra second to access your file," Yan says, "but you'll have a big problem if that file is corrupted." 



The optimal prison stay, mathematically modeled

Incarceration sounds simple: Throw wrongdoers in jail. In practice, it's complicated, especially for correctional staffers deciding which inmates should go to which facilities.

Such decisions could become more efficient and less costly thanks to an analytical system that specialists in mathematical modeling, optimization, process control and logistics are preparing for the Pennsylvania Department of Corrections.

The challenge, says Tamás Terlaky, the George N. and Soteria Kledaras '87 Endowed Professor and department chair of industrial and systems engineering, is to meet inmates' varied needs, which include education, health care, addiction treatment, mental health services and anger management. "Not all prisons have all the necessary facilities," Terlaky says.

Other considerations come into play. Members of the same street gang—or warring gangs—should not be placed in the same prison. Inmate populations should have a wide age distribution, which tends to promote order. If possible, inmates should be incarcerated close to homes and families.

Traditionally, inmates are assigned manually in a way that relies heavily on staff experience and judgment in sorting through myriad combinations of factors.

"A person with moderate needs may get sent to a prison having all the facilities he requires," Terlaky says. "The next person with more demanding needs might go to the same facility. By the time a person with severe needs comes along, the best cells are taken." Such happenstance clogs can result in longer prison terms and higher costs.

In a demonstration project, Terlaky and his colleagues developed a decision-tree process that sequentially makes optimal individual assignments. Now they are developing a large-scale integrated optimization model which balances needs and resources throughout the system. Similar methods are used in industry. Airline crew assignments, for example, factor in pilot qualifications for certain planes or routes, mandated rest time, and crewmembers' ability to work together.

"Mathematically, the problems are very similar," Terlaky says. "Yet as far as I know, this approach hasn't been used for correctional facilities anywhere in the United States."

Terlaky's group, which includes Profs. George Wilson and Louis Plebani of industrial and systems engineering and Ph.D. student Mohammad Shahabsafa, has a grant from the Department of Corrections to produce a system that addresses initial assignments and transfers.

"We aim to facilitate the best possible correction for each inmate in the fastest possible time," Terlaky says. "It's a unique project with a potentially huge impact." 



System fights credit fraud with existing magnetic card readers

It was called the Nightmare before Christmas. From Nov. 27 to Dec. 15, 2013, the personal information of as many as 70 million people—names, addresses, phone numbers, emails—was stolen during a wave of credit card thefts at Target retail stores.

The news did not surprise Yinzhi Cao, assistant professor of computer science and engineering. From large-scale breaches to scams that skim data at gas station pumps, credit card fraud is commonplace. Indeed, the California financial consultant Javelin Strategy & Research estimates that credit card thieves stole \$16 billion from 12.7 million U.S. consumers in 2014.

Because magnetic card readers use plain text to store confidential information, says Cao, they are vulnerable to untrusted card readers and skimming devices. Proposed solutions—integrated circuit cards and mobile wallets—are incompatible with current systems and too costly and time-consuming for retailers to implement.

Cao and his colleagues have developed the first inexpensive, secure method of preventing mass credit card fraud using existing magnetic card readers. Their technique—SafePay—transforms disposable credit card information to electrical current and drives a magnetic card chip to simulate the behavior of a physical magnetic card.

The group, which includes Xiang Pan and Yan Chen of Northwestern University, won the Best Paper Award when they presented SafePay at IEEE's Conference on Communications and Network Security in September in Italy.


"Because SafePay is backward

compatible with existing magnetic card readers, it will greatly relieve the burden of merchants in replacing card readers," says Cao. "At the same time, it will protect cardholders from mass data breaches."

SafePay consists of a mobile device and a server that distributes disposable credit card numbers. A magnetic credit card chip is controlled by an app inside the mobile device. The system costs about 50 cents, not including the mobile device.

A SafePay user downloads and executes the mobile banking app, which communicates with the bank server. During a transaction, the mobile app acquires disposable credit card numbers from the bank server, generates a wave file, plays the file to generate electrical current, and then drives the magnetic card chip via an audio jack or Bluetooth.

SafePay has several unique features. Disposable credit card information expires after a limited time or number of usages, so leaked information cannot be used in future transactions. A magnetic credit card chip makes it compatible with existing readers. The mobile banking app automates the process making it extremely user-friendly.

Cao's group has conducted successful real-world experiments with SafePay at a vending machine, a gas station and a coffee shop. Their work is supported by Qatar National Research Fund and NSF. 

"It will greatly relieve the burden of merchants in replacing card readers."

—Yinzhi Cao



Phase change materials to improve power plant performance

As global freshwater supplies shrink, the rejection of power plant heat using waterless Air Cooled Condensers (ACCs) is becoming increasingly essential. But many challenges remain to make ACCs work without sacrificing plant performance.

A few statistics illustrate the need for ACCs, say Sudhakar Neti, a professor of mechanical engineering and mechanics, and Carlos Romero, who directs Lehigh's Energy Research Center:

- Of the freshwater used in the U.S., 41 percent is withdrawn by thermal power plants to condense plant steam into water so it can be reused in the boiler.

- According to ARPA-E (the Advanced Research Projects Agency-Energy of the U.S. Department of Energy), more than 1.1 billion people lack access to clean water.

- By 2025, the International Food Policy Research Institute forecasts that shortages in fresh water could cause global food prices to more than double.

Only 1 percent of U.S. thermal power plants cool steam with direct dry ACCs. ACCs are more expensive than conventional once-through condensers and they cool steam less efficiently, especially in regions with high ambient air temperatures.

Neti and Romero are working with Advanced Cooling Technologies Inc. (ACT) of Lancaster, Pa., to improve the efficiency of ACCs with phase-change materials. PCMs absorb thermal energy as latent heat at a relatively constant temperature as they melt, and release thermal energy as they freeze. Neti showed in a recent DOE study that encapsulated PCMs can effectively store solar thermal energy at high temperatures.

The Lehigh-ACT group will develop a prototype and test several hydrated salts to determine each one's energy storage capacity, thermal cycling performance and material compatibility.

"Our goal," says Romero, "is to develop PCMs that take heat from the steam, store that heat during the day and then reject, or release, it at night, when air temperatures are lower."

The project, supported by ARPA-E, also involves the University of Missouri and Evapco Inc., a manufacturing company specializing in heat transfer applications. 





THE ENDURING VALUE OF FLEXIBILITY

BALANCING RESILIENCY AND SUSTAINABILITY IN AN AGE OF CONSTANT CHANGE.

Clifford C. Eby '73 is former president of the U.S. Transportation sector for WSP | Parsons Brinckerhoff, a global engineering and professional services organization. In that leadership role, he led 4,000-plus planners, engineers and managers. Previously, as senior vice president for Parsons Brinckerhoff's Technical Excellence Centers, Eby supported the firm's strategic efforts in rail and infrastructure markets, particularly high-speed rail. He has worked more than 40 years in the transportation industry, with expertise in rail safety, regulatory practices, transportation policy and rail infrastructure design. Eby has also served as acting administrator of the Federal Railroad Administration. He holds a B.S. in civil engineering from Lehigh and an MBA from George Washington University.

Q: How do you define resilient infrastructure?

A: I think of resilient infrastructure as assets—such as buildings, transportation, water, power—that have the ability to create long-term public value over periods of social, economic, political, and environmental change. The ability to recover from short-term disruptions has been a recent focus—can you recover quickly from a disaster? I have no problem with that, but we need to ask if that rapid recovery makes economic sense. Designing resilient systems and improving “mean time between failures”

generally come with a cost. Resiliency, like quality, needs to meet user requirements.

Q: How long has resiliency been an issue for civil engineers?

A: You could say the profession of civil engineering was founded on the need for resiliency. Owners and master builders could not afford to invest in buildings or infrastructure that wouldn't provide long-term public value. For the past 100 years, the civil engineering role in public infrastructure has primarily been design. Engineers have generally done a good

job of increasing size, strength, speed and capacity of infrastructure assets, while using fewer resources. Recent use of alternative project delivery has moved ownership responsibilities back into the engineer's portfolio.

Q: The United Nations' Brundtland Commission defined a sustainable society as one that meets its needs without limiting the ability of future generations to meet theirs. Is the concept of resilient infrastructure compatible with these aspirations?

A: In general, resiliency focuses on the performance of resources over the life cycle while sustainability focuses on the use of resources over the life cycle. The two—resiliency and sustainability—can be completely compatible. But one does not necessarily drive the other. You can have something that performs very well over the life cycle and is extremely resilient, but uses tons of resources. That would not measure up to the sustainability model. You can also have something sustainable but not resilient.



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A solar power system, for example, is sustainable but may not be resilient to some weather conditions.

To me, a big issue on sustainability is the hidden, unknown cost—so-called externalities. As you use up environmental resources with no way of passing that cost on to the consumer, that enters into the sustainability side of the economics. On the resiliency side, the question becomes this: Is that asset providing consistent economic benefit or public value over its life? That's the distinction I'm trying to make.

Q: How can policy makers promote a safer, more resilient, more sustainable infrastructure?

A: Policy makers must play a central role. Take auto safety. Despite years of focusing on vehicle safety and a declining percentage of deaths, we still accept more than 30,000 motor-vehicle-related deaths per year. Today's vehicles are becoming connected and automated. Roadways can collect data and even charge electric vehicles. The traveling public has more information than ever about how

to get around. These new technologies can all but eliminate our leading national cause of accidental death, but we need supportive laws, regulations and policies to create new infrastructure. WSP | Parsons Brinckerhoff is a leader in promoting these policies. One of our young engineers recently published guidelines on how local governments can plan for driverless vehicles. I'm confident we will see a much safer driving environment in the next decade.

Q: How do resiliency and sustainability align with the goals of creating smart, attractive city habitats with reduced size and scope of infrastructure?

Q You have worked four decades in America's transportation infrastructure. How would you rate its resiliency?

Much better than ever expected. Our infrastructure failures are remarkably small and are primarily due to lack of maintenance of public assets. Extreme flooding is an area of concern and is occurring much more frequently and severely than predicted by 50- and 100-year storm criteria. It's a good example of where engineers need to assess options beyond the code to ensure resiliency.

A: They align well, but we must be mindful of changing demographics and related needs. Population growth is often viewed as a constant, but it's affected by two variables—improved longevity and replacement levels, or children per couple. Analyzing these independently informs us why some K-12 schools closed in the 1980s and 1990s but now may be reopening. And why 65-year-olds may not be looking for retirement living. City leaders and investors who research these trends, who plan with some flexibility, and who evaluate multiple design options will have a greater likelihood of producing resilient and sustainable infrastructure.

Q: What are the special challenges of infrastructure design in megacities? What about in the developing world, given their fast-growing populations and acute need for housing and transportation services?

A: Resiliency and sustainability needs for the developing world are significantly different from the projects I work on. New York City, for example, has extended the No. 7 subway from Times Square to 34th Street and is erecting buildings over the train marshaling area near Penn Station, the so-called Hudson Yard Overbuild. Both projects are resilient and sustainable.

For developing countries, I suspect rural agricultural roads, drinking and agricultural water, and

hospitals are likely to provide higher returns on infrastructure investment. I look to organizations such as the Millennium Challenge Corporation or the Gates Foundation as informed sources.

Q: How do the challenges of designing resilient transportation infrastructure differ from the challenges of designing skyscrapers?

A: Transportation infrastructure, bridges and tall buildings are long-lived assets and, in general, have very similar resiliency challenges. One unique aspect of transportation assets is the network they create—rails, railcars, highways, taxis, private vehicles—and the

great mix of public and private resources they rely on. When those networks are efficient, positive social and economic effects are multiples of a single project.

Another difference is that skyscrapers typically stand on one property. Transportation crosses physical and geopolitical boundaries. That creates a new set of challenges and usually involves many more public and private stakeholders whose interests need to be met during the life of an asset.

Q: You have said that the creation of resilient transportation systems requires a better understanding of travel demands and the value of time. Please explain.

A: For transportation, travel time is a major factor in determining the value of the service. From our work on the Northeast Corridor Environmental Impact Statement [the rail corridor linking Washington, D.C., New York City and Boston], we see declining travel-time value when compared to prior years. For example, slower, but less expensive bus service is growing rapidly, because the value that passengers once put on time is declining.

I speculate that for many, being connected to the Internet and the opportunity to be productive during travel reduce the value of getting there quickly and make shorter travel time less important. If your transportation mode can become a moving office, or be more entertaining, it will have a profound effect on future infrastructure needs. ①

THE BROADER IMPACT

Lehigh infrastructure researchers include (l-r): Paolo Bocchini, civil engineering; Linh Nguyen, industrial and systems engineering; Sicong Kuang, computer science and engineering; Larry Snyder, industrial and systems engineering; Brian Davison, computer science and engineering; Alberto Lamadrid, economics; Aman Karamlou and Richard Sause, civil engineering; and, at top, Liyang Ma and Ebrahim Tahmasebi, civil engineering.





STORY BY **KURT PFITZER**



RESILIENT INFRASTRUCTURE STRENGTHENS THE FABRIC OF COMMUNITIES. IT REQUIRES IMAGINATION, PREPARATION, MULTIFACETED CONTRIBUTIONS AND LONG-RANGE THINKING.

The 21st century is not yet two decades old but it has already witnessed some of history's worst natural disasters. The 2004 tsunamis in the Indian Ocean, Hurricane Katrina in 2005, and the Tohoku Tsunami of 2011 are three examples. Each was a compound catastrophe. The Tohoku Tsunami was triggered by earthquakes, while Hurricanes Katrina and Sandy wreaked havoc with wind and floods.

And each event, say Lehigh infrastructure researchers, overwhelmed disaster preparation efforts. Hurricane Sandy cut power to 8 million homes. Hurricane Katrina destroyed 50 of New Orleans's levees and flood walls. The Tohoku Tsunami knocked out emergency power to reactors at Japan's Fukushima Daiichi nuclear power plant, causing cores to melt and releasing nuclear radiation.

These examples, say Lehigh researchers, illustrate the need for a new way of thinking about modern infrastructure. No longer is it sufficient to design structures—buildings, bridges, water treatment and power plants—that merely protect people's lives during a disaster. Twenty-first century infrastructure must be *resilient*. Infrastructure systems—transportation and communications, the distribution of electrical power and potable water—must be able to withstand and recover rapidly from all natural and manmade hazards. Resilience must account for environmental impacts, energy use, economic events and the effects of climate change, while considering the performance of structures over their life expectancy (see sidebar, page 13).

The design of resilient infrastructure, says Richard Sause, director of Lehigh's ATLSS (Advanced Technology for Large Structural Systems) Center, requires contributions from scientists, engineers, policy-makers, data scientists and social scientists. It requires the imagination to anticipate all potential hazards and their consequences, and the ability to engineer robust systems to withstand and recover from them.



The Tohoku Tsunami of 2011 caused \$230 billion in damage in Japan.



331,105
NUMBER OF
EARTHQUAKES
WORLDWIDE
2000-2012



Experience with hybrid simulation tests, says Ricles (center), helped Lehigh secure the NHERI grant from NSF.



“Our approach to resilience,” says Sause, “attempts to consider all possible sources of hazard that can negatively affect the normal activities and long-term development of a community.

“In the past, we focused on natural hazards like earthquakes, hurricanes and floods, and manmade events like blasts and fires. But social, economic and political events, like the refugee crisis in Europe, can affect infrastructure systems.”

“The broader impact”

Paolo Bocchini, an assistant professor of civil and environmental engineering, sees infrastructure as an interdependent network of structures and systems, in which one system’s disaster recovery is often contingent on another’s. Bocchini’s group has an NSF grant to develop Probabilistic Resilience Assessment of Interdependent Systems (PRAISys), a platform that will predict disaster outcomes and develop strategies to enable structures to resume operating quickly (See story, page 24).

James Ricles, the Bruce G. Johnston Professor of Structural Engineering, says the concept of resilient infrastructure is tied closely to the concept of community.

“Suppose an earthquake hits Los Angeles,” says Ricles, “and destroys the headquarters of a company with a worldwide market. The impact of the disruption can be very broad. One structure is important, but you have to integrate its performance with the goals and needs of the community so the functions and activities of the community itself are not disrupted.

“Engineers today have to expand the boundaries of community and look at the broader impact of a disaster.”

Ricles is principal investigator and director of the NSF-sponsored Natural Hazards Engineering Research Infrastructure Experimental Facility at Lehigh. NHERI supports research facilities at seven universities that evaluate the performance of engineering designs and materials.

Lehigh was chosen for the NHERI



program because its ATLSS facilities enable researchers to conduct real-time, large-scale and multidirectional structural experiments that mimic the loads imposed on structures by natural disasters.

Researchers at ATLSS have also evaluated the resilience of structural designs by conducting hybrid simulation (HS) tests, which combine physical experiments with numerical analysis to incorporate an entire structural system into a simulation. These tests have also been performed at geographically distributed sites, in which the components of a simulation are located at different labs while data is transmitted via the Internet and interpreted in real time. Lehigh researchers conducted more than 1,800 hybrid tests from 2004-14 with support from NSF’s George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) program.

One NHERI goal, says Ricles, is to apply the lessons learned from studying structures’ resilience to earthquakes to their resilience to other disasters.

“We want to conduct real-time HS tests to improve structures’ resilience to tornadoes and hurricanes. Windstorms, in general, cause different loading from earthquakes. We’re collaborating with fluid mechanics experts to conduct HS tests with wind experiments.”

“The design of resilient infrastructure requires contributions from engineers, policy-makers, data scientists and social scientists.”

— Richard Sause





Another NHERI goal, says Ricles, is to open ATLSS's testing facilities to outside researchers. "At one workshop, we conducted a real-time HS test of a three-story building with nonlinear viscous dampers under earthquake loading. We had 43 participants from across the U.S. They designed the building's structural system, performed numerical modeling and set up the simulation algorithms. We plan to do this every year with updated capabilities."

New guidelines for fire resistance

Blast and fire loads, says Spencer Quiel, an assistant professor of structural engineering, are typically more localized than those from earthquakes and severe winds. Blast and fire can also trigger a local failure that progresses into other portions of a structure. On Sept. 11, 2001, for example, following the impact of the two airliners, fires progressed through several floors of the World Trade Center towers, weakening their load-carrying capability and setting off a catastrophic "progressive" collapse.

Quiel has performed high-temperature experimental tests on steel strands used in bridge cables, with the goal of developing new input data for computer models of cable-supported bridges under fire.

"The high-temperature data for steel strands in suspension and cable-stayed bridges," he says, "is 50 years old in many cases. Since these bridges were built, we have updated our standards for fabricating these cables. Our group has looked at two types of modern bridge cables to determine how they weaken when heated. The results will help us

PIONEERING LIFE-CYCLE

The emergence of engineering for risk, resiliency and sustainability

In October 1997, the *Journal of Structural Engineering* published a paper that gave the field a new way to define success in the design and assessment of infrastructure systems—a paper that, two decades later, has formed the very basis of a global refocusing on building for long-term risk, resilience and sustainability.

Written by Dan Frangopol with two former Ph.D. advisees, the paper, "Life-Cycle Cost Design of Deteriorating Structures," offered a modest but revolutionary concept: the cost and performance of a structure or a network of infrastructure systems over its entire lifetime are far more crucial to quantify than the initial cost and "day one" performance levels.

Frangopol emphasizes this concept in a simple question: "How do we encourage policy makers and engineers to take the long view rather than focus on the upfront sticker price?"

Frangopol, now the first Fazlur R. Khan Endowed Chair of Structural Engineering and Architecture at Lehigh, is widely recognized as the creator of the field of life-cycle civil engineering. He continues to research, educate students and mentor colleagues. He and his research team perform complex, computationally intense analyses to determine the value and risk of infrastructure investments over the long term.

"The philosophy behind life-cycle engineering is relatively easy to understand,"

he says. "Infrastructure systems are societal investments. As such, they must be optimized over their entire life spans while adequately serving society's needs along the way. To do this, engineers must balance many requirements—safety, serviceability, economy, resiliency, and sustainability—despite imperfect information and knowledge."

Using probabilistic modeling and analysis, as well as advanced computer simulation, Frangopol leads a generation of engineers in developing the tools and techniques necessary to assess the effects of uncertainties and find optimum solutions that can save money, time and even lives.

"In many ways," he says, "life-cycle engineering is where the rubber meets the road in terms of risk, resilience and sustainability."

The American Society of Civil Engineers (ASCE) has asked Frangopol to help lead its efforts to achieve a "Grand Challenge" of reducing the life-cycle cost of infrastructure by 50 percent by 2025. ASCE recently bestowed upon him its prestigious OPAL Award for Lifetime

Achievement in civil engineering education. According to ASCE, his contributions "have defined much of the practice around design specifications, management methods, and optimization approaches," and his research "has not only saved time and money, but very likely also saved lives."

The structural network

Among Frangopol's contributions, however, is a different type of infrastructure—intellectual networks that link the brightest structural engineering minds from all over the world and help guide the development of more safe, resilient and sustainable infrastructure systems.

Frangopol has played a leading role in building an interconnected set of professional networks that drive collaboration around some of his field's most vexing issues. These networks, formalized through international associations that regularly meet and publish cutting-edge research, support the sharing of crucial information across the global structural engineering research community.

In 1999 Frangopol helped create the Inter-

national Association for Bridge Maintenance and Safety (IABMAS) and became its founding president. IABMAS encompasses all aspects of bridge maintenance, safety and management. Its more than 1,600 members from 55 countries meet regularly, with international conferences occurring every two years. Frangopol was also instrumental in the creation of the International Association for Life-Cycle Civil Engineering (IALCCE), with about 500 members from 50 countries, and the ASCE's Technical Council on Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems.

"Over time, new concepts in our field introduce even more complex sets of variables into research around structural design and decision making," Frangopol says. "At each step, it is critical to support these conceptual shifts with professional networks that integrate expertise and form the basis of broader understanding and application."

"Ultimately, life-cycle engineering is about more than us," he says. "We're trying to optimize our world for future generations."



Frangopol (right) with former advisees Duygu Saydam Ph.D. '13 and Benjin Zhu Ph.D. '15



Yen Fellowship recipient Tsampras (above, with ATLSS lab manager Darrick Fritchman, left) is developing an earthquake-resistant building system. Insulation in a plastic hinge (right) shows the effects of spalling from simulated earthquake loading.

better model these structures under fire and mitigate the effects of this hazard.”

Recently, Quiel helped the American Society of Civil Engineers (ASCE) develop new guidelines for the design of structures that resist the effects of fire. This year, for the first time, ASCE will include fire-resistance guidelines as an appendix in its design load criteria for buildings.

In an NSF-funded project, Quiel and Ricles are seeking to make the cladding, or façade, of a building, more versatile to resist extreme loads. “We want to design cladding not just to protect the inside of a building from blast or wind,” says Quiel,

“but also to allow it to interact with the structural system and provide better overall resistance to a variety of hazards.

“We’re designing a new connection between the structure and cladding to allow the latter to move and dissipate energy during an extreme event. We want to find out if it’s possible to reduce damage from an event by tuning the movement of the cladding relative to the rest of the structure.”

Post-earthquake fires

The aftermath of a major earthquake, says Stephen Pessiki, a professor of structural engineering, often strains a structure’s inherent fire resistance. Spilled fuel and damaged electrical equipment can ignite combustible material. Impaired water sprinkler systems delay firefighter response times, and damage to thermal barriers and windows can increase the likelihood of fire spreading.

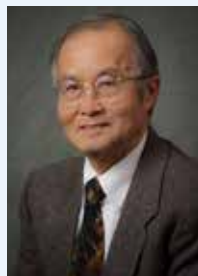
To improve the fire resistance of steel frame structures, engineers often coat the framework with spray-applied fire-resistive material (SFRM). This insulating material—if undamaged—impedes heat penetration into steel and prevents appreciable heat-induced mechanical degradation.

Pessiki’s group conducted large-scale simulated tests on SFRM in steel moment frame plastic hinge regions and in steel gravity frame beam-column connection regions. They found that the insulation is prone to cracking, debonding and spalling during seismic response. This can expose bare steel in the connections to extreme heat during a post-earthquake fire.

“Our research shows that the greatest concern may be the gravity connections,” says Pessiki. “These play a critical role in maintaining the load-bearing capacity and integrity of the floor system during fire exposure. Failure of the floor system can reduce the stability of gravity columns and increase the risk of fire spread.”



THE LEGACY OF BEN YEN



Ben Yen has left an indelible mark on Lehigh’s department of civil and environmental engineering. He completed his Ph.D. at Lehigh in 1963, joined the faculty and retired in 2001. Since then, he has mentored dozens of students.

Yen’s generosity led him to endow the Yen Family Fellowship for civil engineering graduate students, which has helped more than a dozen M.S. and Ph.D. students pursue advanced research.

“Without question, Dr. Yen’s help was invaluable,” says Dr. Matthew Yarnold, ’03 ’05G, one of the first recipients of the fellowship. Yarnold studied orthotropic bridge decks at Lehigh, has become a leader in the field and is now an assistant professor of structural engineering at Tennessee Tech University.

“Dr. Yen has been a part of so many interesting research projects over his time at Lehigh,” says Georgios Tsampras, another fellowship recipient who will receive his Ph.D. in structural engineering this year. “He’s been a great mentor and set a wonderful example for every Lehigh civil engineering student.”

Tsampras came to Lehigh in 2011 to work with Richard Sause, director

of the Advanced Technology for Large Structural Systems (ATLSS) Center, on an NSF-funded project with researchers from the University of Arizona and the University of California-San Diego. “Our goal was to develop a reduced damage earthquake-resistant building system,” he says.

The project inspired Tsampras and classmates to found the Lehigh student chapter of the Earthquake Engineering Research Institute, which introduces undergraduate students to structural engineering by organizing talks by practicing engineers, research seminars, field trips and other events.

Tsampras is grateful to the Yens for their generosity. “The Fellowship makes possible a smooth continuation of our studies, which is so important,” he says.

Nicole Leo Braxtan ’10 Ph.D., another fellowship recipient, worked with Stephen Pessiki, professor of structural engineering, to study the resistance of steel buildings to the fires that often follow earthquakes. Braxtan is now an assistant professor at the University of North Carolina-Charlotte, where she studies fire resistance as well as bridges and other civil infrastructure.

Braxtan has fond memories of the Bethlehem bridge tour Yen led every year with the Lehigh Valley chapter of the American Society of Civil Engineers. “His love of bridges and engineering, and his kind heart and spirit, have inspired me to become a better engineer and professor,” she says.

An envelope and a comb

Clay Naito, an associate professor of structural engineering, has helped ASCE write new design standards for buildings to resist loading from tsunami-borne debris like the 50,000-pound shipping containers that smashed Japan's coast during the Tohoku Tsunami.

In a project funded by PITA and the Precast Concrete Institute, Naito and Quiel are designing and testing a prefabricated concrete structure that resists progressive collapse.

Naito also has an NSF grant to design and test an insulated, energy-efficient wall panel envelope system for building exteriors. The envelope is a sandwich with a plastic middle layer for greater thermal resistance. An innovative plastic "comb" improves blast resistance by tying together, or connecting, the concrete walls of a building.

Naito, who has a provisional patent on the tie comb, fabricates injection-molded prototypes of the comb in Lehigh's 3D printing lab. His group has performed computational modeling and physical tests on the prototype and is planning full-scale blast tests of the wall panel.

"We're trying to create wall panels that are more resilient, easier to assemble and more cost-effective than other methods while performing better during extreme hazards," he says.

Ubiquitous, dynamic sensing

When a disaster occurs, Shamim Pakzad seeks to determine the location and severity of damage and the best way to allocate resources to repair and restore infrastructure. Automated accurate information, he says, plays a vital role in emergency response and recovery.

Pakzad, an associate professor of structural engineering, obtains information from countless thousands of mobile device users. As people drive over a bridge, for example, the gyroscopes, accelerometers, GPS and other sensors in their devices could transmit a steady stream of useful data to engineers. What are the orientation and acceleration of each vehicle? How is the bridge

"Consider the thousands of smartphone users. This gives us a dynamic sensing capability that is missing from a fixed sensor network."

— Shamim Pakzad



responding to vehicle loading? What are the temperature, wind speed and environmental conditions?

Pakzad, who has an NSF CAREER Award, has installed networks of wired (on the Washington Monument) and wireless sensors (on the Golden Gate Bridge) to monitor structural response. In the age of ubiquitous digital devices, however, these technologies are outdated.

"Fixed sensor networks," he says, "have limitations. These include the cost of installation, maintenance and operation. Compare this to the sensors in mobile devices. The location they provide is almost continuous. You can pick a point almost anywhere on a bridge and analyze data from that point, interact with nearby points and build a sensor network wherever you want."

"Now, consider that thousands of smartphone users cross that bridge every day. We take all of their data and chart acceleration at certain points on the bridge. We get a lot more data from a lot more locations than you get from sensors that are installed physically."

"This gives us a dynamic sensing capability that is missing from a fixed sensor network. It makes this one of the first applications of crowdsourcing in structural engineering."

Bacteria for a firmer foundation

Much of the damage caused by earthquakes in Alaska and Japan in 1964 was attributed to liquefaction, says Muhannad T. Suleiman. Three conditions—sandy soil, excessive water pressure in soil and earthquake loading—are necessary for liquefaction to occur, says Suleiman, an associate

professor of geotechnical engineering.

"Soil naturally gains strength from the forces between soil particles," he says, "but as water pressure builds up during an earthquake, water separates these particles and the soil loses its strength."

"Even if a structure is sound, liquefaction during an earthquake, as happened in Alaska and Japan in 1964, can cause buildings to tilt."

Suleiman, who has two NSF grants, is testing several techniques for strengthening soil in a soil box that measures 2 cubic meters. One involves injecting bacteria into soil and into a porous concrete foundation to induce calcite precipitation.


"Bacteria create an environment for calcite to precipitate between soil particles and cement them together," he says. "We inject calcium into the soil to



precipitate calcite. The process happens naturally over a long period of time; we can engineer it to control the quality, quantity and rate of precipitation."

Suleiman's group, working with Derick Brown, an associate professor of environmental engineering, recently performed vertical load tests on soil samples and permeable foundations. Some soil samples and foundations were injected with bacteria, others were not. Some foundations were subjected to axial tension, others to axial compression.

"We observed an increase in foundation load-bearing capacity of two to four times in the permeable foundation injected with bacteria," he says.

Suleiman's group is one of a very few in the U.S. working in this field. 

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

THREE PRECONDITIONS OF LIQUEFACTION

- 1 SANDY SOIL
- 2 SEVERE SHAKING
- 3 EXCESSIVE WATER PRESSURE IN SOIL

STORY BY RICHARD LALIBERTE

An illustration showing a man in a dark suit and a woman in a white lab coat standing on a bridge made of large orange puzzle pieces. They are both reaching for a single puzzle piece that is being lowered into the bridge. The bridge spans a dark, jagged chasm. The background is a solid teal color.

A WIN-WIN-WIN SITUATION

IN NSF'S I-CORPS PROGRAM, STUDENTS AND FACULTY LEARN HOW INNOVATION INTERSECTS WITH THE MARKETPLACE.

MOST RESEARCHERS HOPE THEIR INSIGHTS AND INNOVATIONS WILL MAKE THE WORLD A BETTER PLACE. In practical terms, that often means finding a market. But it's easy to become enamored with hard-won discoveries without understanding their real value to others.

"The attitude often is, 'I just invented this cool thing and I don't know what it's for but I'm sure 3 million people want to buy it,'" says John Coulter, professor of mechanical engineering and mechanics and interim dean of the P.C. Rossin College of Engineering and Applied Science.

To ground such thinking more firmly and specifically in real-world needs and opportunities, Lehigh has joined forces with the National Science Foundation (NSF) and research institutions across the country to embrace a new kind of innovative thinking—not about technology but the marketplace. Working through Lehigh's Office of Technology Transfer, the university has become a leading participant in an NSF program called Innovation Corps, or I-Corps.

I-Corps' goal is to foster entrepreneurship that will help commercialize the technology that NSF-funded research has supported. The program centers on an intensive seven-week training experience for a team of three people.

Each team contains a principal investigator who has led research into a commercially viable innovation and an entrepreneurial lead—often a post-doc or graduate student—whose daunting task is to identify a market need for the innovation, to develop insights into customers who might pay to use it, and to build a business model and potentially launch a start-up company. The third team member is a business mentor who helps find customers and who understands market realities and guides business planning.

I-Corps requires participants to conduct personal interviews—often in face-to-face meetings—with 100 different customers who can provide insight into the marketplace.

"Customers can be end users, manufacturers, suppliers, distributors, small businesses or research institutions," says Yatin Karpe, associate director of the Office of Technology Transfer.

The needs of these customers, and their perceptions, shape the business vision—and often redirect the research that is being done in the lab, says Coulter.

"You need to have an awareness of what problem you're solving and for whom. People don't walk into your office and tell you what they

need. You have to go ask them."

By the end of 2015, six Lehigh teams had gone through the I-Corps program. Four more are expected to participate in 2016. "We're ranked fifth in the nation in terms of I-Corps applications," Karpe says. "That's an extremely high level of participation, especially given that we're a small school next to universities whose research expenditures are measured in billions of dollars."

Lehigh has long had a reputation for producing innovators "who can hit the ground running and get things done effectively," Coulter says. "We're very proud of that." Yet entrepreneurship—the process of perceiving new business opportunities and building commercial enterprises around them—has not been emphasized in the past.



"Our core mission is teaching, research and service," Karpe says. "Encouraging entrepreneurial activity is like adding a fourth leg to that stool."

THE PIVOTAL MOMENT

Researchers stepping for the first time into the hurly-burly marketplace can face culture shock.

"It's very humbling," says Sabrina Jedlicka, assistant professor of materials science and engineering and a faculty member in Lehigh's bioengineering program. "I was put in my place very quickly."

After an intended entrepreneurial lead left the project to take a job, Jedlicka stepped into that role on a project with Coulter pertaining to mechanotransduction, the process by which cells translate mechanical stimuli into biochemical activity.



I-Corps calls them pivot moments—times of "aha" understanding that can change the direction of a project.



"I-Corps trainers didn't care about our research or understand what we were doing," Jedlicka says. "They just wanted us to tell them what the market was." With limited experience in industry, she adds, "I was shocked and appalled that none of what John and I had done mattered unless we could find customers for it. That was the first hour of Day One."

But the conversations that Jedlicka and Coulter had with customers proved revealing.

"We pivoted to a market we hadn't envisioned," Coulter says. Their innovation was to use injection molding to create nanostructured polystyrene consumables for the biomedical industry. To potential customers, that sounded like "bumpy petri dishes."

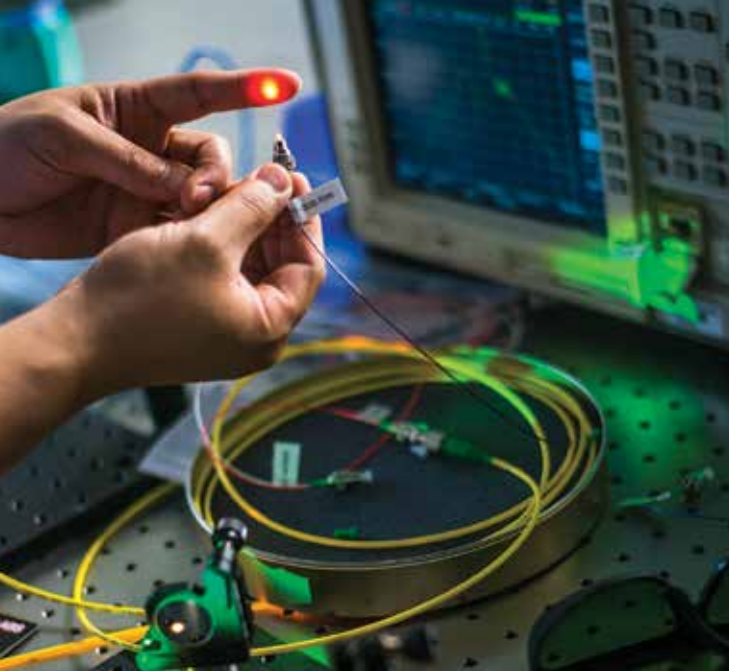
"It sounds like the least sexy thing in the world," Jedlicka says. "But many cells respond to mechanical input so that their behavior in vitro changes depending on the properties of the surface they grow on. So knowing that, why not make petri dishes specialized instead of a dime a dozen?"

As they listened to the people they interviewed, the team turned toward the in vitro fertilization market.

"Cell division on our bumpy surfaces is more consistent," Jedlicka says. "If you can improve cell division when you grow embryos, you significantly change a limiting factor. That's a natural and very human market." The team also sees potential applications for drug testing, academic research, and tissue engineering. "We're looking to disrupt



Their quest to "disrupt" the petri dish industry led Coulter (above, center) and Jedlicka (top photo) to the in vitro fertilization market.



"We learned that people in a doctor's office don't say they care about speed," Zhou says. "They care about image quality and patient comfort." Undergoing an eye scan—which can take up to 10 seconds using current technology—made clear the challenges of obtaining clear images from squirming patients.

"When something doesn't work in the lab, we can just repeat the scan," Zhou says. "I took for granted that you could repeat scans and patients would be okay with it, but that's not the case."

This insight shifted Zhou's business

pitch from speed to quality and comfort—which speed happens to allow. The team's field research revealed that the immediate market for the system isn't the end user in a doctor's office but manufacturers. It also highlighted the need for a chip-based device that could be retrofitted onto existing equipment.

"I-Corps helped us clarify our targets," says Zhou, who subsequently applied for a second I-Corps session to hone the focus on manufacturers.

Martin Harmer, the Alcoa Foundation Professor of Materials Science and Engineering, experienced multiple pivots with his I-Corps training. His team's innovation was a pre-treatment process for a ceramic powder of magnesium aluminum oxide. The treatment optimally combines temperature and pressure to remove impurities so that when a

powder is fired, the resulting ceramic is transparent, with impressive ballistic protection capabilities—like bulletproof glass, only lighter.

"We thought it might be useful for windows in military vehicles like tanks and Humvees, where saving weight is important," says Harmer.

After digging into the market, however, Harmer's team gained a valuable insight: It can often be difficult for a small start-up to build a sustainable business relying on the Department of Defense.

"It's not a very steady market," says entrepreneurial lead Animesh Kundu, a research scientist in the Center for Advanced Materials and Nanotechnology. "Demand for an item for, say, the Navy, might go from zero to \$50 million, then back to zero. I didn't realize the market was so volatile."

The team also discovered that few companies in the world manufacture tank windows or deal with transparent ceramics, reducing options.

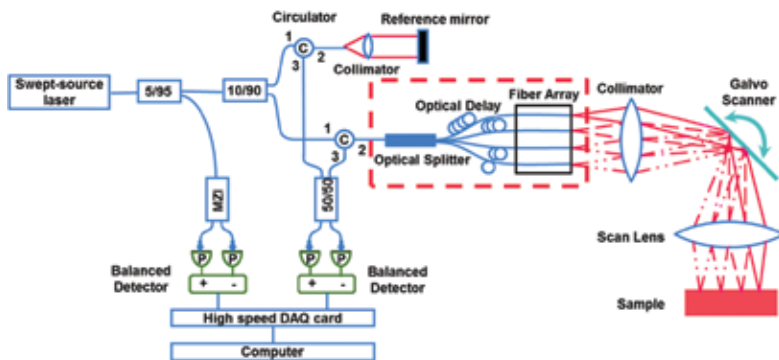
"There wasn't one main obstacle," Harmer says. "There were just many elements that we thought would be viable but were problematic." The team pivoted away from armor and toward specialized niche markets in optics and optical sensors such as protective housings for drone cameras and lasers or guidance domes at the front of heat-seeking missiles.

"Smaller, high-cost, very value-added optoelectronic components are a better way to go," Harmer says.



"There wasn't one main obstacle. There were just many elements that we thought would be viable but were problematic."

—Martin Harmer



Zhou's group created a technique to speed eye scans but shifted their pitch to quality and comfort and their target market to manufacturers.

the petri dish industry," Jedlicka says.

Such experiences are common. I-Corps calls them pivot moments—times of "aha" understanding that can change the direction of a project.

AN UNEXPECTED REVELATION

Chao Zhou had his eyes opened when undergoing an optical coherence tomography (OCT) scan during one of his customer interviews. Zhou, assistant professor of electrical and computer engineering, and his group were exploring the market for a faster form of OCT—widely used in ophthalmology to produce 3D diagnostic images of the eye.

Using a method called space-division multiplexing, Zhou's group had developed a process that splits a beam of infrared light into 16 different beams and creates nanosecond delays to encode the signals into different frequencies. The technique allows eye scans to be done 10 times faster than is possible using current technology.

ASKING THE RIGHT QUESTIONS

Mayuresh Kothare has learned that being enamored with an innovation can cloud one's vision in the marketplace and in the lab unless one guards against bias.

Kothare's team has investigated the market for a new kind of portable, battery-operated medical oxygen concentrator (MOC). Such devices have been a

"I learned that how you pose questions is important."

—Mayuresh Kothare

godsend to people suffering from chronic obstructive pulmonary disease (COPD) and other lung conditions that make breathing difficult. Instead of needing to be confined to beds and connected by breathing tubes to large machines filled with compressed oxygen, patients using MOCs that extract oxygen from ambient air can carry on their normal daily activities.

Kothare's team offered a new MOC design that uses one instead of two adsorbent beds to capture nitrogen from air under high pressure, obtain high-purity oxygen and then release nitrogen under low pressure. The simplified design allows a unit to be smaller and lighter than existing MOCs while potentially producing greater volumes of oxygen.

Yet simply asking pulmonologists if they could use such a device wouldn't be helpful. "Of course they'll say yes," Kothare says. "That doesn't tell you anything because you've already biased the question in favor of the device."

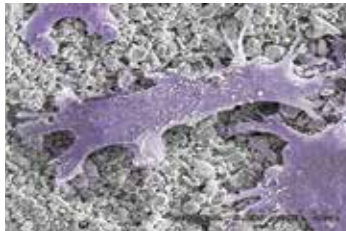
A better query, says Kothare, "is to ask, 'What are your biggest challenges?' The more you listen, the more likely you are to hear hidden things that wouldn't be revealed with a biased question."

Such an approach is often vital to simply getting in the door, much less finding out anything useful, says Himanshu Jain, the T.L. Diamond Distinguished Chair in Engineering and Applied Science.

His team investigated the market for a biocompatible, biodegradable glass that is porous on both macro and nanoscales, making it highly conducive to cell growth and for use as a scaffold for regenerating bone.


"We're not trying to sell anything," Jain says. "That made things a lot easier with people who get all kinds of calls and emails. If you try to convince them how exciting your technology is rather than listen to their needs, they take you differently."

Jain's team discovered that the orthopedic market they had in mind is conservative and resistant to adopting innovations not proven through clinical trials and experience. The team pivoted to dental applications.



"One dental customer said, 'Really, this is the kind of thing we need,'" Jain says. "That boosted our excitement and faith in the usefulness of our material."

I-Corps alumni see many advantages to participating. It can open the door to renewed funding from the NSF and other sources. Some say it has changed how they think, teach and write grants.

"We want to educate students to be better at entrepreneurship, and the best way to do that is to surround them with people who are involved with it," Coulter says. "That enhances both education and faculty careers, and in some cases will lead to positive financial outcomes in the near term. It's a win-win-win situation." 

Jain (left) gained a greater appreciation for the value of listening while concluding that dental applications were the best match for his dually porous glass.





A HEART-HEALTHY LASER

COMBINING GENETICS AND OPTICS, RESEARCHERS NONINVASIVELY PACE THE HEART OF A FRUIT FLY.

Electric pacemakers are used by people worldwide to help control abnormal heartbeats. The devices have helped scientists learn more about the heart's physiology and disorders, says Chao Zhou, but they have their limits. Pacemakers must be surgically implanted. They can cause unwanted contractions in other areas of the chest, alter pH levels and cause tissue damage.

Zhou, an assistant professor of electrical and computer engineering, and his colleagues have taken the first step toward developing a laser pacemaker that could one day stimulate the human heart noninvasively with light signals.

The researchers have built a microscope that paces the heart of the common fruit fly without touching it, while controlling its function, monitoring its performance and taking high-resolution images of it at the microscale.

The system uses two relatively new optical technologies—optical coherence tomography (OCT) and optogenetics—to generate pulsed blue light signals

that pace the fruit fly's heart during the three stages of its life: larva, pupa and adult.

The group reported its results recently in *Science Advances*, a *Science* magazine journal. Their article, "Optogenetic pacing in *Drosophila melanogaster*," was written by Aneesh Alex, a former postdoctoral research scientist at Lehigh, and coauthored by Zhou and by Airong Li and Rudolph E. Tanzi of Harvard Medical School's Department of Neurology. The project has been funded by the National Institutes of Health (NIH).

Optogenetics uses light to control and study the activities of living cells that have been genetically modified with a light-sensitive protein. OCT combines light waves (usually near infrared) with interferometry

to capture microscale images from deep within biological tissue and other media that scatter optical signals.

As a postdoctoral researcher five years ago, Zhou worked with Harvard Medical School researchers to study fruit flies using OCT. "I came up with a new idea," he says, "which was to use optogenetics to stimulate



THANKS TO A RECENT BREAKTHROUGH, THE HEART RHYTHM OF A FRUIT FLY AT EACH DEVELOPMENTAL STAGE CAN BE NONINVASIVELY CONTROLLED BY LIGHT USING OPTOGENETICS.

heart pacing and OCT to monitor heart function.

"We found we could shine a light to control the heart rhythm and use OCT to confirm that the heart was beating and to see how it was beating in real time."

OCT, says Zhou, is similar to ultrasound, which sends sound waves into tissue and measures the reflections.

"OCT uses near infrared light, which has a shorter wavelength than sound waves and gives us much finer microscale resolution. As the light is reflect-

ed from different depths of tissue, the delay in the reflecting of the light signal tells you how deep the signal has penetrated into tissue. From this, we generate a cross-section of a sample from beneath the surface of the tissue."

The fruit fly, known scientifically as *Drosophila melanogaster*, offers advantages for optical study, says Zhou. Biologists have obtained the complete genome sequence for the fly and developed ways to modify the genome. And despite differences in scale and complexity between humans and fruit flies, Zhou says, the genomes of the two are similar.

"For human beings and fruit flies," says Zhou, "70 to 80 percent of the genome is the same. You can easily test a human gene type in the fruit fly and then in a mouse."

The heart of a typical adult fly lies about 200 microns below the fly's outer tissue surface. It varies in size between 10 and 20 microns when contracting and about 100 microns when dilating. It beats 300 to 400 times per minute.

"It is possible to observe the heartbeat of an intact fly only with near-infrared OCT

technology," says Zhou. "Because the fruit fly heart is so small, we need an imaging technique with a high resolution that works quickly. Otherwise, the image we get is blurry."

Zhou and his group bred a genetically altered strain of fruit flies by inserting a light-sensitive protein (taken from algae) into their cardiac cells. They anesthetized a fly, taped its wings to a glass slide and shined a low-power, 16-milliwatt blue laser at its heart. When they altered the frequency of the laser, the fly's heart rate changed accordingly. When the laser pulsed 10 times per second, for example, the heart rate accelerated to 10 beats per second.

To monitor the fruit fly's response to the laser, Zhou and his group developed an optical coherence microscopy (OCM) system that enables nondestructive microscale imaging in real time. They were able to monitor and analyze the structure and function of the fly heart at the larva, pupa and adult stages. OCM, they wrote in *Science Advances*, allowed the group to "quantitatively determine cardiac physiological parameters, such as refractory period [recovery time] and contraction time, of the *Drosophila* heart at different stages of its life cycle."

"One of the key advantages of our system is that it is completely non-invasive," says Zhou. "We can do experiments again and again on the same specimen and see how the same fly heart grows and develops."

During their three-year study, Zhou and his collaborators have observed that the fruit fly's heart slows down in the early pupal stage, stops beating for about a day, and resumes beating at its normal heart rate of 300-400 beats per minute in the late pupal and adult stages.

"We were the first group to observe this dynamic change in the fly heart rate," says Zhou. "It is difficult to detect this without

the noninvasive imaging tools we have."

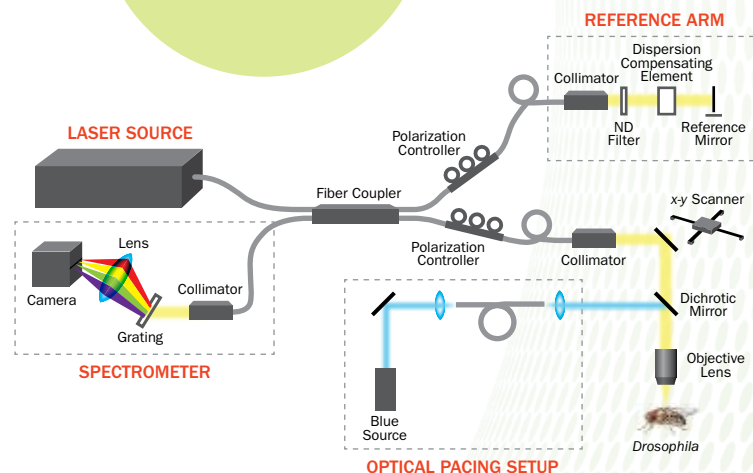
Zhou has a second NIH grant to explore different pacing strategies using OCM. He says it will take many years before optical pacemakers can be used in humans.

"Our initial goal was not to develop optogenetic pacing for humans," he says. "Instead, we wanted to do this in small animals to verify and refine the effectiveness of using near-infrared light signals to stimulate and image heart muscle cells. Also, we wanted to find out how different genes affect heart development. To learn this, we first needed to develop a good research tool."

"With bigger animals come challenges.

How do you insert light-sensitive proteins? How do you do near-infrared stimulation? An optical fiber or LED would need to be implanted, which is invasive."

Zhou's combination of OCT and optogenetics was recently covered in *Science Advances*.



Improving the ability to do noninvasive pacing with optical signals, however, can also help advance the development of novel medical treatments, says Zhou.

"For example, if a person is born with a congenital defect in his heart, can we shine a light on his heart early in his developmental stages, to help correct the defect? Can we use therapeutic tools to correct human heart diseases?

"We don't know the answer to these questions yet, but the technology now exists to make it possible to think about them."

HEEDING THE CALL OF THE FUTURE

A research institute goes global to reinvigorate glass education.

STORY BY ROBERT W. FISHER '79

The United States glass industry faced a dim future when NSF established the International Materials Institute for New Functionality in Glass (IMI-NFG) at Lehigh in 2004.

Following the decline of major U.S. industries, like steel, “we saw the writing on the wall,” says Himanshu Jain, director of IMI-NFG. “And we wanted to do something about it.”

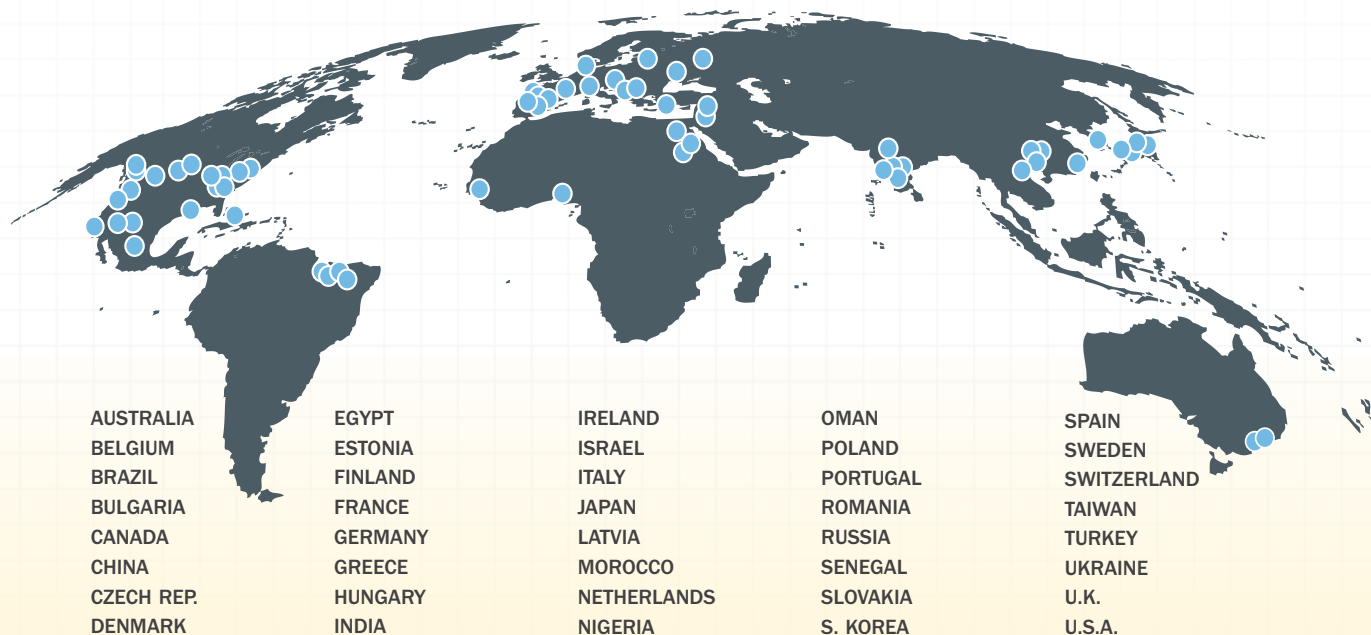
Despite 5,000 years of history and major supporting roles in fiber optics, computers, skyscrapers and many other 20th-century technologies, glass had lost its luster as commodity production, and even research, moved overseas.

Education in high-tech glasses, like the bioglass and photonic glasses that Jain specializes in, was also struggling. Americans were authoring fewer research articles, student interest was falling and the number of university glass experts in the U.S. was declining.

“Glass education became fragmented,” says Jain. “One person at a school like Lehigh cannot train a student in an entire technology.”

In response, the IMI-NFG assembled professors from universities across the U.S. and other countries to teach advanced courses to students around the world via Internet. In 2007, the institute connected professors at five universities with 60 learners for a semester-long course using a new teaching paradigm called multi-institution team teaching (MITT).

The IMI-NFG offered several more courses, says Jain, and now holds a library of more than 300 video lectures. “It is the largest video collection for glass education in the world. And it



The IMI-NFG held a Winter School in Japan and formed a partnership with Tuskegee (far right).



is available anytime, anywhere through the Internet.”

Jain experienced the global reach of the video courses on a trip to Turkey, when engineers at a glass company recognized him on sight from his video appearances.

IMI-NFG also fostered international relationships through a sabbatical program that brought professors from countries including South Korea and Portugal to Lehigh to teach and conduct research. Research exchanges connected graduate students and post-docs from U.S. universities with colleagues from China, Egypt, Italy, Brazil and 25 other nations.

The institute also conducted international glass schools in Japan and China, enabling U.S. students to share classes, industry visits and hotel rooms. The schools sought to build relationships among academics, industry leaders and students who might not otherwise meet, in order to seed future collaboration.

To address the low representation of African-Americans in materials science, Jain launched a partnership with Tuskegee University to bring glass engineering courses to the historically black institution. IMI-NFG also reached out to pre-college educators, training hundreds of teachers to share glass science with younger students—through candy.

“The chemical system of candy—sucrose, water and corn syrup—mimics the window glass system,” Jain says. “Sugar behaves like silica, which is the sand in common glass. Water is analogous to the soda used in glass, and corn syrup acts as aluminum oxide. So here was a way to teach the breadth of glass science in the kitchen.”

William Heffner, IMI-NFG associate



In one research project, Jain is developing biocompatible glass to promote bone regeneration.

director, developed experiments to study glass formation and created a drawing tower that used the principles of cotton candy-making to explain the extrusion of optical fibers.

“We now have an extensive curriculum for middle and high schools,” Jain says. “And I use the same experiments with my Ph.D. students.”

The institute also broke ground in forging industrial partnerships. “The glass field is notorious for secrecy,” Jain says. “This goes back to Roman times. If you leaked out a secret recipe for glassmaking, the punishment was death.

“To develop new functionality it became clear to us that we should work with industry because they are closer to the products and needs of the market,” Jain says. The institute brought together experts from the world’s largest glassmakers and industry representatives—Corning, PPG and GMIC in the U.S.; Schott in Germany; Ashai and Nippon Glass in Japan; and Saint Gobain in France. In 2005, the firms’ chief technology officers sat at

the same table for the first time as IMI-NFG’s Industry Board of Advisors.

Industry partners have played a major role in the institute’s final project, a roadmap with promising directions for future research. “We asked industrial leaders and academics to identify the major scientific questions that should be answered so we can come up with better glass,” says Jain.

Though IMI-NFG’s work has wound down, its model for international, multidisciplinary, academy-industry collaboration has become a durable concept. Programs similar to the IMI-NFG have sprung up in Russia, India and the Czech Republic, and a new center in Brazil has been formed at the behest of a member of the institute’s international advisory board.

The decline in U.S. research activity has stopped. “There is still a lot more activity in China than the U.S., but we are better off than we were,” Jain says. “The downward trend has reversed.”

And Corning has stepped up its academic outreach, establishing new programs for academia-industry partnerships. In one such project, two Lehigh graduate students are performing a part of their graduate research at Corning with guidance from its researchers.

“The IMI-NFG legacy is in two directions,” Jain says. “On the educational front, more qualified students are choosing to study glass, and we are seeing the quality of the workforce improve.

“Second, IMI-NFG has helped universities, academia and industry work better together.

“This is the call of the future, and I think we are there now.”

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Paolo Bocchini applies probabilistic analysis to project the spread of disease and to develop more intelligent disaster recovery plans.

Prioritizing the probabilities of infrastructure performance

A panoramic—and realistic—assessment brings interdependence into focus.

“Civil engineers have done a fantastic job in the last few centuries. We can build anything,” says Paolo Bocchini, assistant professor of civil and environmental engineering. “Yet we keep having significant systemic failures.”

In 2011, for instance, the six boiling water reactors at Japan’s Fukushima Daiichi Nuclear Power Plant reactors survived an earthquake and a tsunami, but subsequent power failures caused several of the reactors to overheat and release radiation.

From buildings and reactor vessels to roads and bridges to the electrical grid and emergency response workers, engineers and disaster planners have traditionally looked individually at each component of infrastructure. In reality, says Bocchini, they comprise an interdependent whole. “The recovery of one infrastructure system usually depends on another.”

Bocchini was one of the first engineers to create computer models that factor the resilience of larger infrastructure systems into disaster planning. Today he leads a multidisciplinary, nationwide team with a \$2.2 million National Science

Lehigh, Florida Atlantic University and Georgia State.

“Resilience brings to the table the idea that we shouldn’t just look at the extreme event itself,” Bocchini says. The long-term effects are important, and the losses are usually much larger than the initial impact.

Bocchini’s work zooms out from traditional engineering thinking, giving a higher priority to the overall recovery of a system than to the integrity of a system’s individual components.

“The problems we are trying to address make sense when you think about communities and functionality,” he says. “We don’t care so much if there is a crack in a column. We want to know if the bridge will be open.” Ultimately, planners want to know that traffic can reach its destination.

With limited resources and decaying infrastructure, says Bocchini, community leaders need to make decisions with the greater good in mind. After Hurricane Sandy, for example, New York’s public transit system spent an extraordinary sum to drain flooded subway tracks quickly, only to find there were no riders because many

casualties, long-term socioeconomic losses, and environmental impacts.

“We never try to give a single answer,” Bocchini says. “We provide a set of trade-offs” that officials can use to make better decisions.

It’s usually not politically useful for leaders to shore up systems that are mostly invisible to their constituents, so infrastructure issues are not high on the public’s wish list. Bocchini believes the engineering profession has a role to play in educating citizens.

“We have to make the case with credible numbers that infrastructure resilience is valuable,” he says. One goal of PRAISys is to provide those numbers by quantifying how improvements could save lives and dollars.

“I can see this as the first seed of a life’s work,” he says. “If at the end of my career I have completed such a platform, I will call it a success.”

Bocchini applies the same probabilistic analysis to predicting how Ebola virus spreads, in collaboration with Javier Buceta, associate professor of chemical and biomolecular engineering. Ebola is carried by bats, and migration patterns are affected by complex factors, including temperatures and other weather patterns, he says. Knowing the probabilities of how, and in what direction, an outbreak will spread can allow officials to rapidly direct doctors and supplies.

Bocchini’s research group is also working with Bethlehem city government on its entry for the Rockefeller Foundation’s “100 Resilient Cities” project. And he has developed software that uses guided ultrasonic waves to test pipelines and rail tracks.

In 2009, when Bocchini began working with the probabilistic assessment of complex systems with Dan Frangopol, the Fazlur R. Khan Professor of Structural Engineering and Architecture, only a few research groups in the world were working in this area. Today, infrastructure resilience is a hot topic in government and industry circles.

“Everyone is going this way now,” Bocchini says. “We’re just trying to run a little faster.”



Foundation grant to develop a platform—called Probabilistic Resilience Assessment of Interdependent Systems, or PRAISys—“that will provide decision makers with a prediction of what will happen” after a disaster and “prioritize strategies that will bring back functionality most quickly,” he says.

The PRAISys team includes engineers from several disciplines, as well as experts in economics and the social sciences, from

offices and attractions in Manhattan were still closed. “It was a loss that could have been avoided with more coordination,” Bocchini says.

As the federal government and many states push to develop better disaster plans, PRAISys researchers are using a probabilistic approach to assess how a community’s systems interact and to give decision makers better options to reduce

LEHIGH'S ADVANCED TECHNOLOGY FOR LARGE STRUCTURAL SYSTEMS (ATLSS) CENTER

, established in 1986 within the NSF's Engineering Research Center program, is globally renowned for research on the performance of large structural and infrastructure systems. Herbert Imbt Laboratories, home of the ATLSS Center, was first built in 1961 as the crown jewel of Bethlehem Steel's Homer Research Laboratories. Lehigh acquired the facility a quarter century later, as part of the Lee Iacocca-brokered deal that established the university's Mountaintop Campus.



- It would take more than **300** concrete trucks to contain the material used in its **4,000** square feet of strong floor and **50-foot** fixed reaction walls.
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BALANCING RESILIENCY AND SUSTAINABILITY

The challenges of designing resilient infrastructure, says Clifford C. Eby '73, former president of the U.S. Transportation sector for WSP | Parsons Brinckerhoff, are driven by changing demographics and the emergence of new technologies.

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