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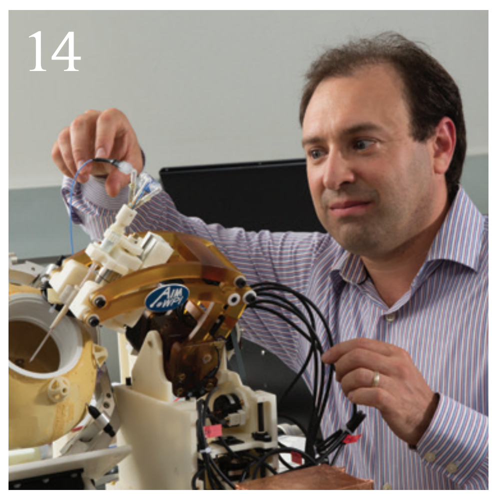
KEEP UP WITH RESEARCH AT WPI > Read the latest WPI research news, watch videos about research, and read stories from this magazine at **wpi.edu/+research**.

ON THE COVER: Wearable devices developed by Ivon Arroyo and her students make learning math an action-packed game (story, page 20). The device seen here (for a game called "Tangrams Race") was designed by Shadi Ramadan '16 as part of an undergraduate Interactive Qualifying Project advised by Arroyo. Other IQP team members (all Class of 2016) were Dylan McCarthy, Alex Silva, Dalton Tapply, Peter Leondires, and Christopher Cerruti. Photo by Patrick O'Connor. Art direction by Pamela Mecca. Model: Jack Morriarty, Karon Shea Model Management.



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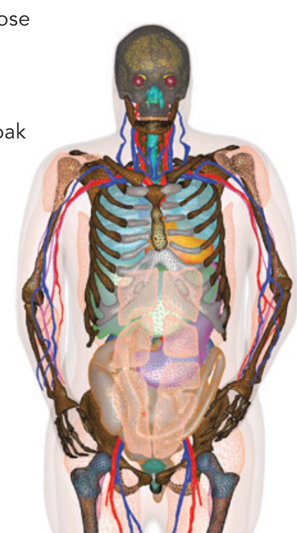

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Peggy Isaacson, *Copy Editor*
Joan Killough-Miller, *Contributing Editor*
Dianne Vanacore, *Production Manager*

DESIGN
Pamela Mecca

PHOTOGRAPHY
Patrick O'Connor

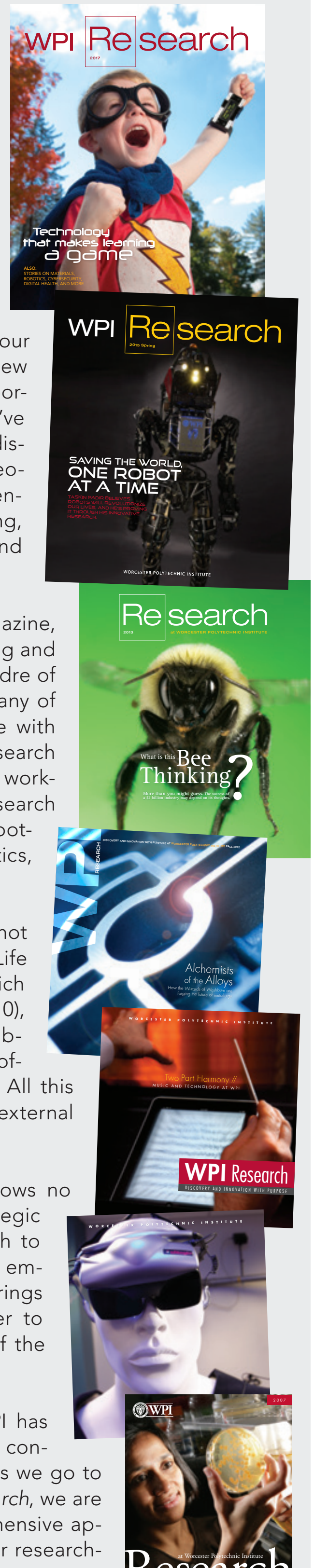
WPI Research is produced for the Division of Academic Affairs by the Division of Marketing and Communications.

Address correspondence to:
Michael Dorsey, Editor
WPI Research
Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609-2280
508-831-5609
research@wpi.edu

WPI

> ABSTRACT

TELLING AN EVER EXPANDING STORY



This annual research magazine debuted 10 years ago. Its mission, expressed in the motto "Discovery and Innovation with Purpose," was to tell stories about applied science, technology, engineering, and mathematics research at WPI, work by our faculty members and students that seeks new knowledge and innovative solutions to important problems. Over the past decade, we've chronicled advances in a broad range of disciplines, from aerospace engineering to zeolites, and covered impactful work in regenerative medicine, fire protection engineering, metallurgy, clean energy, digital health, and dozens of other areas.

While we have been bringing you this magazine, WPI's research enterprise has been growing and evolving—driven, in part, by a growing cadre of outstanding full-time faculty members, many of whom have arrived over the past decade with well-developed and, often, well-funded research programs. Many of these researchers are working in areas that were not part of WPI's research landscape 10 years ago, fields such as robotics engineering, cybersecurity, bioinformatics, autonomous vehicles, and data science.

Some are working in facilities that were not available a decade ago, including the Life Sciences and Bioengineering Center, which opened its doors in the fall of 2007 (page 10), and the Fire Protection Engineering Laboratory (page 48), one of the few state-of-the-art fire science facilities in academia. All this has helped fuel greater success in winning external research funding.

The rise of WPI's research enterprise shows no signs of slowing. In fact, WPI's new strategic plan, *Elevate Impact*, calls for that growth to accelerate, as the university places a new emphasis on cross-disciplinary work that brings large teams of faculty members together to seek substantial awards to tackle some of the grand challenges facing our world.

The truth is, the story of research at WPI has become too rich and too expansive to be contained in this one annual publcation. So as we go to press on this, the last edition of *WPI Research*, we are also preparing to roll out a more comprehensive approach to sharing the remarkable work our researchers do, around the clock and throughout the year.

Watch for more robust coverage of WPI research in the *WPI Journal*, our university magazine. Check the research section of the WPI website (wpi.edu/+research) regularly for news, feature stories, videos, and other content. And stand by for some new ways we are exploring to share the discoveries and innovations from our research programs and to capture their impact on our lives.

We hope you've enjoyed *WPI Research*. We look forward to continuing to share WPI's ever expanding research story with you in the years ahead. As always, we value your feedback. Write to us at research@wpi.edu.

—the editors

notebook

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HOT FLAMES AND COLD STEEL

SITTING ATOP one of the world's most active geologic areas, Southern California is particularly prone to earthquakes. A 2008 U.S. Geological Survey report warned that a 7.8 magnitude tremor on the San Andreas Fault could cause more than 1,800 deaths, 50,000 injuries, and $200 billion in damage. While the shaking from a quake is destructive, fires that can break out afterward can do even greater damage. A 2012 study by WPI fire protection engineers showed that earthquake-related damage to a building's structural elements and fire protection systems can accelerate the spread of fires and make it harder for firefighters to respond and occupants to evacuate.

That study, led by **Brian Meacham**, PhD, associate professor of fire protection engineering, was conducted in a five-story concrete building constructed atop one of the world's largest outdoor shake tables. Located at the Englekirk Structural Engineering Center, the facility is part of the University of California San Diego Jacobs School of Engineering. WPI's tests were part of a larger study, sponsored by the National Science Foundation and industry, on the effects of quakes on building structures and systems.

In June 2016 Meacham returned to San Diego with a new research team to conduct a series of tests aimed at determining how a structure made from panels composed of lightweight cold-formed steel (CFS) frames with gypsum board cover would respond to a post-earthquake fire. The use of lightweight, prefabricated CFS panels in residential and commercial construction is increasing because they make it possible to build taller structures, they cut construction times, and they are fire-resistant and recyclable. But little is known about how buildings constructed with these new materials will perform during and after quakes.

"Anytime there's a new building technology it's good to do full-scale tests because then you can understand how the technology is likely to perform in real life," says Meacham, who worked closely on the design and execution of the overall research project with co-principal investigators Tara Hutchinson and Gil Hegemier of the Center for Extreme Events Research at UC San Diego.

According to seismic codes, buildings in quake-prone areas can suffer some damage during strong shaking, though they should remain structurally sound. But that damage can leave a building more vulnerable to fire, and a blaze that erupts soon after an earthquake could exploit those weaknesses, posing the threat of collapse. Meacham notes that existing codes often do not explicitly consider damage associated with fire following an earthquake.

The tests were conducted in a six-story building, the tallest cold-formed steel-frame structure ever constructed on a shake table.

Above: A fire test under way in a cold-formed steel structure built atop the University of California San Diego's outdoor shake table. Left, Brian Meacham, at left, watches the test with Tara Hutchinson (UC San Diego) and Dan Arthur (WPI research assistant).

First, researchers from UC San Diego put it through rigorous tests to mimic the seismic activity of moderate to severe earthquakes. After the damage was assessed, the WPI team carried out fire tests in several rooms to study the fire performance of the damaged building. They ignited pans of heptane and observed temperature impacts, flame spread, and smoke movement. The goal was to determine the damage to the interior and exterior CFS panel systems and interior doors and frames from a 10–12 minute significant fire exposure.

"Within 10 minutes much of the gypsum board cover became significantly degraded," says Praveen Kamath, PhD, a WPI postdoctoral researcher who is assisting with the study. "This equates to a loss of structural strength and fire protection capacity. With the data we collected we're trying to quantify the loss in structural capacity in order to help advance our ability to predict if such a building could collapse, and when, in longer duration fires."

The tests were sponsored by several government and industry stakeholders, including the U.S. Department of Housing and Urban Development, the California Seismic Safety Commission, CEMCO, Sure-Board, USG Building Materials, State Farm Insurance, and Suffolk Construction.

While the research team analyzes the data collected in San Diego, plans are also in the works to conduct similar tests on structures built with other emerging building materials.

—Colleen Wamback

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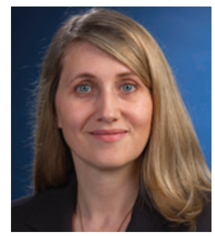
USING NEUTRONS TO SHED LIGHT ON DIABETES

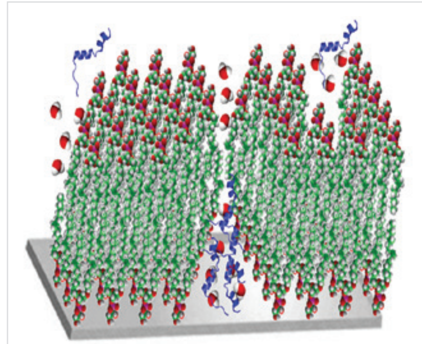
AMYLOID POLYPEPTIDES are short chains of amino acids that have been linked to a variety of diseases, including Alzheimer's



and Parkinson's. Their tendency to aggregate into fibers leads to the disruption of the normal functioning of cells and organs. In a recent paper published in the journal *Langmuir*, WPI physicist **Izabela Stroe**, PhD, in collaboration with colleagues at Los Alamos National Laboratory, the University of California Davis, and Yale University, reported on discoveries that shed new light on the role of amyloid polypeptides in type 2 diabetes, the seventh leading cause of death in the United States.

While the genesis of diabetes remains unknown, it is clear that the disease occurs when cells in the periphery of the body become less sensitive to insulin. Beta cells in the pancreas then step up their production of the hormone, which regulates blood glucose. Along with insulin, the beta cells produce islet amyloid polypeptide (IAPP). As insulin production increases, the excess amyloid molecules begin aggregating into fibers. Somewhere along the way, the beta cells begin to die (leading to insulin deficiency) through an as yet unknown mechanism that appears to involve damage to the cell membranes.

To get a better idea of the process that may lead to beta cell death, the research team conducted studies of the interaction of human IAAP and rat IAAP with several model cell membranes. Rat IAAP, which differs from the human variant by only a few amino acid sequences, was used because it does not form fibers; in the studies, it appeared to have no interaction with the membranes, leading the researchers to conclude that the beta cell damage is connected with amyloid fibers.



Amyloid peptides may disrupt the cell membranes of beta cells in the pancreas, a possible contributor to type 2 diabetes.

Using specialized equipment at Los Alamos, the team observed what happened to the model membranes when they came in contact with human IAPP. One of the tools they used, neutron reflectometry, is able to produce images of the membranes with high spatial resolution due to the way neutrons scatter from biological objects. The images showed that membranes with negatively charged and unsaturated lipids were particularly vulnerable to damage from the positively charged aggregated amyloid molecules. Since the negatively charged lipids tend to be in the inner leaflet of cell membranes, the researchers speculated that defects in the membrane might be an entry point for the IAAP fibers.

"There is more work to be done to fully understand how the amyloid fibers and the lipids in the membrane interact to produce membrane disruption," Stroe says. "This knowledge could be crucial in developing strategies to counter the development of type 2 diabetes and physiochemically similar neurodegenerative diseases like Alzheimer's."

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WPI PLAYS PIVOTAL ROLE IN NATIONAL REPORT ON ADVANCED MATERIALS

IN EARLY OCTOBER 2016, the U.S. Council on Competitiveness (CoC) unveiled a major report on the link between advanced materials and America's future economic vitality. The report, reflecting more than a decade of study on advanced materials by the council, was the product of an April 2016 dialogue on the subject organized by the council's Energy and Manufacturing Competitiveness Partnership and chaired by WPI president **Laurie Leshin**, along with council president and CEO Deborah Wince-Smith and Aziz Asphahani, CEO of QuesTek Innovations.

The panel discussion included national leaders and materials experts from all sectors of the economy. Among the participants from WPI were **Danielle Cote**, assistant research professor of materials science and engineering; **Diana Lados**, associate professor of mechanical engineering and director of the Integrative Materials Design Center; **Brajendra Mishra**, Kenneth G. Merriam Distinguished Professor of Mechanical Engineering and director of the Center for Resource Recovery and Recycling; and **Bogdan Vernescu**, vice provost for research.

Diran Apelian, Alcoa-Howmet Professor of Engineering at WPI and founding director of the Metal Processing Institute (MPI), gave a presentation during the April CoC meeting on barriers and impediments to deploying the full potential of advanced materials. Subsequently, Apelian and Asphahani participated in a panel on Capitol Hill on Oct. 4 (National Manufacturing Day), where the council report was made public.

"Throughout history, materials have marked eras in our development as a society, civilization, and culture: Stone Age, Bronze Age, Iron Age, and so on," Apelian said during the Capitol Hill event. "In the 21st century, it is the Innovation Age, which is enabled and fueled by advanced materials. For the United States to maintain its competitive advantage, we must invest in the engine that fuels the innovation economy: advanced materials. It's that simple."

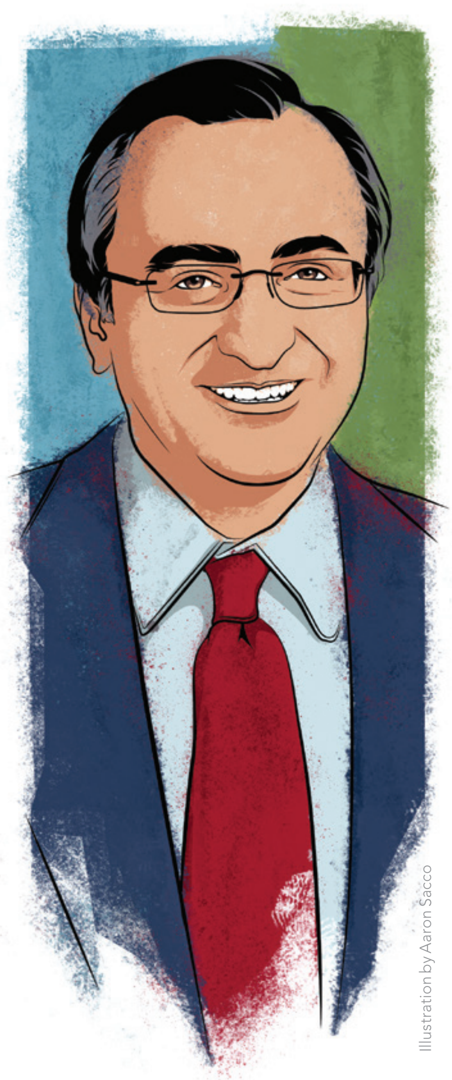
The report, *Leverage: Advanced Materials*, explained how new materials will be critical building blocks that can drive significant enhancements in America's energy production, manufactured products, and overall economy. "Advanced materials are a key enabler to enhancing U.S. manufacturing competitiveness and ensuring its sustained growth by increasing products' performance and durability, and by lowering their cost via improved energy efficiency," said Asphahani. He noted that the report offers these clear recommendations for the design, development, and deployment of novel materials at a faster pace and reduced cost:

- Take a deeper dive into the full life cycle of rare earths and other critical materials.
- Develop a better understanding of the risk aversion among manufacturers to using new materials in systems.
- Dedicate area-specific pilot-plant facilities to collaborate with national laboratories, universities, and companies to accelerate deployment and decrease the commercialization time horizon for advanced materials.
- Address the skills gap in the advanced materials and manufacturing sector by embracing an interdisciplinary approach to education that combines traditional materials science curricula with data science, modeling, and computational sciences.
- Develop a national platform to promote the generation and sharing of data to support the creation, processing, modeling, and manufacturing of advanced materials.

In this vein, WPI's MPI is launching the multi-university Center for Materials Processing, with Danielle Cote as director. It will generate and manage in-process, transient materials properties used in modeling and simulation.

The U.S. Council on Competitiveness is a nonpartisan leadership group of CEOs, university presidents, labor leaders, and national laboratory directors working to ensure U.S. prosperity.

Top: WPI president Laurie Leshin, center, and vice provost for research Bogdan Vernescu, far right, participate in a dialog on advanced materials at the Council on Competitiveness; Leshin co-chaired the discussion, which led to a council report. Left: Diran Apelian, founding director of WPI's Metal Processing Institute, discussed the report on Capitol Hill in October 2016.



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JAMAL YAGOOBI ON THE NEW CENTER FOR ADVANCED RESEARCH IN DRYING

What do potato chips, copier paper, and aspirin tablets have in common? They all have to be carefully dried as part of their manufacture. In fact, drying is one of the most energy-intensive processes in manufacturing, one that uses about 2 percent of all the energy consumed in the United States each year. A new multi-university research center led by WPI aims to dramatically reduce that energy consumption while also improving the quality of products made by a wide swath of industries (the center's initial focus will be the food and agriculture, forestry, textile, chemical, and biopharmaceutical industries).

Led by **Jamal Yagoobi**, George I. Alden Professor and head of WPI's Department of Mechanical Engineering, the Center for Advanced Research in Drying (CARD) brings together researchers at WPI and the University of Illinois at Urbana-Champaign. It is funded by the National Science Foundation (NSF) through its Industry/University Cooperative Research Centers (I/UCRC) program and by annual fees paid by its corporate members. The center held the inaugural meeting with its Industry Advisory Board in fall 2016 and will begin work on eight pre-competitive research projects in early 2017.

WHY FOCUS ON INDUSTRIAL DRYING?

Yagoobi: First of all, many industries must dry moist porous materials. These drying processes use tremendous amounts of energy, and large volumes of water. Major innovations in drying, when commercialized, will positively affect production costs, process efficiency, energy sustainability, and product quality. By reducing the energy now wasted by drying processes, CARD will help cut annual U.S. energy consumption by at least 0.2 quads of energy (a quad is 1,015 BTUs), which is the equivalent of more than 36 million barrels of oil. Since drying frequently involves the use of steam, we can also save the equivalent of about 4,000 Olympic-size swimming pools of water each year.

HOW WILL CARD CONTRIBUTE TO NATIONAL ENERGY SAVINGS GOALS?

Yagoobi: The U.S. Department of Energy's (DOE) Advanced Manufacturing Office has recognized the importance of the energy savings that one can achieve from efficient drying and related processes (including heating, frying, cooling, and baking, which could also become the subjects of CARD research). CARD will contribute to national energy savings goals by making drying and other related processes more energy efficient. In fact, CARD is a member of two of the DOE's National Network for Manufacturing Innovation (NNMI) institutes. The NNMI is a network of research institutes that focuses on developing and commercializing manufacturing technologies through public-private partnerships between U.S. industry, universities, and federal government agencies. [At press time, there were 12 institutes, led by the DOE and the Department of Defense, with more planned in the near future.]

AS INAUGURAL DIRECTOR OF CARD, WHAT IS YOUR GOAL IN THIS FIRST YEAR?

Now that our advisory board has met for the first time and selected the first set of research projects from the pool that CARD faculty members presented, our focus will turn to research by teams of faculty members at WPI (11 faculty researchers) and Illinois (10 faculty researchers), along with a large cadre of graduate students. These projects are designed to address issues that are of concern to many of our members, and to develop new technologies that can have a positive impact on energy and water use and product quality across entire industries. It is important to note that the participation of graduate students ties into one of our core missions, which is to assist in preparing a highly trained workforce to help advance U.S. manufacturing.

WHAT'S THE SIGNIFICANCE OF RECEIVING FUNDING THROUGH THE NSF'S I/UCRC PROGRAM?

This 40-year-old highly competitive and rigorous NSF program is all about stimulating innovation and economic growth. Being accepted is very prestigious; it raises WPI's status nationally and internationally. It will also enable us to more effectively recruit additional member companies.

WHAT INSPIRED YOU TO LAUNCH THIS NEW CENTER?

My own research on transport phenomena in porous moist materials led me to establish a drying research center at Texas A&M University when I was a faculty member there. Then, about four years ago, after I had joined the WPI faculty, I first envisioned CARD. I began discussing the idea with Irfan Ahmad, executive director of the Center for Nanoscale Science and Technology, and Hao Feng, professor of food science and human nutrition, both at the University of Illinois (Feng is now the Illinois site director for CARD).

I wanted to achieve transformative breakthroughs in drying technologies. We expect these technologies will have a profound impact on U.S. manufacturing capabilities. In the long run, the magnitude of the changes our research could bring about may very well foster a new era of U.S. manufacturing competitiveness and job creation.

Learn more at dryingresearch.org.

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THE BRAIN ON JAZZ: FUNCTIONAL MRI STUDY IDENTIFIES THE COGNITIVE ROOTS OF IMPROVISATION

Time and again I've longed for adventure
Something to make my heart beat the faster
What did I long for? I never really knew.

—*All the Things You Are* (Jerome Kern, Oscar Hammerstein II)

Patrick O'Connor

LOUIS ARMSTRONG once said the essence of jazz is, "never play anything the same way twice." Indeed, free improvisation is at the heart of jazz and is what distinguishes it from many other musical forms, including classical music. It's why each performance of a jazz standard like *All the Things You Are* constitutes a new creative adventure for the musician and a unique experience for the listener.

While improvising is clearly a distinct creative process, does it also reflect a unique state of mind? And if so, can that state be identified in the way the brain behaves during musical improvisation? And if one can connect the improvisational process to patterns of brain activity, can that knowledge help educators teach students to be better improvisers and more confident performers?

These are among the questions that drove two music faculty members at WPI to become brain researchers. For jazz guitarist **Rich Falco**, director of jazz studies at WPI and founder of the Jazz History Database, that transition began when he first noticed a set of common behaviors in musicians playing improvisational jazz. "They have a relaxed posture, slow breathing, and a sort of calm," he says. "The tension seems to drain away as their focus shifts internally. I like to say, they're 'in the zone.'"

Composer and musician **Frederick Bianchi**, director of computer music research at WPI and developer of music technology, including the Virtual Orchestra, also has observed and experienced the zone. "In the zone, action and awareness merge," he says. "Inner analysis is bypassed and the brain's predilection to micromanage is denied. Time becomes suspended, ideas begin to flow, and the performance unfolds without effort."

By chance, one of Falco's and Bianchi's colleagues, Karl Helmer, PhD, is assistant professor in radiology at Harvard Medical School and assistant in research at Massachusetts General Hospital (MGH). He conducts cognitive research using the MRI scanners at MGH's renowned Martinos Center for Biomedical Imaging.

Helmer, Bianchi, and Falco reviewed the handful of previous studies on cognition and musical improvisation. These had identified different patterns of brain activation and deactivation during improvisation, particularly in a region known as the dorsal lateral prefontal cortex (DLPC), which controls executive functions (attentional control, decision making, planning, etc.). Activation of the DLPC is associated with a state of focused attention, while deactivation can indicate mind wandering.

The previous studies seemed inconclusive. A study using classically trained pianists observed DLPC activation during improvisation, with the level of activation increasing along with the level of complexity of the task the musicians were asked to perform. In a study using jazz musicians as subjects, the DLPC seemed to shut down altogether when the subjects improvised.

Is improvisation an active, creative process that requires focused attention on a goal, or is it necessary for the brain's self-monitoring center to get out of the way to achieve the spontaneous, unfettered "zone" that Bianchi and Falco had observed in themselves and their students? The WPI team wondered whether the truth might lie somewhere in between.

Bianchi, Falco, and Helmer decided to design a new study aimed at closely simulating the actual experience of jazz improvisation; they received support from WPI's dean of arts and sciences to carry it out at the Martinos Center. Eight experienced jazz musicians each

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Frederick Bianchi, left, and Rich Falco are musicians, music educators, and innovators. Through their own experience and their work with students, they observed a set of behaviors associated with jazz improvisation and wondered if those behaviors correlated with specific brain states. With a colleague at Massachusetts General Hospital, they conducted a functional MRI study that revealed how the brain moves in and out of what they call "the zone" during a jazz performance.

spent an hour performing and improvising *All the Things You Are* while lying in a functional MRI (fMRI) scanner with a specially designed two-octave keyboard, headphones, and a mirror on which music could be projected.

Reviewing the results, the researchers observed more DLPC deactivation during improvisation than during the periods when the musicians were simply playing or embellishing on the melody, tasks that seemed to require more focused attention. But even during the improvisation, periods of deactivation alternated with shorter periods of activation, as if the brain were drifting in and out of the zone. "The mind wandering associated with deactivation is akin to creative daydreaming," Falco says. "It tunes out the conscious act of playing and lets the musical performance 'take you someplace.'"

But too much wandering leads to errors. In the study, errors seemed to jolt the improvising musicians' brains from the inactive to the alert state. In practice, Falco says, a jazz musician needs to be able to move between brain states. At times, the executive functions need to turn off to permit unbridled creativity. But the musician must also be able to pop back into focused awareness to monitor where the improvisation is going and how he is responding to and building on the playing of other musicians in the ensemble.

The study showed that it is this flow between attention and mind wandering that truly characterizes improvisation, Bianchi says. "It's similar to having one of those dreams where you are aware that you're dreaming. You're monitoring the dream, but you're also careful not to leave the dream by coming too close to the waking surface."

With the knowledge they've gained, Bianchi and Falco plan to develop a seminar to teach students how to enter the zone and achieve the critical balance between self-awareness and creative daydreaming. They will likely turn to the tools of meditation, yoga, and breathing exercises, which are known to help people achieve similar mental states.

"In my own teaching, I have found that focusing on one's breathing helps you move from awareness of the task of playing to a state where you are a witness—a place where self-criticism is nonexistent," Falco says. "Yoga can also help the state of self-awareness melt away, while other kinds of meditation focus on making the performer more aware of mind wandering. We believe that we can use a combination of these techniques to replicate the mental states we observed in our fMRI study."

<
U.S. Education Secretary John King Jr., left, and Neil Heffernan observe students using ASSISTments at a recent event at the White House.

>
CLOSING THE LEARNING GAP

NEIL HEFFERNAN, PHD, professor of computer science and director of WPI's Learning Sciences and Technologies Program, developed the intelligent tutoring system ASSISTments 15 years ago. Though it has been widely used, Heffernan has often faced an uphill battle in getting the free program accepted by skeptical school districts, which tend to be wary of pricey but unproven computer-based "ed-tech" programs.

"We'd seen the positive effect of ASSISTments on teachers and students in every school we worked with," Heffernan says, "but we didn't have hard data to show it." Today, he does.

A randomized control trial conducted in public schools in Maine and published in the journal *AERA Open* quantified the program's benefits. "Students in schools using ASSISTments scored about 75 percent higher than students in schools that were not using the program," Heffernan says.

The study of the effectiveness of ASSISTments used for mathematics homework was conducted by SRI Educational Research and stemmed from a $3.5 million grant awarded to SRI in 2012 by the U.S. Department of Education's Institute of Education Sciences. The University of Maine assisted with the study by conducting classroom observations and other research.

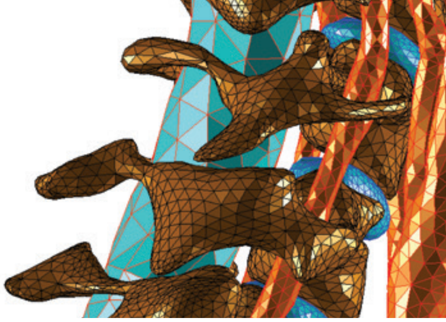
The study examined test scores of 2,850 7th graders at 43 public schools in Maine, which has provided laptop computers or iPads to 7th and 8th graders in all schools across the state since 2002. Schools were matched in terms of demographics and socio-economic status and then randomly assigned by SRI to the test group or control group.

According to national data provided by test publisher McGraw Hill, TerraNova scores generally increase by an average of 11.66 points per year between 6th and 9th grades. In the Maine study, however, students using ASSISTments scored an average of 8.84 points higher than those in the control group. Presuming the control group in Maine met the national average, the added 8.84 points gained by students using ASSISTments is a large and meaningful effect.

"This rigorous, randomized study by SRI—a well-respected educational research organization—has given us the gold-standard proof schools want," Heffernan says.

Notably, ASSISTments proved most beneficial for students who began the year with lower math scores. "Some 60 percent of the schools that used ASSISTments are in towns with lower socio-economic status, where students tended to have lower scores," he says. "Using ASSISTments brought those students up to the level of their peers in towns of higher socio-economic status."

—Alison Duffy



HOW A VIRTUAL HUMAN AIDS MEDICAL RESEARCH

THANKS TO THE GENEROSITY OF A WOMAN who donated her body for research and the ingenuity of a team of engineers at WPI, medical researchers and physicians now have a remarkable new computational tool for research and diagnosis. Called the Virtual Human Project, Female, the tool, developed by a team led by **Sergey Makarov**, professor of electrical and computer engineering, is a highly detailed digital model of the human body created by assembling and processing images of 5,000 cross-sectional slices of the donated female cadaver.

Matthew Burgos

Developed over the last four years by a team that includes faculty members and students at WPI, engineers at NEVA Electromagnetics (a company founded by Makarov), and clinicians at Beth Israel Deaconess Medical Center in Boston, the computational human phantom contains all of the body's 206 bones, 26 different kinds of tissues, and 270 individual tissue parts.

The model is the product of thousands of hours of painstaking work using proprietary software developed under Makarov's guidance. The software made it possible to combine the high-resolution color photographs of the donor's external and internal composition (each a frozen slice just one-third of a millimeter thick) created for the National Library of Medicine and made available to Makarov and his team. A variety of image processing techniques were used to align the images and digitally stitch them into a highly detailed three-dimensional virtual body.

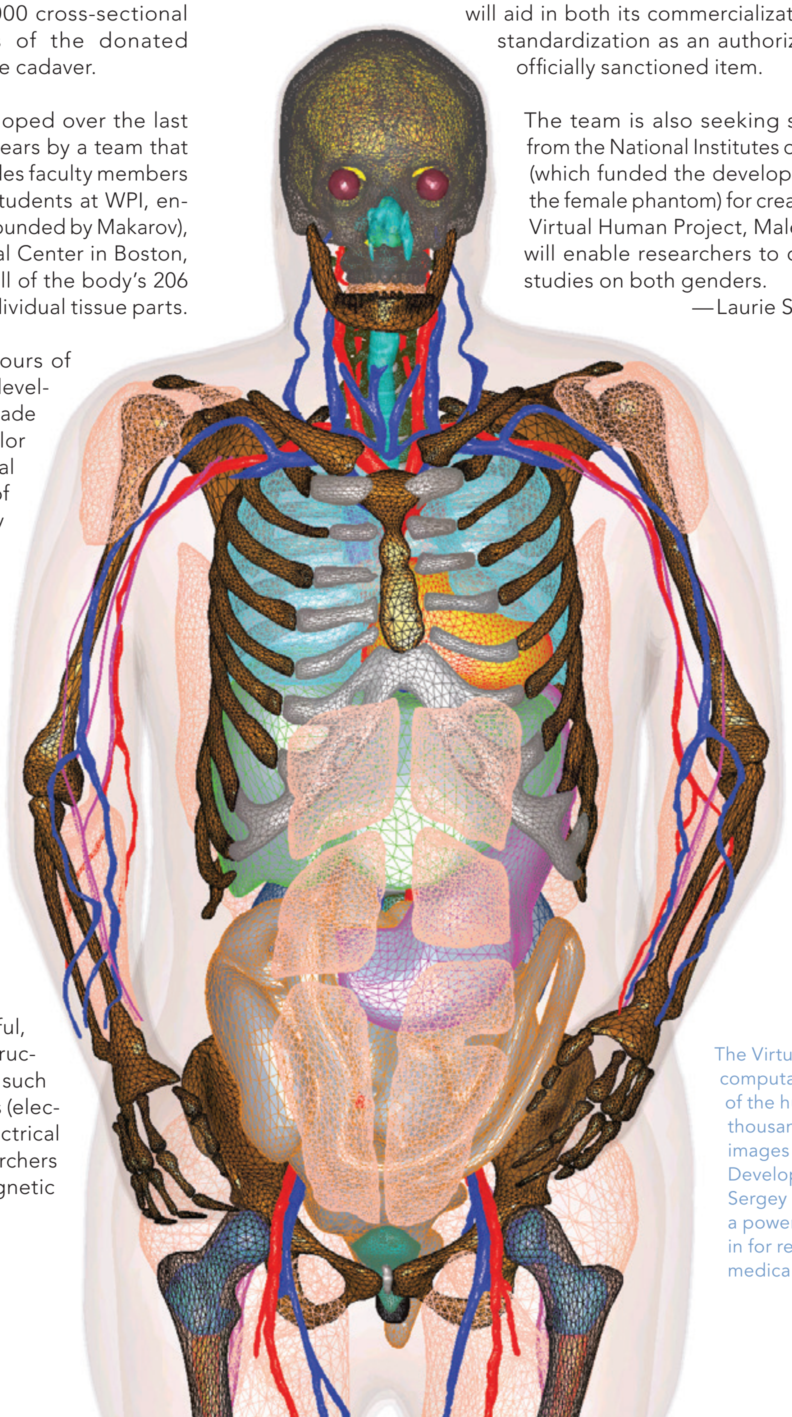
The Virtual Human is designed to be a tool for conducting virtual medical procedures and experiments. Among research that could be undertaken with the phantom is the development of new metal implants for restoring joint function, tests of radiation treatment for cancer, work on neurotransmitters for treating Parkinson's disease, experiments with endoscopic video capsules for colon screening, and even studies of the effects of car crashes on the body.

One area where the tool can be particularly useful, Makarov says, is the study of how the body's structures respond to electromagnetic energy from such diagnostic tools as MRI and CT scans and EEGs (electroencephalography, a tool used to record electrical activity in the brain). With the virtual body, researchers can see how the body will absorb electromagnetic radiation of different strengths and test out new diagnostic and treatment protocols in cases where testing on live humans or animals is neither easy nor cost-effective.

The Virtual Human model is available to researchers for free upon request to NEVA. To date, more than 200 individual users worldwide, in academia and industry, have registered to use it; three simulation software companies, one in the United States and one two in Germany, have licensed the technology. Makarov has applied to the U.S. Food and Drug Administration to have the model, which is compatible with all major commercial electromagnetic simulation packages, approved as a medical device development tool, which will aid in both its commercialization and standardization as an authorized and officially sanctioned item.

The team is also seeking support from the National Institutes of Health (which funded the development of the female phantom) for creating the Virtual Human Project, Male, which will enable researchers to conduct studies on both genders.

—Laurie Schlatter



The Virtual Human, Female, is a computational representation of the human body made from thousands of cross-sectional images of a donated body. Developed by a team led by Sergey Makarov, the model is a powerful tool that can stand in for real human subjects in medical research.

BEATING THE HEAT IN SPACE

IN SPACE, IT'S HARD TO KEEP YOUR COOL — especially if you're a high-powered electronic device. Much of the electronic hardware found in modern satellites and space vehicles generates considerable heat. If not adequately removed, that heat can impair the performance of these devices or even cause them to fail.

For many years, NASA has been in search of a new way to deal with that heat to improve the performance and reliability of electronics in its satellites, planetary robots, and manned platforms, including the International Space Station. As with all space hardware, the solution should use little electric power, be lightweight, and have few moving parts, which could create noise and vibrations.

A promising answer has emerged from work conducted over the past decade by a research team led by **Jamal Yagoobi**, professor and head of WPI's Department of Mechanical Engineering. (Yagoobi is also director of the new National Science Foundation-funded Center for Advanced Research in Drying; see page 5.)

With continuous support from NASA over that period, and working in collaboration with researchers at the agency's Goddard Space Flight Center in Greenbelt, Md., and its Glenn Research Center outside Cleveland, Yagoobi and the team in his Multi-Scale Heat Transfer Laboratory have developed a novel cooling technology that appears to meet all of NASA's requirements. After extensive testing on the ground and in the air, the innovation will fly aboard the International Space Station later this decade.

The cooling solution is based on electrohydrodynamics (EHD), which involves the use of electrically charged fluids. EHD devices convert electrical energy directly into kinetic energy, or motion. In the devices developed in the Multi-Scale Heat Transfer Lab, a nonsymmetrical electric field is used to move a charged liquid through tubes as thin as a human hair. The fluid picks up heat from a hot surface (such as an operating electronic device) and begins to boil. The EHD pump moves the vapor away from the surface, where it is cooled back into liquid form so it can be circulated through the EHD pump again.

Prototypes of the cooling technology have been tested by Yagoobi and his team on NASA's reduced gravity aircraft, a modified Boeing 727 popularly known as the Vomit Comet, which follows a steep parabolic trajectory in order to generate 20-second periods of microgravity—up to 40 per flight. To date, team members have made 10 research flights, which have allowed them to test variations in the design of a single-phase EHD system (one where the liquid does not boil) and an EHD-driven liquid film-flow boiling system. After additional ground tests of an improved two-phase (liquid/vapor) system, preparations are under way for a new test flight on the Vomit Comet in 2017.

Yagoobi's team is also preparing for an even loftier milestone: developing an experiment for the International Space Station (ISS). NASA will spend about $7.5 million over the next several years on research into heat transfer using Yagoobi's technology. Their mission is to develop an experiment to prove the ability of their two-phase EHD system to keep high-performance electronics cool on orbit. The experiment is expected to fly in 2020.

Jamal Yagoobi, left, floats beside a prototype of the EHD pump during a test on the Vomit Comet. To the left, the mission patch for the planned test of the pump aboard the International Space Station.

"We have successfully passed NASA's science review of our project," Yagoobi says, "and we are scheduled to pass the engineering review in late 2017 to conform to strict ISS requirements."

Once the experiment is in orbit, Yagoobi and his team will have to be available around the clock to monitor and troubleshoot it. Duplicate experiments will be run on the ground at WPI and at either the NASA Goddard or NASA Glenn facility.

While work begins on the final design and fabrication of the experiment, other efforts are under way to demonstrate the usefulness of the EHD heat transfer pump in terrestrial applications. For example, Yagoobi says, he is working with three universities in France to enhance the energy efficiencies of thermal devices used in industry and in HVAC&R (heating, ventilating, air conditioning, and refrigeration) systems.

Keeping things cool, it seems, has become a hot field.

—Laurie Schlatter

notebook

HOW ONE BUILDING CREATED A CASCADE OF CHANGE

IT'S BEEN NEARLY A DECADE since the doors to WPI's Life Sciences and Bioengineering Center (LSBC) opened. The first building to rise at Gateway Park, an 11-acre mixed-use campus taking shape just north of downtown Worcester and a short walk from the main WPI campus, the LSBC, formally dedicated on September 17, 2007, represented something of a gamble. In building the 125,000-square-foot research facility, the university was betting that by making a $65 million investment in the life sciences (the cost of the building and the site clean-up), it would realize dividends down the road.

That bet has paid off, and then some, says **Eric Overström**, professor of biology and biotechnology, who joined WPI in 2004 as head of that department. "This building has produced a return on investment well beyond anything we anticipated at the time," he says.

The LSBC was the answer to a question that had been nagging at WPI since it acquired the Gateway Park property in 1999, jointly with the Worcester Business Development Corporation: How could that former industrial brownfield benefit the university? The idea of constructing a building to provide much-needed space for a growing a research enterprise emerged early on, but what kind of research would be represented was unclear.

Overström recalls a meeting where several faculty members described the facilities they envisioned for the new center, including fire labs and a drop tower for impact research. He and his fellow life sciences department heads, the late Chris Sotak in Biomedical Engineering and Jim Dittami in Chemistry and Biochemistry, huddled and decided to propose a more focused approach: move all of WPI's graduate research programs in the life sciences and bioengineering to the new building.

The idea had a practical motivation. The wet labs in the 115-year-old Salisbury Laboratories building, where the biologist and biomedical engineers worked, were poorly suited to modern research, while lab space in the newer Goddard Hall, home to chemistry, biochemistry, and chemical engineering research, was running short as the WPI faculty grew.

World-class lab space would not only accelerate WPI's research in these fields, it would help attract outstanding new faculty members in areas that were important to the future of WPI and the region. That's what Overström, Sotak, and Dittami maintained when they pitched the idea to President Dennis Berkey. The president found the vision compelling and timely. He convinced the Board of Trustees to break with its longstanding practice of waiting until buildings are largely paid for before putting shovels in the ground, believing that if WPI was to maintain its competitive edge and realize its vision of being recognized as a robust STEM research university, it needed to be willing to issue debt with the promise of an adequate return sometime down the road.

That decision set the stage for other key strategic investments by WPI that followed, including East Hall (a residence hall with Worcester's first green roof), the Sports and Recreation Center, the Park Avenue Garage (with its rooftop playing fields), Faraday Hall (a residence hall built near Gateway Park), and the Foisie Innovation Studio and Messenger Residence Hall (now rising on the Quadrangle), which were also partly financed with debt.

WPI built the LSBC with the intention of occupying only about half the building. Space on the first floor was allocated to a life sciences business incubator managed by Massachusetts Biomedical Initiatives (MBI) and WPI's Corporate and Professional Education staff moved into offices on the second floor. The balance of the building was available for lease by life sciences companies.

"Putting our researchers in the same building with private companies was met with skepticism," Overström says. "There was concern that the companies would steal our ideas." In fact, the move proved beneficial. Faculty members forged research partnerships with MBI tenants, which also hired students to work on research projects (some parlayed that experience into full-time jobs). In addition, company employees have enrolled in WPI graduate programs.

Opening in 2007, the WPI Life Sciences and Bioengineering Center (top), with its modern, open laboratory facilities (left), helped the university recruit top faculty members, accelerate research, and build partnerships.

“Gateway Park, once a decaying relic of the city’s industrial past, has, through WPI’s leadership, become a center of innovation and economic development in such 21st century industries as biotechnology, chemical biology, and biomedicine.”

Over time, as some tenants departed, the university would fill about 85 percent the LSBC with its own research labs. “As had been hoped, the building did help the university recruit a growing cadre of talented faculty members, many of whom arrived from top-tier graduate schools with well-established research programs,” notes WPI provost Bruce Bursten.

By design, lab space was assigned by research focus area, rather than department, which led to productive interdisciplinary research partnerships, growing success in winning research funding, and growing enrollments in WPI’s life-sciences related departments. Today, almost 40 faculty members and about 60 graduate students from six departments (including Mechanical Engineering and Physics) have lab space in the LSBC.

The move of labs and faculty offices to Gateway Park freed up room on the main campus just as rapid growth in the undergraduate and graduate programs created a pressing need for more space. With a gift from the Alden Trust, labs emptied in Goddard Hall’s north wing were transformed into cutting-edge undergraduate teaching labs for biology, biomedical engineering, and chemistry and biochemistry. Former wet labs in Salisbury Laboratories became classrooms and offices for WPI’s Humanities and Arts and Social Science and Policy Studies Departments, as well as space for Faculty Governance, the Dean of Arts and Sciences, and other programs.

The impact of the first Gateway Park investment was also felt beyond the WPI campus, Bursten notes. Worcester was ramping up its efforts to revitalize the city’s downtown and was happy to have WPI (which in 2010 acquired WBDC’s interests in Gateway Park, becoming the site’s sole owner) as a partner in that effort. “Gateway Park, once a decaying relic of the city’s industrial past, has, through WPI’s leadership, become a center of innovation and economic development in such 21st century industries as biotechnology, chemical biology, and biomedicine,” he says.

That transformation was noticed in Boston. After then-Massachusetts governor Deval Patrick launched the state’s $1 billion Life Sciences Initiative in 2008, WPI’s success with the LSBC helped bolster its successful application for a $5.2 million grant to support the next phase of development at Gateway Park, including the construction of the Biomanufacturing Education and Training Center (BETC). (The second building, Gateway II, which also houses the Foisie Business School and the Department of Fire Protection Engineering, with its new state-of-the-art burn labs, was constructed by a private developer on land leased from WPI). The BETC, which provides training, workforce development, and consulting, has become a highly valued resource for the state’s rapidly expanding biomanufacturing industry.

Today the Gateway Park campus is poised for further growth (a third building is in the planning phase and others will likely follow in the years ahead). At the same time, the development has been the catalyst for the revitalization of the Prescott Street and Grove Street corridor, where Faraday (residence) Hall, the Massachusetts Academy of Mathematics and Science (a high school affiliated with WPI), offices and labs for WPI’s Robotics Engineering Program and Healthcare Delivery Institute, and spaces developed by individuals affiliated with WPI for business incubation have all taken root, and where other new residential and commercial developments have been completed or are in the works.

“Ten years ago, this was a dormant place with potential, just waiting for the right spark to set things in motion,” says Laurie Leshin, who joined WPI in 2014 as the university’s 16th president. “The LSBC was that spark, and the ripple effect from that one building has been truly remarkable. It will be quite exciting to see what the next decade brings as WPI expands our commitment to making cutting-edge discoveries right here in Worcester.”

The LSBC helped WPI win state funding for the Biomanufacturing Education and Training Center (top), while the funding model for the building paved the way for other WPI capital investments, including Faraday Hall (left).

Steven King

>
MEGAN CHROBAK, PHD CANDIDATE

Seeking a PhD to expand her career opportunities, **Megan (O'Brien) Chrobak** discovered WPI's NSF-funded IGERT program in biofabrication.

With an undergrad degree in chemical and petroleum engineering from the University of Pittsburgh ('09) and an MS in bioengineering from Temple University ('12), Chrobak did R&D work at the Musculoskeletal Transplant Foundation for several years before noticing that the jobs she aspired to were held by folks with PhDs. "I was worried that my lack of credentials would hinder me in the future," she says, "and I made the decision to go back to school."

She noticed that WPI offered an NSF-funded IGERT (Integrative Graduate Education and Research Traineeship) program with a focus on biofabrication. With that, she thought, she could learn how to translate benchtop research into what might be meaningful innovations in the marketplace. "As someone whose goal is to end up back in industry, this was perfect for me," she says. "The program allowed me to take business classes, culminating in a business certificate. It gave me a fresh perspective that I'm sure will benefit me in the future."

Now that's she's in, Chrobak is making the most of every minute. Partnering with her advisor, biomedical engineering associate professor George Pins, and collaborator and fellow BME professor Glenn Gaudette, she's been working on a cardiac patch that could help regenerate damaged heart tissue after a heart attack. "We are hopeful that our work can contribute toward the development of better treatment options for patients," she says. Since heart attack victims are often left with scar tissue that can prevent the heart from working at full capacity, it can ultimately lead to further heart failure. That, along with the fact that cardiovascular disease is currently a leading cause of death with limited treatment options, gives Chrobak much inspiration for her work toward a PhD in biomedical engineering.

It both deepens her existing research experience, and allows her to return to her career with stronger leadership skills and a higher level of impact. "I want to be able to contribute to discussions at a company that ultimately influence the projects that are pursued," she explains.

So far, the most challenging aspect of her graduate program was simply figuring out where to begin her journey. Tackling a topic very different from anything she had previously researched, Chrobak says she's had "a wonderful network of supportive staff and fellow students that helped along the way. WPI has definitely challenged me mentally and emotionally, and has pushed me to become a better researcher." She says she's lucky to have an incredible support system.

"Research is funny," muses Chrobak. "It's definitely discouraging at times when experiments you believed were well thought out end up failing. But when things start coming together, it's such a great feeling!"

HONORABLE MENTIONS: NSF IGERT Fellow • Competitive Innovation Fund Recipient (Co-PI with Katrina Hansen) • Alpha Eta Mu Beta Honor Society member • 1st Place award in bioengineering in WPI's Graduate Research Innovation Exchange (GRIE) poster competition (2016) • Overall People's Choice Award recipient for GRIE poster presentation (2016) • 2nd Place GRIE poster presentation for bioengineering (2015) • Mentor to SURF, REU, RET, MQP, and undergraduate students.

> WPI'S SUSAN LANDAU ON WHAT THE FBI NEEDS TO LEARN ABOUT SECURITY

IT WAS A BATTLE of security vs. security, as **Susan Landau** saw it. On the surface, it was about the fate of one encrypted iPhone. But for Landau, PhD, professor of cybersecurity policy at WPI, the stakes were far higher: the potential to put the private information of millions of smartphone users at risk and the likelihood of undermining a powerful new security tool: using smartphones as trusted authenticators for accessing online information.

After the December 2015 attack on the Inland Regional Center in San Bernardino, Calif., the FBI recovered a smartphone used by the terrorists. The phone was encrypted and protected by a passcode. Knowing that attempting to break the code by brute force would result in the phone's contents being deleted, the FBI won a court order directing Apple to write new software that would have given the agency the ability to circumvent the iPhone's security safeguards. Apple contested the order, arguing that the software "would be the equivalent of a master key, capable of opening hundreds of millions of locks."

The skirmish set the stage for a hearing before the U.S. House Judiciary Committee in March 2016, titled "The Encryption Tightrope: Balancing Americans' Security and Privacy." FBI director James Comey testified, as did Apple senior vice president and general counsel Bruce Sewell. In her testimony, Landau argued that technology that keeps mobile devices secure is vital to national security and that instead of seeking to weaken those protections to make law enforcement investigations easier, Congress should invest in strengthening the FBI's technological capabilities.

She countered the FBI's argument that encrypted devices (which Comey called "warrant-proof spaces") hinder the agency's ability to investigate crimes. Landau says the FBI is looking at smartphones through a 20th century lens, a perspective that is particularly troubling given that companies like Facebook and Google (and even some high-level government agencies) are using smartphones as authenticators for logging into computers or accessing online accounts. Using smartphones to bolster login credentials (a favored target of hackers) can work only if smartphones, themselves, are secure, Landau noted.

"We need 21st century techniques to secure the data that 21st century enemies—organized crime and nation-state attackers—seek to steal and exploit," she said in her testimony. "Twentieth century approaches that provide law enforcement with the ability to investigate but also simplify exploitations and attacks are not in our national security interest. Instead of laws and regulations that weaken our protections, we should enable law enforcement to develop 21st century capabilities for conducting investigations."

She expanded on that theme in an essay published in *Science* magazine in June 2016, in which she wrote that the FBI's efforts to weaken smartphone security reflect its outdated approach to investigating crime and its inadequate resources for conducting modern cyber investigations. Landau argued that the agency (which ultimately purchased a software tool for unlocking the San Bernardino terrorists' iPhones) needs to invest in building up its own "21st century investigative savvy," including creating "an investigative center with agents with deep technical understanding of modern communications technologies and computer science."

Nicholas Kamm/Getty Images

At a hearing of the U.S. House Judiciary Committee in March 2016, Susan Landau argued against the FBI's attempt to weaken smartphone security and for beefing up the agency's technological investigative capabilities.

With the ability to develop new surveillance approaches and tools matched to the latest advances in communications technologies, the agency will no longer need to seek to weaken the devices that people, corporations, and government agencies worldwide depend on to securely communicate, transact business, and transmit sensitive information.

The FBI's attempt to force Apple to unlock a phone was part of a broader campaign for what the agency has called "exceptional access" to encrypted communications and, more recently, devices. Landau and 14 other pre-eminent experts on electronic security and privacy addressed the risks inherent in that pursuit in a July 2015 report, "Keys Under Doormats: Mandating Insecurity by Requiring Government Access to All Data and Communications." They noted that not only is such access technically infeasible, it would actually increase the risk of foreign governments, criminals, and terrorists gaining access to confidential information, critical infrastructure, and government secrets.

The report and its authors were honored with the 2015 J.D. Falk Award from the Messaging Malware Mobile Anti-Abuse Working Group (M3AAWG) and a 2016 Pioneer Award from the Electronic Frontier Foundation. At the Pioneer Award ceremony, Landau spoke for the authors. A member of the Cybersecurity Hall of Fame and the author (with Whitfield Diffie, the inventor of public-key cryptography) of *Privacy on the Line: The Politics of Wiretapping and Encryption* (MIT Press 1998; revised in 2007), she recalled a 1997 report written by the same group that argued against an earlier attempt by the federal government to compromise the integrity of digital information in the name of security: the Clipper chip, promoted by the Clinton administration as a way to give the NSA back-door access to encrypted communication over telecommunications systems.

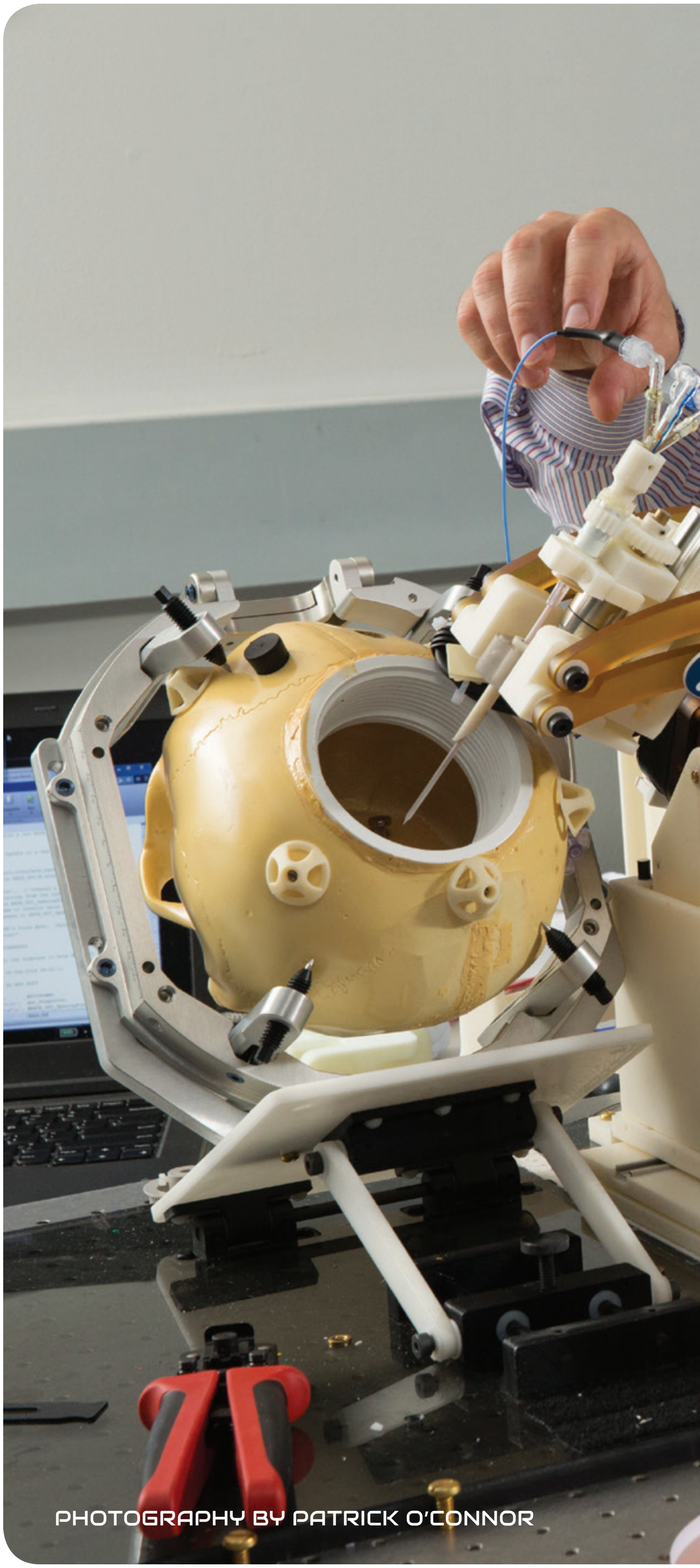
Any effort to give the government exceptional access will not only undo encryption and forward secrecy, but open the door for other law enforcement agencies, at all levels, as well as foreign governments with poor records on human rights and espionage to demand the same access. The fight about encryption, Landau said, "is, at its core, about freedom and liberty."

THE ROBOTICS WAR ON CANCER

BY ALEXANDER GELFAND

Some people design robots that can assemble circuit boards or vacuum your floor. Gregory Fischer, PhD, professor of mechanical engineering and robotics engineering and director of WPI's Automation and Interventional Medicine (AIM) Laboratory (aimlab.wpi.edu), has other things in mind: He *wants* his robots to take biopsies from cancer patients more accurately and efficiently, and perform brain surgery more safely and effectively.

And he is tantalizingly close to achieving both milestones.



PHOTOGRAPHY BY PATRICK O'CONNOR

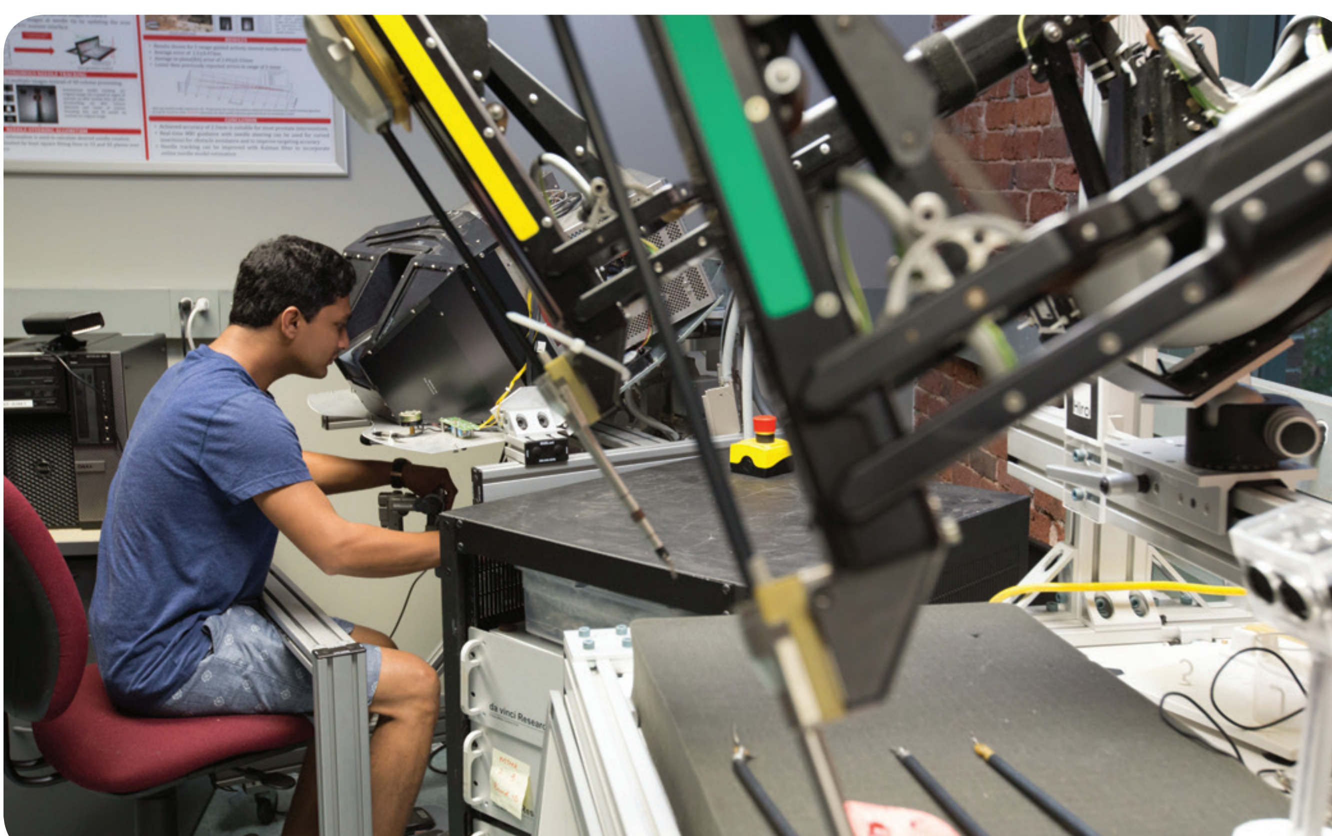
Gregory Fischer adjusts an MRI-compatible robot designed to treat deep brain tumors.

By improving accuracy and reducing guesswork, MRI-guided robotic needle placement ought to make the act of taking a biopsy cheaper and faster—and less taxing on the patient.

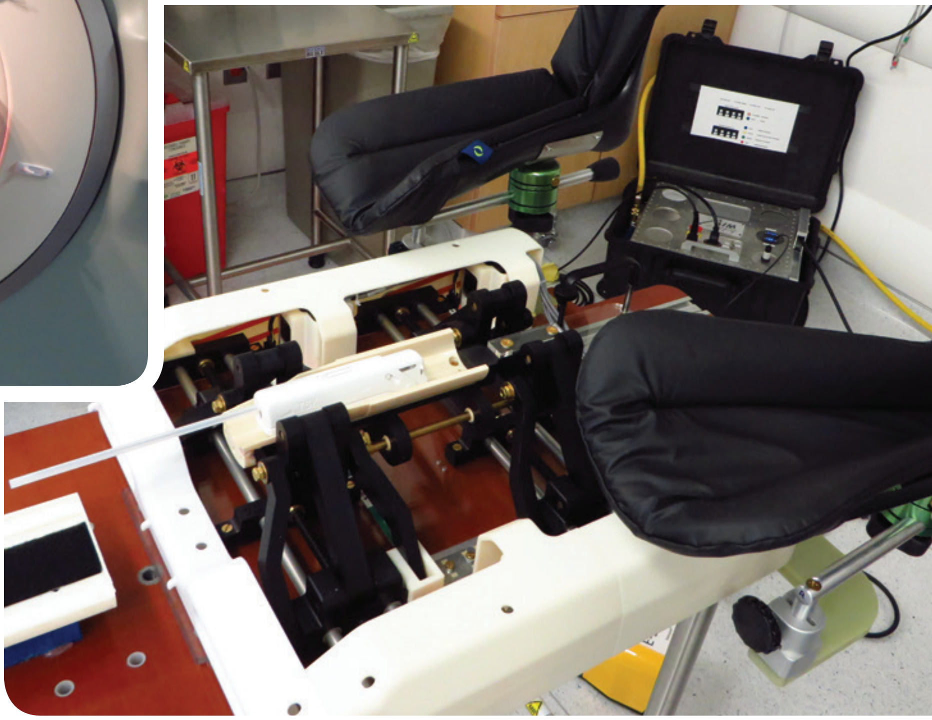
Fischer has made his mark by developing robots that can work inside MRI scanners, enabling surgeons to operate guided by real-time medical images. One robot, which he spent years developing in conjunction with colleagues at Johns Hopkins University, is in clinical trials at Brigham and Women's Hospital (BWH) in Boston, where it is being used to help take biopsies from prostate cancer patients. (The trials are part of a program led by Clare Tempany, MD, a professor of radiology at Harvard Medical School and chair of research radiology at BWH, and supported by the National Institutes of Health's National Center for Image Guided Therapy and with a Bioengineering Research Partnership grant from the National Cancer Institute.)

Another robot will blast brain tumors using high-powered, MRI-guided, robotically manipulated ultrasound. Now a fully functional prototype, that robot, supported by an NIH Academic-Industry Partnership grant and developed in collaboration with the University of Massachusetts Medical School, Albany Medical Center, and Acoustic MedSystems, could begin human trials in a few years.

While MRI-compatible robots are the main attraction in the AIM Lab, Fischer and his collaborators have also developed a custom research-focused controller for the da Vinci Surgical System, a tele-operated surgical robot made by Intuitive Surgical that is used to perform minimally invasive procedures. The controller, which includes both hardware and software and is completely open-source, is enabling researchers around the world to use a common, shared infrastructure to investigate methods for extending the da Vinci system's capabilities, with an eye toward automating surgical procedures and improving their safety. Fischer's team in the AIM Lab is also actively pursuing wearable soft robotic assistive devices and socially assistive robots (see sidebar, page 18).



PhD candidate Nirav Patel tests a custom research-focused controller developed by the AIM Lab for the da Vinci Surgical System.



Right: A robot designed by Fischer and his team to assist with needle guidance and insertion for prostate cancer biopsies and, to its right, a custom controller for MRI-compatible robots developed in the AIM Lab. Above: Physicians at Brigham and Women's Hospital (BWH) in Boston perform a biopsy using the WPI robot. The robot is being tested as part of a clinical trial led by BWH researchers and funded by the National Institutes of Health and the National Cancer Institute.

THE DAWN OF MRI-COMPATIBLE ROBOTS

Fischer, who also holds an appointment at WPI in biomedical engineering and is faculty director of WPI's Healthcare Delivery Institute (see page 40), has been developing innovative medical technologies since he was a graduate student at Johns Hopkins, where he helped design an augmented reality system for surgeons that projected MRI scans directly onto patients. He also worked on the early forebears of the robot that is currently in trials at BWH: a robot that sits inside the cylindrical bore of an MRI scanner along with the patient, helping a doctor guide a biopsy needle far more accurately into a walnut-sized prostate gland with the aid of up-to-date images.

In conventional prostate cancer biopsies, doctors determine where to insert their needles by relying on previously acquired, preoperative imaging; they can also use intraoperative ultrasound, whose resolution pales in comparison to that of MRI. Some hospitals combine preoperative MRI scans with live ultrasound images taken during the procedure itself, but that, too, is not ideal, Fischer notes. Patients (and their organs) can shift and move, and the very act of inserting a needle in soft tissue can cause it to swell and deform, altering the position of the target and rendering those high-resolution pre-operative scans obsolete. As a result, doctors often must perform multiple needle insertion attempts, and the low sensitivity of biopsies means they may have to be redone, ratcheting up the procedure's cost and the patient's discomfort.

Hence the attraction of Fischer's robot: by improving accuracy and reducing guesswork, MRI-guided robotic needle placement ought to make the act of taking a biopsy cheaper and faster — and less taxing on the patient.

OVERCOMING TECHNOLOGICAL HURDLES

Turning that dream into reality hasn't been simple, though. Creating mechanical systems small and precise enough to perform delicate medical procedures inside the confined space of an MRI scanner — a cylinder roughly half a meter wide that must also accommodate a patient, other medical equipment, and sometimes even a clinician — was enough of a challenge. But MRI machines create images using radio waves and a powerful magnet, so nothing designed to go inside them can be made from ferrous metals like iron and stainless steel. Fischer ultimately met that requirement by using plastic parts, piezoelectric ceramic motors, and only small bits of non-ferrous metals, like brass.

The electronic noise generated by commercially available motion control systems created another headache, since those stray signals will seriously degrade the quality of a magnetic resonance image. So Fischer and his students had to design and build custom controllers capable of feeding signals to the robot's ceramic motors with high precision and zero noise.

In addition, achieving true "closed loop medicine," in which procedures are guided by real-time feedback, meant continuously updating the robot's trajectory. MRI machines are true 3-D scanners that can generate images in any position or orientation. Fischer and his team had to figure out how to integrate the communication protocols and software interfaces used in commercial MRI scanners with the custom versions they had developed for their robots, so the system could acquire images; use image processing to determine the location and orientation of the instrument; update the robot's path based on that information; and repeat the process in a continuous loop so that the robot could hit the bull's-eye. "That," Fischer says, "was especially difficult."

Safety was also a critical consideration. The robot currently undergoing trials at BWH is a first step toward MRI-guided, robot-assisted procedures, and its job is to align the biopsy needle; but when the time comes to insert it, the robot disengages and a doctor pushes it in. Fischer envisions a day when the robot will steer and insert a needle or probe, either autonomously or semi-autonomously (these features are currently in development on preclinical prototypes). Toward that end, he's designed his latest model "from the ground up" with safety in mind. He overhauled the already sophisticated controllers to gain more coordinated command of the robot's moving parts, giving the system the capacity to detect and recover from errors, and granting users the ability to selectively disable axes of motion so that the robot can't realign itself at the wrong moment and harm the patient.

TARGETING THE BRAIN

That may be especially important for the neurosurgical robot that Fischer is currently developing.

Soon after Fischer joined the WPI faculty in 2008, he was contacted by Julie Pilitsis, MD, PhD, a neurosurgeon specializing in deep brain stimulation who was then director of functional neurosurgery at UMass Memorial Medical Center and is today a professor of surgery at Albany Medical Center Hospital. She recognized that Fischer's MRI-compatible robots could also be useful in the neurosurgical suite, where precision is paramount. The two began working on a unit that could be used to insert electrodes into the brains of Parkinson's patients to control their tremors. Soon, though, they turned their attention to cancer therapy.

Working with colleagues at the University of Massachusetts Medical School and Acoustic MedSystems, an Illinois-based company that develops image-guided ultrasound and radiation therapy systems, they are developing an MRI-compatible robot that can destroy brain tumors using high-intensity beams of focused ultrasound. The work is funded by a five-year, $3 million award from the NIH.

ROBOTS LEND A HAND

Fischer and his students are also working on a number of assistive robots to help the disabled. Many of these involve restoring function lost due to injury: a robotic glove (at right, with PhD candidate Chris Nycz) designed to help stroke victims retrain their grip, for example, and a robotic socket for a lower limb prosthetic that can dynamically adjust its hold so it is neither too tight (cutting off the circulation) nor too loose (making movement difficult).

And then there's PABI (Penguin for Autism Behavioral Interventions), a cuddly robot that looks like a penguin plush toy but that Fischer's team, along with collaborators at Salem State University, created specifically to help therapists and teachers deliver therapy to children with autism.

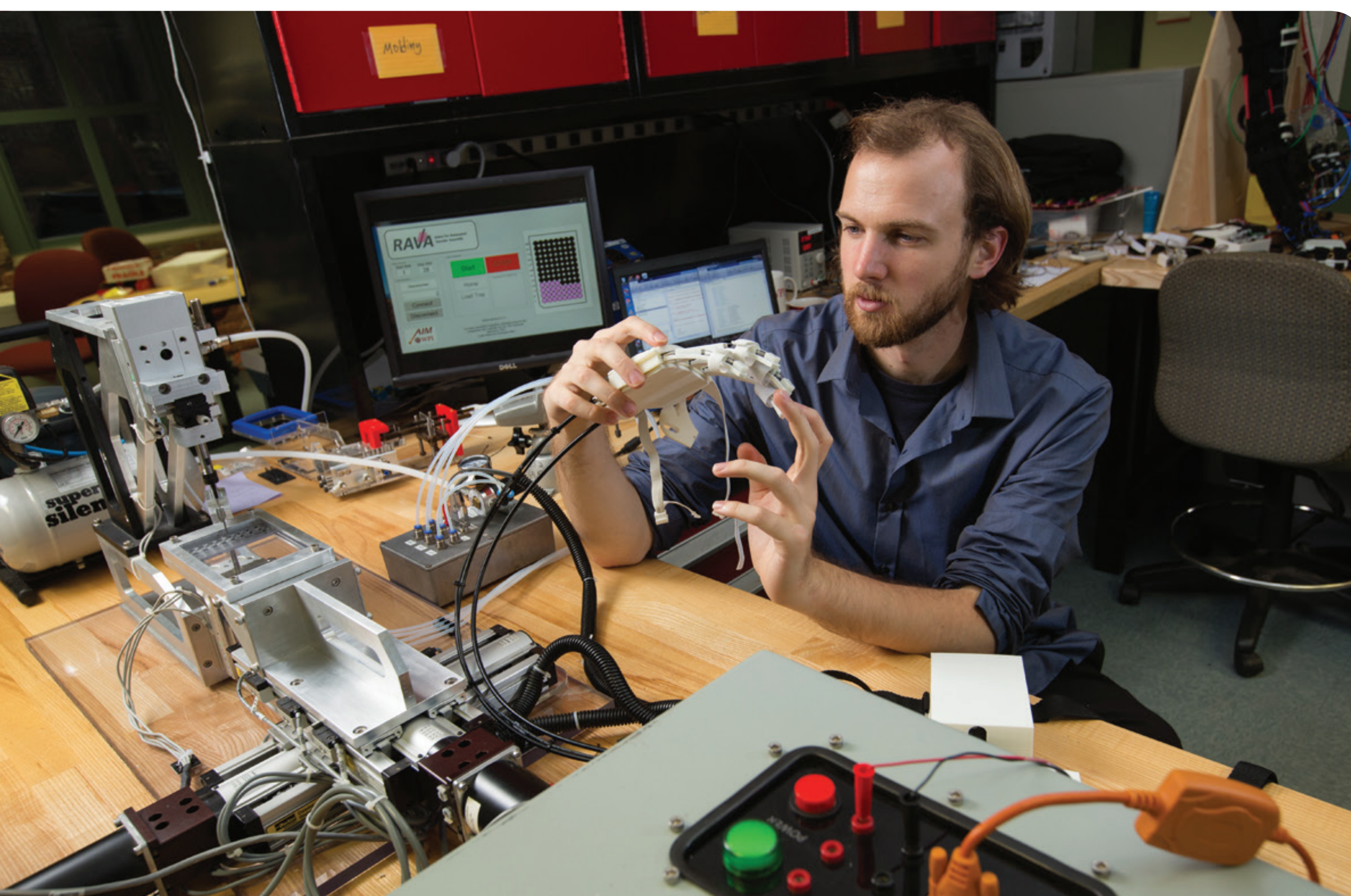
PABI prompts a child to respond to the kinds of flashcards typically used in school-based therapy sessions; thanks to the cameras embedded in its eyes, it can also record the child's responses, gathering valuable data and freeing the teacher or therapist running the session to focus on interacting with the child as much as possible.

Laurie Dickstein-Fischer, Fischer's wife, is a professor of psychology at Salem State who serves as clinical lead on the PABI project. She recently coordinated a pilot study at a school in central Massachusetts. While the results have not yet been analyzed, early indications are promising, she says. "It was a really big hit with the kids and the teachers."

Fischer says that kind of minimally invasive ultrasound ablation would avoid some of the problems associated with current treatment methods like radiation-beam therapy and open-brain surgery. And the focused nature of the ultrasound beams, coupled with the real-time MR imaging and precision placement afforded by the robot, should allow surgeons to accurately and completely target even irregularly shaped tumors without damaging the healthy tissue around them.

What's more, because ultrasound ablation destroys tissue by heating it, and because MRI scanners can detect temperature changes, surgeons will be able to use live thermal imaging to generate real-time temperature maps of their patients' brains during a procedure to ensure that just the right amount of ultrasound energy is delivered to just the right spot — an approach that could be used to zap other kinds of tumors, as well. Fischer plans to conduct preclinical evaluation of the system over the next two years, with the goal of securing approval for human trials when the grant ends.

For Fischer, the ability to translate technological innovations into the clinic so quickly is what makes the field of medical robotics exciting. Other areas, such as gene therapy and immunotherapy, he says, may hold great promise for cancer treatment; but significant breakthroughs could be many years away. By comparison, his robotic systems could be ready for prime time in as little as two to three years. And the potential to improve the quality of patient care in the near term makes all the difference.



Demonstrating the concept behind Graspable Math are, from left, Lindsay Braith '17, Erin Ottmar, and Daniel Manzo '16 (MS), a PhD candidate in learning sciences and technologies.

WPI researchers are making math lessons jump off the page with "embodied" games that engage the mind—and muscles.

math in mo

Photography by Patrick O'Connor

Say the words "math class" and you're likely to picture rows of desks with somber students hunched over endless worksheets—the only things moving are the points of their pencils.

Two professors in WPI's Learning Sciences and Technologies Program seek to shake up that paradigm by tapping into the learning power of children's natural inclination to move and play. Although the two have taken different approaches in their design of game-based classroom technology, the underlying principles, and the questions they seek to answer about learning and thinking, spring from a similar place.

Swooping and Learning

What does it mean to be "good at math?" And what can teachers do to get more students interested and engaged in a subject many find intimidating? **Erin Ottmar**, PhD, is intrigued by questions like these. The key to finding answers, she says, is to worry less about whether students can correctly answer a bunch of math problems and to focus more on the process they use to attack them. In her research, she seeks a deeper understanding of the strengths (or weaknesses) of a student's comprehension of mathematical concepts. She starts by comparing the strategies and approaches employed by math "experts" (including some

tion

By Joan Killough-Miller

WPI undergraduates) and "novices" (who tend to struggle with math problems).

She's noticed that the experts tend to be especially good at visualizing and identifying mathematical patterns. They seem to literally see chunks of expressions floating before them with components that can be manipulated in space. "When they talk and think about mathematics, they tend to gesture and move," Ottmar says. "When asked how they solved an algebra equation, they'll say, 'Oh, I took this 4 and I moved it over there,'" she says, swooping a finger from right to left. "They often use verbs like combine, split, and move to describe what they're doing — and they'll actually make a corresponding motion."

Believing that this way of envisioning and doing math can aid learning, she collaborated with colleagues at Indiana University to develop several touch-based technology tools that let students manipulate the elements of an algebraic equation on a screen until they arrive at a specified goal or solution. The programs don't just teach math or record who got the correct answer — they capture the steps each student takes to arrive at an answer, so the data can be aggregated and analyzed. This rich information can be used to better help teachers help students. It also gives scientists a glimpse inside the minds of learners as they

“Creating math games requires a process of very deep thinking about what mathematics really is.” –Ivon Arroyo

grapple with mathematical concepts. Ottmar says her research produces tools for teaching, learning, and assessment; they, in turn, generate data that feeds back into her research.

One tool she’s developed is a puzzle-based iPad app called *From Here to There* (FH2T), which lets students move, swipe, and transform numerals and mathematical expressions, manipulating these elements until they reach a set goal. Instead of waiting days for a grade, they get immediate feedback about errors, process, and strategy, and they can keep trying until they arrive at the solution. The program (free in the iTunes store) has been tested in middle school classrooms, where it’s been shown to improve learning and engagement. Ottmar will conduct further tests of the app’s effectiveness in preparation for a larger-scale implementation.

Graspable Math

The concept behind *From Here to There* has evolved into a more advanced program called *Graspable Math* (GM). With functions similar to those of FH2T, *Graspable Math* gives students and teachers an open “canvas” onto which they can apply their own problems. GM, free on the Web (www.graspablemath.com), works with any standard computer operating system — an advantage for schools not equipped with iPads.

Ottmar says math games and technology don’t need flashy graphics or superhero sagas to capture kids’ interest. When designed right, mathematical tasks can be fun and engaging in their own right. Her puzzle-based goal approach relies on the intrinsic challenge of complex strategy games such as chess and checkers, which excite minds with risk-taking opportunities, open-ended options, and consequences.

Some educators and parents may think of educational games as “sugar coating,” and insist on the rigor of more traditional pencil-and-paper, “show your work” approaches. But Ottmar and her Indiana colleagues David Landy and Erik Weitnauer believe the development of *Graspable Math* has led to a “better paper,” which captures the power of learning through onscreen manipulation. With its flexibility, their better paper also lets kids discover there is often more than one way to approach and solve a math problem. What’s more, by tapping into different ways of thinking and being creative, the technology may boost confidence and short-circuit the anxiety that too often turns kids off to math at a young age.

Ottmar points out that many high-level mental processes have always been enacted physically. Imagine playing chess without moving pieces; or think about writing out all the steps to solve a Rubik’s Cube, instead of manipulating the colored squares. The act of writing things down can support learning, Ottmar says. But physical movement or gestures — such as counting on one’s fingers — shouldn’t be looked down on as a shortcut or cheating. “There’s evidence that motion and action are actually useful in visualizing and understanding. It’s a natural way of processing, and it’s especially useful in mathematics.”

Math on Your Wrist

Ivon Arroyo, PhD, also works with the concept of embodiment and learning, transforming traditional children’s games with Wi-Fi connected “wearables” that offer learning challenges and feedback. Her games teach the basics of number sense, measurement estimation, and geometry while letting children run and play in open spaces as they search for objects that match specified mathematical parameters.

In her early work, Arroyo developed e-Textiles — for example, hoodies with attached sensors and LED displays on the sleeves. Children wore them to play a version of hide-and-seek, as they were challenged by constraints such as “Hide behind an object that has a volume of greater than 50 cubic feet.” Some practical problems emerged in testing — the sweatshirts were bulky and unattractive, the wiring was fragile, and teachers wanted to know, “Who’s going to wash these shirts?” Arroyo has advanced the concept with sleeker “learning assistants,” such as smart watches and cell phones anchored to arms with sports holsters.

The theory of embodied cognition links thinking skills with social, sensory, and motor functions. “It is believed that motor action is encoded within the brain — not just abstract ideas,” Arroyo says. She adds that this is not new — especially at the elementary school level, teachers are already intuitively incorporating touch and motion in learning activities by using hands-on activities that involve the manipulation of concrete objects in the classroom. Her aim is to understand the connections between embodied hands-on activities and learning in a scientific manner,

Ivon Arroyo watches as her son, Nicolás Arroyo Lisle, tries out the game "Estimate It!" with the aid of clues on the smartphone strapped to his wrist.

deciphering what are important components of motor action that may be conducive to learning while leveraging the power of lightweight, mobile technology in games that combine learning and fun.

Arroyo's undergraduate students (working on IQPs and MQPs) have created a new software and hardware infrastructure that supports embodied games. The "Wearable Game Engine" is a Web-based platform that allows teachers and students to play games outside or inside with one mobile device per student, provided there's a Wi-Fi or cellular connection available. Arroyo's graduate students have created games that make use of these wearables, such as "Tangrams Race" — a relay race that has students running to fetch puzzle pieces that match specified geocentric constraints, then working as a team to assemble them to fit an intricate pattern (Yuting Liu, MS candidate, IMGD). "Estimate It!" sends students outside to seek objects that fit the specified criteria, equipped with only crude measuring tools, such as a 12-inch dowel (Leigh Rountree, MS candidate, IMGD). Students can press colored buttons on their watches for cues and hints; they also use the buttons to input sequences of colored dots that appear on target objects, thus indicating they've found the correct object. They can also scan the objects using the NFC (near field communication) capability available in cell phones and smartwatches.

Beyond the empirical results Arroyo gathers is the joy captured in her videos of children engaged in these educational games. She also uses video as a tool in re-cap discussions that can inspire children to review their actions as a group, and reflect on the choices they made during play.

Posing Problems; Making Games

Arroyo and Ottmar are joining forces to work on an NSF-sponsored research project that merges computational thinking, mathematics education, and embodied technology. They'll take the game concept to the next level by having game players become game developers through an authoring tool in the online platform. First, teachers — then, students — will use it to play and modify existing games to get familiar with the concepts. They will move on to creating their own games, specifying the behavior of watches at a high level of detail for each moment of the game.

"Creating math games requires a process of very deep thinking about what mathematics really is," Arroyo says. "I've always been an advocate of problem posing, instead of mere problem solving. We want students to explore the flexibility and limits of mathematics, to ask themselves where else and in what other contexts and situations these math concepts apply."

Says Ottmar, "There's a lot of math in the world around us. If we get kids engaged by asking them to do mathematical things, there's clearly a value to that. It's unchartered territory — a whole new world in defining what it means to be successful in math." Re

PHOTOGRAPHY BY PATRICK O'CONNOR

As founding director of the Metal Processing Institute, Diran Apelian in 2010 launched CR^3, whose mission is keeping valuable metals from ending up in scrap yards and landfills.

WPI's Center for Resource Recovery and Recycling is developing innovative technology to recover valuable metals from products and materials that now, more often than not, get thrown away. The work is yielding significant economic and environmental benefits.

THE ROAD TO RECOVERY

BY JOSHUA ZAFFOS

"CR^3 is the first and only NSF-supported research center in the United States dedicated to resource

Each year Americans throw away more than 3 million tons of unused or obsolete electronic products and waste — roughly the equivalent of 8,300 Boeing 747s. While some of these appliances, cell phones, TVs and other electronics, and batteries will be diverted from the trash and recycled, most end up in landfills, representing an enormous lost opportunity for industries, consumers, and the planet. That's because this electronic scrap, or e-waste, contains a bounty of valuable and increasingly rare metals and elements.

"The things we're making now are not made to last a long time," says Diran Apelian, PhD, Alcoa-Howmet Professor of Mechanical Engineering and founding director of WPI's Metal Processing Institute. "And then, they're not repairable, they're not reusable, they're not manufactured for disassembly. And the materials they contain cannot be recycled or recovered so easily."

This dilemma first grabbed Apelian's attention in 2004 as he prepared to deliver the Distinguished Lecture on Materials and Society at the ASM-TMS Congress in Columbus, Ohio. Well into a long and illustrious career dedicated to improving the performance and strength of steel, aluminum, and other materials, Apelian realized that researchers in his field were ignoring the "three Rs" — recycling, reuse, and recovery — at a significant cost to society. Half a century ago, when home and industrial goods used only 15 elements from the periodic table, the issue may have seemed less pressing. "But today," Apelian says, "we use them all. A smart phone, alone, contains 56 elements."

Apelian took the challenge personally. In 2010 he led a team that won a five-year, $400,000 award from the National Science Foundation (NSF) to establish the Center for Resource Recovery and Recycling (CR^3), headquartered at WPI. A research collaborative of universities and industry partners, the center develops new technologies and processes to boost recovery and recycling of metals and other materials used in everything from consumer goods to buildings, as well as metals landfilled as part of industrial process waste. Professors from four universities—WPI, KU Leuven in Belgium, the University of Tokyo, and Colorado School of Mines—bring the expertise. About 20 companies, including General Motors and Alcoa, bring industry needs and additional funding ($35,000 per member per year). They also help direct the center's research and share in its outcomes.

recovery. It's a hallmark, and something people at WPI should be very proud of." —DIRAN APELIAN

At WPI, 11 affiliated faculty members and their students are applying the techniques of metallurgy, chemistry, and engineering to improve recycling practices and technologies for lithium-ion batteries, cell phones, appliances, and other materials that are now thrown away, while also increasing recovery rates for aluminum, rare earth metals, gold and silver, and other valuable materials.

CR^3 is "the first and only NSF-supported research center in the United States dedicated to resource recovery," Apelian says. "It's a hallmark, and something people at WPI should be very proud of."

ENHANCING SORTING, CREATING VALUE

Apelian's own research through CR^3 focuses on increasing recovery rates for aluminum from vehicles, a project undertaken with support from Alcoa, the global metals and materials manufacturing giant. Modern vehicles contain up to 500 pounds of aluminum. And while more than 90 percent of that is reclaimed, there is good reason to try to do better, Apelian says. Recycling aluminum uses 95 percent less energy and produces 95 percent less carbon dioxide than making aluminum from bauxite ore. In addition, each ton of aluminum made from ore produces three tons of "red mud," an extremely hazardous and alkaline sludge that has to be pumped into holding ponds to avoid contaminating other resources.

Vehicle recyclers remove ferrous metals from junked cars with magnets. The nonferrous leftovers, typically treated as scrap, contain valuable minerals and metals, including up to 300 aluminum alloys that can be further separated, recovered, and reused — if technologies can be developed that make those efforts economical. "If I can separate that nonferrous part into its components, whereby I know what it is, definitely, I can remelt it and reuse it, and that's where the value comes from," Apelian says.

To achieve that enhanced sorting and separation, Apelian and his lab have developed chemistry-based technologies, such as laser-induced breakdown spectroscopy and X-ray fluorescence, which can provide a precise analysis of the various alloys and other materials in the scrap passing by on a conveyor belt. "There are some very sophisticated ways in which we can create value from scrap just by knowing what is in it and separating it accordingly," he says.

Starting with support from CR^3, the project was able to win a $3 million award from the U.S. Energy Department's Advanced Research Projects Agency-Energy to develop a scrap sorting and aluminum recovery factory. "We want to have a 100 percent recyclability," Apelian says. "Why not? It's doable."

FROM E-WASTE TO GOLD DUST

Brajendra Mishra, PhD, Kenneth G. Merriam Professor of Mechanical Engineering and director of CR^3, is exploring how to recover more valuable materials from e-waste, particularly large appliances such as dishwashers and laundry dryers, and electronics, including cell phones and computers. When they are discarded, these products can be shredded and then melted in high-temperature furnaces to separate out some of their materials, including metals. But the process produces a lot of fine materials, or flue dust, that is now often landfilled.

Discarded with those "fines," however, are a number valuable metals, particularly gold, silver, copper, and iron, says Mishra, who came to WPI from Colorado School of Mines in 2015 with a background in process metallurgy.

A toxic waste product of aluminum production, red mud contains metals worth recovering.

Each year Americans throw away **more than 3 million tons** of unused or obsolete electronic products and waste — roughly the equivalent of 8,300 Boeing 747s.

“This is exciting work. If we come up with processes that work, we can have a huge impact, not

Mishra’s lab is working with Aurubis, a German-based copper producer and recycler, to look for ways to separate this metallurgical wheat from the chaff. Using flue dust samples supplied by the company, his team is testing a number of physical and chemical techniques, including magnets, electrostatic processes, and density separation, to see if they can enhance the extraction of metals from the fines.

“We have been quite successful doing that,” says Mishra, who notes that flue dust can contain up to 10 percent copper and a few thousand parts per million of silver and gold. If that sounds like a modest return, consider that while a ton of quality ore can yield 35 grams of pure gold, after processing, a ton of old cell phones contains 350 grams of already purified gold, along with silver and copper.

“Without industry support, we can’t do this,” Mishra says. “They’re looking for solutions to handle all the effluents and waste that they create. On a society level, people are looking for ways of recovering valuable materials from something that’s used up or not working anymore. It makes sense to recover metals, but you need structures like the CR^3 to do it.”

A RARE EARTH SOLUTION

It’s not surprising that metals recovery and recycling are sensitive to regulations and fluctuating market prices, meaning manufacturers typically balance their costs and bottom lines with sustainability or environmental benefits. So CR^3 researchers are also working on projects to make recovery processes cheaper and easier than mining, which is the case with their work on rare earth metals.

Smartphones, hybrid-electric cars, solar panels, and wind turbines all use various rare earths, a class of 17 elements, including neodymium and dysprosium, that, for example, enable touch screens to function. Rare earths aren’t necessarily rare, but most of those used by manufacturers worldwide are mined in China, giving that country a near monopoly on supplies. When China began slowing production several years ago and prices spiked, industries began paying more attention to recycling rare earths.

As a result, General Motors, which like other vehicle manufacturers faces tougher recovery and efficiency regulations in the next decade, joined CR^3 to support research for rare earth recovery from magnets within vehicle drive units — the motors in electric and hybrid cars. But shredding

Below: Postdoctoral researcher Remya Narayanan, PhD, prepares a red mud sample for spectrographic analysis. Right: Narayanan and Marion Emmert examine the results of a chemical process they are developing to recover rare earth metals from red mud. In earlier work, Emmert’s lab developed a method for recovering rare earths from magnets in electric vehicle drive units.

just on the aluminum industry, but also in terms of environmental remediation." —MARION EMMERT

motors was considered a low-efficiency and thus prohibitively expensive process.

Marion Emmert, PhD, assistant professor of chemistry and biochemistry, worked with GM to alter those views. "We weren't discouraged by this mantra that you cannot shred motors with high recovery efficiency," she says.

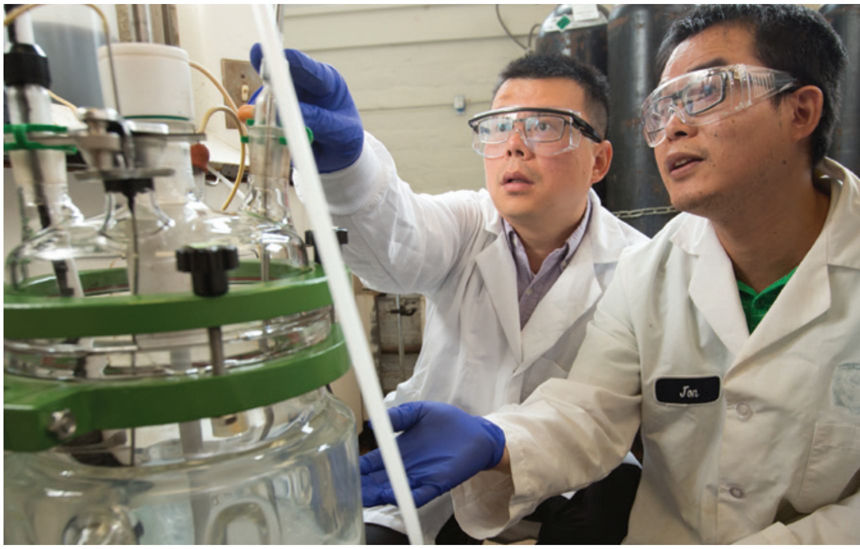
Emmert developed a three-step solution, taking inspiration from "green chemistry" and a little bit of home economics. Her process starts with baking the motors at 450° C in an oven for an hour. That weakens the magnetic strength of motor components so they can be run through an industrial shredder. Then the researchers apply a chemical solution that selectively dissolves the remaining smaller bits of magnet, filtering off the steel and copper, and leaving behind a dark solution of rare earths, iron, and boron. Finally, Emmert's team introduces an acid that extracts a rare-earth powder that can then be reused in a new generation of magnets.

Above: Brajendra Mishra, right, and postdoctoral researcher Hyunju Lee, PhD, test technology that uses a strong magnet to recover iron oxide from treated red mud. Iron oxide, left, which makes up 60 percent of red mud, can be used in products for construction and agriculture.

“We work with companies directly, and we can get real valuable input from industry members. We’re fortunate to have the CR³.” —YAN WANG

The process taps existing technologies but integrates them in a new way on auto motors with complex material mixtures. “The technological breakthrough is that we’ve shown that we can selectively attack and remove the magnets from these materials mixtures,” Emmert says, adding that her group has filed for a patent and is talking to companies about commercialization. Eventually, the process could also be applied to cell phones and other electronics.

“With rare earth recovery, there’s huge interest out there because people are aware of the sustainability issues,” Emmert says. “One of the things that is really exciting to me is that I feel we are making a difference with our research. We’re providing guidelines on how to better recycle, and we’re providing ideas that other people with different backgrounds don’t have.”



TURNING RED MUD GREEN

In addition to electronics and electrical devices, rare earths can be abundant in certain forms of industrial production waste that is now typically landfilled. One form currently being targeted by CR³ researchers is red mud, the caustic material left over after aluminum is extracted from bauxite. “Nearly three billion tons of this highly caustic material sits in holding ponds all over the world, often in developing countries,” Emmert says. “When those ponds leak, it kills the surrounding ecosystems.”

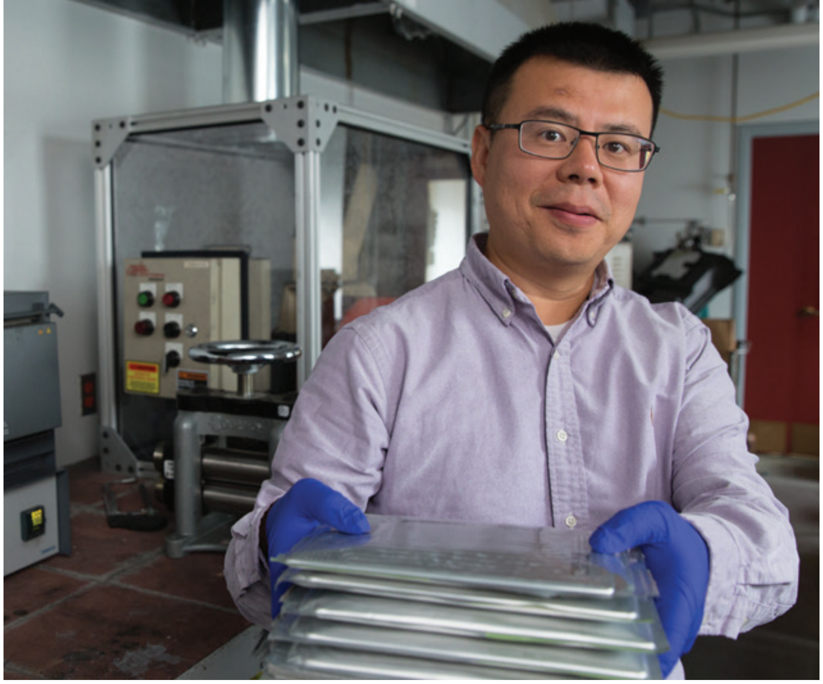
In her lab, Emmert is just beginning to explore various approaches to chemically treat red mud to extract the rare earths. As with the approach taken with vehicle drive units, the solution will likely be a multistep process that separates the rare earths from the many other components of red mud. She is collaborating on the project with Mishra, whose target is another of those components: iron oxide (also known as magnetite). The material is used in pigments for construction materials and in a variety of agricultural products, and depending upon its purity, it can sell for $300 to $6,000 per ton. Since magnetite can make up as much as 60 percent of red mud, a viable recovery method could be lucrative.

PhD candidate Sumedh Gostu prepares red mud for the magnetic separation process by chemically reducing it through exposure to carbon monoxide.

Mishra and his students have developed a process that involves chemically reducing the iron in red mud by exposing it to carbon monoxide. The processed material is then poured into a device that exposes it to a strong, revolving magnet. The magnetic iron oxide is pulled from the solution, while the remaining residue is recovered for further processing (including the recovery of titanium in the Mishra Lab and rare earths in the Emmert Lab). Having demonstrated the process in the lab, Mishra is currently working with Paul Kennedy ’67, president of Kennedy Affiliated Industries, to explore how to scale it up.

“We’re the only ones who have developed a process for producing magnetite from red mud and converting it to a saleable product,” Mishra says.

Adds Emmert, “this is exciting work, because if we come up with processes that work, we can have a huge impact, not just on the aluminum industry, but also in terms of environmental remediation.”



Left: Yan Wang has developed a method for recycling lithium ion batteries, such as these cells, used in electric vehicles. Below, master's candidate Jing Liu works in a glove box on a process used to recover the metals from the batteries' cathodes. Opposite page: Wang and postdoctoral fellow Zhangfeng Zheng, PhD, with a chemical reactor used to create new cathode materials from the recovered materials.

CLOSING THE LOOP

In his Electrochemical Energy Laboratory, Yan Wang, PhD, associate professor of mechanical engineering, is developing technologies for effectively recycling lithium-ion batteries, which power everything from cell phones to electric cars. Battery makers use a variety of chemical formulations for the cathodes in these rechargeable units (various combinations of lithium, nickel, manganese, and cobalt), which requires recyclers to carefully sort the batteries to avoid mixing incompatible chemistries. But as it is often difficult to determine what is in a particular battery, most of these devices are tossed. Since analysts project that the resources needed to keep making them could be scarce by 2050, interest in finding a viable recycling method for these batteries is growing.

With more than $2 million in funding from the NSF and the United States Advanced Battery Consortium (USABC), an alliance of FCA US LLC, Ford Motor Company, and General Motors, Wang has developed and is now testing a chemical process that can recover the cathode materials from lithium-ion batteries, regardless of their formulation, size, or shape. It can then produce new cathode material to fabricate new batteries.

The $1 million USABC award, which is 50 percent funded by the U.S. Department of Energy, is supporting a pilot project aimed at scaling up the process Wang and his team have developed, from the coin cells he can produce in the lab to the 25 Ah cells used in electric and hybrid vehicles. The new batteries will be made by manufacturer A123 Systems LLC and will be tested to see if they perform as well as new batteries.

The answer to that question could have enormous economic implications, since Wang's research has shown that his recycling process, by recovering and reusing up to 80 percent of the cathode materials from unsorted batteries, could cut the cost of cathode materials for vehicle batteries by more than 30 percent. His industry partners project a $2 billion recovery market if the process can be successfully commercialized.

Additional grants from the NSF and the Massachusetts Clean Energy Center have helped advance the recycling technology for commercialization. Wang has co-founded Battery Resourcers LLC with Apelian and former postdoctoral fellow Eric Gratz; the company was one of 26 (from among 4,200 applicants) selected as finalists in the 2016 MassChallenge Start-Up of the Year competition. Wang also credits CR^3 with helping nurture the process that has taken an idea proven in the lab to the brink of a potential new industry.

"The center has helped me a lot," Wang says. "We work with companies directly, and we can get real valuable input from industry members. We're fortunate to have the CR^3."

Apelian sees continuing efforts focusing, not just on technology, but also education and policy. He adds that the center and its mission aren't just gaining momentum with CEOs and company researchers, but also with students who are eager to join labs where they can learn about and contribute to solutions. "Young students are extremely inspired and interested in this topic," Apelian says. "They want to make the world a better place." Re

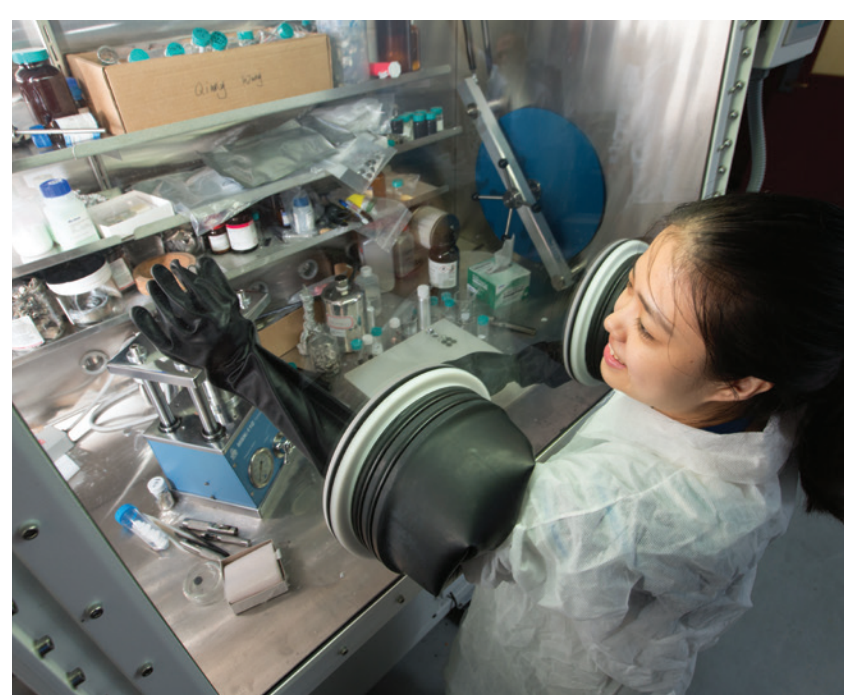
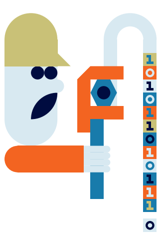


ILLUSTRATION BY GREG MABLY

Keeping the Clouds from Leaking

BY NEIL SAVAGE



Like cryptographic plumbers, WPI's Vernam Group develops sophisticated tools that identify leaks that put sensitive data at risk — whether on our computers, on smartphones, or in the cloud — and finds ways to keep that data secure.

In the Vernam Group's computer security lab, a venerable piece of electronic test equipment is at work protecting today's modern flood of information. The device is an oscilloscope, hooked up to a computer chip running some software routines. As the transistors on the chip quietly do their work, the oscilloscope measures tiny fluctuations in the amount of electrical power they consume.

A transistor uses a slightly different amount of power performing an operation that generates a 1, than one that produces a 0, explains Thomas Eisenbarth, PhD, assistant professor of electrical and computer engineering. By measuring the fluctuations, he can eventually figure out what the chip is doing. "If you look at hundreds or thousands of operations, you can see quite a bit," he says.

By carefully observing similar changes in a computer's performance, Eisenbarth and Vernam Group director Berk Sunar, PhD, professor of electrical and computer engineering, were able to decipher cryptographic keys (known as RSA keys) from virtual machines running on Amazon Web Services (AWS) servers. In doing so, they got their hands on what is supposed to be one of the most tightly guarded secrets on the Internet — a sequence of numbers that protects data from prying eyes as it's transmitted over unsecured communications channels. "Our attack was really the first that successfully recovered an RSA decryption key from a neighboring instance in the cloud," Sunar says.

Navigating the Side Channels

The Amazon attack, part of a project supported by a $500,000 award from the National Science Foundation (NSF), wasn't as straightforward as hooking up an oscilloscope, but it nonetheless provided new evidence that the way a computer behaves — the time it takes to complete a function, for example, or the amount of power an operation consumes — can provide clues about what is transpiring inside its electronics. These so-called side channels can leak sensitive information from otherwise secure systems.

Eisenbarth and Sunar first reported on their attack in 2015 at the IEEE Symposium on Security and Privacy. That work was followed by a paper and presentation at the Conference on Cryptographic Hardware and Embedded Systems (CHES) 2016; CHES is an annual conference for computer security experts founded at WPI in 1999. Sunar and Eisenbarth also shared their results with engineers at Amazon. "They weren't very happy," Sunar says, "but they were cooperative and very open to our feedback."

Spies in the Cloud

Cloud computing is increasing rapidly in popularity. A 2015 Goldman Sachs study predicted that spending on cloud infrastructure and platforms will grow by 30 percent per year through 2018, compared with a 5 percent overall growth rate for enterprise IT. For businesses, renting space and computing power in the cloud can be cheaper than investing in new hardware and employees, and if the need declines, companies are not stuck with unneeded resources. Cloud computing has become a big business for Amazon, which earned more than $6 billion from its AWS operation in 2015.

Many users think of the cloud as a place to store photos and other files, but cloud computing also enables customers to create “virtual machines,” essentially private computers that will run their software and perform their business functions. This is what Amazon offers with its AWS servers. To achieve economies of scale, cloud providers will load as many as 10 virtual machines on a single server. Each acts as an isolated, stand-alone computer, though they do share resources, including memory.

Hardware and software safeguards prevent one virtual machine from directly observing what another is doing. So even though they operate side by side, the information they process should be secure. But in their groundbreaking study, Sunar and Eisenbarth showed that they could eavesdrop on another user just by observing how it was using the CPU’s shared resources.

“Any process on the same system can spy on other processes through the shared resources,” Eisenbarth says. “If you do that in a smart way you can figure out something about the process. If you can see accesses that are dependent on a secret, then you can learn something about that secret.”

Clues in the Last-Level Cache

In this case they focused on the last-level cache, a form of memory that saves processing time by temporarily storing data so that it doesn’t have to be fetched from the main memory. That area of memory is shared by all of the virtual machines running on a server. Data stored there by one user will be overwritten if another process needs the space.

If a process needs to grab something from or write something to the last-level cache and it takes longer than normal, that means another program is also accessing the cache at the same time. By observing this give-and-take, the researchers were able to deduce how much of the cache was being used by each operation. That turned out to be an important clue to what kind of data was being processed.

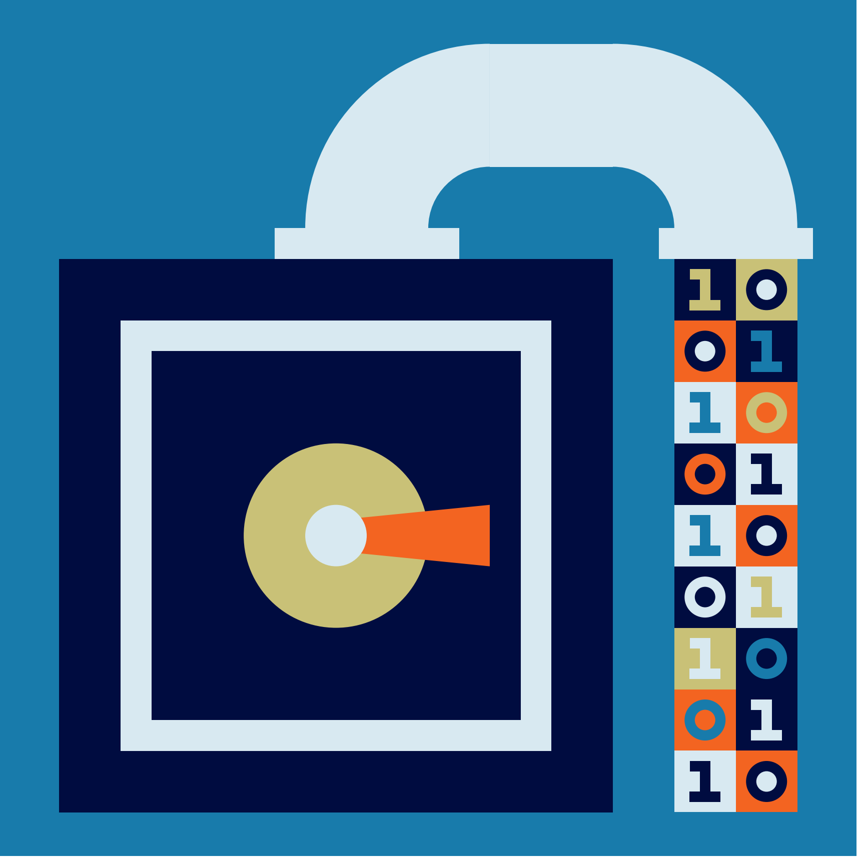
With enough observations, and the application of clever statistics, patterns in the memory usage emerged. Sunar and Eisenbarth were able to determine when they were watching the RSA key being processed. Like safecrackers carefully listening to the sound of the tumblers in the lock, they parsed out the code, digit by digit. “It’s like trying to hear a whisper in a train station,” explains Mehmet Inci, a PhD candidate who worked with Sunar and Eisenbarth on the project. If the whisper is repeated, an eavesdropper can pick up different pieces of whatever’s said each time.

The virtual machine the team monitored was one that they, themselves, had installed on the server. In fact, for the attack to work, they had to find a way to co-locate two machines, the attacker and the victim, on the same server — no small feat since machines are assigned to servers randomly to make it all but impossible for malicious parties to co-locate their machines with particular targets. A team at the University of California San Diego and MIT first showed that co-location was possible in 2009 by making assumptions about where a server might be placed and then deploying large numbers of machines until two popped up on the same server. The WPI team devised a new co-location technique that makes use of characteristics of the last-level cache.

Leaks Beyond the Cloud

After the researchers revealed the vulnerability they’d uncovered, Amazon issued an update to its cryptographic libraries intended to fix the problem. They also pointed out that it would be difficult for less sophisticated and less diligent users to duplicate what the WPI team had accomplished. Eisenbarth agrees: “This is not an easy attack to perform,” he says.

Still, he notes, even with the software patch, “the underlying mechanisms we used are still in place.” And, since computer users are often reluctant to install patches, fearing they will disrupt their computers (about half of Amazon AWS users are still running outdated libraries), the door the WPI team walked through is far from closed.



Security is really a process. If there's any opening in any system, sooner or later it will be attacked.

But the other issue is that computers are always going to leak some information. With a $500,000 NSF award, Eisenbarth and Sunar have been studying such leakage in the cloud in a project called RAIN. Their work demonstrates the need for constant vigilance in the cloud to find leaks and plug them before torrents of secrets are lost. And it isn't just a problem for companies that trust their computing to Amazon's cloud. "Whether you know it or not, you're already using a cloud service provider," says Sunar. Anyone using Dropbox or Evernote to store files or Netflix to watch movies is putting their data in the cloud, and it might be stolen if security breaks down.

And it's not just the cloud that leaks. Recently, the Vernam Group received another $500,000 NSF grant for MIST, a project to identify vulnerabilities on mobile platforms, such as smartphones. Malicious apps, perhaps in the guise of something benign like a game, can gather information about the processes running on a phone to access information about the user, for example, tracking the user's location or capturing credit card numbers. The team hopes to develop ways to manage the processes differently so they don't leak information, and to provide tools app developers can use to prevent leakage.

Attacks don't have to be remote, of course, which is where the work with the oscilloscope comes in. A growing number of devices can be physically accessed by people with a reason to hack them (the way some people have tried to steal cable service for years). Figure out what a chip is doing, and one might be able to steal money from a smart card. Hack a car's computer, and one can gain access to services from satellite radio.

Keeping Computers from Peeking

Another Vernam Group project may make at least some data safer. With a $275,000 NSF grant, Sunar is working with Jeffrey Hoffstein and Joseph Silverman, mathematics professors at Brown University, to investigate new methods for achieving fully homomorphic encryption. This cryptographic technique makes is possible to send data in encrypted form to another computer for processing. The other computer performs its computations and returns an answer, also encrypted, though the other computer never "sees" the actual data.

Imagine you wanted to research something about a sensitive topic, such as mental health, and didn't want anyone at Google to know about it. With homomorphic encryption, the search query would be turned into a cipher and Google would perform an encoded search, then send back the results without ever knowing what you asked or what the answer was.

Homomorphic encryption already exists, but it's inefficient; a query that Google currently answers instantly in unencrypted form could take hours if encrypted. But Sunar thinks that within 10 years, better algorithms and more advanced computers will have mitigated that delay. "This is one of those big technologies that's supposed to change everything," he says.

But as long as there are computers processing data, there will be attackers trying to steal it, keeping security experts like the Vernam Group busy finding holes and closing them. "Security is really a process," Sunar says. "If there's any opening in any system, sooner or later it will be attacked."

Digging Deep to Improve Healthcare

BY MICHAEL COHEN

They call it "mining" for a reason. Like prospectors driven to dig through mountains seeking a small, yet valuable vein, data scientists, technologists, and medical researchers see tantalizing opportunities hidden deep in the mountains of digital medical data piling up around the world. They have no doubt that clues to better treatments—perhaps even cures—for many diseases lie undiscovered within the data. At WPI today, researchers are pushing the boundaries of data science and technology development to bring to the surface new knowledge that will help clinicians and patients.

Information Overload

When a medication harms instead of heals, a report is made to the U.S. Food and Drug Administration (FDA) so the agency can act to prevent others from suffering the same fate. That's the theory. In practice the system is far from foolproof, due to the huge volume of data flowing in to the FDA and the almost impossible challenge of extracting key information from that deluge of electronic reports.

"It's information overload," says Elke Rundensteiner, PhD, professor of computer science and founding director of WPI's Data Science Program. And making matters worse, she says, "the information they need to know is buried deep in the data."

Rundensteiner and a team of students are collaborating with the FDA to help them tackle this problem. The project began in the summer of 2015 when Marni Hall '97, PhD, MPH, now senior vice president of research and development, informatics, and policy at PatientsLikeMe, was in charge of the office that runs the FDA's Adverse Event Reporting System. As a member of WPI's Arts and Sciences Advisory Board, Hall was familiar with WPI's faculty and its research programs. "Marni explained the problem the FDA was having and asked if we could help," Rundensteiner says. "This led to a working relationship between the university and the FDA. Now we have two PhD students who are being supported by a fellowship to work on this important project."

With a digital archive that already contains 10 million adverse event reports dating back to 1969, the FDA receives another 1.5 million new reports every year. "The first problem the FDA staff faces is which reports to read, because they can't closely investigate them all," Rundensteiner says.

"I have no doubt that there is information deep in the data that could help many people. We just have to find it."

—ELKE RUNDENSTEINER

PHOTOGRAPHY BY PATRICK O'CONNOR

Furthermore, each new report needs to be compared in meaningful ways to the archive to look for patterns that could shed light on the case. “So one of our long-term goals is to develop a data exploration system that will read all of the new reports, relate them to the archives and to other pieces of related information, and then identify the critical reports the examiner should focus on,” she says.

One major challenge concerns the way the data is “structured.” The online adverse event reporting form has a number of fields and drop-down items that physicians, patients, or medical device providers can use to input data about the patient and the adverse event. That is known as structured data because the information is uniform across all reports and is easily mined. But the form also includes a text box where physicians can write a narrative about the event, using their own style and grammar. This “unstructured data” is difficult for a computer to parse. “The reality is, there is missing information in that structured data,” Rundensteiner says, “with additional valuable information to help understand the particular case often hidden in the narrative.”

The WPI team aims to develop machine-learning algorithms that will be able to “read” the doctors’ notes and extract the key concepts characterizing the adverse events. The key words will be assembled into a structured format so it can be mined. “Dealing with natural language is very complex,” she says, “which makes this an extremely challenging albeit important problem.”

For example, a note may include the name of a medication and the word "rash." Does that mean the patient had a rash and used the medication to treat it? Or was the rash a reaction to a medication taken for another purpose? Context is key, and most cases are not as simple as one patient taking one medication for the first time.

"This is a very challenging project," Rundensteiner says, "and it deals with a widespread issue with important ramifications well beyond this particular FDA scenario. I have no doubt that there is information deep in the data that could help many people. We just have to find it."

Machine Learning

"We design intelligent algorithms that can learn from experience, and that experience is represented as data," says Carolina Ruiz, PhD, associate professor of computer science.

Working in collaboration with clinicians at the University of Massachusetts Medical School (UMMS) and UMass Memorial Medical Center (UMMC), both in Worcester, Ruiz has mined the medical records of 500 pancreatic cancer surgery patients for information that might help physicians predict how other patients will fare after pancreatic surgery.

But before that quest could begin, she and her team had to collect and integrate the medical records consistently and enter them into a structured database. "Preparing the data is a time-consuming but essential task," she says. Once it was structured, Ruiz developed and applied machine learning algorithms to sift through the data and bring to light features of the medical records that were good predictors of surgical outcomes.

After the key features were selected, she "trained" the algorithm by running it on small portions of the data and evaluating its performance against the patients' known outcomes. Adjustments were made to help the algorithm learn better, then it was applied to the entire data set. For comparison, a group of physicians who treat pancreatic cancer were asked which features they use to predict a patient's likely outcome.

"The physicians were surprised," Ruiz says. "They had all selected different features than the algorithm, based on their experience and intuition. But the algorithm had better performance with the features it selected."

Among the important features the algorithm focused on were the number of drains used during the surgery, the amount of postoperative bleeding, and the number of days until the patient was able to resume a regular diet. "Pancreatic cancer is a very difficult disease to treat," she says, "so it is helpful for physicians to have this data-inferred knowledge as they develop treatment plans for their patients."

Using similar approaches, Ruiz and her team are mining data from patients with sleep disorders, searching for patterns and identifying features that could lead to improved treatments. In an ongoing partnership with neurologists at UMMS, she has established a structured database that currently contains the medical records of 1,000 sleep disorder patients — about half a gigabyte of data for each patient. "One sleep study records data from 55 sensors worn by the patient for the entire night's sleep, which generate an enormous amount of data," she notes.

Unlike the pancreatic surgery project, which sought to answer a specific question, the sleep data mining project is open-ended and "unsupervised," she says. Her research group has developed techniques that are able to automatically discover patterns across a wide spectrum of patient data: patterns that relate demographic information, medical history, family history of disease, exercise habits, drinking and smoking habits, biomedical signals, medical treatments, and medications. "In this case, we did not tell the algorithm how to organize the data," she says, "because we didn't want to bias it and prevent it from discovering novel patterns on its own. If we knew what the important patterns were, we wouldn't need machine learning."

Using these unsupervised techniques, Ruiz's group has discovered novel patient subpopulations that exhibit distinct medical and behavioral properties. "By analyzing the subpopulations uncovered by our algorithm," she says, "we determined that they can be characterized by their dynamic sleep properties — high vs. low efficiency — and that static properties, including age, collar size, smoking frequency, heart disease, and BMI [body mass index], differ across these populations in a statistically significant manner."

The project is ongoing. Ruiz says she expects that many other medically meaningful patterns will be uncovered that will shed light on the nature and treatment of sleep disorders.

RESEARCH THAT DELIVERS

WPI's work in digital health is one of several areas of health-related research and development that receive support from the university's Healthcare Delivery Institute (HDI). Founded in 2011 to have an impact on the future of healthcare, nationally and globally, HDI is a hub for the university's patient-centric health and healthcare-related research and education programs. It builds partnerships with industry, healthcare providers, and academic and government organizations that help energize those programs. More than 30 WPI faculty members, working in such areas as health systems engineering, health and medical informatics, privacy and security in healthcare, and healthcare and medical robotics, are affiliated with HDI. For more: **wpi.edu/+HDI**

Translating Data for Patients

In WPI's Foisie Business School, professor Diane Strong, PhD, and associate professor Bengisu Tulu, PhD, are leading several teams developing smartphone-based applications that extend the impact of knowledge gleaned from digital health data.

"All the apps you see on the market today are trackers: tracking physical activity, tracking what you eat," Tulu says. "With our apps, tracking is just the start."

Tulu and Strong partner with clinicians and researchers at UMMS to embed evidence-based medical guidance in their apps to provides users with clinically sound prompts and action items. "In our view, a health app has to do more than tell you your numbers," Strong says. "It should also be able to give you evidence-based information that will help you manage your own care."

Among the smartphone apps developed by the WPI teams, which include several other WPI faculty members and students (graduate and undergraduate), is Sugar, which helps people with type 2 diabetes control their blood glucose levels and monitor severe foot ulcers, and RELAX, which helps people lose weight and overcome stress. Both are in early clinical testing with patients at UMMC.

One of the latest apps leverages a national database managed by UMMS on outcomes of total joint replacement surgeries. Patients will track their pain levels and other metrics on a daily basis using their smartphones. When they come to the clinic, the app will summarize their data and relate it to cases in the database, to give the clinician better information to assess progress and plan treatment. The app will soon be tested with UMMC patients.

"We hope the app will make the time patients spend with their physicians more meaningful," Tulu says. "Currently, a lot of time is used going over the patient's pain history. With the app, that information will be summarized for the provider and set in context with the known trends from the database. So more time will be available for patient and provider to discuss treatment and answer questions."

Learning from early patient usage of the apps in development, Tulu and Strong continue to explore ways to optimize the user experience and present data in ways that are relevant for both the patient and the healthcare provider.

"Physicians and patients need different data and they expect it to be presented in different ways. We are still working on closing that gap," Tulu says. "Usability, visual design, and novelty are all important. You can't just bring people back to the same message all the time. They will get bored or discouraged and stop using the app."

In addition to a firm foundation in clinical data, building an effective app requires a multidisciplinary team with data scientists, software engineers, web developers, cybersecurity experts, and digital designers, Tulu says.

"You only see your doctor a couple of times a year, if that," Strong says. "Your health is not your doctor's responsibility, it's your responsibility. So our aim is to build out a platform and standards for apps that can help people better manage their own well-being."

And whether the task is building more useful health management apps, mining data for leads on improved treatments, or developing tools to surface critical health information, promoting well-being and helping patients have the best possible outcomes from their interactions with the healthcare system is the goal that continues to guide WPI's researchers.

> "In our view, a health app has to do more than tell you your numbers. It should also be able to give you evidence-based information that will help you manage your own care."
>
> —DIANE STRONG

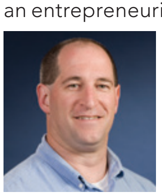
"Physicians and patients need different data and they expect it to be presented in different ways. Usability, visual design, and novelty are all important."
—BENGISU TULU

highlights

MAJOR RESEARCH AWARDS

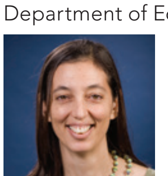
Here is a small sample of the many notable awards from federal agencies, corporations, and other entities that have supported research at WPI in recent months. Other recent awards are covered elsewhere in this edition of *WPI Research*.

HELPING STUDENTS DEVELOP AN ENTREPRENEURIAL MINDSET



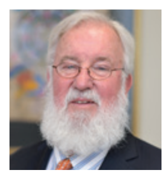
According to The Kern Family Foundation, an entrepreneurial mindset helps engineers and scientists recognize opportunities and respond creatively to make a positive impact. With a $1.76 million award from the foundation, WPI will incorporate that mindset into its renowned project-based undergraduate program. The grant expands on a previous $500,000 award from the foundation. Under the direction of principal investigators **Glenn Gaudette**, PhD, professor of biomedical engineering, and **Curtis Abel**, PhD, professor of practice in Undergraduate Studies, the new grant will support, among other activities, professional and leadership development for faculty members and adding extracurricular activities to 100 courses that will expose students in all disciplines to entrepreneurship.

INTRODUCING STEM TO THE YOUNGEST LEARNERS



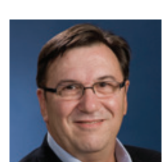
A four-year, $1.5 million award from the U.S. Department of Education (Institute of Education Sciences) is funding the development of a new curriculum designed to introduce STEM principles to preschoolers. Called Seeds of STEM, the program harnesses the knowledge of a team of teachers, engineers, and scientists led by principal investigator **Mia Dubosarsky**, the director of professional development for WPI's STEM Education Center. (**Martha Cyr**, executive director of K–12 Outreach at WPI, is on the project's advisory board.) The project grew out of a collaborative between the center and Worcester's Head Start program, which sought to bring the center's extensive experience with STEM education and teaching at the elementary and secondary levels to students as young as three. The researchers hope the curriculum they are developing can become a model for pre-school STEM education nationally.

FILLING THE KNOWLEDGE GAP IN ADDITIVE MANUFACTURING



Additive manufacturing (AM) with metals is a relatively new technology that could enable manufacturers to make complex components that can't be produced with traditional casting and machining methods (see "It All Adds Up," *WPI Research*, Spring 2015). There are, however, unanswered questions about the composition and performance of components made with AM, which involves building up parts layer after layer. With a two-year, $2.7 million award from the U.S. Army, a research team led by **Richard Sisson Jr.**, PhD, George F. Fuller Professor of Mechanical Engineering and director of WPI's Manufacturing and Materials Science and Engineering programs, will develop computational models that can be used to predict the state of finished parts. Additional models under development will help the Army reduce the use of costly elements, or even eliminate them, in metal parts used in military vehicles.

EXPLORING THE ROLE OF COPPER IN BACTERIAL VIRULENCE

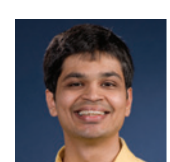


Copper is an essential micronutrient that all organisms need to maintain healthy metabolism. But unless it is bound to proteins, copper is also toxic to cells. With a $1.3 million award from the National Institutes of Health (NIH), a team led by **José Argüello**, PhD, Walter and Miriam Rutman Professor of Biochemistry, will conduct a systematic study of copper in the bacteria *Pseudomonas aeruginosa*, a leading cause of hospital-associated infections, which is becoming increasingly resistant to antibiotics. The goal it to discover new drug targets that might allow cells in the body to use copper to fight back against this bacterial invader. Of particular importance for this research, copper is a key factor in both the virulence of pathogenic microorganisms and in the ability of human cells to fight them.

THE LINK BETWEEN G PROTEINS AND HEART ATTACKS

For reasons that are not well understood, cells in the heart become enlarged (a process called hypertrophic growth) following a heart attack, weakening the heart and making the patient more susceptible to heart failure. With a four-year, $1.1 million award from the National Institutes of Health (NIH), **Suzanne Scarlata**, PhD, Richard T. Whitcomb Professor of Biochemistry, will explore a novel theory about the physiological and biochemical mechanisms that may underlie this maladaptive change. Scarlata studies a group of cellular signaling molecules known as G proteins. In previous research, she observed that G proteins are released when caveolae, invaginations in the cell membrane, expand to accommodate changes in cell volume. In heart muscle cells, this response appears to initiate a sequence of reactions that leads to a large increase in microRNAs that have been implicated in heart disease. A better understanding of this sequence could lead to new therapies for treating heart attacks.

HELPING BURN OIL MORE EFFICIENTLY TO CLEAN UP SPILLS



When an oil spill occurs in open water, it is important to respond quickly to keep the oil from spreading into the water column and harming marine life. One of the quickest ways to remove the oil is to burn it, but burning rates for oil on water can be poor and the process produces significant airborne pollutants. With a $1.1 million award from the U.S. Department of the Interior (DOI), **Ali Rangwala**, PhD, associate professor of fire protection engineering, will lead a team that will conduct large-scale tests at a U.S. Coast Guard outdoor test facility in Mobile, Ala., of a new technology developed in Rangwala's lab that can greatly improve the efficiency of crude oil fires on water while reducing emissions. Developed, in part, with earlier Interior funding, the Flame Refluxer uses metal coils and a mesh of copper fibers to transfer heat from the fire into the floating oil slick to improve combustion efficiency.

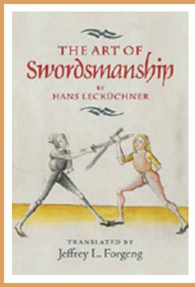
HELPING MEET A CRITICAL NEED FOR DATA SCIENTISTS

The nation is facing a critical shortage of data scientists, professionals who have the knowledge and skills to develop computational tools that can synthesize large volumes of information from multiple sources, derive new insights, and convert data into actionable information. With a $856,000 grant from the U.S. Department of Education through its Graduate Assistance in Areas of National Need (GAANN) program, WPI will be able to help fill that need by providing three-year fellowships for six PhD candidates in the field. According to the principal investigator, **Elke Rundensteiner**, PhD, professor of computer science and director of WPI's Data Science Program, the fellows will prepare for professional leadership by conducting research on big data analytics, large-scale data management, and data mining and by engaging in professional development sessions and honing their teaching skills.

FINDING THE GENES THAT LINK ALL LIFE

If a human being, a worm, a broccoli plant, and a yeast cell share common genetic elements, those snippets of DNA, having remained unchanged over millions of years of evolution, are likely to perform fundamental biological functions. With a $768,000 award from the National Science Foundation (NSF), **Dmitry Korkin**, PhD, associate professor of computer science, is seeking to identify such elements across all known genomes of plants, animals, fungi, and other complex organisms to gain insight into the roles they play in normal development and the onset of disease. He will use mathematical algorithms and advanced computing technology to analyze vast amounts of genomic data to identify these long identical multispecies elements, or LIMEs. "To be conserved across species that diverged hundreds of millions of years ago, these elements must carry out some very basic and vital functions in the cells," he says.

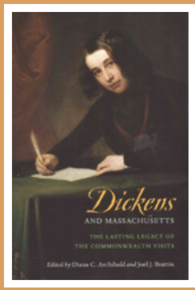
NEW BOOKS BY WPI FACULTY



THE ART OF SWORDSMANSHIP BY HANS LECKÜCHNER

Translated by Jeffrey L. Forgeng
Boydell and Brewer, 2015

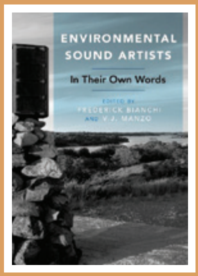
Forgeng, adjunct associate professor in the Department of Humanities and Arts and an authority on the history of arms and armor, translated this treatise by Johannes Lecküchner, a German priest. It is the most substantial surviving document on the medieval techniques of swordplay. This lavishly illustrated work marks the first time the book has been in print since its completion in 1482.



DICKENS AND MASSACHUSETTS

Edited by Diana C. Archibald and Joel Brattin
University of Massachusetts Press, 2015

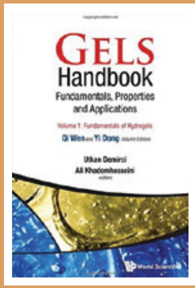
Massachusetts was the one state that met and even exceeded Charles Dickens's expectations during his two visits to North America. This volume, co-edited by **Brattin**, professor of literature, provides insight from leading scholars on the significance of the commonwealth in the author's life and work. Brattin contributes an essay, "Slavery in Dickens's Manuscript of *American Notes for General Circulation*."



ENVIRONMENTAL SOUND ARTISTS: IN THEIR OWN WORDS

Edited by Frederick Bianchi and V. J. Manzo
Oxford University Press, 2016

Environmental sound art incorporates processes in which artists actively engage with the environment. Edited by **Bianchi**, professor of music, and **Manzo**, assistant professor of music, this book presents a perspective on the environmental sound art movement through essays by contemporary artists who've used environmental sound as a vehicle for addressing political, social, economic, scientific, and aesthetic issues.



FUNDAMENTALS OF HYDROGELS

Edited by Qi Wen and Yi Dong
World Scientific Publishing, 2016

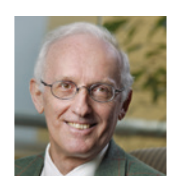
Volume 1 of the three-volume *Gels Handbook: Fundamentals, Properties and Applications*, the book explores the fundamental aspects of hydrogel physics and chemistry with an eye toward bioengineering applications. Co-edited by **Wen**, assistant professor of physics, it covers the chemistry of natural and synthetic hydrogels, hydrogel formation via photo-crosslink and self-assembly, and methods for tuning hydrogel mechanical properties and architecture, among other topics.

highlights

NEW FELLOWS

José Argüello, Walter and Miriam Rutman Professor of Biochemistry, and **Ramdas Ram-Mohan**, professor of physics, were elected fellows of the American Association for the Advancement of Science, the world's largest general scientific society. Argüello was honored for his research on the mechanisms underlying metal ion transport and the role of bacterial metal transporters in agriculture and infectious disease. Ram-Mohan was recognized for major contributions to the development of computational algorithms and important advances in the theory of electronic and optical properties of solid-state and semiconductor materials.

Kristen Billiar, professor and head of the Department of Biomedical Engineering, was inducted into the College of Fellows of the American Institute for Medical and Biological Engineering (AIMBE) for outstanding research on the micromechanics of cardiovascular tissues and for leadership in bioengineering education. The College of Fellows is composed of the top two percent of medical and biological engineers in the country.

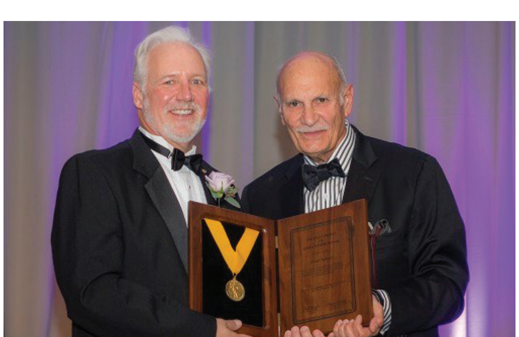


Umberto Mosco, Harold J. Gay Professor of Mathematical Sciences, was elected a fellow of the American Mathematical Society in recognition of his contributions to analysis and partial differential equations, particularly for introducing a theory of variational convergence. He is the first WPI faculty member to receive this honor.

FACULTY ACHIEVEMENTS

HOFFMAN RECEIVES ASME SPARKS MEDAL

Allen Hoffman, professor of mechanical engineering and co-director of WPI's Assistive Technology Resource Center (ATRC), received the 2016 Ben C. Sparks Medal from the American Society of Mechanical Engineers (ASME). The award, which recognizes outstanding service to mechanical engineering education, honored him for his seminal contributions to the WPI Plan, the university's groundbreaking undergraduate curriculum. With support from the National Science Foundation and Worcester's Fairlawn Foundation, he and associate professor **Holly Ault** developed design courses and undergraduate major projects focused on rehabilitation engineering and assistive technology. This work led to the ATRC, which supports undergraduate and graduate projects in this field.



APELIAN RECEIVES ASM GOLD MEDAL

Diran Apelian, Alcoa Howmet Professor of Mechanical Engineering and founding director of the Metal Processing Institute (MPI), received the Gold Medal from ASM International in the fall of 2016. He was honored for "his leadership and vision in establishing and executing a model for industry-university collaborative research, and for his pioneering work in metal processing." An internationally recognized pioneer in metals research, he founded MPI in 1996. The largest industry-university alliance in North America, it is dedicated to research in metal casting, heat treating, and resource recovery and recycling. A fellow of ASM International, he has received numerous other professional honors, including election to the National Academy of Engineering.

NEW SOCIETY PRESIDENTS

Milosh Puchovsky '88, professor of practice in Fire Protection Engineering, became president of the **Society of Fire Protection Engineers** in early 2016. He is a fellow of the organization, which has 4,200 members.

Suzanne Scarlata, WPI's inaugural Richard T. Whitcomb Professor of Biochemistry, assumed the presidency of the 9,000-member **Biophysical Society** in the spring of 2016. A 30-year member of the society, she has served the international organization in a number of senior capacities in the past.

Alexander Wyglinski, associate professor of electrical and computer engineering, is president-elect of the Institute of Electrical and Electronics Engineers **Vehicular Technology Society**, which includes researchers and industrial practitioners engaged with all manner of electrical and electronics technology for vehicles.

NEW CAREER AWARDS

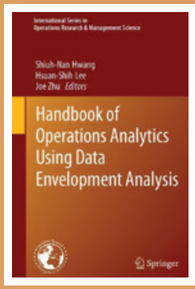
Three WPI researchers have received CAREER Awards, the most prestigious NSF award for young faculty members.

Sarah Olsen, PhD, assistant professor of mathematical sciences, received her award to develop new computational tools to understand the complex intertwining of physical and chemical factors that govern the movement of sperm.

With her award, **Scarlet Shell**, PhD, assistant professor of biology and biotechnology, will study the genetic mechanism that enable bacteria to modify their physiology to survive stressful conditions, such as lack of nutrients or oxygen.

Michael Timko, PhD, assistant professor of chemical engineering, received an award to develop a practical and economically viable method for deriving liquid fuels from lignocellulosic biomass, the indigestible part of plants.

NEW BOOKS BY WPI FACULTY



HANDBOOK OF OPERATIONS ANALYTICS USING DATA ENVELOPMENT ANALYSIS

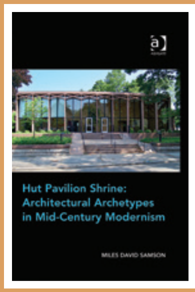
Edited by Shiuh-Nan Hwang, Hsuan-Shih Lee, and Joe Zhu
Springer, 2016

Co-edited by **Zhu**, professor in the Foisie Business School and one of the most prominent researchers in the field, the book focuses on applications of data envelopment analysis that provide fundamental tools and techniques for improving operation functions and attaining long-term competitiveness.

HANDBOOK OF RESEARCH ON HOLISTIC PERSPECTIVES IN GAMIFICATION FOR CLINICAL PRACTICE

Daniel Novák, Bengisu Tulu, and Håvar Brendryen
IGI Global, 2016

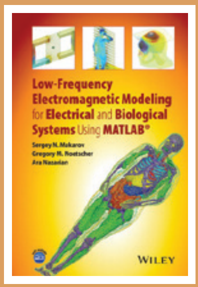
Over the past decade, the healthcare industry has adopted games as a powerful tool for promoting personal health and wellness. Targeting academics, researchers, practitioners, healthcare professionals, and even patients, the book, co-authored by **Tulu**, associate professor in the Foisie Business School, reviews current studies and empirical evidence, highlights critical principles of gamification, and fosters the increasing application of games at the practical, clinical level.



HUT PAVILION SHRINE: ARCHITECTURAL ARCHETYPES IN MID-CENTURY MODERNISM

David Samson
Routledge, 2015

Between 1940 and 1980, mid-century modernism saw the spread of architecture's Modern Movement tenets of functionalism, social service, and anonymity into mainstream practice. In this volume, **Samson**, professor of art history, examines this crossroads of modernism and the archetypal, and critiques its buildings and theory with a focus on one particularly important and omnipresent type: the pavilion.



LOW-FREQUENCY ELECTROMAGNETIC MODELING FOR ELECTRICAL AND BIOLOGICAL SYSTEMS USING MATLAB

Sergey N. Makarov, Gregory M. Noetscher, and Ara Nazarian
Wiley, 2015

Aimed at electrical and biomedical engineering students and practicing researchers, engineers, and medical doctors working on low-frequency modeling and bioelectromagnetic applications, this book, co-authored by **Makarov**, professor of electrical and computer engineering, covers the basic concepts of computational low-frequency electromagnetics in an application-based format.

highlights

EMANUEL EARNS HONORS IN ROMANIA

Alexander Emanuel, professor of electrical and computer engineering (second from left, above), received two distinguished professional honors from institutions in his native Romania. In June 2015 he was elected an honorary member of the Academy of Technical Sciences of Romania, and that fall he received an honorary doctorate from the Polytechnic University of Bucharest, the nation's largest technical university. Both honors recognize him for his more than 45-year career in electric power research and education, specifically for his pioneering work in the area of power quality and power system harmonics—scholarship that has made him a world-renowned expert in that field.

JIUSTO IS CASE PROFESSOR OF THE YEAR

Scott Jiusto, associate professor of geography and director of WPI's Cape Town, South Africa, Project Centre, was named 2015 CASE U.S. Professor of the Year for Massachusetts, becoming the fifth WPI faculty member to receive the honor since 2002. Jointly sponsored by the Council for the Advancement and Support of Education (CASE) and the Carnegie Foundation for the Advancement of Teaching, the program recognizes the nation's most outstanding undergraduate instructors.

He and **Richard Vaz**, professor of electrical and computer engineering and director of WPI's Center for Project-Based Learning, won the Leo Jansen Prize for delivering the best paper at the Seventh International Conference on Engineering Education for Sustainable Development in Vancouver in June 2015. As part of the award, they delivered the keynote address at the 8th Conference on Engineering Education for Sustainable Development in Bruges, Belgium, in September 2016.

KEEN OUTSTANDING FACULTY MEMBER

Glenn Gaudette, professor of biomedical engineering, received the Kern Entrepreneurial Engineering Network (KEEN) 2015 Outstanding Faculty of the Year award. Gaudette led a team that implemented "Developing the Entrepreneurial Engineer," a program designed to infuse the undergraduate experience at WPI with entrepreneurial experiences, challenges, and opportunities as students develop the skills they need to solve the grand challenges of the world. The Kern Family Foundation created KEEN to support colleges and universities interested in developing innovative ways of instilling an entrepreneurial mindset in engineering students to help ensure that the United States remains competitive in the global marketplace.

BEST PAPER AWARDS

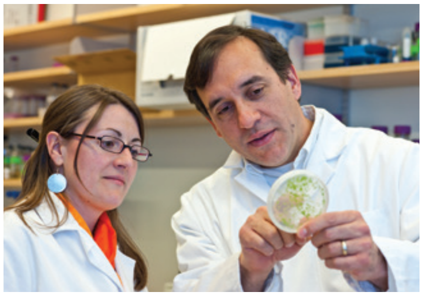
Lane Harrison, assistant professor of computer science, received a best paper award at CHI 2016 (the Association for Computer Machinery's conference on human-computer interaction) for "Learn Piano with BACh: An Adaptive Learning Interface that Adjusts Task Difficulty Based on Brain State," a paper he co-authored.

Cagdas Onal, assistant professor of mechanical engineer, was co-author of two papers honored with recent best paper awards. "Robot Makers: The Future of Digital Rapid Design and Fabrication of Robots" received the 2015 award from *IEEE Robotics & Automation Magazine*. "Regionally Growing Random Trees: A Synergistic Motion Planning and Control Algorithm for Dynamic Systems" was honored in 2016 at the IEEE International Conference on Automation Science and Engineering.

Nima Rahbar, associate professor of civil and environmental engineering, was co-author of "Not Just Lumber: Using Wood in the Sustainable Future of Materials, Chemicals, and Fuels," winner of the *Journal of The Minerals, Metals & Materials Society's* 2016 Editor's Choice Award.

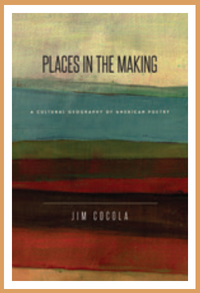
NEW FULBRIGHT SCHOLARS

Brian Meacham, associate professor of fire protection engineering, was one of 19 inaugural recipients of Fulbright Global Scholar Awards, which provide funding for U.S. academics and professionals to engage in multi-nation, transregional research projects. An authority on risk-informed performance-based fire protection design, and fire risk and building regulatory policy, he traveled to Japan, Spain, and Sweden to study performance-based building regulatory systems. He also received the 2016 Harold E. Nelson Service Award from the Society of Fire Protection Engineers (SFPE) and is currently chair of the society's Standing Committee on Research, Technology, and Innovation.



Luis Vidali, associate professor of biology and biotechnology, received a 2016 Fulbright Senior Scholar Award to conduct research at the Universidad Politécnica de Madrid in Spain. He will work on a project titled, "Dynamic Analysis of Signaling and Metals in Plant-Bacteria Interactions Using the Moss *Physcomitrella patens* as a Simple Model System." The senior scholars program is funded by the U.S. Department of State to provide teaching or research grants to U.S. faculty members and professionals.

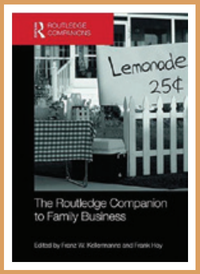
NEW BOOKS BY WPI FACULTY



PLACES IN THE MAKING: A CULTURAL GEOGRAPHY OF AMERICAN POETRY

Jim Cocola
University of Iowa Press, 2016

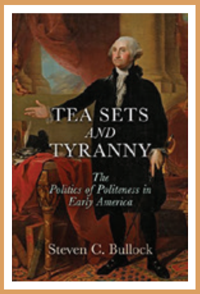
In this book, **Cocola**, associate professor of literature, maps a range of 20th- and 21st century American poets who have used language to evoke the world at various scales. Distinct from related traditions, including landscape poetry, nature poetry, and pastoral poetry, this study traces a poetics centered on more particular and situated engagements with actual places and spaces.



THE ROUTLEDGE COMPANION TO FAMILY BUSINESS

Edited by Franz W. Kellermanns and Frank Hoy
Routledge, 2016

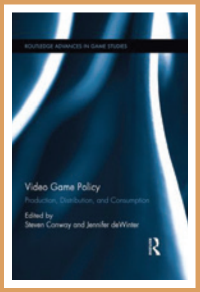
Co-edited by **Hoy**, Beswick Professor of Entrepreneurship and Innovation, and with contributions from the top minds in family business from around the world, this is the definitive survey of a field that has seen rapid growth in research in recent years. Its 25 chapters cover such key research themes as corporate social responsibility and bank debt rationing, with a host of international examples.



TEA SETS AND TYRANNY: THE POLITICS OF POLITENESS IN EARLY AMERICA

Steven C. Bullock
University of Pennsylvania Press, 2016

Bullock, professor of history, explores the connection between two trends in 18th century America: efforts to restrain power and the rising interest in ideals of refinement, moderation, and polished self-presentation. Though the trends have long seemed separate, Bullock contends the politics of politeness helped make opposition to overbearing power central to early American thought and practice.



VIDEO GAME POLICY: PRODUCTION, CIRCULATION, CONSUMPTION

Edited by Steven Conway and Jennifer deWinter
Routledge, 2016

Co-edited by **deWinter**, associate professor and director of WPI's Interactive Media and Game Development Program, this book explores the effect of policy (the rules governing the production, distribution, and consumption of digital games) on the digital game complex (government, industry, corporations, distributors, players, etc.) and how policy effects our understanding of the game medium.

BY JENNIFER WYGLINSKI

IGNITING INNOVATION

In the spring of 2013, WPI opened one of the most sophisticated fire science laboratories in the nation with one overarching mission: to enable researchers to set things on fire and study how they burn.

Since then the Fire Protection Engineering Laboratory, located at WPI's Gateway Park campus, has more than lived up to that promise. The facility, which actually consists of two laboratories, has played host to faculty and student researchers who are advancing the study of fire science by learning more about the burning characteristics of materials and structures, and applying their findings to help make the world a safer place.

Nicholas Dembsey, professor of fire protection engineering, says the lab was a natural fit for WPI's trailblazing Department of Fire Protection Engineering (FPE), which is home to the nation's first master of science and doctoral programs in the field. The department is also a leader in research in such areas as fire dynamics, building design, and human response to fire-related emergencies.

"The FPE lab at Gateway is one of a few facilities of its kind in academia in terms of both capabilities and size," Dembsey says. "It has enhanced the unique nature of WPI's FPE program by greatly expanding our research, project, and teaching potential."

The smaller of the two labs, the Honeywell Fire Protection Engineering Fundamentals Lab, houses equipment for conducting micro- to bench-scale studies using small samples (up to about 100 millimeters on a side). Funded in part by Honeywell Life Safety, the lab can generate data on fundamental fire science variables.

The lab's cone calorimeter, an advanced bench-scale instrument, radiatively heats samples uniformly with electric coils located in its cone-shaped heater. The smoke is collected and analyzed in an exhaust hood.

"By measuring oxygen depletion in exhaust fumes as well as factors like temperature and pressure, the calorimeter calculates heat release rate — the rate at which a fire generates energy," Dembsey says. Our researchers use this

Opposite page: In the UL Performance Lab are, from left, Combustion Lab manager Trevor Borth, Joseph Igoe '16, Jenna Troio '18, Kevin O'Hara and Panyawat (Oat) Tukaew, MS candidates in fire protection engineering, and FPE Lab manager Raymond Ranellone '11, '14 (MS). Below: Running a test on the cone calorimeter in the Honeywell Fundamentals Lab are FPE lab assistants Troio and Michael Friedman '18.

data, as well as variables such as smoke production rate and time to ignite, to create and test fire simulation models."

Researchers in the Fundamentals Lab also have access to a thermogravimetric analyzer that measures changes in the weights of samples as they are heated; a differential scanning calorimeter that measures temperature and heat flow associated with transformations like melting and crystallization; and a fire propagation apparatus in which samples are placed in a tube so environmental factors can be controlled.

Faculty and student teams have used this equipment to improve the accuracy of wildfire modeling, generate biochar for wastewater treatment, and investigate the burning properties of fiber-reinforced polymers (FRPs), composite materials such as fiberglass that are increasingly used in modern building construction. Working with graduate and undergraduate students, Dembsey has gathered fundamental data on the material properties of FRPs, evaluated the effectiveness of flame-retardant additives, and refined computer testing models that simulate the material's decomposition.

The lab has also helped advance work by Ali Rangwala, associate professor of fire protection engineering, who is exploring ways to more efficiently burn crude oil as a means for cleaning up open water oil spills. Funded by $2 million from the U.S. Department of the Interior, the work began by exploring the challenge of getting oil to burn in the extreme cold of the Arctic, which holds large oil reserves. That led to the invention of a technology, called the Flame Refluxer, that increases burning efficiency by channeling radiative heat from a fire back into its fuel.

Trevor Borth, who manages Rangwala's Combustion Laboratory (located in WPI's Salisbury Laboratories building), says the research began at the fundamental level, providing data on flame spread, heat release rates, and other qualities of crude oil burning that helped develop computer models. To test those models at larger scales, the research team heads to the UL Fire Protection Engineering Performance Lab, the second of the FPE labs at Gateway. Funded in part by the UL science safety company, the 190-square-meter room features equipment and space for burning structures up to two stories tall.

The centerpiece of the lab is a 6-megawatt calorimeter that functions in much the same way as the cone calorimeter, but on a significantly larger scale. The calorimeter's large hood, 6 by 6 meters, is located 6 meters above the floor. That creates a 6-meter cubic volume where assemblies of various configurations can be tested. With the lab's controlled propane supply, researchers can create small- to very large fires that can be used to evaluate the reaction of assemblies to fires of varying intensities.

"The space works well for large-scale burns because its air diffusers neutralize air currents, letting the fires behave naturally without wind effects," says Borth. "For our crude oil Refluxer project, we were able to scale up from a 10-centimeter burner to a 70-centimeter burner."

Dembsey notes that the lab is ideal for testing not only larger samples of materials, but also how those materials are structured.

"The large hood is frequently used for industry projects that involve the study of fire spread behavior in assemblies or systems," says Dembsey. "One research team recently burned a mock-up of a railway car, while other teams have burned an exterior cladding system and a soft wall shelter. In all these projects, the clients learned key details of system behaviors, which they then used to improve fire safety."

The Performance Lab will also play a vital role in a research project led by Brian Meacham, associate professor of fire protection engineering. The work is part of a study, funded by a $1 million award from the Department of Homeland Security, of fire performance of interior and exterior green building features. Meacham's team recently constructed a large test rig that can simulate a two-story timber house. They will construct test structures within the rig using three different framing methods and expose them to fires of up to 4 megawatts in intensity to gather data on temperature, heat flux, and fire induced strains.

As preparations continue for those large-scale burns, the fundamentals and performance labs, which are now under the direction of Raymond Ranellone '11, a 2014 graduate of WPI's FPE MS program, are being put to good use, Dembsey says. "The FPE labs at Gateway are home to innovative research on a daily basis, from large initiatives to student projects and collaborations with industry. These facilities have truly been a game changer for WPI."

WPI
Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609-2280

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AN ACT OF GENEROSITY, some ingenious engineering, and four years of hard work combined to produce the Virtual Human, a remarkable new computational tool for medical research and diagnosis developed by a WPI research team. Story on page 8.