Solutions

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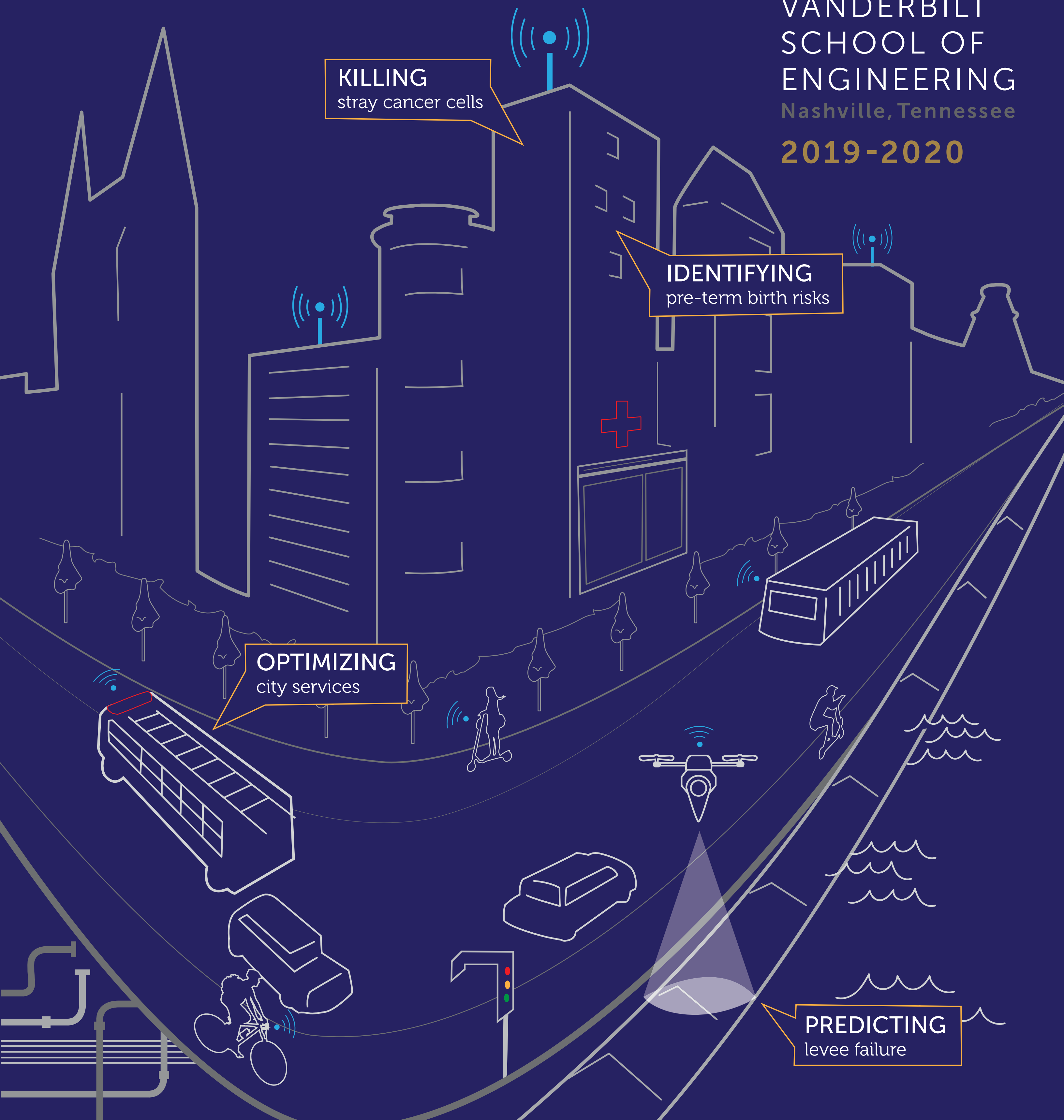
VANDERBILT
SCHOOL OF
ENGINEERING
Nashville, Tennessee

2019-2020



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EDITOR
Pamela Coyle

WRITERS
Pamela Coyle, Brenda Ellis and Heidi Hall

DESIGN AND ILLUSTRATION
Mary Alice Bernal, Corporate Design

PHOTOGRAPHERS
Shun Ahmed , Daniel Dubois, Steve Green, Joe Howell, Anne Rayner, John Russell and Susan Urmy.

Cover: Pamela Saxon, Saxon Creative

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Inside cover photo: Rapid commercial and residential growth light up downtown Nashville though the iconic AT&T "Batman" building remains a focal point. A $1 billion redevelopment project will include the new home of the Amazon Operations Center of Excellence and a huge entertainment complex with a 4,000-seat music venue, club, boutique hotel, movie theater and bowling facility. Construction began in February 2019.

Back cover: The Engineering and Science Building, with several floors ready to be built out for new faculty, continues to win accolades for design and programming. The U.S. Green Building Council awarded the interdisciplinary structure LEED Gold status in 2019. ESB also won an international S-Lab award in the category of Engineering and Related Buildings for Wilson HGA, a national design and architecture firm specializing in science and technology facilities for higher education.

Also, The Wond'ry, Vanderbilt's epicenter for innovation, creative collaboration and entrepreneurship, is designated an Outstanding Emerging Entrepreneurship Center by at the Global Consortium of Entrepreneurship Centers. The building opened in 2016.

Defining how we approach inclusion

'Inclusion Engineering' encompasses neurodiversity and mobility

by Philippe Fauchet
Bruce and Bridgitt Evans Dean of Engineering

The School of Engineering has become significantly more diverse, dynamic, and a creative place to learn and teach *because of* focused efforts to ensure inclusion of students and faculty who were too long underrepresented. For the 2019-2020 academic year, I am delighted to share:

- 42 percent of our first-year undergraduates are women;
- 38 percent of our first-year undergraduates are from underrepresented minority groups; and
- Over half of the female faculty were hired in the last five years.

But, we are just getting started. And, I am thrilled to announce the school has embraced what we call "Inclusion Engineering."

The term recognizes the school's long-standing leadership in areas such as rehabilitation engineering, which develops technology that restores mobility, independence, and societal participation to individuals with physical limitations. Joining Michael Goldfarb, H. Fort Flowers Professor of Mechanical Engineering, and Karl Zelik, assistant professor of mechanical engineering, the school welcomes another faculty member, David Braun, PhD'09, as an assistant professor of mechanical engineering. Professor Braun enhances our efforts with his expertise in robotics, superhuman actuation, and augmentation technologies.

Additionally, we have broadened our definition of inclusion engineering to encompass neurodiversity and the ways people, specifically those with autism spectrum disorders, learn and process information.

Our new Frist Center for Autism and Innovation embodies this idea. A generous $10 million gift in 2018 from Jennifer R. Frist, BS'93, and husband William R. "Billy" Frist paved the way for a home that brings engineers together with a broad interdisciplinary group of experts to understand and promote neurodiverse talent.

The need is clear. People with autism are chronically underemployed, if they are employed at all. An estimated 35 percent of 18-year-olds with autism go to college, but among those who graduate, at least 80 percent are unemployed.

This dismal track record comes as U.S. unemployment sits at historic lows and employers in every sector scramble to fill jobs. The status quo ignores traits in many people with autism who have high value in the workforce: concentrated focus, great attention to detail and accuracy, innovative thinking, honesty, and loyalty among them.

The Frist Center will develop and commercialize devices, algorithms, and systems both in support of and inspired by neurodiverse abilities. Several engineering faculty members have been involved in such projects for years, and the Frist Center will enhance the visibility of their important work.

We already see this happening. With a $3 million National Science Foundation grant, Vanderbilt will establish a first-of-its-kind graduate traineeship program called Neurodiversity Inspired Science and Engineering. NISE will support training the next generation of engineers and scientists to develop innovations that connect 21st-century workforce needs to the talents and abilities of neurodiverse individuals. The five-year grant, announced in September 2019, will fund fellowships for about 50 graduate students.

Also in September, Nilanjan Sarkar, professor and chair of mechanical engineering, received a $1 million NSF Convergence Accelerator Pilot grant to advance

Maithilee Kunda, assistant professor of computer science and computer engineering, demonstrates visual thinking concepts to Jennifer R. Frist (seated), husband William R. "Billy" Frist with graduate students and other visitors.

From the left, Interim Chancellor Susan Wente, Bruce and Bridgitt Evans Dean of Engineering Philippe Fauchet, Jennifer R. Frist, BS'93, William R. "Billy" Frist and Frist Center Director Keivan Stassun celebrate at the grand opening.

research on workforce development and training projects for individuals with autism spectrum disorders. The initial work is an interactive prototype he developed to prepare applicants with autism for job interviews. The AI-based program measures a user's anxiety level and eye contact with a virtual interviewer.

Professor Sarkar is the lead investigator on the nine-month grant, which includes Vanderbilt University Medical Center and collaborators at other universities, participation of industry partners, and analysis of employer feedback. Keivan G. Stassun, Frist Center director, Stevenson Professor of Physics and Astronomy and professor of computer science, will coordinate employer outreach.

Separately, Maithilee Kunda, assistant professor of computer science and computer engineering, looks at how visual thinking contributes to learning and intelligent behavior, with a focus on artificial intelligence applications. Many people with ASD are visual thinkers, thus Kunda wants to leverage visual thinking to make AI more creative and effective as well as develop educational tools specifically for people with autism.

Job seekers who have autism can practice interviewing skills with an AI program developed by Nilanjan Sarkar, professor of mechanical engineering. The program tracks stress levels and eye contact with a virtual interviewer.

These are issues we as engineers are uniquely suited to tackle. Our mission is and always has been to take on complex problems with the purpose of improving the human condition. This exciting new focus addresses needs of an evolving workplace. Most importantly, it will broaden meaningful participation for people who have been left out for too long. **V**

Transported into smart city research

by Caroline Janssen

This summer, I worked with engineering professors Mark Abkowitz and Dan Work on the MoveVU Digital Gateway, an initiative to install a series of sensor packages at major campus entry points. The sensors will collect environmental measurements, transportation mode counts, trajectories and other data to paint a full picture of how we use Nashville and campus infrastructure.

I am a senior majoring in civil engineering. When I arrived at Vanderbilt as a first-year student, I wanted to pursue structural engineering, in large part to gain the technical skills necessary to design and build communities in poor areas. However, in the classes I took, the conferences I attended and the wonderful people I met, I found a new passion in smart cities and sustainability, particularly in the profound impact of transportation design on social equality. I discovered how research is forefront of transportation innovation, and when the opportunity arose for me to work with a research lab, I couldn't refuse. My research opportunities have been extraordinary and opened my eyes to the breadth of vocations available in transportation engineering.

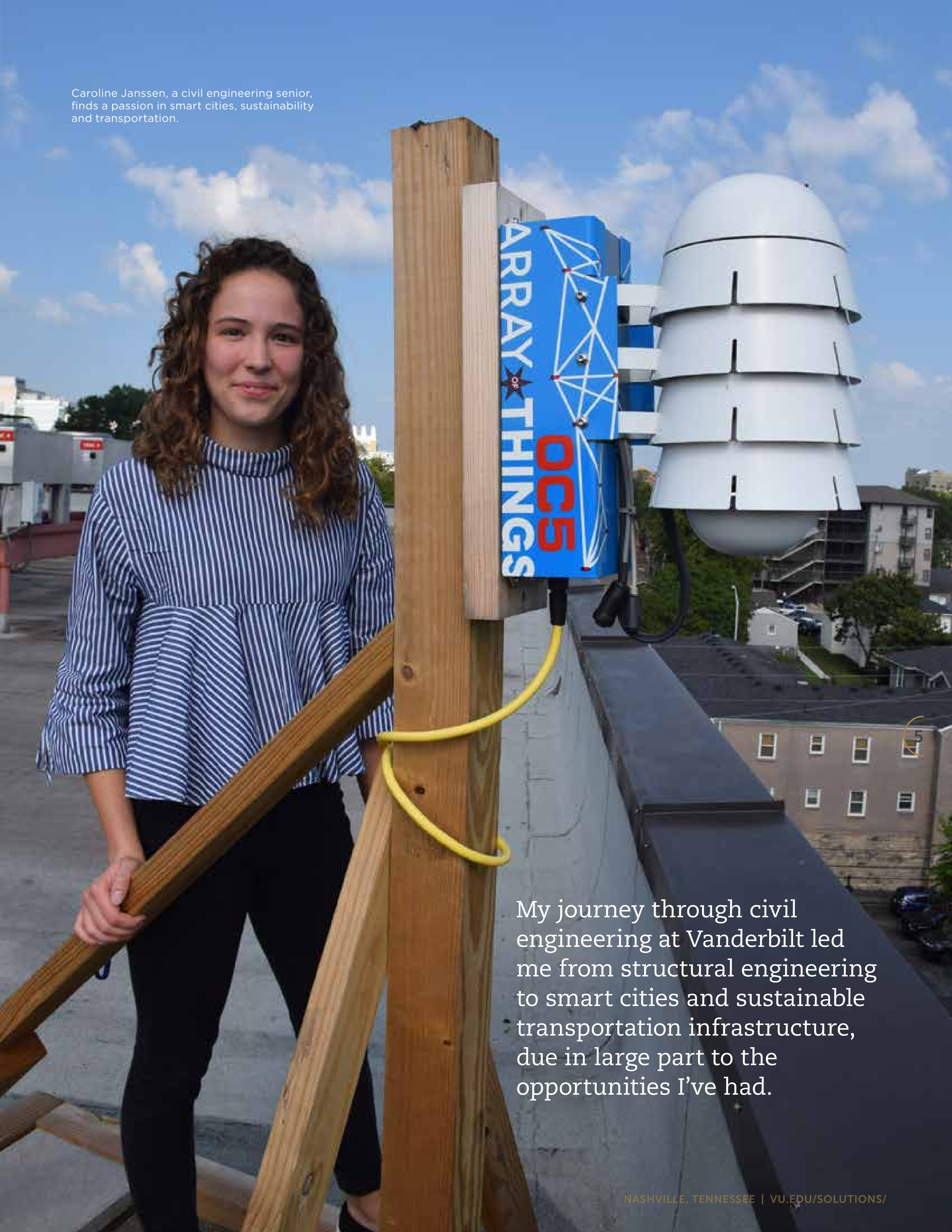
My experience in Professor Work's lab began in the summer of 2018, investigating semi-autonomous functions on commercially available cars. During the 2018-19 school year, William Barbour, a Ph.D. student in the lab, was starting a connected-sensors project, enhancing existing sensor nodes to capture the full transportation scene that plays out on key corridors around Vanderbilt and Nashville. With that data, we can measure the effectiveness of newly installed infrastructure, evaluate renovation needs of old infrastructure, and see where different modes (driving, biking, scootering, walking) are most popular.

The lab environment is a key component to the success of our projects. As an undergraduate, I work one-on-one with several graduate students, collaborating and advocating for new ideas. Many projects run simultaneously, and in weekly meetings we share progress and results that may benefit a parallel project. A certain energy comes with research, whether it's the rush to meet a journal deadline or stay on top of the newest mobility trend.

Most meaningful in recent months has been the interdisciplinary work I've been so fortunate to lead. Half the time, I worked in the lab on analytics and furthering the sensor installations. This included guest teaching a class at the Vanderbilt Summer Academy, taking high school students through an analytical exercise on preliminary data we had collected. The other half of the time I interned with Erin Hafkenschiel, Vanderbilt's Executive Director of Mobility, to advance Vanderbilt's MoveVU plan. I analyzed the results of a commuter survey to identify the share of the university community that gets to campus in a single occupancy vehicle as Vanderbilt sets goals to lower that figure and encourage more sustainable options.

With scooters in Nashville at a tipping point, we advised Nashville's Transportation Licensing Committee on how to proceed. Vanderbilt is a big stakeholder here, as one in seven Nashville scooter rides begin or end on campus. We have the processing power to perform meaningful analytics on the scooter data.

My journey through civil engineering at Vanderbilt led me from structural engineering to smart cities and sustainable transportation infrastructure, due in large part to the opportunities I've had. The impact of collaboration with others has become a central tenet in my work, as we all work together to create communities that cultivate healthy lives. V



Caroline Janssen, a civil engineering senior, finds a passion in smart cities, sustainability and transportation.

My journey through civil engineering at Vanderbilt led me from structural engineering to smart cities and sustainable transportation infrastructure, due in large part to the opportunities I've had.

Strong mentors eased my shift to photonics

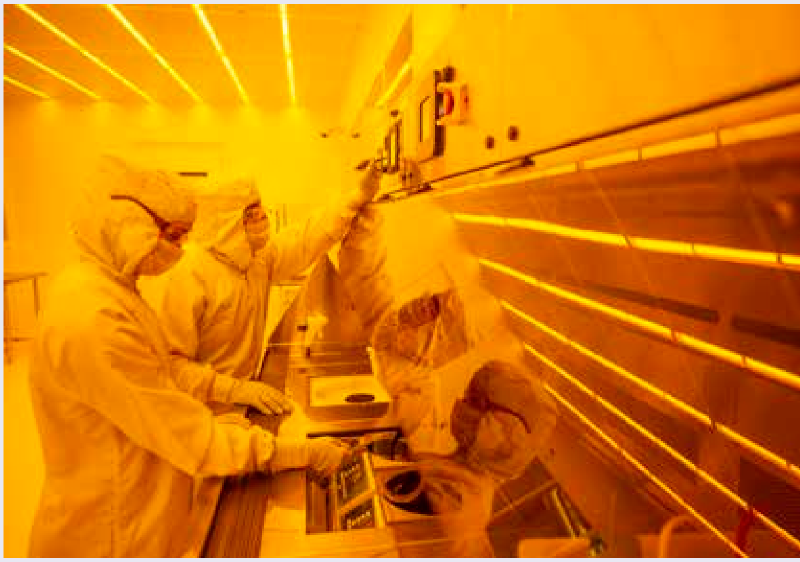
by Sami Halimi

As I prepared to graduate with my degree in electrical engineering from Lipscomb University, I remained unsure about which path to take. I applied and was accepted at Vanderbilt, but I was conflicted because my original plan was to work in industry for a couple of years before going to graduate school. Then, I received an email message from Sharon Weiss, Cornelius Vanderbilt Professor of Engineering and professor of electrical engineering, and she wanted to meet with me.

Professor Weiss's enthusiasm for her work and her research group was contagious. From graduate students both within and outside her group I heard nothing but positive things, which assuaged some of my apprehension about continuing straight into grad school. My interests at the time were in nanoscience, but more specifically in carbon and graphene as materials for new transistor technologies. Photonics had not been on my radar. Still, I felt comfortable shifting my focus to photonics and joining the Weiss Lab knowing I would have a well-respected adviser who cared about her students.

At an engineering school the size of Vanderbilt, a professor's attention is divided among fewer graduate student advisees. When I do need assistance, Professor Weiss always is attentive and available. She is actively involved in my research projects and provides direction. During my first years, graduate students with more experience offered important guidance, as well. This guidance and Professor Weiss's patience were crucial for me as I


Sami Halimi



dove headfirst into the field of photonics, an area in which I had a limited background at first but have come to feel at home in.

This was especially true in navigating the process from research to writing to journal acceptance and publication. Even an academic paper needs a narrative, and for my inaugural effort as a first author I had some difficulty crafting a compelling narrative with my results while drafting the article. Talking through how to plan and structure experiments around a specific vision with Professor Weiss and my coauthors helped me to be a better conductor of research instead of just a collector of data.

I've also benefited from the guidance of William Robinson, a professor of electrical and computer engineering who also is associate dean for Academic Success. I was his teaching assistant my first semester, and he encouraged me to apply for a coaching program he helped put together for black Ph.D. students in engineering who are considering academic careers. Twice a month for seven months, a handful of us met via conference calls with external mentors on topics that included crafting a statement of purpose, writing grant proposals, applying for post-doc and faculty positions, and working in academia as an underrepresented minority.

I try to make time to reciprocate by providing guidance for others younger than me. I take part in volunteer and outreach events to get students of all grade levels excited about science and engineering. I also have had the privilege of advising, or to some degree mentoring, Vanderbilt undergraduates. As a teaching assistant, I ran small lab sections where talk at times would turn to classes and college life, and students welcomed my input. A former student even asked me to look over his statement of purpose as he prepared graduate school applications.

Graduate school can be extremely challenging and demanding and often is a test of perseverance more than it is of learning or intellect. Having support and guidance from amazing professors who are renowned in their fields has kept me motivated and helped me become a more well-rounded researcher and engineer. V

"Having support and guidance from amazing professors who are renowned in their fields has kept me motivated and helped me become a more well-rounded researcher and engineer."

Sami Halimi

Reducing uncertainty in sea level rise projections

Photo: NASA

By 2100, average sea level is estimated to rise by one to three feet, possibly up to six feet and likely will accelerate after that. Such a large range vastly complicates planning for sea level increases and understanding of the socioeconomic risks.

The behavior of Antarctic sheets—when, how and why icebergs fracture and detach, or calve—is the biggest factor in the uncertainty.

It is a complex problem, one which Ravindra Duddu, an assistant professor of civil and environmental engineering, wants to solve. He received a $555,000 NSF CAREER grant in 2019 to work toward that goal.

The aim, Duddu said, is not to predict when a specific glacier or ice shelf will break off, but to develop fracture-physics-based calving laws to represent mass loss from the Antarctic ice sheet decades to centuries. Integrated with ocean and climate models, new models will improve estimates of average sea level rise and reduce the uncertainty.

"Owing to its complexity and the challenges or rewards it presents, iceberg calving has been called the 'holy grail' problem in glaciology," he said.

Cancer cells move quickly but take a lazy path

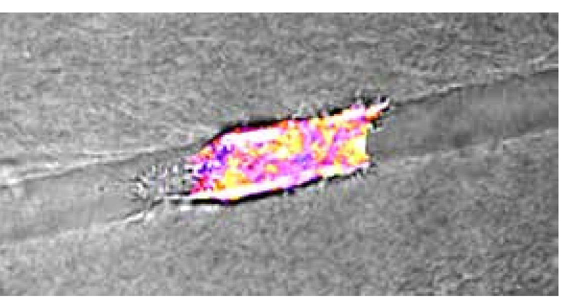


Photo: Reinhart-King Lab

A cancer cell (in shades of pink and yellow) migrates through a collagen track with fluorescent biomarkers showing cellular energy levels. Purple denotes low energy.

New research led by Cynthia Reinhart-King, Cornelius Vanderbilt Professor of Engineering, is the first study to quantify the energetic costs of cancer cells during metastasis—enabling the prediction of specific migration pathways.

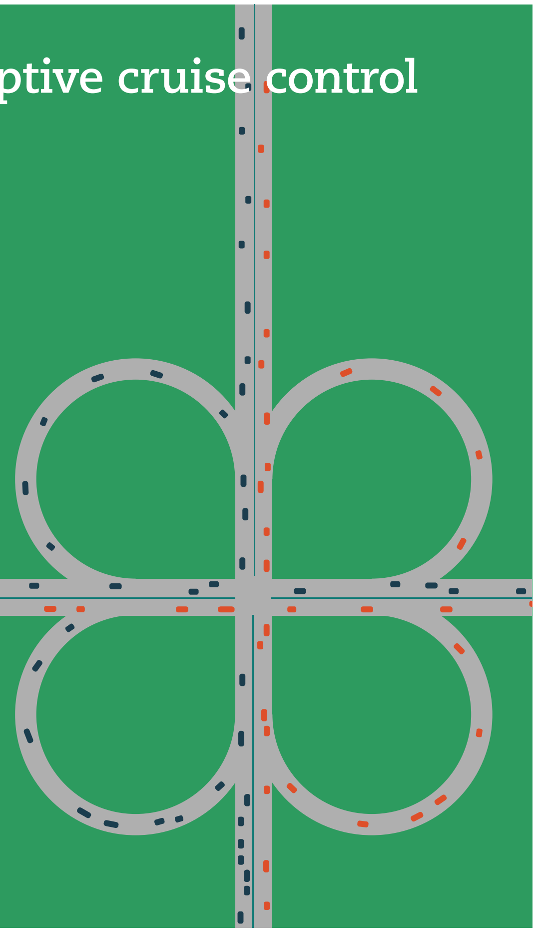
While cancer cancer cells move quickly in metastasis, they seek out paths of lesser resistance. Migrating cancer cells decide which path in the body to travel based on how much energy it takes, opting to move through wider, easier to navigate spaces rather than smaller, confined spaces to reduce energy requirements during movement.

These findings suggest energy expenditure and metabolism are significant factors within metastatic migration, which lends credence to recent clinical interest in the study of metabolomics and the targeting of cellular metabolism as a way to prevent metastasis.

"These cells are lazy. They want to move, but they will find the easiest way to do it," said Reinhart-King, professor of biomedical engineering.

The discoveries, published in September 2019 in *Nature Communications*, build on research from the Reinhart-King Lab, published earlier this year, which discovered "drafting" techniques used by cancer cells to conserve energy during migration.

Phantom traffic jams persist with adaptive cruise control



Regardless of speed, cars with adaptive cruise control driven over 1,000 miles of open-road testing showed the feature does not yet solve the problem of phantom traffic jams.

One experiment used seven identical vehicles running the same ACC system in a single lane of traffic. Once all the cars reached a cruising speed of 50 mph, the pace vehicle quickly reduced its speed by 6 mph. In a domino effect, each of the following vehicles slowed more and more dramatically so that, by the seventh car, its speed dropped below the minimum required for the ACC system to operate.

"Our experiments show that today's driver-assist systems are not yet able to overcome the worst driving behaviors of humans that lead to extremely frustrating traffic jams," said Dan Work, associate professor of civil and environmental engineering. He helped lead the multi-university, multidisciplinary research team of experts in vehicle automation, traffic flow theory, control theory and cyber-physical systems.

Researchers simulated different driving conditions with a pace car changing its speed, followed by a vehicle using adaptive cruise control. The team measured how quickly and aggressively the ACC system responded to the pace car speed changes.

RESEARCH BRIEF: REGENERATIVE MEDICINE

Cultured 3D blood-brain-barrier model

In a significant milestone toward building a "brain in a dish," Vanderbilt researchers successfully created a model brain organoid that will advance disease research and blood testing.

The team of Ethan Lippmann, assistant professor of chemical and biomolecular engineering, and Leon Bellan, assistant professor of mechanical engineering, cultured induced pluripotent stem cells into a successful three-dimensional blood-brain barrier model.

"Before, it was enough to develop drugs by doing an initial test in animals and then going to humans, but now we're realizing that method has its limitations," said Ethan Lippmann.

"These models are meant to complement all the other preclinical work."

The team's work published in *Stem Cell Reports*, in February 2019, found the brain microvascular endothelial cells they cultured were 10-to-100 times less permeable to molecules of various sizes when compared to human endothelial cell controls that lack barrier function.

Engineering Neighborhoods

In a global world where Skyping with a colleague half a world away or reviewing medical test data via email from remote areas of Africa is commonplace, the term “neighborhood” is redefined and revitalized. At Vanderbilt University School of Engineering, neighborhood is how we describe our distinctive culture of trans-institutionality, collaboration and cross-pollination both within and beyond the traditional walls of departments, schools, institutions and disciplines.

Vanderbilt Engineering has a long and successful tradition of collaboration with colleagues at other universities and at Vanderbilt University Medical Center, the College of Arts and Science and the other colleges and schools that comprise one of the nation’s top research universities.

In developing its own bottom-up strategic plan, the School of Engineering identified major areas of emphasis—nine neighborhoods drawing faculty, staff, students and outside researchers together in the search for solutions. A Vanderbilt engineer’s research routinely spans more than one neighborhood.

Rehabilitation Engineering
develops mechanical devices and robotics to help restore lost physical and cognitive functions.

page 20

Cyber-Physical Systems
technology develops processes, protocols, networking and technology needed for the seamless and secure integration of cyber (software) and physical (hardware, networks and users) systems.

page 22

Regenerative Medicine
involves tissue engineering, drug delivery, drug efficacy and molecular biology and works to replace and heal damaged cells, tissues and organs.

page 14

VANDERBILT SCHOOL OF ENGINEERING

Risk, Reliability and Resilience

advances risk quantification; improves predictability; increases reliability of systems, infrastructure and materials; and creates technology and materials with more resilience.

page 30

Nanoscience and Nanotechnology

concerns the discovery and application of how materials and processes behave on the nanoscale in diverse areas of engineering, science and health care.

page 18

Energy and Natural Resources

targets transformative research that will enable sustainable resource and energy conservation, production and recovery.

page 25

Biomedical Imaging and Biophotonics

uses physical phenomena such as magnetic fields, radiation and light to aid diagnoses and treatments of disease and dysfunction.

page 12

Surgery and Engineering

concentrates on the collaborative efforts of engineers and surgical experts to create, develop, implement and evaluate technology, methods and tools that improve patients' outcomes and experiences.

page 33

Big Data Science and Engineering

develops tools and processes to harvest and leverage knowledge from data sets too large and complex for traditional software to handle, often involving predictive or user behavior analytics.

page 27

Pre-term birth risks evaluated under new light

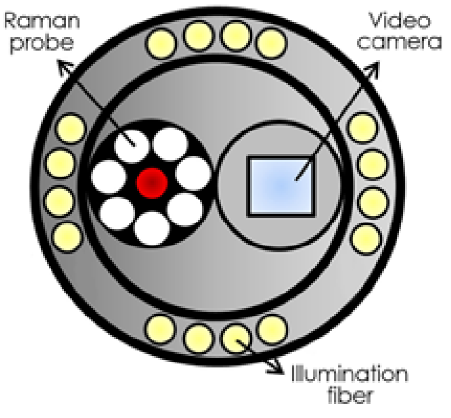
U.S. Air Force photo by Master Sgt. Ken Wright.

Above: In almost half of the cases the cause of preterm birth is unknown. A new optical device designed by Vanderbilt biomedical engineers has the potential to predict risks of preterm labor.

Anita Mahadevan-Jansen and her team are working to help more babies arrive safely.

A small optical device has the potential to predict risks of preterm labor that could result in preterm births. Each year, 15 million babies worldwide are born prematurely, arriving at least three weeks before their due dates. Globally, prematurity is the largest cause of death before age 5.

"Light-based methods for early monitoring of the cervix, an organ that biochemically changes during pregnancy, have potential to predict risks of preterm birth but those approaches require a speculum examination that many patients find uncomfortable," said Mahadevan-Jansen, Orrin Ingram Professor of Engineering and director of the Biophotonics Center at Vanderbilt. "Plus, they are not considered standard practice during prenatal care."



The new speculum-free probe tool combines a fiber optic Raman spectroscopy probe and a camera for visual guidance, all contained in a small two-inch long stainless steel tube at the end of a probe. In fact, patient discomfort is what motivated development of the visually guided probe.

"We think this tool has the potential to improve patient care by arming providers with information on the biochemical state of the cervix, closing gaps in our understanding of cervical maturation, and identifying women at risk for preterm birth," she said.

This is the first work to demonstrate the utility of Raman spectroscopy as a basic research tool in obstetrics and marks an important step toward development of a clinical tool, Mahadevan-Jansen said.

Raman spectroscopy uses laser light, a spectrometer and either a microscope or a fiber optic probe to provide information about tissue biochemistry for noninvasive examination of altered molecular signatures in a cell or tissue.

The cervix experiences numerous changes throughout the 40 weeks, more or less, of a pregnancy. Raman spectroscopy allows tracking of a multitude of biochemical components during a single measurement, Mahadevan-Jansen said.

"In our probe, the camera delivers light, collects a signal, takes measurements detecting changes in the cervix, and tells doctors what's going on chemically," she said. "If you can find out what's going on and identify that really early, you can dramatically change how pregnancies and preterm births can be affected."

Mahadevan-Jansen said the optical tool assessed cervix tissue biochemistry noninvasively without sacrificing data quality.

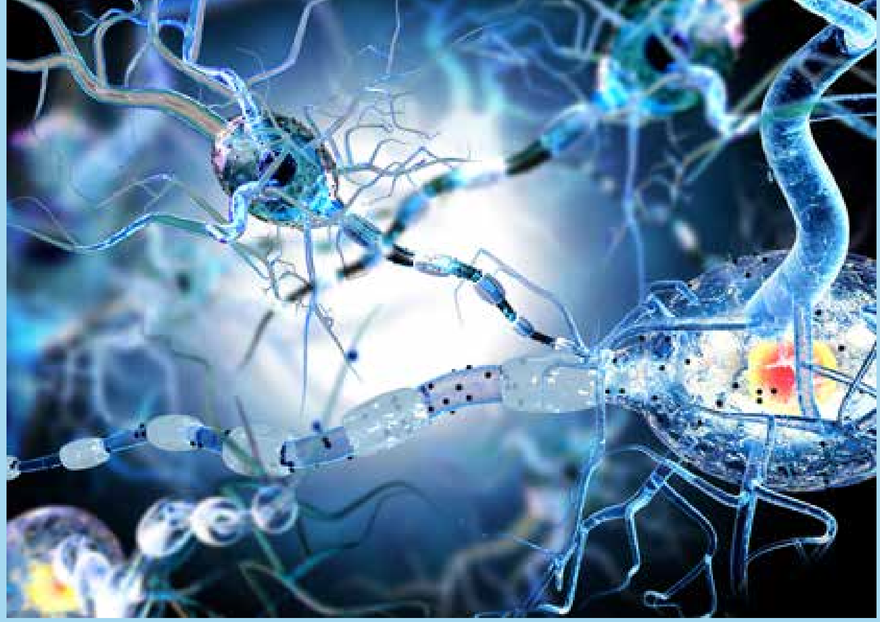
Photo: Lab of Anita Mahadevan-Jansen

A small, new device combines a fiber optic Raman spectroscopy probe and a camera for visual guidance in assessing preterm birth indicators and risks.

"We think this tool can reduce some barriers to clinical examination of cervical changes during pregnancy and help incorporate optical technologies into obstetric care," she said.

The team used the Raman tool to track chemical signals and identify biochemical markers that changed in 68 healthy women throughout their pregnancies and during postpartum repair. Those results were published in *American Journal of Obstetrics and Gynecology* in May 2018. Related work was first published in September 2018 and appeared in the February 2019 *Journal of Biophotonics*.

The research was funded by NIH grant Number R01 HD081121 and Clinical and Translational Science Award UL1TR000445. **V**



NEW FINDINGS AND $8 MILLION IN NIH GRANTS PROPEL EPILEPSY RESEARCH

Vanderbilt University engineering faculty and Vanderbilt University Medical Center neurosurgeons are developing early biomarkers of treatment outcomes for patients with temporal lobe epilepsy. A related project will investigate disturbances in brain networks related to attention lapses and cognitive deficits in patients with the same disorder.

The projects have received $8 million in new NIH funding since November 2018.

Victoria Morgan, PhD'96, associate professor of biomedical engineering and radiology and radiological sciences, said a better understanding of the progression of epilepsy may aid clinicians in making treatment decisions, with a goal of providing quicker relief to patients who are suffering.

She and Dario Englot, surgical director of epilepsy at Vanderbilt University Medical Center, lead the group that secured two $2.5 million NIH grants to compare the brain networks of patients with focal epilepsy to healthy counterparts of a similar age to see how the connectivity varies throughout the treatment process.

"The interesting thing to me as an engineer is that 60 to 75 percent of the patients who have their seizure focus removed will end up seizure-free," Morgan said. "Why is it about 70 percent? Why do some of these patients not have a good outcome?"

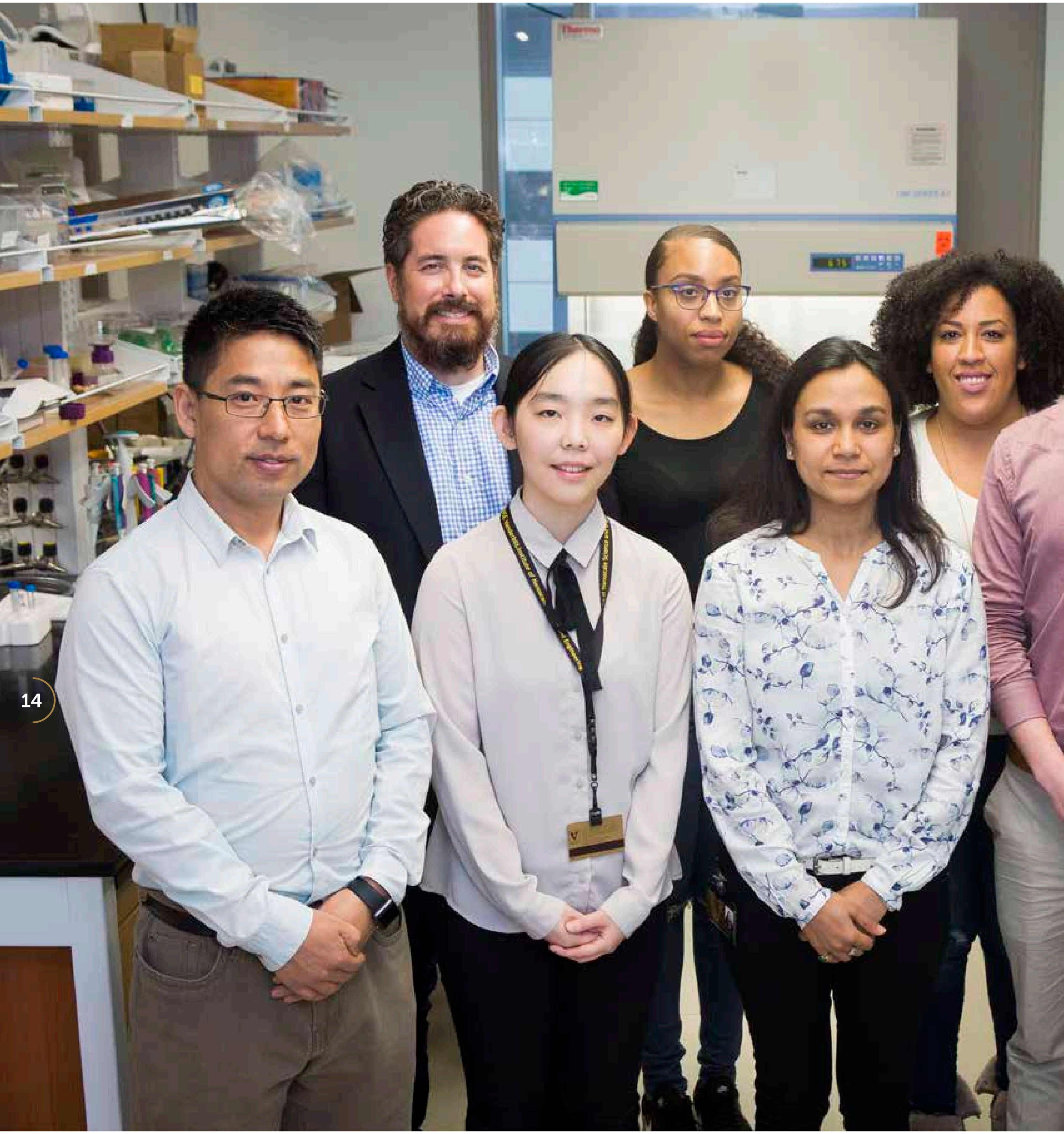
The team, which includes Bennett Landman, associate professor of electrical engineering, found significant functional connectivity decreases across the brain after surgery not present before surgery.

Results published in the June 2019 *Journal of Neurosurgery* suggest "these changes may be a reflection of an ongoing epileptogenic pro-gression that has been altered by the surgery, rather than a direct result of the surgery itself," the researchers said. "This interaction between surgical treatment and network evolution may play a significant role in the long-term divergent outcomes after surgery."

In a separate study, Englot and Catie Chang, an assistant professor of computer science, electrical engineering and computer engineering, aim to identify specific areas of brain connection where vigilance, or sustained attention, is impaired. They received a $3 million NIH grant in July 2019.

The project will use a novel approach that integrates multi-modal imaging with in-depth neurocognitive assessments. Chang specializes in techniques for analyzing and interpreting functional neuroimaging data.

The epilepsy projects are collaborations among VUSE, the Vanderbilt Institute for Surgery and Engineering, the Vanderbilt University Institute of Imaging Science and the Vanderbilt University Medical Center Departments of Neurology and Neurological Surgery. The NIH grants involved include R01 NS110130-01 and R01 NS112252.



Members of J. Lawrence Wilson Professor of Engineering Michael King's lab. Front row, left to right: Jason Zhang, research assistant professor of biomedical engineering; Su Bin Hahn, biomedical engineering undergraduate; Nidhi Jyotsana, post-doctoral scholar and first author of the paper; Josh Greenlee, BME graduate student; and Jacob Hope, BME graduate student Back row, left to right: King; Korie Grayson, visiting Cornell University Ph.D. student; Nerymar Ortiz-Otero, visiting Cornell Ph.D. student

Escaped cancer cells killed by cellular soldiers that curtail metastasis

Surgical intervention in breast cancer is a known cause of metastatic growth and accelerated tumor relapse. Targeting tumor cells that enter the bloodstream has been difficult because they lack identifiable markers.

Michael King, J. Lawrence Wilson Professor of Engineering and chair of the biomedical engineering department, and his team found a way. The group leveraged the body's own defenses to track down and kill cancer cells escaped during surgeries. The discovery points to a promising treatment path for multiple cancers but is especially relevant in cases of triple negative breast cancer, for which surgery and chemotherapy have been the only option.

Using small doses of a specially packaged protein—one that's otherwise been difficult to administer—the researchers curtailed metastasis without side effects in mice with triple negative breast cancer whose tumors had just had been removed.

They attached two proteins to the surface of lipid nanoparticles: tumor necrosis factor-related apoptosis-inducing ligand—or TRAIL—and the adhesion receptor E-selectin. The injected nanoparticles then adhere to white blood cells. The introduction of coated leukocytes into the bloodstream before, during and after tumor removal kills all cancer cells set loose as a result.

"Collisions between the TRAIL-coated leukocytes and cancer cells in the bloodstream are happening constantly," King said. "We've tested this both in the bloodstream and in hundreds of blood samples from cancer patients being treated in clinics across the country. In all cases, within two hours the viable cancer cells are cleared out. This has worked with breast, prostate, ovarian, colorectal and lung cancer cells."

The group's past experiments with TRAIL-coated leukocytes effectively blocked metastasis but required multiple repeated injections to sustain their beneficial effect. This new breakthrough overcomes those issues by designing three simple doses to coincide with the surgical procedure, King said.

Not only can this method work during surgeries, King said, but it also has potential for patients who already suffer metastatic cancer in

Continued on next page

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multiple sites and have no other viable treatment options.

"Our study indicates that TRAIL liposomes, along or in combination with existing clinically approved therapies, may neutralize distant metastasis of a broad range of tumor types systemically," concluded post-doctoral scholar Nidhi Jyotsana and the research team.

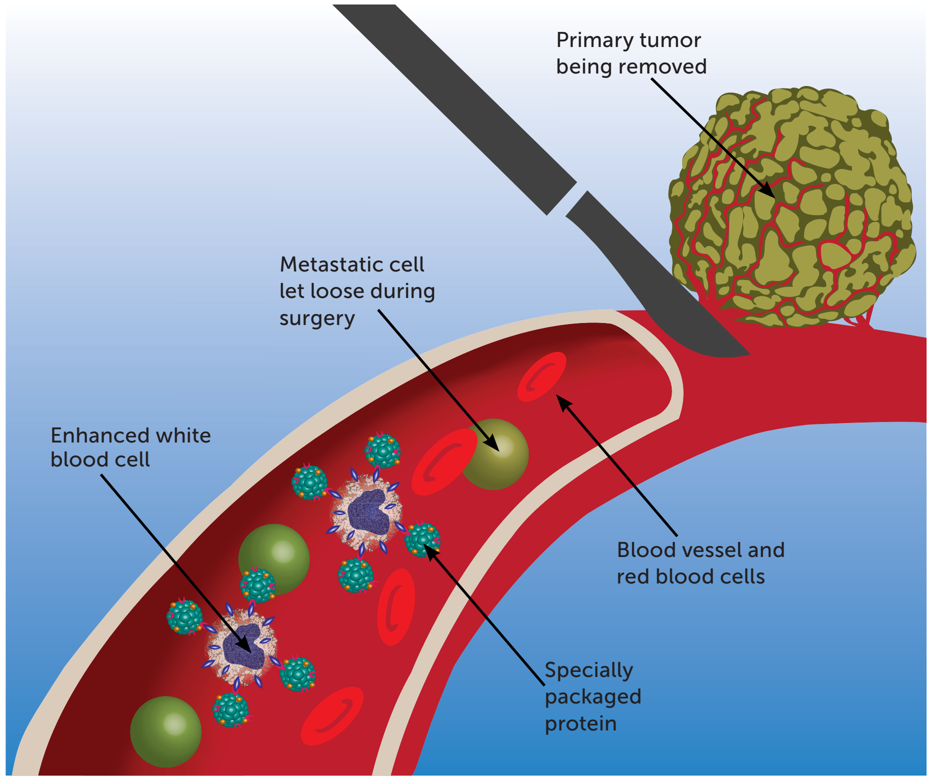
Tumor removal surgery contributes to metastasis because of cancer cells shed during the process, inflammation at the wound site or a combination of both factors. Ninety percent of all cancer-related deaths are due to metastasis, and effective treatments are among the great challenges in experimental and clinical cancer research. Chemotherapy is the most widely used treatment for the resulting metastasis, but the five-year survival rate for triple negative breast cancer sits well below 30 percent.

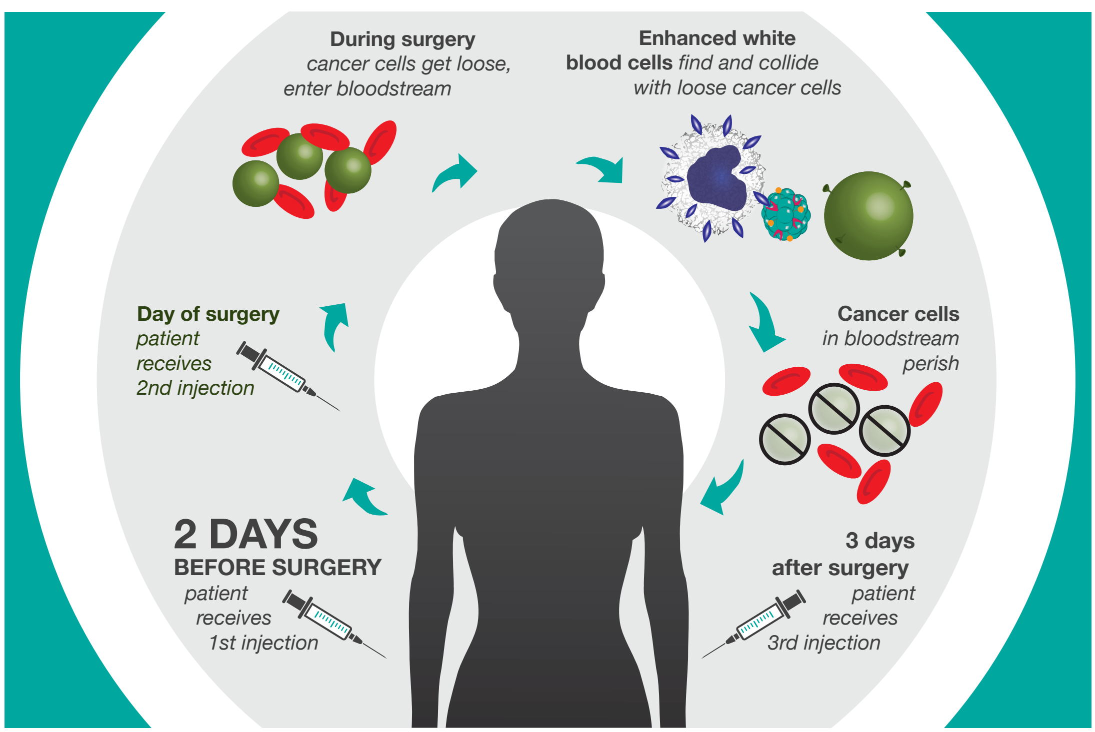
Significantly, because all the components of these "cellular soldiers" occur naturally in the body, the progression to human trials could be accelerated.

The study was published in *Science Advances* in July 2019. This work was supported by the National Institute of Health grant R01 CA203991 and the NCI/NIH Cancer Center grant 5P30 CA68485-19. V

Using small doses of a specially packaged protein, the research team curtailed metastasis without side effects in mice with triple negative breast cancer

The treatment, below, involves three timed injections before, during and after surgery.Illustrations: Pamela Saxon, Saxon Creative





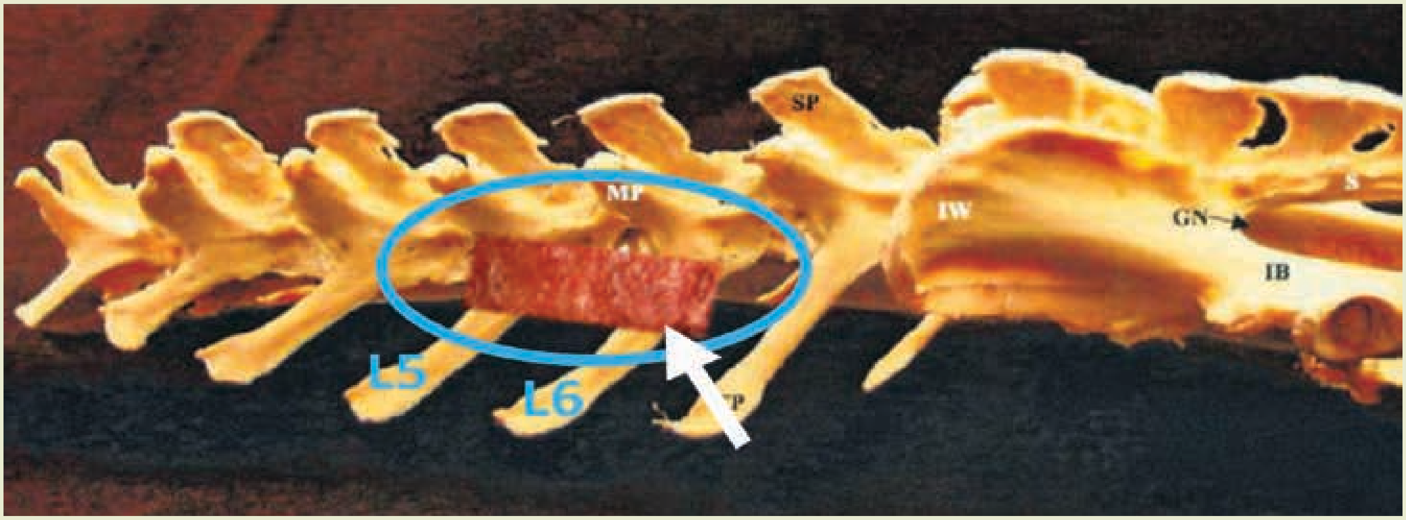


Photo: Lab of Scott Guelcher

A newly developed biomaterial-based bone extender shows great promise, particularly in cases involving critical-sized bone defects.

NEW BIOMATERIAL COULD IMPROVE BONE GRAFTING

A new biomaterial-based bone graft extender created by Vanderbilt and U.S. Army researchers has the potential to improve treatment of critical orthopedic conditions.

Researchers and surgeons seek alternatives to common bone grafting practices, which have limitations that include strength, weight and severity of the bone loss injury. More than a million bone grafting procedures are performed in the United States annually.

Scott Guelcher, professor of chemical and biomolecular engineering, working with colleagues at Vanderbilt and the U.S. Army Institute of Surgical Research in Houston, Texas, presented the findings in an article in *Tissue Engineering*.

The material, Guelcher said, "is a promising candidate for use as a settable autologous extender that can be molded to conform to the geometry of the defect and forms new bone."

The team reported the first use of PTKUR (polythioketal urethane) as an autologous graft extender with bone-like strength and handling properties comparable to ceramic bone cements. Significantly, the new material required using about half as much autograft material, which is harvested from the patient's body, than the current practice without significantly compromising bone healing.

The standard technique to repair, replace or regenerate bone tissue involves re-implanting material taken from the patient's pelvis or femur but the approach has limitations. Combining that autologous bone with bone substitutes such as ceramics and polymers maximizes the properties of the human graft while minimizing the amount of it needed to support the reconstruction.

John P. Fisher, director of the NIH Center for Engineering Complex Tissues at the University of Maryland, said the team's advancement is significant because the material "can be used to treat critical-sized bone defects that may not heal with bone cements or void fillers alone."

This work is supported by the National Institutes of Health (R01AR064772 and T32DK101003), a National Science Foundation Graduate Research Fellowship to Madison McGough (Grant No. 1445197), and the United States Army Institute of Surgical Research. V

> "The material is a promising candidate for use as a settable autologous extender that can be molded to conform to the geometry of the defect and forms new bone."
>
> **Scott Guelcher**

Simple nanofilms can add disease detection to iPhone camera

Don't tell anyone, but smart phones are not phones at all. They are handheld computers with phone apps. And GPS apps. And social media, shopping, fitness tracking, camera, banking and game apps.

Technology developed by electrical engineer Sharon Weiss, Cornelius Vanderbilt Professor of Engineering, and students in her lab may soon add quick home medical tests to the lineup. Their low-cost, porous silicon biosensor could detect drugs in the blood, proteins in the urine indicating an infection, and bacteria in water suggesting it isn't safe to drink. Add the fluid in question, snap a photo and an app analyzes structural changes in the thin films based on the molecules captured inside nanoscale pores.

Silicon chips coated in porous, nanoscale films could be used with an iPhone and future app to quickly detect infection and water potability with a drop or two of the liquid.

"The novelty lies in the simplicity of the basic idea. The only costly component is the smart phone," Weiss said.

"Most people are familiar with silicon as being the material inside your computer, but it has endless uses," she said. "With our nanoscale porous silicon, we've created these nanoscale holes that are a thousand times smaller than a strand of your hair. Those selectively capture molecules when pre-treated with the appropriate surface coating, darkening the silicon, which the app detects."

With their advanced computation capabilities, smartphones have emerged as a promising platform for point-of-care diagnosis. The School of Engineering team plans to develop an app that could handle all data processing necessary to confirm that the film simply darkened with the adding of fluid.

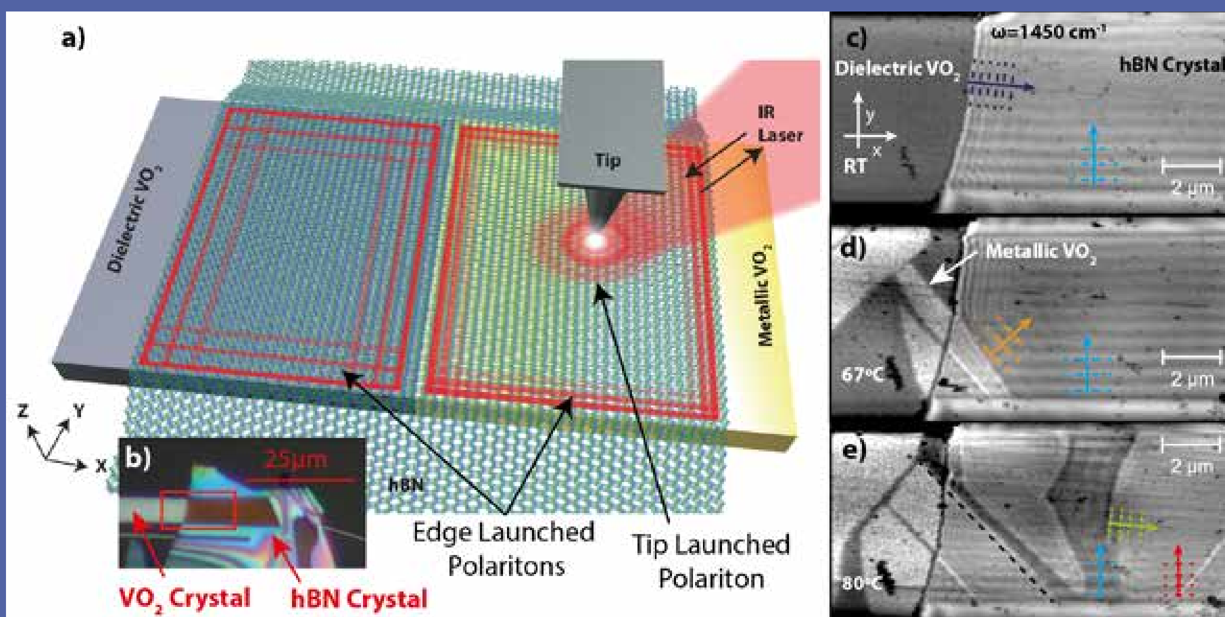
A commercialized version would significantly advance point-of-care testing in counties such as the United States, where smartphones are ubiquitous, and in global regions with little or no access to mainstream sensing technologies. Such options, including mass spectrometry, surface plasmon resonance, polymerase chain reaction and electrochemical immunoassays, require expensive instrumentation, strict sample prep procedures and well-trained personnel. Their utility for point-of-care diagnostics is extremely limited.

Weiss, Ph.D. student Tengfei Cao, and their team used a biotin-streptavidin protein assay and an iPhone SE, model A1662, to test their silicon films and found the accuracy to be similar to that of benchtop measurement systems.

Similar technology being developed relies on expensive hardware that compliments the smart phone. Instead, Weiss' system uses the phone's flash as a light source. Other home tests rely on a color change, which is a separate chemical reaction that introduces more room for error, Weiss said.

Additionally, many available portable sensing technologies, such as glucose meters and paper-based test strips, are designed for a single purpose and lack data processing capabilities for more advanced detection and analysis.

Their results were published in the August 2019 of *Analyst*, one in the Royal Society of Chemistry family of journals. This work was funded by Army Research Office grant W911NF-15-1-0176 and National Science Foundation grant DMR-1263182. **V**



MANIPULATING OPTICAL DATA TRANSMISSION AT NANOSCALE

On-chip manipulation of light at nano-length scales would transform optical data transmission, particularly in big data "farms" where thousands of computers must communicate to provide answers.

A multi-university team led by Joshua Caldwell, associate professor of mechanical engineering, studied the phase-changing capabilities of vanadium dioxide and infrared properties of hexagonal boron nitride.

Their finding that the broad gradient in the infrared optical properties of vanadium dioxide, as it transitions from insulating to metallic, holds promising implications for nanophotonics and more efficient transmission.

"By using this phase-change material, you change the local environment and, thus, wave propagation," Caldwell said. "To achieve on-chip control of light propagation, this is required, not simply modulating the light on and off."

On a chip, wiring takes up 80 percent of the real estate, said co-author Richard Haglund, Stevenson Professor of Physics.

"Wires have resistance, their transmission speed is limited and they get hot. Likewise, data lines that transmit signals using electrons have the same problem," he said. "If you could use photons to move information from Point A to Point B, you'd be making extremely high-speed data transfers without generating heat."

The research, "Reconfigurable infrared hyperbolic metasurfaces using phase change materials," was published in *Nature Communications*. It was funded by NSF grants CMMI 1538127 and 1553251 and Air Force Office of Scientific Research grant FA9559-16-1-0172.

Smart wearable running sensor research hits its stride

Numerous wearable sensors on the market want to help runners avoid over-use injuries like stress fractures by signal-ling heightened risk. Vanderbilt mechanical engineers who specialize in human motion share that goal.

New research suggests potential placement for sensors to more accurately capture the forces on the lower leg while running.

But commercially available wearables don't measure the right stuff, researchers found. In fact, the most commonly used metrics—how hard and how fast your foot hits the ground—have little or no correlation to the biggest contributors to running-related lower leg stress fractures.

The team led by Karl Zelik, assistant professor of mechanical engineering, and Emily Matijevich, an avid runner and mechanical engineering Ph.D. student in Zelik's lab, are out to develop an algorithm that could be deployed in a smart wearable running sensor. The group has filed a U.S. patent applica-tion on a new sensor fusion algorithm approach for estimating the forces on the lower leg while running.

In June 2019, Zelik and the team received additional internal funding from Vanderbilt University to continue the work. Matijevich was among four recipients of the 2019, Women in Sports Tech Fellowship and is working with Brooks Sports Inc. in Seattle this fall to explore other applications of wearable sensors for runners.

Her recent research uses 13 different metrics from three potential sensors on the lower leg and shoe to predict forces on the lower leg bone and has attracted significant industry and academic interest. Her presentation at the industry-heavy 2019 Footwear Biomechanics Symposium won the Best Methods award. She presented the same work at the 2019 International Society of Biomechanics conference.

Research is a marathon, not a sprint. This larger investi-gation began two years ago when a VUMC-based orthopedic specialist who advises the NFL Players Association asked Zelik what, on the surface, seemed a simple question: Could wearable sensors be used to prevent stress fractures he saw in clinic visits every day?

> "A major challenge is how to use wearable sensor signals to monitor the dynamics of structures *inside* the body."
>
> **Emily Matijevich**

Working with a local running club, the team discovered that sensors measuring only the impact of the foot hitting pavement —which is what many commercially available devices do—tell users little about the forces on the lower leg bone that contrib-ute to stress fracture risks. The research confirmed that the vast majority of force on the bone is actually from muscles contracting, not from the foot's impact on the ground, a finding widely overlooked by both the wearables industry and many scientific studies.

"We looked through the recent scientific literature and we found that more than 50 scientific publications each year report or interpret their results based on this incorrect assumption that the force between the foot and the ground is representative of internal structure loading—the stress on bones and muscles inside the body," said Zelik, a former college track and field standout. "Measuring how hard your foot hits the ground may be convenient, but it's the wrong signal."

Emily Matijevich

Their study was published in the peer-reviewed journal *PLOS One* in January 2019. Newer work digs deeper into body mechanics and potential sensor placement, with significant findings.

"A major challenge is how to use wearable sensor signals to monitor the dynamics of structures *inside* the body," Matijevich said.

The team explored two new approaches for estimating the force on the lower leg bone with wearable sensors. First, they took a physics-based approach by using sensors to monitor the motion of the body and the forces under the foot to then use a lower limb musculoskeletal model. Second, they examined machine learning techniques to use features of wearable sensor signals to estimate the force of the lower leg bone, an analysis done in collaboration with Peter Volgyesi of the Vanderbilt Institute for Software Integrated Systems. The machine learning model ranked which potential wearable features were most important in predicting the forces on the lower leg bone. Of the 13 measurements, the most important were (1) peak force between the foot and the ground, (2) the center of pressure under the foot, and (3) the orientation of the foot.

"These models used simulated wearable signals from sensors already being used in commercial running wearables," Matijevich said. "The sensor hardware exists, but the solution may lie in creative sensor fusion algorithms." V

NEW UNPOWERED, LIGHTWEIGHT ANKLE EXOSKELETON FITS UNDER CLOTHES

A new lightweight, low-profile and inexpensive ankle exoskeleton could be widely used among elderly people, those with impaired lower-leg muscle strength and workers whose jobs require substantial walking or running.

Developed by Vanderbilt mechanical engineers, the device is believed to be the first ankle exoskeleton that could be worn under clothes without restricting motion. It does not require additional components such as batteries or actuators carried on the back or waist.

"We've shown how an unpowered ankle exoskeleton could be redesigned to fit under clothing and inside/under shoes so it more seamlessly integrates into daily life," said Matt Yandell, PhD'19, and lead author of the study, published online in March 2019 by *IEEE Transactions on Neural Systems & Rehabilitation Engineering*.

Photo: Lab of Karl Zelik

The significant design advancement is an unpowered friction clutch mechanism that fits under the foot or shoe and is no thicker than a typical shoe insole. The complete device, which includes a soft shank sleeve and assistive spring, weighs just over one pound. It also naturally adapts to different walking speeds to assist the ankle muscles.

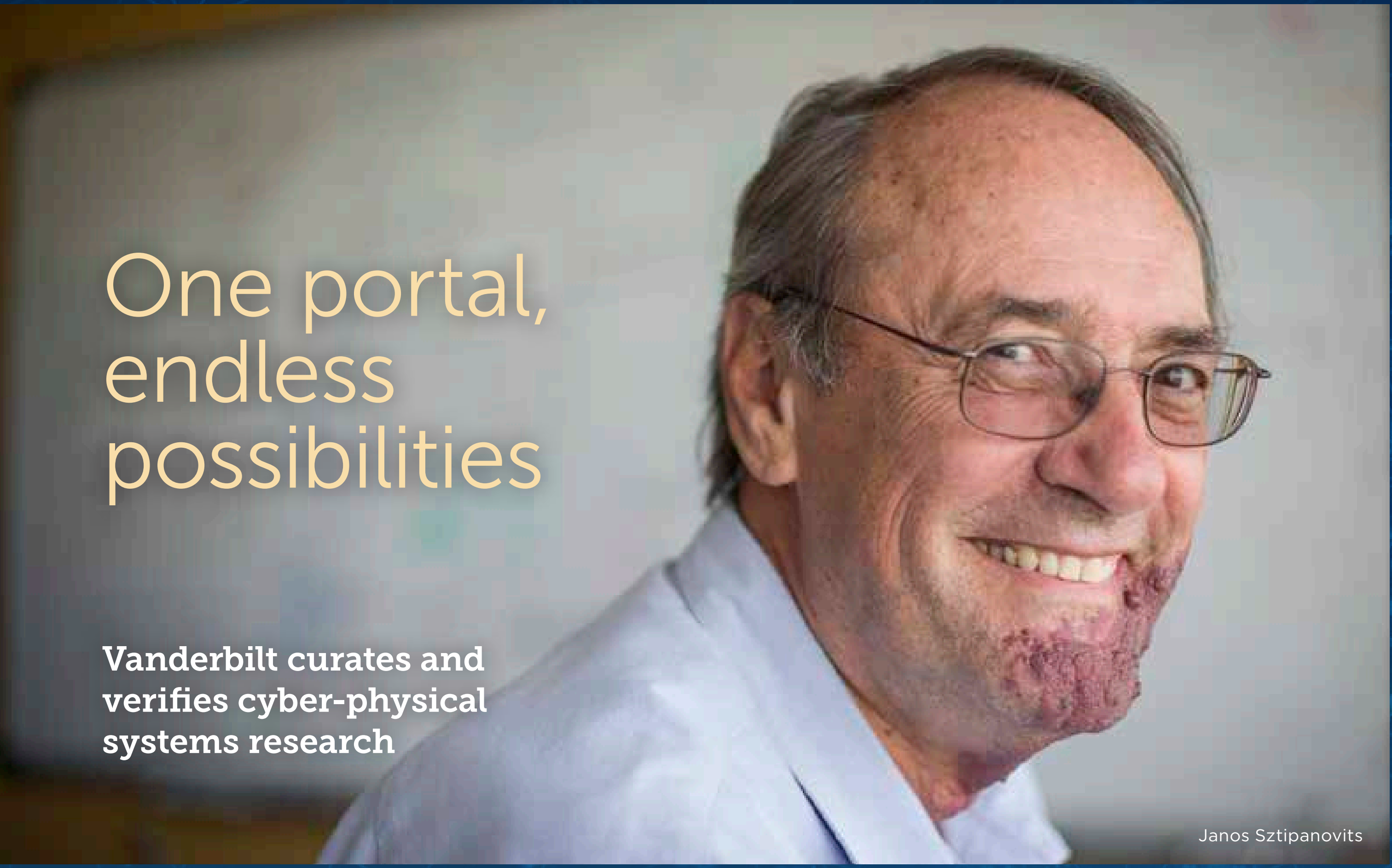
The unit costs less than $100 to fabricate, without factoring in optimized design for manufacturing and economies of scale.

The potential applications are broad, from helping aging people stay active to assisting recreational walkers, hikers or runners, said Karl Zelik, assistant professor of mechanical engineering and senior author of the study.

"It could also help reduce fatigue in occupations that involve lots of walking, such as postal and warehouse workers, and soldiers in the field," Zelik said.

The research, to which several undergraduate engineering students contributed to device design and testing, was funded by the National Institutes of Health (K12HD073945) and institutional support from Vanderbilt University.

Above, a new prototype device is believed to be the first ankle exoskeleton that can be worn under clothes without restricting motion.



One portal, endless possibilities

Vanderbilt curates and verifies cyber-physical systems research

Janos Sztipanovits

By 2025, industry experts predict there will be more than 64 billion Internet of Things devices worldwide. Nearly 130 new ones connect to the Internet every second. The average consumer owns at least four, from GPS-enabled cars to fitness trackers to home electronics and, of course, smart phones.

Connections between the "cyber" and physical worlds are transforming the economy at a breathtaking pace. The new reality is exciting—an emerging world that can make life safer, energy-efficient and more convenient—and unnerving. An estimated 84 percent of organizations that use this technology have experienced a related security breach.

Long an international powerhouse in CPS, Vanderbilt's Institute for Software Integrated Systems is on the forefront of improving the connections between humans, computers and the physical world. With a $5.6 million NSF grant, the institute has unveiled the latest version of a virtual repository of vetted research results, software, data, design studios and other tools.

Called the Cyber-Physical Systems Virtual Organization Portal, this one-stop shop for computer scientists around the globe is created and curated by researchers at Vanderbilt, Arizona State University, University of Pennsylvania, UCLA and University of Arizona. The goal is improving the impact of research by ensuring that these artifacts can easily be found, reproduced and transitioned after the projects are completed.

BY THE NUMBERS

84% of organizations with IoT tech have experienced a related security breach

$158B

estimated size of global health care IoT market by 2022

$45B

estimated size of global manu-facturing IoT market by 2022

> In today's increasingly networked, distributed, and asynchronous world, cybersecurity involves hardware, software, networks, data, people, and integration with the physical world. Society's overwhelming reliance on this complex cyberspace, however, has exposed its fragility and vulnerabilities that defy existing cyber-defense measures: corporations, agencies, national infrastructure and individuals continue to suffer cyber-attacks.
>
> **National Science Foundation**

"Universities have an incentive structure that rewards the publication of papers, but agencies funding the research are accountable for something more—showing the impact of the result of an investment," said Janos Sztipanovits, the software institute's director and E. Bronson Ingram Professor of Engineering.

"They need evidence of results that can be reproduced, transitioned and used to build on science, technology and even industrial applications. This is particularly important in cyber-physical systems research that creates new foundations for developing new generations of engineered systems," Sztipanovits said.

Though closely related, IoT and CPS are not interchangeable. Cyber-physical systems enable the Internet of Things.

Vanderbilt launched the CPS-VO in 2010 to create a collaboration platform for researchers and to establish a comprehensive information repository for the then-emerging field of cyber-physical systems. By 2014, the NSF wanted to expand the project to capture and provide access to research artifacts that could be shared among researchers—eliminating the need to reinvent solutions that already worked. A $9 million, five-year NSF grant directed Vanderbilt and collaborating universities to help determine the most efficient approach to designing and operating cyber-physical systems that support national health, energy and transportation priorities.

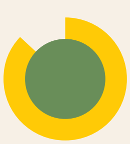
CPS-VO Portal has been so successful, in fact, the model was adopted and co-funded by the National Security Agency's Science of Security program and the NSF's Secure and Trustworthy Cyberspace program.

The newest version of CPS-VO features tools and design studios that researchers and practitioners can access and explore via web interfaces. Each time someone archives a tool in the shareable archives, the CPS-VO staff verifies that it meets quality criteria and remains operational for exploring its capabilities by potential users. Sztipanovits and his team demonstrated the platform's capabilities at the NSF Cyber Physical Systems Principal Investigators Meeting in November 2018.

Vanderbilt faculty, research scientists and Ph.D. graduates created all seven available design studios. One of the authors, William Emfinger, BE'11, PhD'15, is director of R&D at Permobil and an adjunct assistant professor of mechanical engineering. He's also an adviser to the Vanderbilt Aerospace Design Lab.

For the upcoming NSF Cyber Physical Systems meeting in Alexandria, Virginia, Sztipanovits is the organizer for a tutorial on publishing tools and design studios available on the CPS-VO Portal.

"This platform raises the expectation that, if you make commitments for disseminating results in your grant proposal, you can indeed accomplish it," Sztipanovits said. "By removing the technical barriers for disseminating and making results, tools and design studios accessible, researchers can have much greater success in achieving tangible impact with their work. We're in the process of changing a culture." V



87% of health care organizations expected to use IoT tech by 2019

127
new IoT devices every second in 2019

64B
IoT devices expected worldwide by 2025

$104B
estimated size of global automotive IoT market by 2023

FUZZING CPS DEVELOPMENT TOOLS

Fuzz testing, or "fuzzing," is a standard testing approach for most commercial-grade software that provides random inputs in an attempt to identify defects. Cyber-physical system design tools, however, need more sophisticated scrutiny because they already have been extensively tested.

They require advanced fuzzing.

Cyber-physical systems are everywhere. Tech-rich cars, for instance, are computers on wheels that balance advanced sensors and batteries, user interfaces and connectivity, and self-driving capability improvements.

Taylor Johnson is tackling fundamental problems facing engineers who rely on complex software tools to design this interplay, which also takes place in airplanes, medical devices and scores of other high-tech products.

"First, there is little systematic knowledge of the design tools and the resulting designs aren't readily available to guide engineers. Second, complex design tools contain software bugs and these bugs may silently introduce bugs into widely deployed safety-critical systems," said Johnson, assistant professor of computer engineering, computer science and electrical engineering. "Bugs in such systems often lead to costly recalls and may have serious consequences."

As part of a three-year, NSF-funded project that begins in October, Johnson, with collaborator Christoph Csallner at the University of Texas at Arlington, will build the largest curated collection of publicly available cyber-physical system models and related artifacts.

"There isn't much information about how basic design properties like various size measures relate to design quality attributes like comprehensibility, which is the ability to understand all the relevant aspects of the design process," Johnson said.

Johnson also will use the collection as a basis to develop fuzzing techniques in a deep learning framework to automatically find software bugs in such design. The curated collection of CPS design models and artifacts will optimize the random search toward models likely to generate bugs based on prior experience.

This project builds on a related NSF project in which Johnson developed similar testing methods. That work, presented at the 2018 ACM International Conference on Software Engineering, found dozens of confirmed code-generation bugs in commercial design tools.

To address the chronic problem of incomplete formal specifications of cyber-physical system tool chains, Johnson also will design a novel scheme to infer the CPS language validity rules via deep learning from the collected models. Initial experiments have found several bugs in a commercial CPS tool chains confirmed by the tool chain vendor.

The new project is funded by NSF Award 1910017 from the Division of Computing and Communication Foundations. V

Vanderbilt partners with major players in advanced nuclear reactor research

Retro is hot as well as cool in more than mid-century modern furniture and bold fashion choices. In U.S. advanced nuclear energy research, molten salt reactor technology, started at Oak Ridge National Laboratory in the 1960s, is back in fashion.

In partnerships with top industry players and national labs, the School of Engineering is among the trendsetters. Vanderbilt's experts in nuclear environmental engineering are involved with multiple projects to diversify the country's energy mix, boost energy security and reduce carbon emissions by safely adding advanced reactor technology.

One massive project is assessing the commercial viability of a molten chloride fast reactor, and preliminary fuel loop testing began last summer. The five-year, $40 million Department of Energy effort includes Vanderbilt; Southern Company, a U.S. leading energy provider based in Atlanta, Georgia; TerraPower, an advanced energy company founded by Bill Gates; Oak Ridge National Laboratory; Idaho National Laboratory; and the Electric Power Research Institute.

TerraPower announced in August 2019 it had successfully completed 1,000 hours of continuous operation on a test loop that will examine how molten salts would affect other components as they move through a reactor. Construction has begun on a full-scale test platform in Everett, Washington, to validate thermal hydraulics and safety analysis codes. That step is needed before seeking a license for a demonstration reactor.

A molten chloride fast reactor, or MCFR, has significant advantages over U.S. nuclear reactors now in operation, which use solid fuel and water at extreme pressure to cool the reactor core. MCFRs use liquid salts as both a coolant and fuel, said Steven Krahn, professor of the practice of environmental engineering

"You don't need a rigid core and solid fuel. These reactors provide more efficient power production and use less complex nuclear reactor systems than heavy water reactors, which require core walls of eight inches thick to keep the water from boiling," Krahn said. "With molten salts you can take it to high temperatures without high pressures."

The fuel cycle is a major factor driving interest in MCFRs. The molten salts remain in the system for reuse, generating only a small amount of radioactive material that must be removed and cleaned. The reduction in nuclear waste compared with existing reactors is substantial, and such reactors can use multiple fuels, including spent fuel as well as depleted and natural uranium.

Krahn and multiple Vanderbilt doctoral students in environmental engineering have been deeply involved in much of the foundational research. In a four-year project with EPRI, Vanderbilt evaluated the safety, health and environmental impacts of advanced reactor concepts and their readiness to use in the nuclear fuel cycle. The project included safety training protocols.

In partnership with ORNL, they've completed an assessment of a thorium fuel cycle through DOE's Nuclear Energy University Program. A risk

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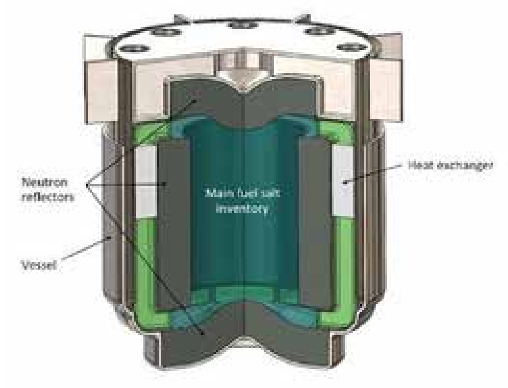

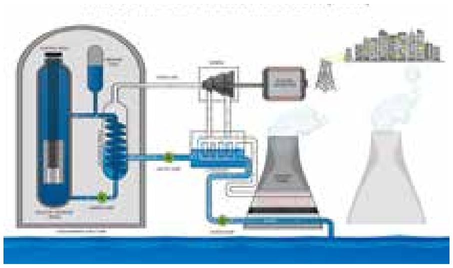

Molten chloride fast reactors (top) have significant advantages over pressurized water reactors (bottom) now in operation, including less complex design, less nuclear waste and reusable fuel. Illustrations: Department of Energy

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assessment of an off-gas system for a molten salt reactor won Ph.D. student Brandon Chisholm first place in energy policy in DOE's 2018 Innovations in Nuclear Technology Research and Development competition.

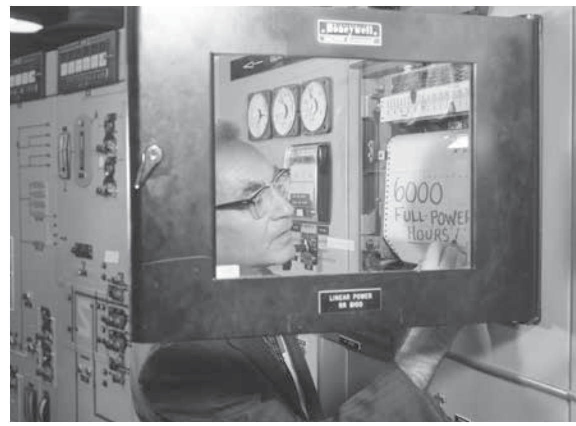
In June 2019, Vanderbilt received another DOE NEUP grant to develop an advanced sampling/enriching system for modern molten salt reactors. Collaborators on the $800,000 project include Idaho National Laboratory, the University of Michigan and Southern Company.

Researchers at Vanderbilt, however, will handle the design, prototype and hot salt testing phases in a non-radioactive environment. The university's Laboratory for Systems Integrity and Reliability, which supports full-scale test beds, will be the proving ground for creating and scaling the technology.

They will combine insights from the Molten Salt Reactor Experiment in the 1960s with decades of technological progress in designing a tested and optimized concept. Although ORNL's experiment was successful in removing small samples of fuel salt for testing and had important flexibility, the sampling system was not consistently reliable. Problems with it required the entire MSRE to be shut down twice.

"New nuclear" is informed by advancements in materials science and system design, research on the complex interplay among components and materials they hold, thorough understanding of fuel cycle and waste issues, and more rigorous regulatory review.

"Advanced nuclear reactor designs have the potential to be among the safest and most efficient options to produce clean electricity," Chisholm said.



ORNL's Molten Salt Reactor Experiment in the 1960s provides a starting point for creating an updated system for sampling radioactive salts. Above, a technician at ORNL prepares salts for use in MSRE in 1964. Right, ORNL Director Alvin Weinberg marks 6,000 full power hours of MSRE operation. Photos: Oak Ridge National Laboratory.

NEW DESIGNS, NOT MATERIALS, WILL IMPROVE SOLAR THERMAL DESALINATION EFFICIENCY

Growing interest in powering water desalination systems with solar energy has produced a bounty of research on high-performance materials to achieve greater efficiencies. But the materials in these systems already absorb 90 percent or more of the sun's thermal energy, so incremental improvements don't advance the needle much.

Even if they do, the systems cannot compete on a large scale with reverse-osmosis desalination installations powered by solar panels, widely used in countries, regions and industries that can afford the technology and maintenance costs. For remote and under-developed areas, however, solar-thermal desalination remains an attractive option because the capital and maintenance costs are significantly lower.

A multidisciplinary, multi-university team whose leaders include a Vanderbilt engineer believes more efficient systems are possible—but only if the focus shifts. Better system design, not advanced and often more costly materials, is the path to higher returns on solar-thermal desalination installations, the researchers concluded.

For the first time, they proposed a simple yet universal formula, or governing equation, for evaluating the efficiency of such systems, which can be as small as those generating water for an individual household or supplying water to small communities in remote regions, said Shihong Lin, assistant professor of civil and environmental engineering and a primary author.

"To look at the bigger picture you need people from different fields," he said.

Lin and Menachem Elimelech, Roberto C. Goizueta Professor of Chemical and Environmental Engineering at Yale University and a global expert on advanced methods for water treatment, led the team.

Their work, published in July 2019 in *Science Advances*, provides a new, uniform framework for evaluating and optimizing solar-thermal desalination design. The team included civil, mechanical, chemical and environmental engineers from Vanderbilt, Yale, Columbia University and the University of Colorado.

The metric is specific water productivity, defined as the volume of water produced per solar radiation area per time. The group's formula accounts for solar irradiance, latent heat of evaporation and the gained output ratio, or kilogram of distilled water produced per kilogram of vapor. How much latent heat of condensation is reused for distilling additional water is a major factor in system efficiency and often overlooked, the researchers said. **V**

Data, partnership, teamwork drive Nashville's connected city progress

It takes more than a village to make the potential of a smart, connected city take shape. The daunting transformation needs experts in computer science, transportation and civil engineering, committed community partners and a whole lot of computational power.

Nashville's rapid growth and growing pains make Music City an ideal test bed for what a smart city can be. The School of Engineering's work with Nashville and regional agencies covers a good deal of ground, involving faculty and scholars from the Vanderbilt Initiative for Smart City Operations and Research, Vanderbilt Center for Transportation and Operational Resiliency, Institute for Software Integrated Systems, Data Science Institute, and Vanderbilt Center for Environmental Management Studies.

"Our team—faculty, students and stakeholders from the partner communities—explores how emerging technical capabilities of the Internet of Things and advances in data sciences and cyber-physical systems can inform, and be informed by, the social sciences to address critical problems around energy, water, transportation and emergency services," said Abhishek Dubey, senior research scientist at the Institute for Software Integrated Systems and assistant professor of computer science and computer engineering.

Projects include prediction and planning for fire and emergency medical services incidents, a close look at vehicle and pedestrian patterns in the thriving Gulch neighborhood, incentivizing mass transit use, and monitor-

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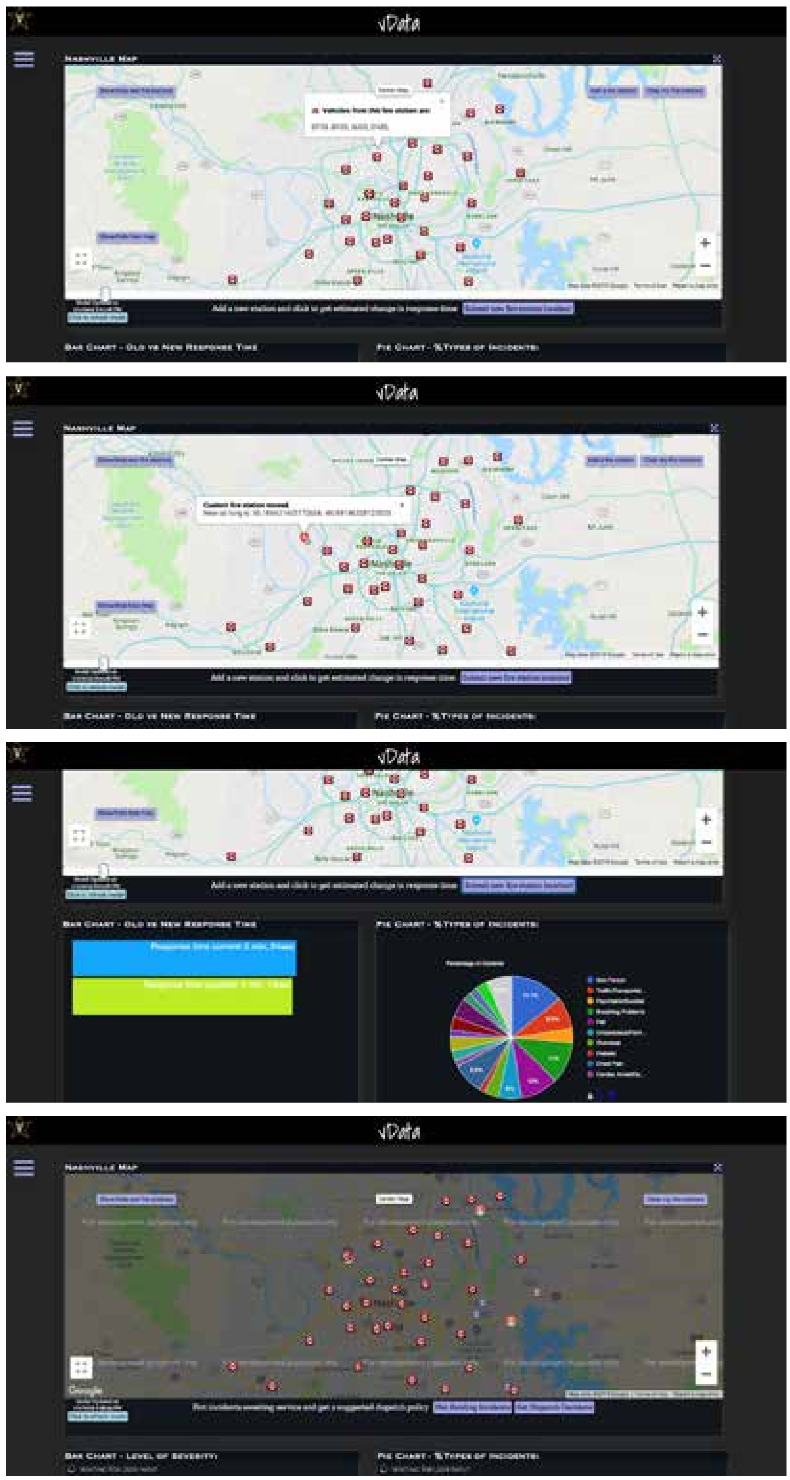

Top to bottom: The prediction and planning tool allows managers to show locations of existing Nashville fire stations and the vehicles assigned to each; add a hypothetical new fire stations and relocate it for different simulations; compare response times with and without the hypothetical new station; and produce a suggested dispatch plan. The simulations are based on three years of historical data and can predict likely location and severity of incidents on a future date.

Images: Courtesy of VISOR

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Data-driven smart city projects with Nashville include sensor arrays that capture air quality and multi-modal transportation details, fire and emergency response incident prediction and planning, and street and sidewalk use in the booming downtown Gulch area. Photos: Vanderbilt, Nashville Fire Department, Explore the Gulch

ing air quality along with scooter, bicycle, automobile and pedestrian traffic on and around the Vanderbilt campus.

Major grants from the National Science Foundation and the Department of Energy are involved, with Tennessee Department of Transportation and Vanderbilt matches for some projects.

Building a foundation for smart city operations with tools and platforms other cities can use is a key goal of this work. Dubey already has fielded inquiries from several cities about the demo dashboard for fire and EMS simulation and planning that Nashville has been evaluating.

Working with the Nashville Fire Department and Davidson County Information Technology Services, that team analyzed more than three years of NFD data for location, time and type of incidents that included motor vehicle accidents, fires and fire alarms and ambulance calls along with the response times for the emergency vehicles dispatched. Data also included incident severity and clearance time. Additionally, the team integrated factors such as traffic congestion, weather, road characteristics and pedestrian traffic.

"The idea is to move to a proactive rather than reactive emergency response strategy," Dubey said.

The researchers developed models for the city that predicted with high accuracy when and where accidents will happen. They found, in effect, a vortex problem, said Geoffrey Pettet, a Ph.D. student working with Dubey.

"A lot of hospitals are clustered near downtown," Pettet said. "Many of the incidents occur there, too, and when an ambulance is dispatched to an outlying neighborhood they'll take patients to the nearest hospital but then be sent back downtown."

The biggest factor contributing to increased incidents was not weather or traffic—it was the occurrence of other incidents nearby, which creates a cascade effect.

> "Most hospitals are clustered near downtown, which is also where many of the incidents occur. So when ambulances stationed in outlying areas take patients to a hospital, they are often dispatched to incidents downtown once they become available, never making it back to their station."
>
> **Geoffrey Pettet**

The team delivered a set of prototype, open-source tools. Managers can see likely incident distribution across different times. Another feature allows users to add, remove and relocate first-response stations and vehicles around the county to see the effect on response times.

"For me, one of the big takeaways is that when operationalized, even in an experimental phase, this gives the Fire Department the data to help justify the need for new stations," said Colleen Herndon, Metro's ITS project manager. "That is a deeper level of information than they have today. That in itself is a benefit and that is the starting point."

The city already is looking at applying the model to other Metro departments. "Any time we have a tool to make city resources more efficient it is a plus," Herndon said.

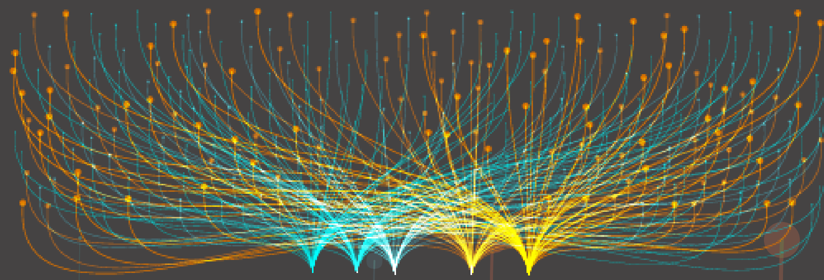
The broader research community also has taken note. "There is a lot of interest in the theoretical validity," Pettet said. "This kind of look-ahead approach hasn't been done before."

That foundation has broad application to any resource allocation problem with spatial and temporal elements. For cities, that includes services such as public works, road configuration, housing distribution and transit planning.

In Nashville's dynamic downtown Gulch area, a pilot project captured two months of data at two intersections for a longer-term study to guide city planners. This data can help inform street layout, use of curb space, number and location of pedestrian crossings, parking utilization and bicycle lanes.

Connected Nashville: A Vision for a Smarter City accelerated the collaboration. Connected Nashville represents, for the first time, publicly reviewed, tech-oriented strategies for Metro Government to follow as it addresses stated priorities, including setting security and privacy standards. Dubey served as the technical standards committee co-chair.

"We had lots of discussion, not only on what kind of technologies were available, but how they could be used to solve old problems in new ways," Herndon said. "We view security and privacy as fundamental requirements for any smart city technology, so having Vanderbilt's expertise in compiling our technical standards was huge." **V**



BIG DATA REAPS BIG PAYOFFS

Some experts define Big Data by petabytes or exabytes of information from multiple different sources, in different formats, structured and unstructured. A less technical definition is a large amount of data that can't be processed using traditional database and software techniques.

Even more basic—if the data breaks or freezes your spreadsheet program, it's big.

What it is, however, is less important than what it does. Big data and data science are transforming our understanding across disciplines of all kinds, inside and outside the School of Engineering.

Some examples of current trans-institutional projects with the Data Science Institute and Vanderbilt Research IT Service:

- Applying state-of-the-art AI-based natural language processing to tens of thousands of legal filings in class action lawsuits. A Vanderbilt Law School professor then wants to classify and explore these documents. The technology may lead to a new approach to legal discovery in court cases.
- Creating a new platform that will allow researchers across the Americas to answer questions on changing opinions and attitudes across countries and over time since 2006. Vanderbilt hosts the Latin American Public Opinion Project, which collects survey data on opinions, democratic values and behaviors in 22 countries.
- Predicting the mobility and satisfaction of patients one and two years after spinal surgery. The DSI is providing training and support to spine surgery resident at VUMC who will apply machine learning algorithms that allow him to provide robust guidance to patients contemplating surgery.

The Data Science Institute last summer hosted its first cohort of undergraduate research fellows. Their projects included work with faculty sponsors on developing an intermediate approach to sampling brain networks with complicated constraints; investigating whether consistent social support can be used to predict risk for metabolic syndrome; and using data science to create models of gene expression networks.

Other undergraduates worked to characterize Alzheimer's disease by selecting and generating the most descriptive biomarkers and looking at potential associations with clinical outcomes. Another project investigated the ethical connections between corporate marketing and political campaign propaganda, individual social networks and voting decisions, and the design and modification of tech company algorithms to boost financial gains.

LiDAR data and computational science improve levee failure predictions

By late May 2019 flooding in at least eight states along the Mississippi River was the longest-lasting since the Great Flood of 1927. Record rains and high runoff from melting snow pushed rivers higher and faster, topping and breaching levees along the Missouri River and its tributaries in Nebraska, Missouri, South Dakota, Iowa and Kansas.

One estimate–as of April 2019–was $12.5 billion in damages to homes, businesses, crops, livestock and drinking water contamination, among others. That early figure does not include the costs of shipping diversions, which continue to rise.

The U.S. flood protection infrastructure is in poor shape. Nearly 50 percent of the nation's population lives in areas protected by earthen or concrete levees, walls and dams, their vulnerability highlighted with each extreme weather event.

So how to know when and which infrastructure needs maintenance and manage resources? How best to prioritize decisions and, for example, retrofit infrastructure in critical condition first to avoid failures and their devastating consequences?

Vanderbilt engineers have one answer—a fully integrated cyber-physical system strategy to monitor the health of flood protection infrastructure and provide detailed information on which decision-makers can act.

Çağlar Oskay, professor of civil and environmental engineering, leads this ambitious and interdisciplinary effort. The Vanderbilt Initiative for Intelligent Resilient Infrastructure Systems includes faculty with expertise in computational mechanics, computer science, field and remote sensing, big data, decision-making and transportation systems networks.

A high-end UAV equipped with

Above, The Army Corps of Engineers works to control seepage and resulting sand boils under the Mississippi River mainline levee near Memphis, Tennessee, in February 2019. *Photo: Army Corps of Engineers, Memphis Division.*

Left, Internal erosion failure at Tunbridge Dam in Tasmania, Australia, illustrates on a large scale the result of piping. *Photo: International Information Center for Geotechnical Engineers*

> "Nearly 50 percent of the nation's population lives in areas protected by earthen or concrete levees, walls and dams, their vulnerability highlighted with each extreme weather event."

a LiDAR sensor has captured data down to an inch along sections of the Cumberland River in Nashville. The equipment maps the earthen levee and also detects unusual geometries, including wet spots and sand boils that indicate internal erosion. Internal erosion is an especially insidious cause of failure because it is difficult to see and has been hard to predict.

Until now. Using physical modeling, system response at different scales and advanced simulations, the team validated the effects of backward erosion piping along 29 miles of the Cumberland River levee. Backward erosion piping typically begins when a tree or watercraft strikes the levee or nearby infrastructure maintenance disrupts levee stability. Backward erosion piping has caused one third of all piping-related levee failures in the last 100 years.

The simulations used three scenarios of varied severity and ran for a year to predict the progression of internal erosion that considered seasonal changes. "The novelty of the proposed methodology is its capability of real-time predictions of the overall response at the system scale," the researchers said.

"With this information, it will be possible to identify critical zones susceptible to localized damage that are more likely to fail in the event of a natural hazard," Oskay said.

Additional field campaigns are exploring how the combination of tools can be scaled. Potential human casualties, physical damage, community disruption and regional, national and international impacts are factored into disruptive scenario models as well. The U.S. Army Corps of Engineers controls only 15 percent of the country's levees, and state, county and community agencies oversee the bulk of them.

"We want to rely on simulations to tell us where stakeholders should retrofit the most vulnerable areas with the limited resources they have," Oskay said. "We hope this approach will help them make more informed decisions." V

EARLY WARNING SYSTEM FOR NUCLEAR POWER PLANT PIPES

A failing pipe can be tough to spot. It may cause a puddle, produce another sign of damage, or simply burst before detection. A flooded kitchen or laundry room is messy and inconvenient, but the stakes are much, much higher in nuclear power plants—which on average contain many miles of pipeline.

As concern about aging plants escalates, Vanderbilt engineers are working on technology to act as an early warning system, using polymer coatings on the inside of the pipe and 3D-printed polymer devices infused with nanoparticles as sensors to signal the changes on the outside of the pipe. And they hope, sound.

A huge challenge is to detect the changes in the polymer film occurring inside the pipe. To create a useful and proactive technique, the team wants to use sound, or vibrometry, to identify these internal changes from outside the pipe.

"We are designing and preparing coatings that can grab or chelate metal ions released from the corrosion process within a pipe," said Kane Jennings, professor and chair of chemical and biomolecular engineering. "The films can chelate metal ions in solution and from a corroding surface. The chelated metals change the properties of the polymer films to effectively cross-link the polymer chains."

Early results are promising. Vibrometry does show slight changes when the metals are bound to the coating, Jennings said, and ongoing research is evaluating reliability at different coating thickness. The sensor for the outside of the pipe works—the coating changes from green to blue on a change in input that could signal the corrosion process.

"Ultimately the sensor would need to interface with the vibrometry to provide a stop/go color signal on the health inside of the pipe," he said.

An Electric Power Research Institute study that reviewed pipe safety at U.S nuclear power stations over a 36-year period found 1,816 pipe failures that were identified by testing and inspection. Another 2,247 failures were found after pipes had leaked, and in some cases, causing worker fatalities.

Pipelines in nuclear power plants transport "cooling" water, which is near boiling, to the reactor and to spent fuel pools. Pipes supply hydrogen gas to generators and transport steam to the main turbine, among many other functions. The idea would be to start by coating cooling pipe junctions and connections.

Research has involved faculty and graduate students in chemical, mechanical and civil engineering. Cole Brubaker, PhD'18, developed the sensors using metal-doped zinc sulfide phosphor materials. "3D-printed alternating current electroluminescent devices" was published in the *Journal of Materials Chemistry* in May 2019. Doug Adams, Daniel F. Flowers Professor and chair of civil and environmental engineering, was the principal investigator. Jennings is the principal investigator on a paper that confirms the foundational chemistry published in September 2019 in the *Journal of Physical Chemistry*. Idaho National Laboratory and University of Notre Dame are also collaborators on the research.

The work is supported by the Department of Energy's Nuclear Energy Enabling Technologies program, grant DE-NE 0008712. V

Robot prototype shows promise for microsurgies on eyes and aneurysms

Nabil Simaan

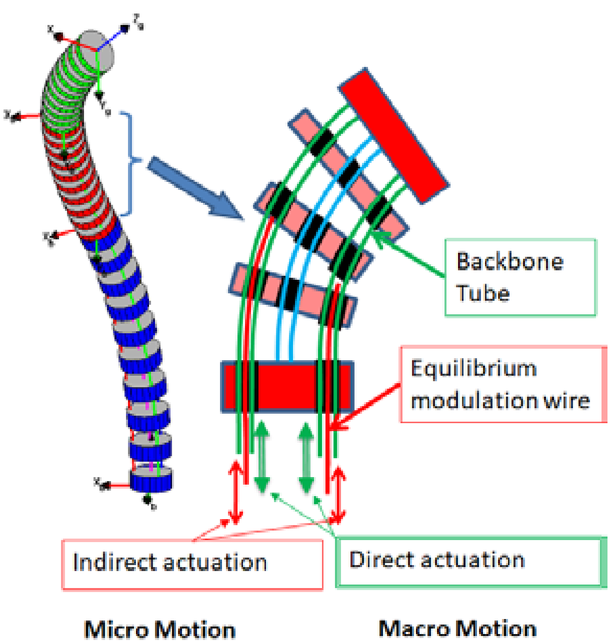
A new continuum robot designed by Vanderbilt engineers achieves motion resolutions of 1 micron or less and may open up a huge world of previously impossible complex microsurgeries.

For a sense of scale, an inch contains 25,400 microns. A human red blood cell is about five microns wide, the same size as some bacteria and significantly smaller than the width of the average human hair.

"Our design achieves motion resolutions of 1 micron or less by using inexpensive actuators. This reconfiguration—with minimal added cost—could accelerate the development of a new class of surgical robots capable of both macro-motion for surgical intervention and micro-scale motion for cellular-level imaging or intervention," said Nabil Simaan, professor of mechanical engineering.

"This greatly expands the capabilities of robotics in minimally invasive surgery," he said.

The miniaturization and range of motion would allow precise control during procedures on complex aneurysms, tiny veins and arteries, nerves and the delicate structures of the eye, the inner ear and the vocal cords.



Potential applications include biopsies, tumor eradication and targeted drug delivery at the cellular level.

Simaan and his team have adapted the flexible architecture of his previous continuum robot to perform at the macro and micro scale by altering the equilibrium pose of the robot, which Simaan calls continuum robots with equilibrium modulation, or CREM.

The flexible architecture of previous continuum robots achieved a worm-like motion for macro-manipulation. The robot is segmented with plates or rings like the body of an earthworm. Each plate is joined together by tiny backbones, or actuation tubes. By adding small elastic wires inside the actuation tubes and moving wires up or down, the static equilibrium of the plates changes, creating motion at the micrometer scale.

"This new class of robots will provide micro-precision while traversing macroscale sinuous pathways to the operation site.

Continued on next page

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Potential benefits include exact tissue reconstruction and complete surgical eradication of tumors," said Simaan, an affiliate of the Vanderbilt Institute for Surgery and Engineering.

The robot uses tubular secondary backbones to achieve the large scale of motion. By pushing and pulling on them, the continuum robot configuration changes. The addition of wires that can slide in and out of the tubular backbones enabled the research team to modulate the equilibrium shape.

Additionally, extensive testing is underway for the incorporation of optical coherence tomography, which is effectively "optical ultrasound" that allows imaging reflections from within tissue.

Simaan and his colleagues, mechanical engineering graduate student Giuseppe Del Giudice and Dr. Karen M. Joos, Joseph N. and Barbara H. Ellis Family Professor in Ophthalmology, have accomplished a preliminary integration of a custom-made OCT probe.

Joos' particular research interest is the use of miniature OCT probes with robotic surgical tools to improve visualization for procedures inside the eye. Del Giudice's expertise is in design and control of micro-continuum medical robots, specifically micromanipulation for ophthalmic surgery.

Extending the capabilities of a standard continuum robot in terms of micro-scale motion and targeting could have a deep impact in microsurgery by providing significantly increased dexterity, controllability and precision to surgeons or even the pioneering of previously impossible procedures, Simaan said.

The Vanderbilt Center for Technology Transfer and Commercialization has filed a provisional application for U.S. patent protection on the invention.

This research is supported by the National Science Foundation (Grant CMMI 1537659). V

CLEARING THROAT OBSTRUCTIONS WITH MORE PRECISION, LESS DAMAGE

A concentric tube robot developed by Vanderbilt engineers provides surgeons more flexibility to remove severe central airway obstructions without the potential side effects—broken teeth, neck trauma and other internal damage—of current methods.

A feasibility study, published in July 2019 in *Annals of Biomedical Engineering*, used the new system to deliver two needle-sized robotic manipulators through ports of a standard rigid 10mm bronchoscope. These design advancements allow more dexterous and intuitive tool control for precision resection. They also require a less intense angle for the endoscope, which minimizes potential secondary damage.

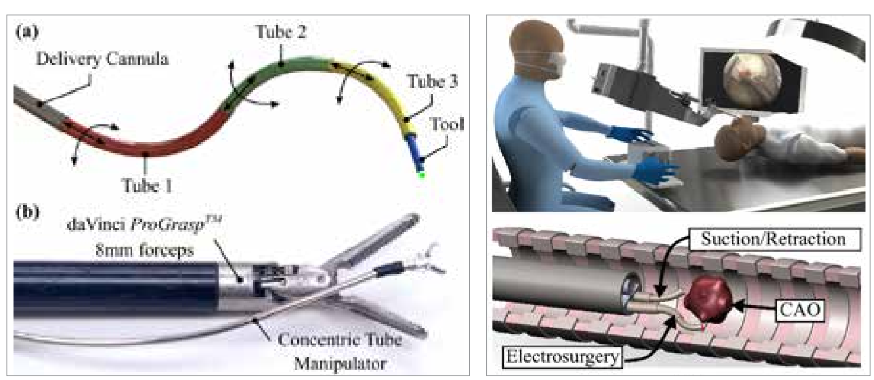
The work, still in the proof-of-concept phase, is under the auspices of the Vanderbilt Institute for Surgery and Engineering. Robert J. Webster III, Richard A. Schroeder Professor of Mechanical Engineering, and S. Duke Herrell, professor of urologic surgery and biomedical engineering, lead the team, which also includes Fabien Maldonado, a pulmonologist at Vanderbilt University Medical Center, as well as several mechanical engineering graduate students.

Cancer and benign diseases cause central airway obstruction in more than 80,000 patients annually in the United States alone, a figure that has been steadily on the rise. Forty percent of lung cancer deaths can be attributed to tumor progression into central airway passages.

"Central airway obstruction can be life-threatening in patients with large tumors, and conventional rigid bronchoscopy is challenging for the physician," the researchers said. "The challenge arises because the only way to aim tools is to tilt the bronchoscope itself. These manipulators bend and elongate to provide maneuverability of surgical tools at the endoscope tip, without endoscope motion."

In the study, the degree of airway obstruction was reduced from an average of 75 to 14 percent in animal models.

The feasibility study was funded by NIH Small Business Technology Transfer grant R41 HL140709.



Illustrations: MED Lab, Vanderbilt Institute for Surgery and Engineering

Needle-sized robotic manipulators used inside a standard, rigid bronchoscope give surgeons more precise control and lessen the angle of the patient's neck. The intense angle required to use existing systems can cause broken teeth and neck trauma.

Numbers of note

first-year students

42% are women

38% undergraduate minority students

#16 best undergraduate engineering program among private research universities***

90% of graduates have job offers before graduation*

#10 most innovative universities in the world**

11% undergraduate international students

55% of undergrads participate in research projects outside the classroom

112 faculty honors from 35 societies

30% have studied or interned abroad for at least a month

17 institutes, centers and groups

*U.S. citizen and permanent residents (Class of 2019)
**Reuters, Oct. 2018
***US News and World Report, Sept. 2019

Selected Honors and Leadership

Vanderbilt School of Engineering faculty are fellows of the following organizations as of Sept. 1, 2019.

American Academy of Environmental Engineers and Scientists

American Academy of Forensic Sciences

American Association for the Advancement of Science

American Geophysical Union

American Heart Association

American Institute of Aeronautics and Astronautics

American Institute of Chemical Engineers

American Institute for Medical and Biological Engineering

American Physical Society

American Society of Civil Engineers

American Society for Engineering Education

American Society for Laser Medicine and Surgery

American Society of Mechanical Engineers

American Vacuum Society

American Welding Society

Association of Women in Science

Biomedical Engineering Society

Combustion Institute

Council on Basic Cardiovascular Sciences of the American Heart Association

Electrochemical Society

Engineering Mechanics Institute

Heart Rhythm Society

Geological Society of America

Hungary Academy of Sciences, External Member

Institute of Electrical and Electronics Engineers

Institute of Physics (U.K.)

Institute of Transportation Engineers

International Society for Magnetic Resonance in Medicine

International Society for Optical Engineering

Materials Research Society

Microscopy Society of America

National Academy of Engineering, Members

National Academy of Inventors

National Academy of Sciences, Advisory Committee Members

National Academy of Sciences, National Associate

Optical Society of America

Prognostics and Health Management Society

Royal Danish Academy of Sciences and Letters

Royal Society of Chemistry (U.K.)

Royal Swedish Academy of Engineering Sciences

U.S. Air Force Scientific Advisory Board, Member

U.S. Nuclear Waste Technical Review Board, Presidential Appointee

Research Groups

As the engineering arm of an internationally recognized research university, Vanderbilt University School of Engineering fosters strong partnerships inside the university and with its research peers. The combination of innovative research, commitment to education and collaboration with a distinguished medical center creates an invigorating atmosphere for faculty members, research staff, graduate students and undergraduates.

Biophotonics Center at Vanderbilt
Anita Mahadevan-Jansen, Orrin H. Ingram Professor of Engineering, Professor of Biomedical Engineering
vanderbilt.edu/vbc

Center for Mechanobiology
Cynthia A. Reinhart-King, Cornelius Vanderbilt Professor Engineering, Professor of Biomedical Engineering

Center for Rehabilitation Engineering and Assistive Technology
Michael Goldfarb, H. Fort Flowers Professor of Mechanical Engineering

Karl Zelik, Assistant Professor of Mechanical Engineering
engineering.vanderbilt.edu/create

Consortium for Risk Evaluation with Stakeholder Participation
David Kosson, Cornelius Vanderbilt Professor of Engineering, Professor of Civil and Environmental Engineering
cresp.org

Frist Center for Autism and Innovation
Keivan Stassun, Stevenson Professor of Physics & Astronomy, Professor of Computer Science
my.vanderbilt.edu/autismandinnovation/

Institute for Software Integrated Systems
Janos Sztipanovits, E. Bronson Ingram Professor of Engineering, Professor of Computer Science, Electrical Engineering, and Computer Engineering
isis.vanderbilt.edu

Institute for Space and Defense Electronics
Ron Schrimpf, Orrin H. Ingram Professor of Engineering, Professor of Electrical Engineering
isde.vanderbilt.edu

Laboratory for Systems Integrity and Reliability
Douglas Adams, Daniel F. Flowers Professor, Distinguished Professor of Civil and Environmental Engineering
vu.edu/lasir

Multiscale Modeling and Simulation Group
Peter Cummings, John R. Hall Professor of Chemical Engineering
my.vanderbilt.edu/mums

Vanderbilt Center for Environmental Management Studies
Mark Abkowitz, Professor of Civil and Environmental Engineering,
vanderbilt.edu/VCEMS/

Vanderbilt Center for Transportation and Operational Resiliency
Craig Philip, Research Professor of Civil and Environmental Engineering
vanderbilt.edu/vector

Vanderbilt Data Science Institute
Douglas Schmidt, Cornelius Vanderbilt Professor of Engineering, Professor of Computer Science and Computer Engineering, and Associate Provost for Research Development and Technologies
vanderbilt.edu/datascience/

Vanderbilt Institute for Energy and Environment
George M. Hornberger, Craig E. Philip Professor of Engineering, University Distinguished Professor of Civil and Environmental Engineering and Earth and Environmental Science
vanderbilt.edu/viee

Vanderbilt Institute for Integrative Biosystems Research and Education
John Wikswo, Cain University Professor, Professor of Biomedical Engineering
vanderbilt.edu/viibre

Vanderbilt Institute of Nanoscale Science and Engineering
Sharon Weiss, Cornelius Vanderbilt Professor of Engineering, Professor of Electrical Engineering
vanderbilt.edu/vinse

Vanderbilt Institute for Surgery and Engineering
Benoit Dawant, Cornelius Vanderbilt Professor of Engineering, Professor of Electrical Engineering
vanderbilt.edu/vise

Vanderbilt University Institute of Imaging Science
John Gore, Hertha Ramsey Cress Professor of Medicine, University Professor of Radiology and Radiological Sciences, Professor of Biomedical Engineering
vuiis.vanderbilt.edu

Deans and Directors

Administration

1 Chief Business Officer
Hector O. Silva
hector.silva@vanderbilt.edu
(615) 875-8079

2 Director, Professional and Masters Programs
Joanne Wang
rong.wang@vanderbilt.edu
(615) 875-8386

3 Associate Dean for Research
Peter T. Cummings, John R. Hall Professor of Chemical Engineering
peter.cummings@vanderbilt.edu
(615) 343-3773

4 Associate Dean for Academic Success
William H. Robinson
william.h.robinson@vanderbilt.edu
(615) 322-1507

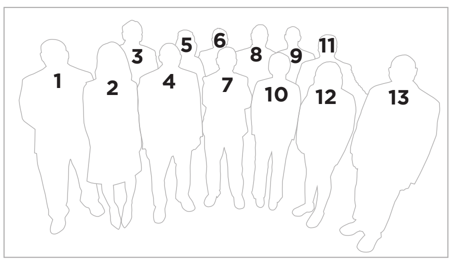
5 Associate Dean for Development and Alumni Relations
Teresa Rogers
teresa.rogers@vanderbilt.edu
(615) 322-4934

6 Associate Dean for External Relations and Director of Communications
Christopher Rowe
chris.rowe@vanderbilt.edu
(615) 343-3773

8 Assistant Dean for Design
Thomas J. Withrow
thomas.j.withrow@vanderbilt.edu
(615) 322-3594

7 Dean
Philippe Fauchet, Bruce and Bridgitt Evans Dean
philippe.fauchet@vanderbilt.edu
(615) 322-0720

9 Senior Associate Dean for Graduate Education and Faculty Affairs
E. Duco Jansen
duco.jansen@vanderbilt.edu
(615) 343-3773



10 **Senior Associate Dean for Undergraduate Education**
Cynthia B. Paschal
cynthia.paschal@vanderbilt.edu
(615) 343-3773

11 **Director of Academic Services and Data Analytics**
Adam McKeever-Burgett
adam.w.mckeever-burgett@vanderbilt.edu
(615) 343-8061

12 **Assistant Dean for Academic Programs**
Julie Vernon
julie.vernon@vanderbilt.edu
(615) 322-2441

13 **Assistant Dean for Student Affairs**
Burgess Mitchell
burgess.mitchell@vanderbilt.edu
(615) 343-8061

Departments

Department of Biomedical Engineering
Michael King, Chair, J. Lawrence Wilson Professor of Engineering
mike.king@vanderbilt.edu
(615) 322-3521

Department of Chemical and Biomolecular Engineering
Kane Jennings, Chair
kane.g.jennings@vanderbilt.edu
(615) 322-2441

Department of Civil and Environmental Engineering
Douglas Adams, Chair, Daniel F. Flowers Professor and Distinguished Professor
douglas.adams@vanderbilt.edu
(615) 322-2697

Department of Electrical Engineering and Computer Science
Dan Fleetwood, Chair, Olin H. Landreth Professor of Engineering
dan.fleetwood@vanderbilt.edu
(615) 322-2771

Department of Mechanical Engineering
Nilanjan Sarkar, Chair
nilanjan.sarkar@vanderbilt.edu
(615) 322-2413

Division of General Engineering
Yiorgos Kostoulas, Director
yiorgos.kostoulas@vanderbilt.edu
(615) 343-4965

Recent Awards

Catie Chang, assistant professor of electrical engineering, computer science and computer engineering, received the 2019 Early Career Achievement Award from the IEEE Engineering in Medicine & Biology Society.

Ravindra Duddu, assistant professor of civil and environmental engineering, received a 2019 NSF CAREER Award.

Michael Goldfarb, H. Fort Flowers Professor of Mechanical Engineering, and Ryan Farris, a Vanderbilt alumnus and engineering manager at Parker Hannifin Corporation, received a 2018 R&D 100 Award Indego, a lightweight exoskeleton they designed that enables paraplegic users to walk more easily.

Kelsey Hatzell, assistant professor of mechanical engineering, received a 2019 NSF CAREER Award.

Piran Kidambi, assistant professor of chemical and biomolecular engineering, received a Ralph E. Powe Award from Oak Ridge Associated Universities.

Ethan Lippmann, assistant professor of chemical and biomolecular engineering, won an inaugural $2.5 million Chan Zuckerberg Initiative grant for neurodegenerative disorders research.

Ethan Lippmann, assistant professor of chemical and biomolecular engineering, received a 2019 NSF CAREER Award.

Anita Mahadevan-Jansen, Orrin H. Ingram Professor of Engineering and director of the Biophotonics Center at Vanderbilt, has been elected as the 2020 vice president of SPIE. She will serve as president-elect in 2021 and as the society's president in 2022.

W. David Merryman, professor of biomedical engineering, was named the Walters Family Professor in the School of Engineering.

Cynthia A. Reinhart-King, Cornelius Vanderbilt Professor of Engineering and professor of biomedical engineering, was the inaugural recipient of the Biomedical Engineering Society's Mid-Career Award.

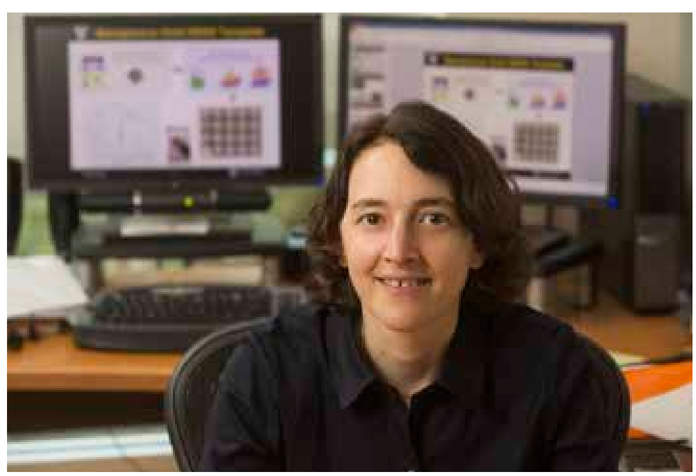
Mikail Rubinov, assistant professor of biomedical engineering, received a 2019 Ralph E. Powe Award from Oak Ridge Associated Universities.

Ronald Schrimpf, the Orrin H. Ingram Professor of Engineering and professor of electrical engineering, is president of IEEE's Nuclear and Plasma Sciences Society, effective Jan. 1, 2019.

Robert J. Webster III, professor of engineering, was named the Richard A. Schroeder Professor of Mechanical Engineering.

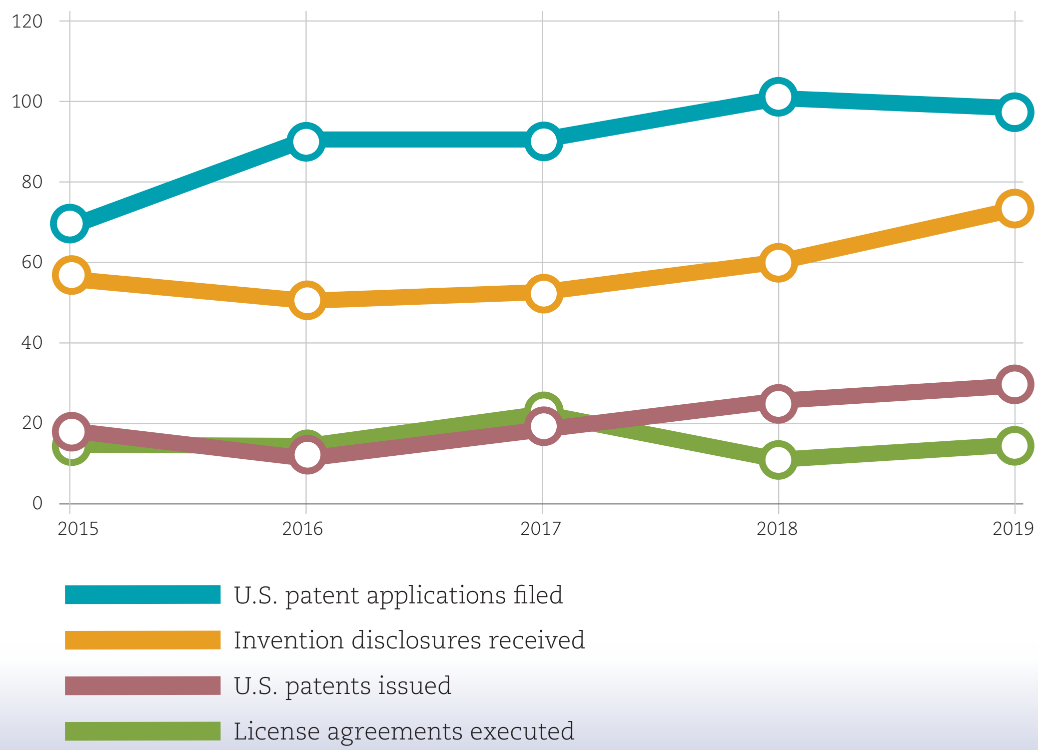
Sharon Weiss, Cornelius Vanderbilt Professor of Engineering, was named director of the Vanderbilt Institute for Nanoscale Science and Engineering, effective July 1, 2019

13 engineering students were awarded NSF Graduate Research Fellowships in 2019.



Cornelius Vanderbilt Professor of Engineering Clare McCabe (left), a professor of chemical and biomolecular engineering, received a Chancellor's Award for Research in 2018. Cornelius Vanderbilt Professor of Engineering Sharon Weiss (right), a professor of electrical engineering, received a Chancellor's Award for Research in August 2019.

Commercial Impact



5-year totals

460
U.S. patent applications filed

306
Invention disclosures received

107
U.S. patents issued

78
License agreements executed

$6,749,920
Revenue generated from VUSE technologies

Most Recent Fiscal Year

99
U.S. patent applications filed

77
Invention disclosures received

30
U.S. patents issued

16
License agreements executed

$1,495,332
Revenue generated from VUSE technologies

These figures were provided by Vanderbilt's Center for Technology Transfer and Commercialization for the most recent fiscal year (July 1, 2018 through June 30, 2019).

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