interface®

California Institute
for Telecommunications
and Information Technology
CALIT2
Volume 14 | Issue 2 | Spring 2019
University of California, Irvine

Data-driven Wellness

features:

departments:

interface

Spring 2019
Volume 14 | Issue 2

The award-winning *Interface* is published semiannually by UC Irvine's CALIT2 Communications Department.

Editor: Shelly Nazarenus
Contributors: Lori Brandt, Sharon Henry, Anna Lynn Spitzer
Art Director: Michael Marcheschi, m2design group
Photographers: Frank Armstrong, Debbie Morales, Jill Steinberg
Publisher: Mike Delaney, Meridian Graphics

UCI CALIT2

4100 CALIT2 Building
Irvine, CA 92697-2800
(949) 824-6900
www.calit2.uci.edu
info@calit2.uci.edu

2

UNDERGRADUATES HELP ACCOMPLISHED VIOLINIST REFINE SENSOR PROTOTYPE

The Sound of MUGIC™

Lori Brandt
Jill Steinberg

When the classically trained violinist Mari Kimura plays her instrument these days, her masterful bow hand creates sound from two sources: an acoustic violin and a wireless motion-sensor device known as MUGIC™.

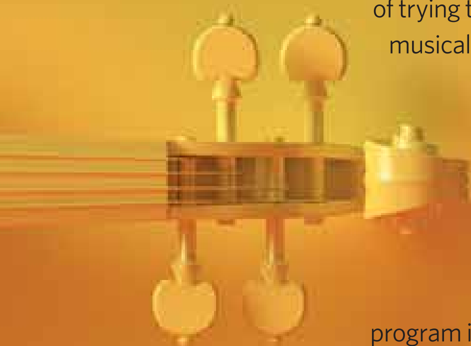
Kimura's concept of using a motion sensor for performance was born in Paris, at the Institute for Research and Coordination in Acoustics/Music, where Kimura was a composer in residence in 2010. She collaborated with engineers to develop the system of motion tracking for a violinist's bowing, enabling the performer's arm motions to provide control of a computer's musical activity.

Kimura then took her creation to New York for help from a media artist and fashion designer, and finally landed in California at UC Irvine's CALIT2. Kimura has shepherded MUGIC™'s development and proof of concept for nearly a decade.

Her device is comprised of a glove-worn wireless sensor linked to a mobile software interface. The system interprets movements and translates them into performance actions. Kimura wears the glove on her bow hand, where the sensor extracts and interprets expression from her gestures while she plays the violin. It seamlessly and intuitively can change the tempo and pitch of the recorded accompaniment coming from the computer. Modulating accompaniment, adding sound effects, controlling images and video on projection systems, and managing stage lighting are a few of the applications of the MUGIC™ system that have been demonstrated and used for real performances.

The Japanese-born violinist became a professor of music in UCI's Claire Trevor School of the Arts Integrated Composition, Improvisation, and Technology (ICIT) program in 2017. Kimura is a pioneer composer, programmer, researcher and performer of music involving the interactive use of computers in live performance. And she is at the forefront of violinists who are extending the technical and expressive capabilities of the instrument.

In the early '90s while a student at Julliard, she invented "subharmonics," an extended bowing technique that allows the performer to play notes below the violin's normal tonal range without changing the tuning. She currently serves as the founding chair of the Future Music Lab at the Atlantic Music Festival and has taught a graduate course in interactive computer music performance at the Juilliard School since 1998.

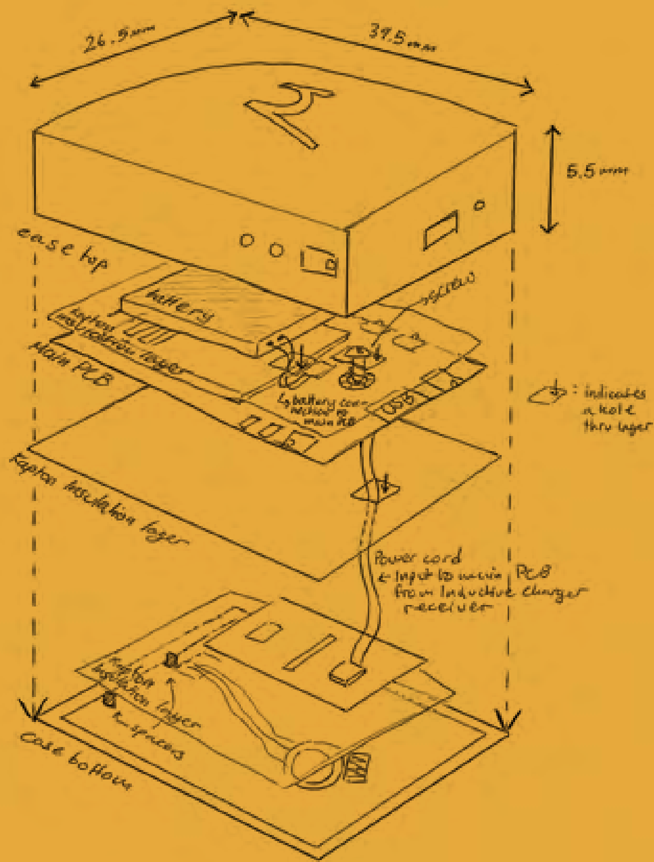


"Mari came to us with this idea of trying to use motion to augment musical performance," said Michael Klopfer, CalPlug technical director and faculty mentor for two multidisciplinary program (MDP) teams that have worked with Kimura on MUGIC™. The MDP program is a collaboration between CALIT2 and the Undergraduate Research Opportunities Program (UROP) that gives undergraduates an opportunity to experience hands-on multidisciplinary research.

Kimura came to the MDP program with demo boards wrapped in a glove. With Klopfer's guidance, students developed a common printed circuit board (PCB) and low form-factor housing, which provide long battery life and a reliable connection while allowing the device to be worn comfortably during performances. "The device has come a long way," Klopfer says.

Taking ideas from concept to early production is how we bring the dreams of researchers to reality at CALIT2," he adds. "We have developed products using music as a tool to heal, and expanding the impact of music is an area of interest for us."

Working with Kimura and Klopfer, the MDP student teams have been deeply involved in the development process. The 2018 team helped with the device hardware and prototype development, while the 2019 team is involved in software and user interface development as well as the design-for-manufacture process to prepare the device for commercial production.



Above: The student team's design integrates the microcontroller, motion sensor, power and battery management, and inductive charging all onto a small wearable circuit board.

Below: The small, wireless motion-sensor device is worn inside a glove on the violinist's bow hand where it extracts and interprets expression from her gestures.

Electrical engineer Andrew Dylan Begey '18, project lead of the first MDP team, was responsible for designing the device's initial printed circuit board. "Our goal was to integrate several different commercial products all onto a single PCB and add more functionality, such as inductive battery charging and battery-level monitoring. In the end, two revisions of the device were completed and proved functional."

Begey says working on MUGIC™ helped him obtain his current position at Northrop Grumman. "Not only were they impressed by the PCB that I brought to my interview, but I also learned important skills related to working on multidisciplinary teams toward common project goals. I have done multiple PCB schematic and layout designs at my job, which I learned in this project."

Kimura says CALIT2 is helping her make a better, faster, smaller device. "There are functions that I don't have and I want."

Klopfer and Mark Micchelli, one of Kimura's graduate students, are working with the second MDP team on the software side to develop more features to allow enhanced control capabilities. These include allowing the user to

Composer and violinist Mari Kimura performs "Kaze" in 2016 at National Sawdust, a nonprofit incubator and performance space for new music in Brooklyn, New York.

customize settings via a smartphone, and configure and use the device right out of the box.

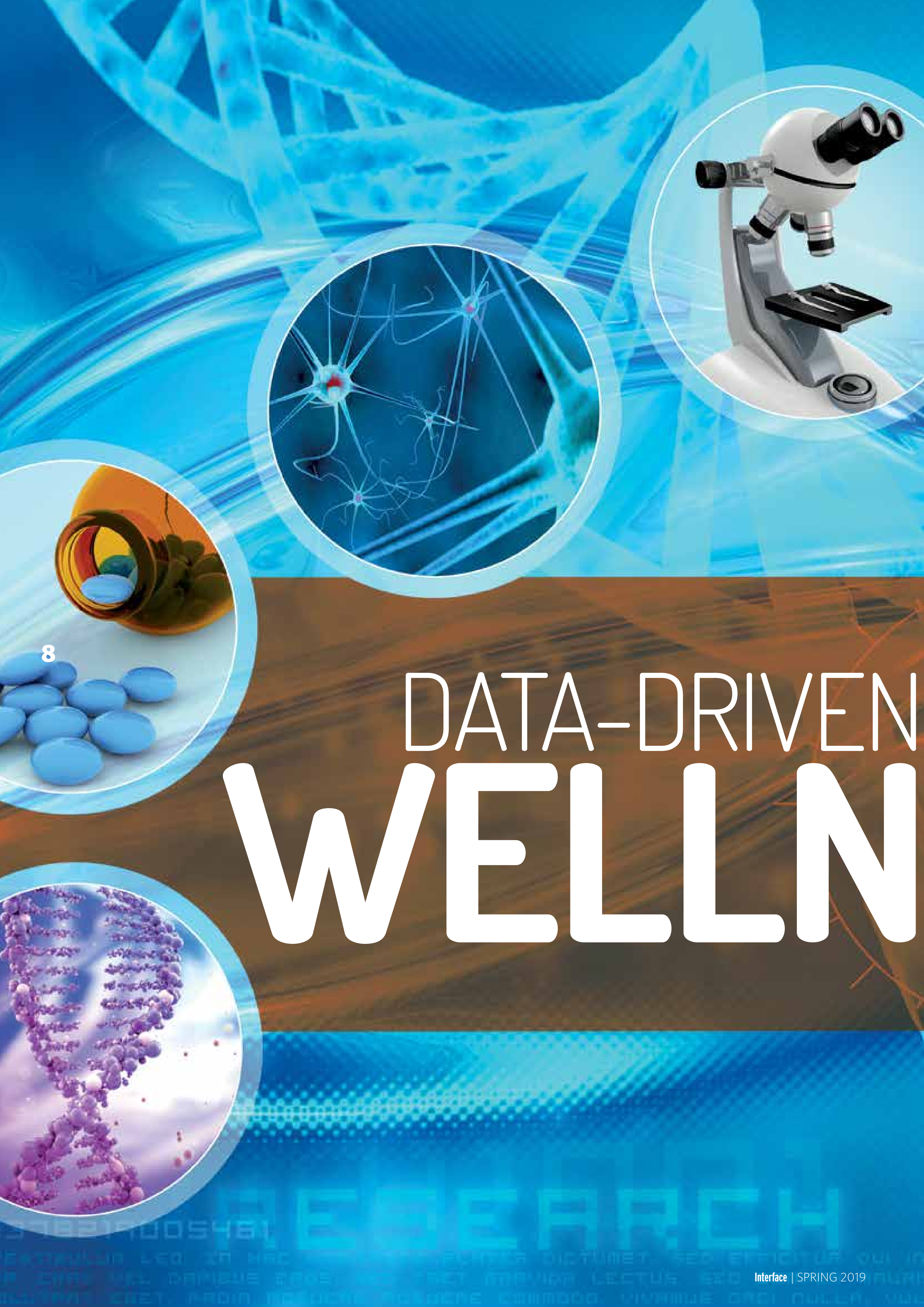
Klopfer says, "We are taking information gathered on our first prototype and using it to develop the next iteration and give Mari a viable product ready to market."

Kimura participated recently in an experimental performance project called Your Ocean, My Ocean (YOMO) where she played her violin and MUGIC™. The 80-minute performance featured dancers and musicians onstage, with a larger virtual cast appearing in video projections, integrated with footage of ocean and coastal locations and fragments of animated films, all evoking aspects of natural beauty and environmental degradation. Kimura improvised her violin playing in a duet with prerecorded sounds of a breeching whale, using MUGIC™ to control the whale sounds. Following a successful run at UCI's Contemporary Arts Center in February 2019, the project was presented at Brown University's Granoff Center last month.

In the meantime, Kimura is working with the other arts disciplines to explore MUGIC™'s potential for additional aspects of performance. "I am working with theater people, dancers, directors and other musicians, including Annie Loui, a professor of drama at the Claire Trevor School of the Arts and an expert on mime." One of Kimura's graduate students who is interested in theater and hand motion will work on the project with her and Loui next quarter.

UCI music professor Christopher Dobrian, a composer of instrumental and electronic music, says that a number of music faculty are working on the issue of real-time interactive use of computers in live performance, but Kimura is the only one working with a sensor and integrated control system. "Obviously she has to do all these things to make the violin sound properly, but she also has to be conscious of what her movements are doing in the way that she's got it mapped to what the computer does. I think that's a really fruitful area of research, trying to see how the movements that one makes when naturally playing an acoustic instrument can be sensed and translated into meaningful control of other sounds."

"I am passionate about this project," Kimura says. "I want others to have a good time with it."



DATA-DRIVEN WELLN

ESS

CALIT2 LEADS THE WAY IN INNOVATING FOR THE NEXT-GENERATION BIOMEDICAL ECOSYSTEM

Anna Lynn Spitzer

In the summer of 2015, young cancer patients at Children's Hospital of Orange County spent two weeks testing a mobile app developed by a multidisciplinary team of collaborators from the UC Irvine Center on Stress & Health and CALIT2. Called Pain Buddy, the interactive app helps children manage pain and other symptoms during cancer treatment.

Featuring a variety of engaging and interactive avatars that encourage kids to answer questions about their pain levels, the app also teaches behavioral skills to reduce pain and improve general wellbeing. In addition, Pain Buddy serves as a tool for doctors, monitoring children's responses to questions about pain, and sending real-time data to the patient's oncology treatment team.

Pain Buddy is but one example of CALIT2's ongoing leadership in advancing a new biomedical ecosystem – one that includes a host of connected devices, apps and processes that use data to improve health outcomes.

Earlier this year, Michelle Fortier, UCI associate professor of nursing and principal investigator on the initial Pain Buddy project, received a $3.195 million grant from the National Cancer Institute to continue research and development of the app, which she believes has "widespread applicability to any illness or condition that involves pain."

CALIT2 researcher Sergio Gago collaborated with Fortier on Phase 1 of Pain Buddy and is continuing the collaboration on Phase 2, which includes improved avatars and animation, as well as larger-scale testing.

"This is just one of many technology-based projects we are creating at CALIT2," says Gago, who runs the ETAD (Engaging Technology and Application Design) lab, where several new prototypes are in development. These include a sensor-controlled pill bottle, an interactive exercise app and online games that help children cope with disease and surgery.

TEAMING WITH TECHNOLOGY

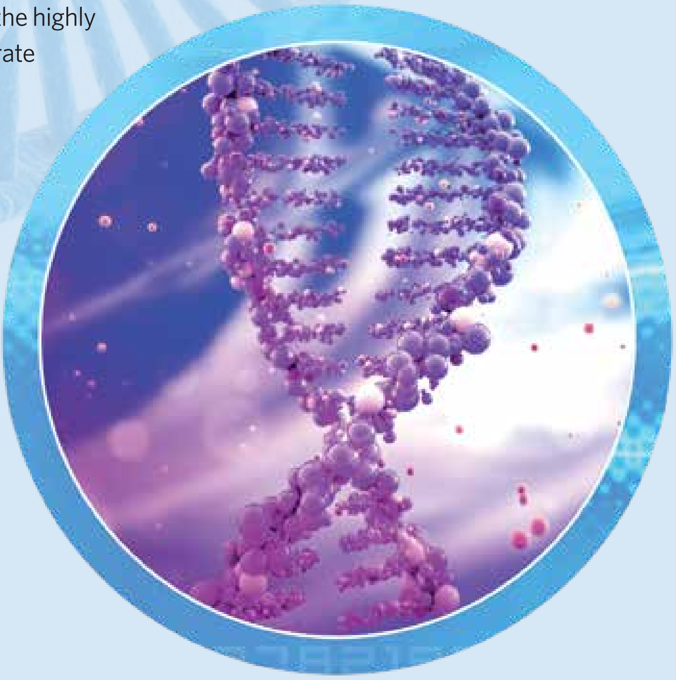
Multidisciplinary collaboration underlies all of CALIT2's biomedical endeavors. From Pain Buddy to a host of other devices and platforms, every project relies on cross-disciplinary expertise.

"We have been fortunate to collaborate with CALIT2 in the development of Pain Buddy," says Fortier, a licensed clinical psychologist. "The team worked with us on the design and function of the program and has gone through countless versions and modifications as we test Pain Buddy and get feedback from our stakeholders. The creativity and expertise of the CALIT2 team has been an invaluable part of Pain Buddy's development."

Urologist, Distinguished Professor and former medical school dean Dr. Ralph Clayman and fellow urologist Dr. Jaime Landman collaborated with CALIT2's technical director Mike Klopfer on Safe Passage – a sensor-laden device that measures the force applied by surgeons as they insert a ureteral access sheath during kidney stone-removal surgery.

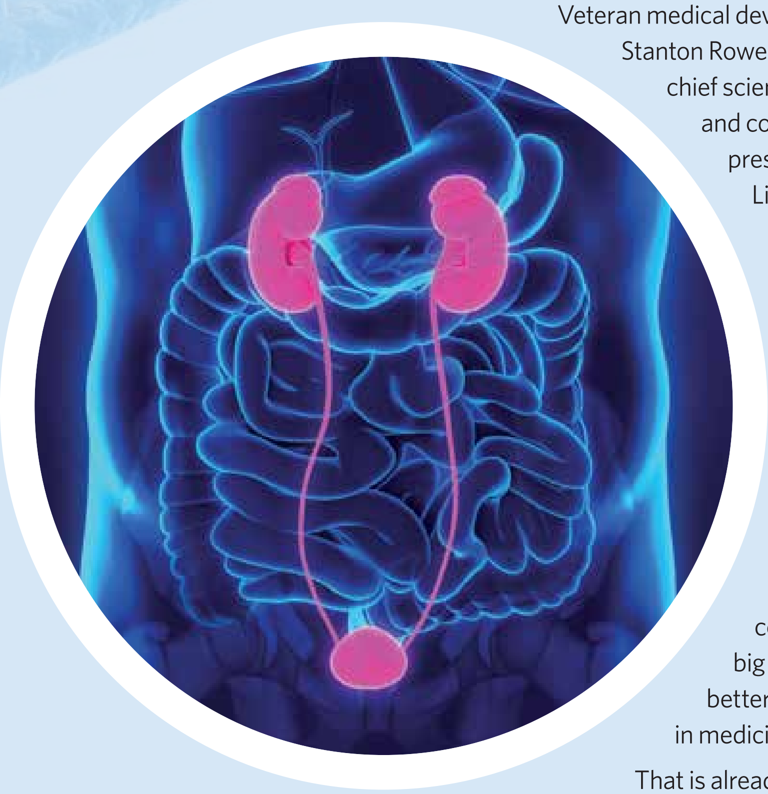
The two also have partnered on other projects with CALIT2-affiliated faculty.

"I believe a major asset of UCI is the broad variety of schools and the highly talented individuals on their faculty who are always willing to collaborate with their medical school colleagues. To my mind, this is one of the major attributes that distinguishes UCI and fosters a collegial environment in which the whole is invariably greater than the sum of its parts," Clayman says.



In February, The New York Times addressed the surge of technologically advanced devices and applications flooding the medical market. The article quoted health care IT expert Jeff Becker, who said, "Advances like robotics, nanotechnology, genetic engineering, 3D printing, artificial intelligence and IoT are fueling an exciting era within health care innovation. Many of these efforts will undoubtedly fall flat, but some could end up as transformative as the X-ray itself."

"Data is the new fuel," says G.P. Li, director of the CALIT2 Irvine division. "Even with biomedical devices, it's about how you use the data. It's not just about making a device and then being done; it's about all the connected services."



Veteran medical device expert Stanton Rowe, former chief scientific officer and corporate vice president at Edwards Lifesciences, recently launched a biomedical device incubator in Orange County. He agrees that a sea change is underway. "With the increase in electronic patient records, and more coherent databases, big data will drive better decision-making in medicine," he says.

That is already happening at Rowe's former company. Edwards Lifesciences, an Irvine-based medical equipment firm specializing in artificial heart valves and hemodynamic (blood circulation) monitoring, recently launched a product that analyzes hemodynamic data from thousands of surgical patients. Using a predictive algorithm, it warns anesthesiologists about 10 minutes before a hypotensive episode will occur in surgery. "This is a great example of the power and utility of big data," says Rowe.

Rowe, who serves on the CALIT2 Advisory Board, says the institute has been "at the cutting edge of big data," with a key focus on health care-related applications. "CALIT2 has also been a leading institution focused on sophisticated imaging and modeling, which remain important areas for advancement in medicine."

IDEAL LAUNCHING PAD

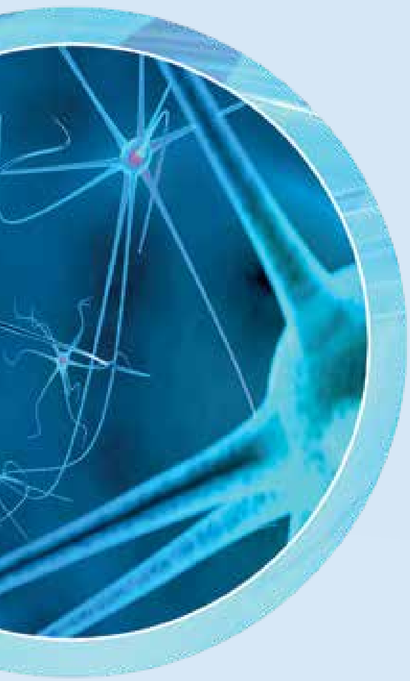
The institute's leadership in reshaping the biomedical paradigm extends beyond the slew of projects underway in laboratories and its expertise in big data, however. CALIT2's TechPortal serves as a pre-incubator for several budding medical and biomedical technology startups, offering a first home to students and faculty as they bring their research to the marketplace.

TechPortal offers startups affordable rent, wet and dry lab space, access to cleanrooms and other prototyping facilities, and a host of networking opportunities.

"It's a stepping stone," says CALIT2's Li. "Faculty and researchers who might be relatively inexperienced in the business world can jump into the muddy waters by tapping the resources in their own back yard."

Translucence Biosystems is one of these companies. It builds and analyzes 3D reconstructions of brain anatomy, employing new chemical techniques for making large specimens of biological tissue optically clear. This tissue-clearing technology makes it possible to scan intact brain tissue with a sheet of laser light, generating new tools for rapid diagnostics of neuroinflammation and brain activity at cellular resolution. (The company recently won an NIH Phase I Small Business Innovation Research Grant for its brain imaging work.)

Translucence Biosystems also has a cloud-based software platform to seamlessly manage the huge amounts of data its technology generates; it will stream 3D visualization of the data over diverse user networks.



Founder Sunil Gandhi, UCI associate professor of neurobiology and behavior, believes the company has tremendous potential. "Translucence Biosystems is keenly interested in moving our tissue-cleaning technology beyond neuroscience," Gandhi says. "In particular, we are interested in developing next-generation histological tools that improve the detection of cancer and skin disorders."

TechPortal offers the nascent company the opportunity to establish a toehold in the market.

"For new companies, there can be somewhat of a Catch-22," says Damian Wheeler, Translucence co-founder and CEO. "Without decent lab space, it is hard for new companies to have any success; however, decent lab space is difficult to afford without having some initial success. TechPortal provides us with an ideal launching pad for our biotech startup.

"In particular, the access to UCI's world-class fee-for-use facilities is a major advantage over alternative incubator space," Wheeler adds. "And CALIT2's programming gives us great opportunities to network with entrepreneurs, investors and business experts."

Another TechPortal tenant, CBio, seeks to measure the unique properties of biological cells nondestructively by using electrical fields to separate and identify them. Company founder David Charlot is collaborating with UCI biomedical engineering and medical school faculty.

While CBio currently markets its product to laboratory scientists, Charlot says the company eventually plans to use its microfluidic platform to advance medical diagnostics, regenerative medicine and possibly even immunotherapy.

"What we do requires photolithography and other types of complex fabrication techniques, microscopy and other metrology techniques, and CALIT2 offers us that," says Charlot, whose startup moved into the incubator in January. "We really appreciate the cleanrooms and this wonderful lab space to put our system together."

And former TechPortal company Integra Devices, LLC is creating a zero-power, implantable pressure sensor called an eyelash sensor, a nod to its smaller-than-a-human-eyelash size. While the company, which recently raised $5 million in Series A venture capital funding, has outgrown its TechPortal space and moved to larger headquarters, its technology was developed in BiON, the CALIT2 cleanroom facility.

> "Data is the new fuel. Even with biomedical devices, it's about how you use the data. It's not just about making a device and then being done; it's about all the connected services."

CONNECTED SERVICES

The institute's cleanrooms figure prominently in CALIT2's contributions to the emergent biomedical ecosystem. One of BiON's industry users, a Dutch company called Access2Bone BV, is developing a system to control quality and assure product safety and efficacy, which will allow it to gain FDA approval to produce prototypes for market-acceptance testing and eventually, clinical testing and market release.

The startup, which seeks to incorporate synthetic materials with cadaver tissue to hasten bone regeneration, saw an opportunity at CALIT2. "The BiON facility gives Access2Bone the chance to expedite market-acceptance testing," says Michael Sickler, company cofounder. "We will also help UCI elevate its quality system to become aligned with FDA standards and regulations."

> “We offer a commanding edge to the next generation of biomedical device companies, as well as connected services and the ability to harness the information those services provide.”

Access2Bone plans to develop the necessary guidelines to obtain FDA acceptance for its specific cleanroom space and product development. Eventually, these guidelines can be adopted by UCI to gain FDA acceptance lab-wide.

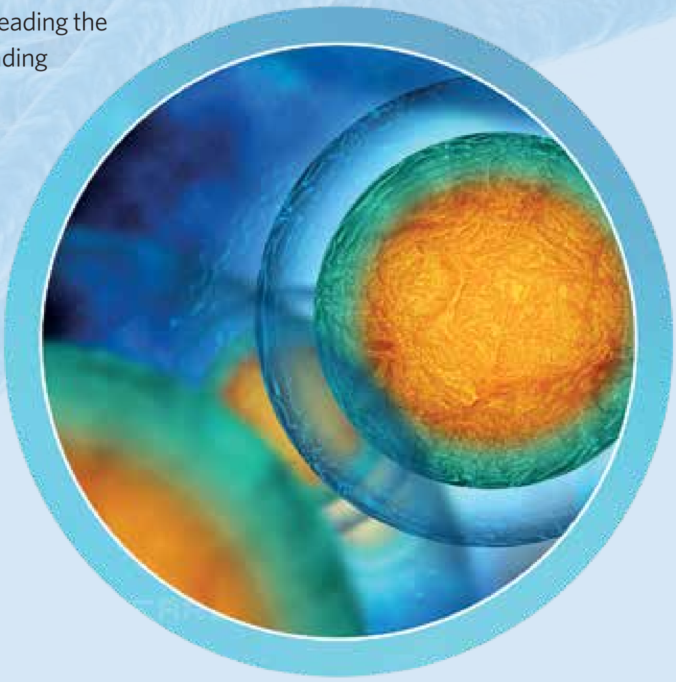
“If we succeed, UCI will be one of the very few FDA-approved prototyping universities,” Li says.

Orange County is a perfect place to develop this new breed of biotechnology companies, according to Rowe. His new incubator, NXT Biomedical, a partnership with health care venture capital firm Deerfield Management, will help develop five to eight startup companies to produce novel therapeutic devices for diseases with significant unmet needs.

He founded NXT Biomedical, Rowe says, because he enjoys the early stage of medical device development. “It is crazy hard, fraught with failure, [only] half the information you want is available, and the potential impact to patients is enormous. Who wouldn’t want that job?” he jokes. On a more serious note, he adds: “The biomedical device area continues to be an attractive market, with many patients still underserved and needing better alternative therapies.”

CALIT2 is committed to leading the charge. “We offer a commanding edge to the next generation of biomedical device companies, as well as connected services and the ability to harness the information those services provide,” says Li.

“This really is about complementary medicine,” he adds. “My hope is that one day we will have a drug-free health care system that uses alternative methods.”



According to a 2019 report by Accenture, about 79% of consumers surveyed in the United States said technology is important to managing their health.

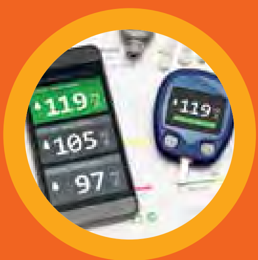
Here is a small sampling of CALIT2-led data-driven health and wellness projects that empower individuals and their health care providers:

PICARD – Patient Initiated Controlled Analgesic Recording Dispenser. This handheld, compact pill dispenser uses a thumbprint sensor to recognize patients and dispense a controlled dose of medication at predesignated intervals. The device's location is registered for security; if it is lost or stolen, PICARD locks itself and sends an alert, including current location, to the patient. Palliative care patients at the UCI Medical Center will begin testing the device this spring.

PET – Personal Embodied Trainer. An interactive physical therapy/exercise application that features an animated virtual coach who encourages users to do their exercises properly and with the correct number of repetitions. Now in Phase 2, PET implements a wristband, similar to a Fitbit, which streams data to the virtual coach appearing on the user's television who uses verbal and nonverbal communication to motivate the user during prescribed exercises. Lab-based usability tests for PET will begin later this quarter.

CHRIs (Child Health Ratings Inventory) – a mobile app that assesses anxiety and postoperative pain in children undergoing surgery or dealing with other serious medical issues. CHRIs uses a collection of animated clips to help children better understand its content. Data from the app are stored in a cloud server and are accessible through a web portal by health care providers who seek the best way to collect information from children dealing with these conditions. A clinical trial involving more than 1,000 participants was completed last summer.

MEDICOM – an application that tracks patient symptoms daily by connecting to several devices, including Fitbit, a blood pressure monitor and a MEMS pill cap. Data are available to both patients and health care providers. Created in collaboration with UCI's Health Policy Research Institute, Medicom's developers hope its use will benefit physicians by helping them calculate medication dosage individually, based on the patient's data. The first version, including backend web and a mobile app, is currently part of an NIH trial.



BASH THE BEAST – a game designed in collaboration with UCI's Health Policy Research Institute, for children who have diabetes. The game, which can be played on a computer or a tablet, teaches users how to manage their disease, emphasizing the best way to check glucose levels and manage doses. It also tracks exercise routines, delves into the use of insulin versus snacks to raise glucose levels and more. A new version for use on phones is in development.

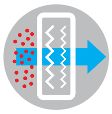
MY HAPPY BLOOD – a mobile health app for patients taking blood-thinning medications called anticoagulants. Featuring a diary, progress charts, medication reminders and an education section, the app aims to improve patient satisfaction with and adherence to anticoagulation therapy, ultimately reducing hospital readmissions. An interdisciplinary team from UCI's schools of nursing and medicine collaborated with CALIT2 to create MHB.

Sharon Henry

INTRO TO CLEANROOMS

Cleanrooms, first developed for the aerospace and microtechnology industries, are used in biotechnology and medical research, where a particle of dust could compromise the integrity of critical wiring connections or biological experiments.

AIR FLOW



HEPA filters remove particles as small as 0.5 microns.

LAMINAR FLOW

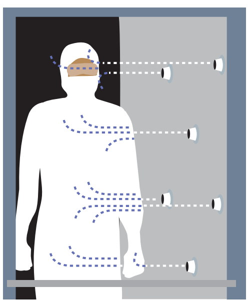
Clean air travels downward at a velocity of about 90 feet per minute, swiftly removing any particles on people or equipment.

AIR RETURN

Air and particles are flushed out through venting placed low in the walls or holes in raised flooring.

BUNNY SUITS

Technicians wear special suits designed to keep contaminants such as skin flakes, hair and clothing fibers from damaging the quality of products and research.

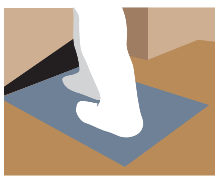


Air shower

In a self-contained passage, blowers use Class 100 air to dislodge and remove particles from workers before they enter a cleanroom.

Sticky mats

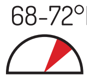
Tacky surface pulls particles from feet.



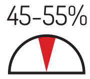
Climate control

Temperature and humidity levels are regulated to ensure peak performance of materials and uniformity of yield.

Temperature
68-72°F



Humidity
45-55%



THE INVENTOR: MR. CLEAN Willis Whitfield (1919 – 2012)

In 1960, while employed as a physicist at Sandia National Laboratories in New Mexico, Whitfield invented the modern cleanroom.

In April 1962, Whitfield presented his first technical paper on the design at the National Meeting of the Institute of Environmental Sciences in Chicago. That same month, Time magazine dubbed him "Mr. Clean."

Before Whitfield's design, the air quality in the best cleanrooms contained 1,000 times more particles than in his. His concept of a laminar flow cleanroom would go on to create a new multitrillion-dollar industry.

Photo: Sandia National Laboratories

YELLOW LIGHT

Cleanrooms that employ photolithographic printing use yellow lights. The photoresist material used to coat wafers is not sensitive to yellow light, but light from other sources will cause chemical reactions in the film and alter the image.

AIR CHANGE

In a typical air-conditioned home, room air changes about twice per hour. Air in a cleanroom, depending on the class, changes from 10 to more than 600 times an hour.

UCI CLEANROOMS

CALIT2 Director G.P. Li oversees two UCI cleanroom facilities: **BiON** (Bio-Organic Nanotechnology) for biomedical device fabrication and testing; and **INRF** (Integrated Nanosystems Research Facility) for semiconductor, micromachining and MEMS (microelectromechanical systems) fabrication. Cleanrooms are available to UCI students, faculty and off-campus users.

INRF is a 9,600-square-foot Class 100/1,000/10,000 cleanroom equipped with all the major tools for micro- and nanofabrication.
http://www.inrf.uci.edu/

BiON is a 4,000-square-foot, Class 1000 cleanroom dedicated to research and development of micro/nano devices using biological and organic materials.
http://www.inrf.uci.edu/bion/

How clean is a cleanroom?

An average cubic meter of city air contains about 35 million particles (.5 micron size or larger) for each cubic meter. A human red blood cell is about 5 microns in diameter.

DIAMETER OF:

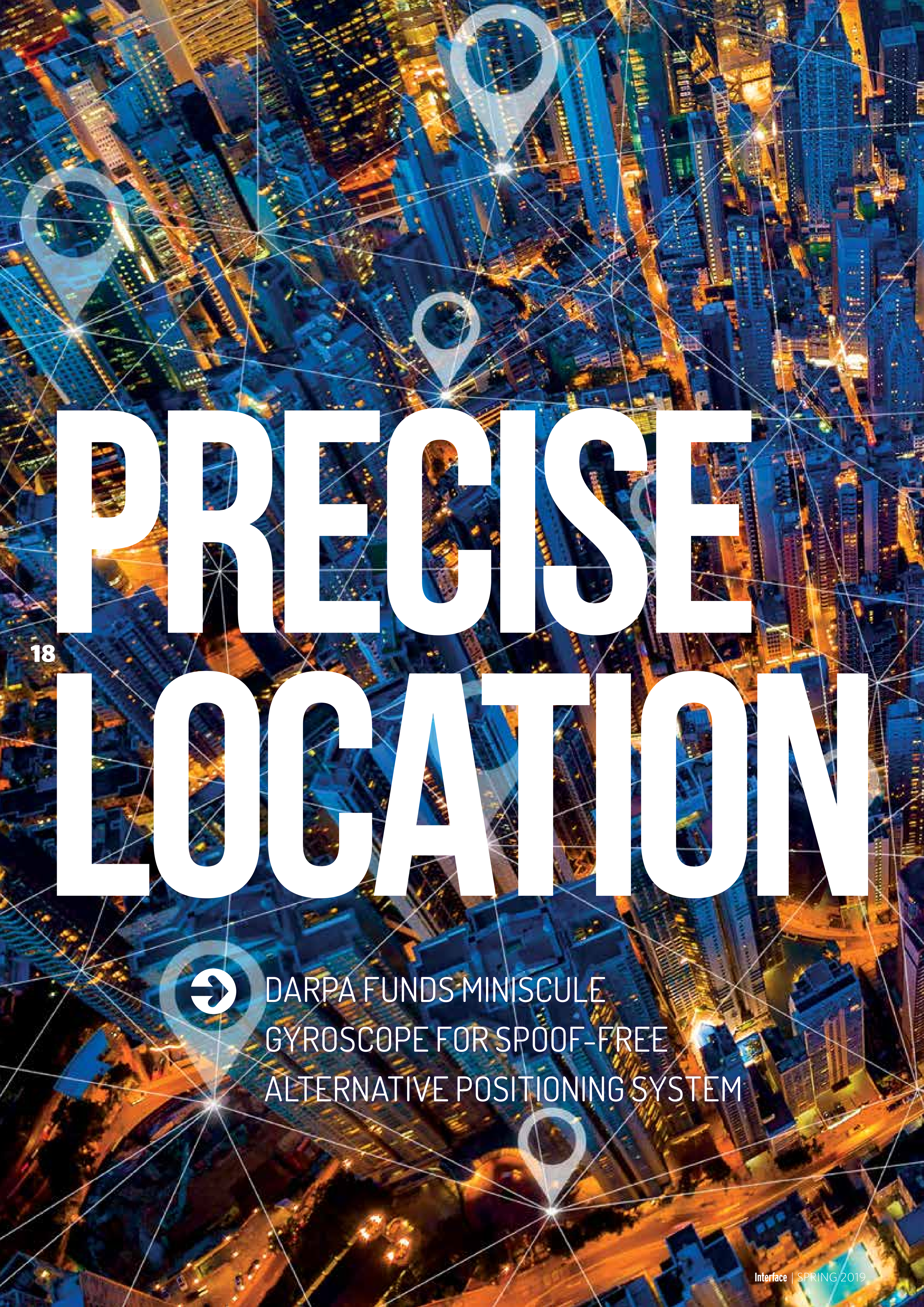
Cleanliness standards

Maximum particles per cubic meter

CLASS	1 micron*	5 microns*
1	8.3	.29
10	83	2.9
100	832	29
1,000	8,320	293
10,000	83,200	2,930
100,000	832,000	29,300

*Less than or equal to

Sources: Intel, NASA, RMG and Associates, Angstrom Technology, Terra Universal, Sandia National Laboratories



PRECISE LOCATION

DARPA FUNDS MINISCULE GYROSCOPE FOR SPOOF-FREE ALTERNATIVE POSITIONING SYSTEM

CURRENT MILITARY INSTRUMENTS, LIKE MISSILES AND GROUND/ AIR VEHICLES, OFTEN RELY ON GLOBAL POSITIONING SYSTEMS FOR LOCATION, NAVIGATION AND CONTROL. THE PROBLEM, THOUGH, IS THAT GPS SIGNALS ARE WEAK AND THEREFORE VULNERABLE TO OUTSIDE INTERFERENCE. "YOU CAN TURN ON YOUR HAIR DRYER AND EASILY JAM OR OVERPOWER GPS SIGNALS," SAYS ANDREI SHKEL, UC IRVINE SAMUELI SCHOOL MECHANICAL AND AEROSPACE ENGINEERING PROFESSOR.

Hackers have turned this susceptibility into a form of modern warfare. They can "spoof" GPS systems, creating havoc by directing instruments away from their intended targets.

So Shkel and his team are working with the U.S. military to develop an alternative positioning system. Armed with DARPA funding of more than $2.9 million, they are fabricating a tiny gyroscope as part of a self-contained inertial measurement unit (IMU). The IMUs can work alone or in conjunction with GPS – taking over during a GPS outage, for example – to provide interference-free navigation.

IMUs contain a minimum of three gyroscopes, which measure orientation in space, and three accelerometers, which document position. "The six sensors give complete information about position and orientation of any object without depending on GPS. They don't require external signals and therefore cannot be jammed or spoofed," says Shkel, who adds that the gyroscopes are the most complicated part of the IMU.

The project incorporates a previously unused – at least in gyroscopes – approach known as mechanical amplitude amplification, which increases the signal-to-noise ratio and therefore the sensitivity of the device. In addition, the gyroscopes vibrate, and they measure the angle of rotation rather than the angular velocity, the way lower-performance devices do. According to Shkel, such mechanization has never been accomplished on the microscale. It involves sophisticated engineering design and requires extremely precise manufacturing techniques.

Unlike GPS receivers, which are relatively inexpensive, high-precision gyroscopes contain nearly 100 parts, which must be assembled, aligned and polished by hand, and can cost tens of thousands of dollars apiece. Shkel is working to create these sensors more cost-effectively by developing new chip-level microfabrication techniques that could lead to mass production.

His team is using off-the-shelf fused quartz to produce sensor chips, in contrast to the silicon used in most MEMS devices. Fused quartz has a higher quality factor than silicon; Shkel compares it to striking a premium quality wineglass and hearing a more sustained vibration than when striking a low-quality glass. Additionally, unlike crystalline material, fused quartz has identical properties in all directions. "If you try to deform a single-crystal material, such as silicon, it will have different deformation and different stiffness levels along different directions of the crystal," Shkel explains. "This is what we are trying to avoid. For high-performance devices, we need to have identical mechanical properties in all directions."

While fused quartz provides mechanical qualities not available in other materials, it is difficult to micromachine. Shkel and his team are using new photolithography techniques, and experimenting with etching recipes and masking materials in an effort to find just the right combination. Using tools in UCI's INRF and BiON facilities, researchers are etching 100-micron-deep structures into the 4-inch wafers. "Fused quartz is transparent; it is effectively a super-high-purity glass. The material has excellent structural and thermal characteristics, but it is extremely inert to the chemicals needed to machine it. Trying to etch these very deep and high-aspect ratio structures into it is difficult," Shkel says. "But we see it as a path to the future of making this very high-precision device."

In addition to designing and fabricating the gyroscope – which can range from 1 millimeter square to about 7 millimeters square – Shkel and his team are creating packaging for the instrument. To function properly, the gyroscope must be vacuum-sealed to isolate it completely from ambient air. "For something like this to oscillate in open air would be equivalent to somebody of our size running in water or in melted caramel," he says.

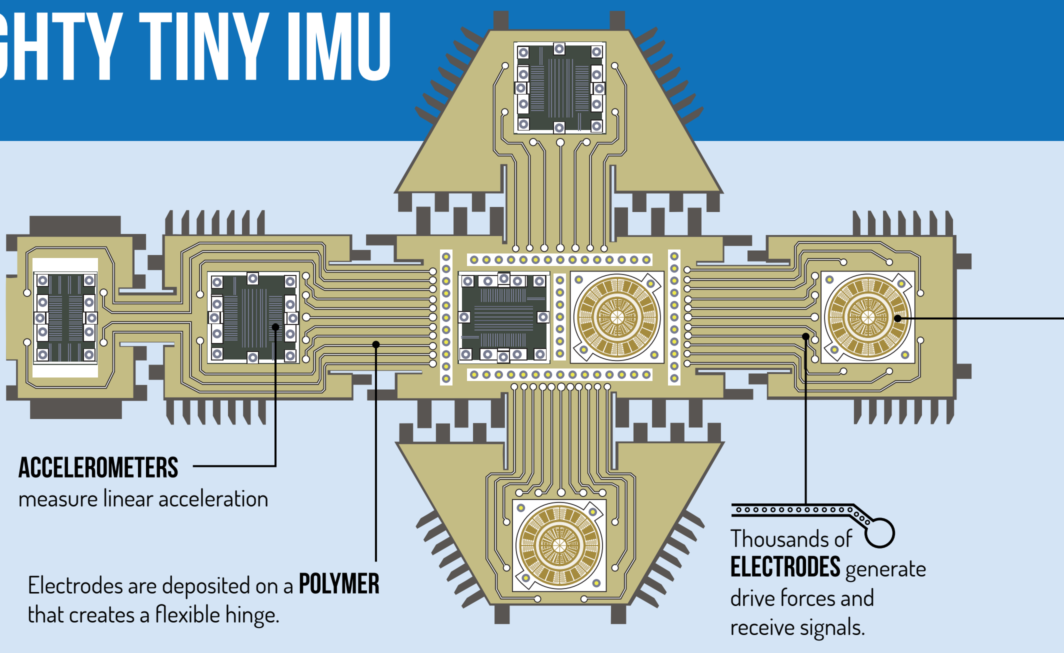
The team also has developed algorithms to control the device's electronics and compensate for residual imperfections. But perhaps more impressive, is the fact that they recently received Phase 3 funding – a rare occurrence in DARPA projects, according to Shkel.

The team learned of the additional $1.05 million in funding after demonstrating the project's technology to a government delegation that visited UCI last summer. DARPA funds projects in phases, and attaining funding beyond the initial feasibility study is uncommon in academic research. "Only after you demonstrate measurable, quantitative results do you transition to the next phase," Shkel says. "The fact that we were transitioned to the final Phase 3 of the program is a big deal and a tribute to our strength at UCI in the development of innovative microsystems."

The additional funding allows the project to expand from a 2D gyroscope

BUILDING A MIGHTY TINY IMU

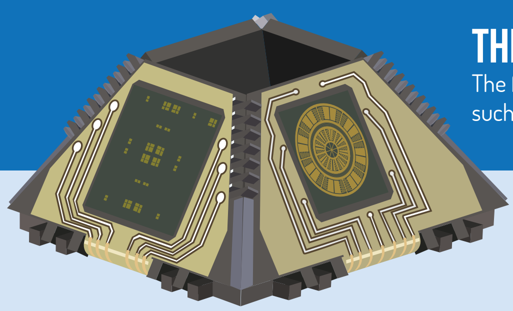
UCI professor Andrei Shkel and his team are working with the U.S. military to develop IMUs (inertial measurement units) for self-contained navigation. The IMUs include three accelerometers and three gyroscopes. They are designed to be much less expensive, and significantly smaller and more durable than traditional navigation systems.



architecture to a 3D version. Each has a separate design and different functionality. The 2D version has been designed to "sleep" through intense shock, like that which occurs during a launch, while the 3D version will continue to operate during this critical window. Shkel expects the two to complement each other. "The 3D gyroscope will be responsible for doing very precise measurements when a missile or a vehicle goes through this very high shock, and the amplitude-amplified 2D sensors are better suited to do very precise measurements when conditions are sort of benign," he explains.

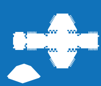
If Shkel's team is successful, the IMUs they are developing will eventually increase exponentially in sensitivity, shrink from the size of an apple to that of an apple seed, and thanks to photolithography, be mass-produced, reducing cost by orders of magnitude. "It's important to have the right tools, the right people and good cleanrooms, which we have at UCI," Shkel says. "It's a very exciting and impactful project."

Mechanical and aerospace engineering graduate student Daryosh Vatanparvar examines a 2D gyroscope prototype made from fused quartz. The tiny gyroscopes will be an integral part of a self-contained inertial measurement unit that can provide interference-free navigation.



THE FINISHED IMU

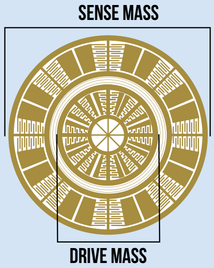
The flat piece is folded origami-style into any number of geometric shapes, such as cubes or pyramids – each about the size of an apple seed.



IMU (ACTUAL SIZE)

DUAL-MASS VIBRATORY GYROSCOPES measure the change in rotational angle per unit of time.

SENSE AND DRIVE MASSES are made from **FUSED QUARTZ,** which holds energy and vibrations longer than silicon and performs better in extreme conditions.



HOW THE GYROSCOPE WORKS

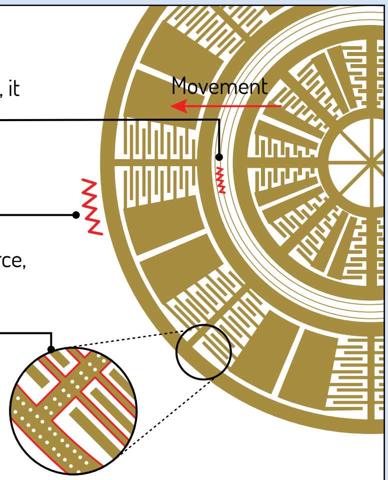
1. When electrostatic forces excite the drive mass, it **produces a vibration** – similar to tapping the rim of a wine glass.

2. Due to its mechanical design, the sense mass **amplifies the vibration**.

The vibration and rotation create the Coriolis force, causing the precession of the vibrating mass.

3. Electrodes **detect the precession** as a low-current electrical signal.

4. **Data are read** by the IMU's microcontroller to determine the rate of rotation.



Transfo

RESEARCHERS EXPAND PERSPECTIVES AND CHALLENGE COMPLACENCIES IN UNEXPECTED WAYS

The Art of rmation

Anna Lynn Spitzer

Frank Armstrong

Many people consider work a four-letter word.

Josh and Karen Tanenbaum do too, except they spell it P-L-A-Y. The husband-wife team runs its Transformative Play Lab on the second floor of the CALIT2 Building, and as its name hints, the Tanenbaums' workspace is no ordinary lab.

Possessing the allure of a high-tech adventure playground, the lab invites exploration and discovery.

Costumes sport RFID tags, a dollhouse waits to be equipped with sensors and turned into an interactive storytelling environment, and 3D printers churn out game pieces and other artifacts of personal fabrication. Students with

laptops sit around several kidney-shaped tables, while pizza boxes tower on another.

One display features a storytelling electronic glove; another, which resembles a theatrical set, is poised to become a groundbreaking virtual reality experience. "Each station in the lab tells a different research story," says Josh, an assistant professor of informatics.

Karen, a project scientist who also is a member of the CALIT2 Division Council, serves as lab manager and collaborates on projects with her husband, whom she met during their first week as college freshmen in the late 1990s.

They came to UC Irvine after finishing graduate school at Simon Fraser University's School of Interactive Arts & Technology in British Columbia, Canada. The two immediately developed a kinship with Geoffrey Bowker, Chancellor's Professor of information and computer sciences, whose Evoke lab also occupies the second-floor space. "We share a lot of interests and research overlap with Geof," says Josh, "and we are kindred spirits in the methods and values we have around our work."

"Josh and Karen bring a marvelous blend of the arts, humanities and computer science to the lab," Bowker says. "The lab's current vibrancy is due in large part to their work."

Because the duo concentrates on large-scale mixed-reality installations and virtual reality research, the CALIT2 lab quickly became home. "This is such a unique space," says Josh, pointing out the lab's high ceilings, theatrical infrastructure and open areas. "We've developed a lot of work that was really only possible because we had a space to install it."

One of those projects, Magia Transformo, or the Dance of Transformation, gives players the opportunity to dress up in an array of hats and cloaks. They dance around an altar, using interactive spell books to unlock an enchanted cauldron's flames and become initiated into a magical society.

The installation debuted at the prestigious IndieCade conference in 2017, an achievement that elated its creators. "No one at UCI has ever produced work that has made it to IndiCade," says Josh, who describes the conference as "the single most prominent festival for up-and-coming independent games. Inclusion in that is something I'm really, really proud of."

Another project, ShadowCast, is an entertainment-based virtual reality installation that combines musical theater and karaoke. Created in collaboration with Broadway producer Tim Kashani, the piece strives to give

Magia Transformo debuts at 2017's IndieCade, a respected festival for promising independent games. Having the installation accepted for display was a proud moment for its creators.

"We have enough in common that it's often hard to tell where one of our contributions ends and the other's begins. I tend to be broader and Karen tends to be practical and focused. I'll be the one who does the associative thinking, then she'll reign me in and we'll focus on what's actually accomplishable."

users a true theater experience as they become characters in a Broadway musical, singing and dancing while seamlessly experiencing a live audience reaction within the virtual reality framework.

Tanenbaum and Kashani are pushing themselves to finish the installation in time for a May debut at the annual Broadway League Conference in New York City, where artists display new work for producers. "Getting this project out in front of a public audience will be an immense accomplishment," Josh says.

While their focus is clearly on play, the Tanenbaums are laser-focused on their goals. Their passion lies in creating experiences that encourage people to interact with new perspectives and develop a deeper bond with unfamiliar points of view. Theater and games provide an inviting backdrop.

Says Bowker: "Josh and Karen are in the vanguard of a movement to reinvent the humanities within engineering and computer science. Through their innovative work in gaming, they demonstrate that we can address fundamental issues through creating new transdisciplinary interconnections."

The couple homes in on art because they believe that is where they can have the most impact. "I don't spend much time arguing about whether games are art, because they are," Josh says matter-of-factly. "We believe deeply that art has always been and will continue to be the most important tool we have as a species for producing those kinds of perspectives – the long-term capacity to meaningfully expand our own individual horizons into somebody else's life experience."

Understanding and sharing unexplored viewpoints is as natural as breathing to Josh and Karen. While Karen had a mostly typical experience growing up in a middle-class suburb outside Chicago, Josh, who identifies as queer and nonbinary, says he experienced gender dysphoria as a child in a small New Hampshire town. He realized he was transgender as early as four or five years old, he says, but didn't have the language to express it. "I was probably the only queer kid in town at that point. I was pretty troubled and pretty lonely."

He spent a lot of time reading and exploring the woods near his home, building a fantasy world in which he could feel comfortable. "I used to construct magical rituals to try to transform myself. It was isolating, and a lot of my early sense of self grew out of my attachment to my isolation and my sense of my own difference," Tanenbaum says with characteristic honesty.

Despite his inherent intelligence and affinity for reading, Josh was a less-than-stellar student. "I was always the kind of kid who didn't do school because I was told to do it. I did the stuff I was interested in."

His family later moved to San Diego, where 10-year-old Josh was "really miserable." That is, until he discovered San Diego Junior Theater. Throughout middle school and high school, he performed and worked behind the scenes. "I found my people there," he says.

Karen was a studious, serious child who loved books, and unlike Josh, was an overachiever. "Karen and I defined our relationship that way," Josh says. "She was the academically successful one, and I was the crazy creative one."

Karen's family moved to Northern California when she was in high school. She met Josh soon after beginning freshman year at University of Redlands, and the two quickly became a couple, even rearranging their housing so they had respective roommates who also were dating.

Both enrolled in a small, hands-on program in integrated studies, which allowed them to create their own majors. Karen chose philosophy and Celtic studies. Josh was a little less conventional. "I specialized in ancient Sumerian and near-Eastern mythology, with a focus on Sumerian myths of the underworld," he says, and after a beat, adds: "And experimental electronic music composition."

"We came out of there, as we like to say, pretty unemployable," Karen quips.

They married after graduation. While Karen got her master's degree in linguistics from UC San Diego, Josh worked "a series of increasingly odd jobs," according to his wife. He read tarot cards for the Psychic Network, worked for an electronics company and backstage in theaters, and did a stint as a lighting technician and engineer for a private company. He also scouted talent for the modeling industry and composed video game music.

Karen, meanwhile, was working part-time at a software company. "That's where I made the transition ... into computational linguistics and technology," she says.

In 2005, at SIGGRAPH, an annual computer graphics conference where Josh helped organize a cyber-fashion show, they saw an art exhibit by two professors from Simon Fraser University. Both Tanenbaums were intrigued, and decided to apply for a doctoral program there. "It was a relatively new program in interactive arts and technology, and at the time it was pretty unique," Karen says. "So we went there thinking, oh, Josh, could do his art stuff and I can do my tech stuff. It's a great program for both of us."

They began the doctoral program, but their plans soon shifted slightly. Karen, who had always envisioned herself in academia, decided she didn't really want to teach. Josh, who had spent his life being called a mediocre student, flourished in the doctoral program and weighed the possibility of pursuing an academic career.

A couple of years later, when UCI posted a computer games and human-computer interaction (HCI) faculty position, Josh applied. He was hooked when he visited the campus. "I was so blown away by the diversity of the community intellectually, by the sense of camaraderie and sanity and kindness, by the commitment to having healthy life and work habits," Josh says. "It was the most welcoming academic environment I had ever experienced."

Karen secured a part-time contract as a CALIT2 project scientist, and they arrived in Irvine in 2014. She also does some virtual reality work on the side with small startup companies, including one called Shovels+Whiskey. Josh lends his expertise from time to time as an unpaid consultant.

"What makes Karen and Josh truly excellent is their commitment to interdisciplinary exploration," says Shovels+Whiskey principal Tawny Schlieski. "In particular with evolving technology and changing patterns of use, Josh and Karen's open exploration of ideas from gaming, HCI and theater help them to uncover truly unique and compelling insights."

Schlieski also praises the Tanenbaums' broad skill set. "They can seamlessly innovate on both the technical interface elements, as well as the instructional design approach to the broader social science objectives," she says.

Josh Tanenbaum, seated, discusses design of a new real-time audio processing virtual reality project with his doctoral students Ke Jing (left) and Saumya Gupta.

"We believe deeply that art has always been and will continue to be the most important tool we have as a species for producing those kinds of perspectives – the long-term capacity to meaningfully expand our own individual horizons into somebody else's life experience."

As much as he loves designing, Josh also has developed an unexpected love for teaching. He relishes the role of supporting his students through the design process, and leads the computer science capstone game project class, a two-quarter-long design collaboration with industry mentors. "My happy place is working in a project-based class where students are doing iterative design," he says.

That enthusiasm – "In the classroom I put on the Josh show," he wisecracks – has led to close relationships with his students. They describe him as passionate, enthusiastic, thoughtful and supportive.

"I think Josh is willing to push the boundaries of what we research in the informatics department, and brings an energy and level of excitement to his mentoring that gets his students and research assistants excited about trying something new and unknown," says former student Nicole Crenshaw.

Crenshaw, who earned her doctorate in 2017, currently works as a user experience researcher at video game company Blizzard. She says she is still in touch with many students in Josh's capstone course. "I know he is what makes that course as enjoyable as it is. It is not at all an exaggeration when I say I have had students tell me that his course is the ONE course they look forward to going to."

Archana Senthilkumar graduated last December with a master's degree and now works as a technical director trainee at Walt Disney Animation Studios. "I always knew that I wanted to work at the intersection of art and technology, and while I had a good technical background, my understanding of the creative process was very limited," Senthilkumar says. "Working with Josh introduced me to the more iterative nature of art and how the creative design process could be understood better through research and quantitative terms. ... I'm sure [his mentoring] helped me obtain my current role at Disney Animation."

Karen and Josh are now parents to a 3-½-year-old blonde bundle of energy named Abigail, who considers her parents' workplace her second home. "Our lab has a lot of attraction for her," laughs Karen after Abigail demands of Josh, "Daddy, can you pay attention to me for a little bit? But you have to be in front of the whiteboard."

"She's an evil genius," Josh says fondly of his daughter, whom he has begun indoctrinating into the world of game design; together they are redesigning the childhood classic Candyland to include a variety of choices and strategies. "She is already a very strong narrative thinker, and she's good at storytelling and at cause and effect," Josh says. "I'm trying to get her to shift that thinking into game design."

Both Tanenbaums describe themselves as creative, curious and cynical. "We're basically the same person," Karen jokes when told that Josh had used the same adjectives.

"We have enough in common that it's often hard to tell where one of our contributions ends and the other's begins," Josh concedes, but he sees their skills as complementary. "I tend to be broader and Karen tends to be practical and focused," he says. "I'll be the one who does the associative thinking, then she'll reign me in and we'll focus on what's actually accomplishable."

Josh considers himself an optimist as well. "I'm torn between wanting the world to be better than it is and expecting better things from the world than it actually provides."

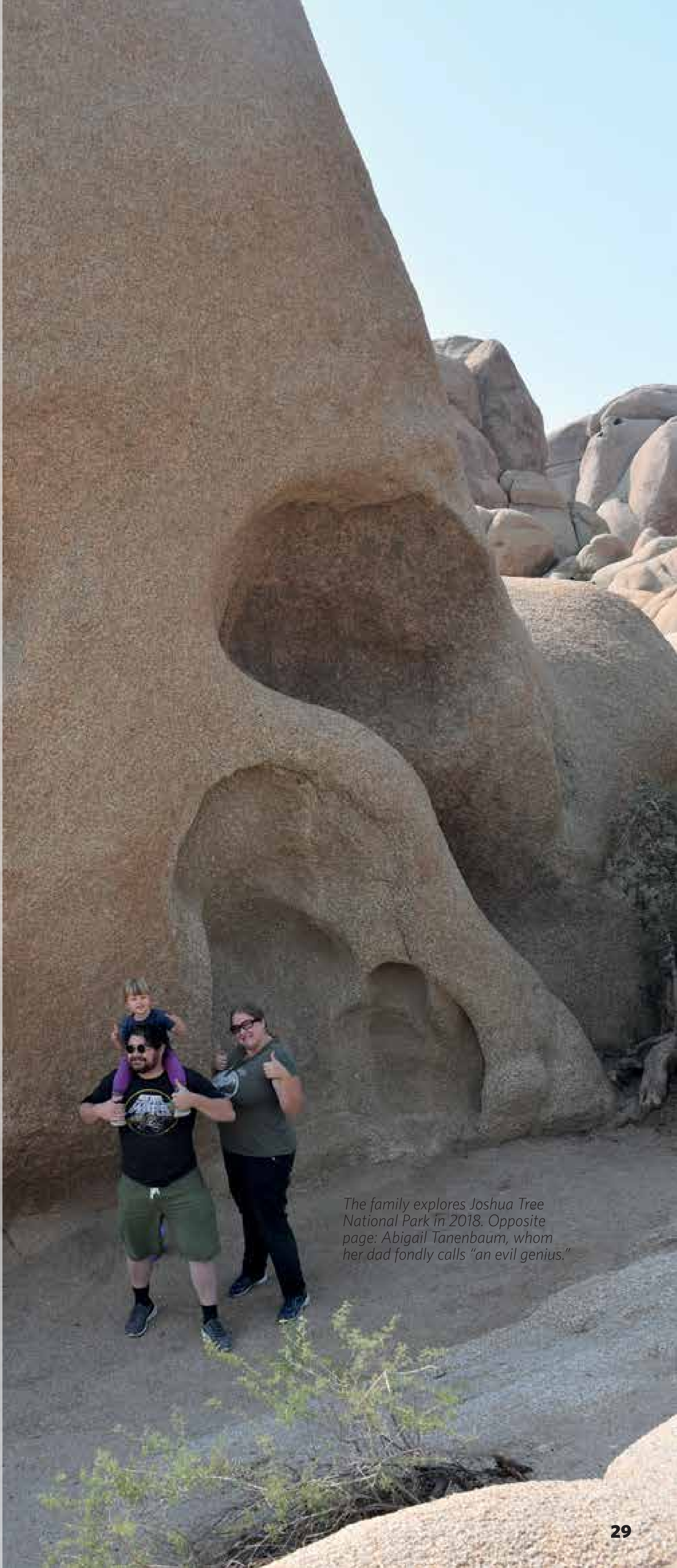
He finds a sort of catharsis through his work. "I'm trying to make things better. The cynicism leads me to deeply and profoundly feel injustice and identify things I want to make better. And the optimism gives me the resources to do that ... the ability to delude myself into thinking that I can actually make a small difference."

Making that difference includes being straightforward about his sexuality, says Josh, who often presents as female on weekends, when not in work mode. "I have a wife, I have a daughter. On the surface, I look like a straight dude. I benefit from a lot of male privilege and a lot of straight privilege," says Josh. "So I feel that I have a responsibility as somebody who is not a straight dude to be a role model to students who are looking for someone like them in the teachers they interact with. I have a responsibility to not just benefit from that privilege but to extend that privilege to people who are more vulnerable or at risk than I am."

Tanenbaum is still incredulous that he ended up on the tenure track at a research university. "It's astonishing and unexpected," he says. "I always assumed I would be the stay-at-home dad, doing odd jobs and writing, and Karen would be in academia."

Adds Karen: "And then we found this field where his crazy creativity could be channeled into something that was also intellectually rigorous."

Josh nods. "I've always been most successful when I'm doing the things that I'm genuinely excited about," he says. "But I mean, I study fun for a living, I study play and art and music and theater. And I believe very deeply that those are the things that matter."



The family explores Joshua Tree National Park in 2018. Opposite page: Abigail Tanenbaum, whom her dad fondly calls "an evil genius."

Bubble

Lori Brandt Debbie Morales

FROM CONCEPT TO PATENT PENDING, RESEARCHERS DEVELOP AFFORDABLE WOUND-HEALING DEVICE

Benefit

What started out as an idea to improve the common bandage turned into a medical device bubble machine called Bubtech. That's what can happen when you put researchers from different disciplines together.

In 2015, Dr. Alan Widgerow, a South African plastic surgeon who now researches tissue engineering and device innovations for wound care at UC Irvine, went to CALIT2's eHealth Collaboratory. He wanted help with a silicone patch to measure fluids from burn wounds. He met Michael Klopfer, a CALIT2 technical professional, who was then a biomedical engineering graduate student with former assistant professor Mark Bachman. Klopfer and Bachman introduced Widgerow to the emerging concept of micro/nanobubbles (MNBs), and the three joined forces to investigate how they could use these tiny bubbles for wound healing.

MNBs are tiny gaseous vesicles in fluid. Composition of the bubbles determines important versatile features such as stability in water, buoyancy, gradual shrinkage and collapse. They are used for a wide variety of purposes, including wastewater treatment, biofuel production and agriculture, but their use in medicine was limited. Considering that oxygen is vital to wound healing, the researchers felt MNBs showed promise.

> **"The idea with Bubtech is several treatments at the bedside over the course of a couple weeks, and you're looking at a high chance of recovery for people with painful open wounds like diabetic ulcers."**

"We realized the bubbles could dynamically act like reservoirs for oxygen and provide wound-cleaning properties," says Klopfer. "We explored different balances of oxygen. You can take pure oxygen, or you can balance it with another gas, such as nitrogen or helium, to provide improved healing for different cell types and treatment conditions. The bubble sizing is critical."

Microbubbles exist from 100 microns to about 1 micron (the size of a human hair to smaller than a bacterium). Even tinier nanobubbles range in size from 1 micron down to 50 nanometers (below the wavelength of light) and can be very long lived. Smaller than approximately 50 microns (half the width of a human hair), the bubbles shrink and deliver the contained gas into the surrounding solution. These bubbles attach to surfaces, provide cleaning action and break up biofilms.

When MNBs are produced in water using oxygen or air as gas in their core, their negatively charged surfaces not only prevent them from merging, which would cause them to lose their properties, but help them attract particulate matter and assist in the removal of debris. In addition, MNBs generate free radicals as they shrink, potentially contributing to their antibacterial effects.

One dissertation (Klopfer's), three engineering student-design teams and four years later, Widgerow and Klopfer are on the cusp of clinical trials with a patent pending. A true translational project between medicine and engineering, Bubtech is a dual-component point-of-care system that combines both MNB technology and negative-pressure wound therapy (NPWT). It provides a steady stream of super-oxygenated fluid (bubbles) to irrigate and aerate a wound through a foam dressing secured under a silicone patch. Simultaneously, it acts as a vacuum aspiration system, sucking up all the debris, fluid and infected tissue in and around the wound and depositing the waste into a disposable container.

The Bubtech researchers believe their device will kick-start the healing process, prevent bacterial infection and reduce the time a patient spends in the hospital as well as the cost of treating wounds and further complications that might require surgery.

"I knew wound healing would be a primary indication due to the amazing capability of these bubbles to store and slowly release oxygen," says Widgerow, whose team, headed by Dr. Ross Sayadi and in collaboration with the Beckman Laser Institute, has been conducting animal studies on the technology. "We've used an animal burn wound model and demonstrated dramatically increased wound healing, tissue oxygenation and collagen formation with the bubbled solution as compared to saline alone."

On the CALIT2 side, Klopfer and the engineering students have been working on refining device designs and creating upgrades. Last year's student team, working with Klopfer and UCI biomedical engineering professor Michelle Khine, won the UCI BioENGINE Fellowship Award ($15,000) and a space in Applied Innovation's Wayfinder incubator.

This year's team consists of five electrical engineering students who created a closed-loop control system to ensure patient safety and consistent device performance.

"We make sure at every single stage, the fluid is being generated and delivered correctly," says Yaxin Deng, a fourth-year student and project lead. "Our pressure sensors, relays and valves all need to perform properly to ensure the safety of the device." An LCD touch screen and Bluetooth compatibility allow for easy setup and use, as the proof-of-concept device transitions into an early product.

Approximately 6.5 million Americans suffer from chronic or non-healing

wounds, according to the National Institutes of Health. The cost of managing these patients' wounds and related complications exceeds $25 billion per year.

Bubtech would cost less than current treatments, which include negative pressure, cell graft, surgery and hyperbaric oxygen therapy. In addition, it's portable and can be tailored to the patient's needs. Bubtech is a rapid, wound-healing device on wheels that delivers custom-controlled oxygen content to help heal diabetic foot ulcers and a range of other open wounds.

Electrical engineering students (from left) Junyang Yao, Junkun Guan, Yaxin Deng, Yongxi Li and Eric Tram present the current version of the Bubtech wound-healing device at UCI Samueli School of Engineering's 2019 Winter Design Review.

"This would be suited to medevac cases with major soft-tissue injuries in the military as well as other acute burn and chronic wound situations," says Widgerow.

Klopfer is excited to see the device progress. "The idea with Bubtech is several treatments at the bedside over the course of a couple weeks, and you're looking at a high chance of recovery for people with painful open wounds like diabetic ulcers."

ZOTERRIFIC!

UCI'S 3D PRINTED MASCOT IS TOO SMALL TO SEE WITH THE HUMAN EYE

Anna Lynn Spitzer

UC Irvine's quirky Anteater mascot comes in many sizes

From the 8-foot tall human incarnation that cheers at basketball games to stuffed animals only inches high, Anteaters are a familiar sight on campus. Now, a novel, 3D-printed version – too small to be seen in detail with anything except a scanning electron microscope (SEM) – could be the smallest Anteater ever.

The tiny mascot, which appears to the human eye to be a small dot, measures 60 microns in length and stands on a 30-micron base. (A micron is one-millionth of a meter. For comparison, a human hair is about 75-100 microns thick.) The miniature Anteater was printed on a Nanoscribe 3D printer, from an acrylate polymer, with a process called two-photon polymerization direct laser writing.

CALIT2 affiliate Lorenzo Valdevit, UCI materials science and engineering associate professor, researches mechanical metamaterials and designs novel materials with a unique combination of properties. He says that two-photon polymerization direct laser writing has allowed researchers to build new materials with nanoscale details. "You can print things of almost arbitrary complexity and fabricate very intricate objects in ways you cannot with traditional subtractive processes." He adds wryly: "We don't only use it to print Anteaters, though. We use it to generate metamaterials that actually have remarkable properties."

Valdevit and graduate students Anna Guell and Cameron Crook fashioned the nanoprinted Anteater in the lab, but a collaborator in Clarksburg, Maryland, created the colorized SEM image. Eric J. Miller, from Hitachi High Technologies America, developed a new method for imaging these tiny polymeric constructions in an SEM. Because polymers are not electrically conductive, a metal coating can help maintain their composition when they're bombarded by the electron beams of an SEM. But the coatings can change the mechanical properties of such small structures, so Miller developed a technique that eliminates the need for any metal.

Miller asked Valdevit for samples to test his new method; that's when the UCI researcher got the idea to build a tiny 3D Anteater (he sent other samples, too).

While two-photon polymerization allows for printing materials at previously unthinkable scales, it still involves writing point by point, an extremely time-consuming process. The nanosized Anteater took about an hour to print, but something visible to the naked eye could take longer than a day, according to Valdevit.

Researchers are trying to figure out ways to scale up the technology. "For this technique to be impactful in structural materials, it would have to become 10,000 times faster," Valdevit says.

In the meantime, the tiny mascot has amassed a large distinction. "It may be the smallest Anteater ever printed," says its creator.

RECYCLING ELECTRONICS CAN REDUCE TOXIC BYPRODUCTS AND RECOVER PRECIOUS METALS IN SAFE AND USEFUL WAYS

e-wa

Sharon Henry

sted

Last year, the world generated nearly 50 million metric tons of e-waste – nonworking electronics like computers, laptops, TVs and cellphones. To envision the enormity of this, imagine the weight of 15 million elephants.

What happens to these obsolete devices, the people who recycle them and the limited natural resources needed to continuously manufacture new devices?

Our e-waste problem began in the late 1990s. The Environmental Protection Agency began noticing landfills loaded with junked electronics, says CALIT2 academic affiliate Oladele Ogunseitan, chair of UC Irvine's Department of Population Health and Disease Prevention. "Cellphones soon became, in terms of individual items, the largest number of e-waste items."

Rapid innovation encouraged users to upgrade devices often, a practice that continues today. The average U.S. mobile phone owner gets a new model every 22 months. According to the EPA, we get rid of more than 416,000 mobile devices every day.

Below: Oladele Ogunseitan is working to prevent pollutants in everyday electronic products from contaminating landfills and endangering public health. Photo: Steve Zylius.

Opposite page: A man in Ghana scavenges an e-waste dump to recover copper from disposed electronics.

Twenty years ago, cellphones were cheap. Telecommunication companies made money from selling minutes rather than the hardware itself, and many of those phones ended up in the trash. The EPA reports that about 60% of American e-waste goes to landfills in the country and abroad.

Ogunseitan has studied the impact of all this e-waste. More than a decade ago, he headed a National Science Foundation-funded project that investigated how hazardous materials, such as toxic metals and brominated flame-retardants found in e-waste, break down and contaminate landfills and groundwater.

Most early cellphones contained tin-lead soldering in their circuit boards. "The electronics industry was already thinking this might come under regulation because lead is never good for health. Over time, after a little rain, things leach out," Ogunseitan says. Lead can contaminate groundwater and soil, as can other materials, including mercury, nickel and cadmium.

Efforts by the EPA to stimulate recycling have resulted in generous trade-in incentives and a burgeoning global market for refurbished mobile phones. But that industry also faces challenges. "There is a huge number of phones coming in that are not usable and they have to be disposed of, often by shipping overseas," Ogunseitan says.

This e-waste is nearly always exported to impoverished areas, where e-waste-foragers comb through the refuse searching for parts to resell. Burning e-waste is the fastest and cheapest way to get at the tiny bits of gold and silver embedded in the circuitry. One smart phone has 0.034 grams ($1.39) of gold (a metal that never corrodes, and conducts even a very weak electric current), 16 grams (12 cents) of copper, 0.35 grams (17 cents) of silver, and 0.00034 grams (two cents) of platinum. Precious metal in cell phones discarded by the U.S. alone has been valued at more than $60 million.

“There’s a lot of waste in e-waste that shouldn’t be waste. We need to take it back.”

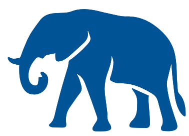
Initially, China imported much of the e-waste. The notorious village of Guiyu, in the eastern Guangdong province, was known as the electronic graveyard of the world. For decades, nearly 60% of the village’s 100,000 residents made their living processing e-waste, typically using their bare hands to dismantle the old electronics. Circuit boards were “cooked” over coal fires or dipped into hydrochloric acid to recover precious metals and lead.

Once a rice village, noxious fumes from smoldering fires polluted Guiyu’s air and soil, making crop production unsafe. Acid wastewater discharged into the local river rendered the water undrinkable. A 2007 study by researchers at Shantou University Medical College found that 80% of the city’s children had dangerous levels of lead in their blood. Another study showed e-waste workers in China had high concentrations of toxic flame-retardants in their bodies; one person tested at the highest concentration ever reported.

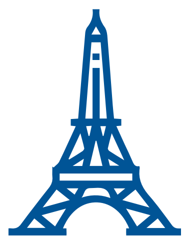
In 2013, China imposed stringent regulations on e-waste dismantling and disposal. In Guiyu, workshops relocated to an industrial zone, where better facilities helped reduce pollution and offered better protection for workers. Even with these new safeguards, the U.N. warns that China is rapidly generating its own super-surplus of e-waste. In 2018, the nation produced more than 1.6 billion cellphones.

There’s no shortage of unregulated recycling operations in developing countries. Ogunseitan has traveled to Accra, Ghana, home to another iconic hazardous-waste dumping ground. He recalls the ground littered with fragments of broken electronics. “There’s a river system that runs along the village that is stagnant and filled with black water, and there are lots of young men and some women taking things apart, trying to extract a little copper by burning off the plastics, with the result that they are inhaling lead, cadmium, dioxins, furans and brominated flame retardants. There’s always this incentive for people who need the labor and money, and are somewhat aware of the risks, but it’s not enough to deter them,” he says.

THE AMOUNT OF E-WASTE GENERATED GLOBALLY LAST YEAR (50 MILLION TONS) IS EQUIVALENT TO:



15 MILLION ELEPHANTS



4,500 EIFFEL TOWERS

100,000 LOADED 747s

Back in the U.S., the EPA has the authority to control the transportation, treatment, storage and disposal of hazardous waste. Some e-waste, such as cathode ray tube (CRT) TVs and monitors, is classified by the EPA as hazardous waste, making their transportation subject to regulation under the Resource Conservation and Recovery Act. However, regulations against shipping hazardous waste don't apply to items being exported for recycling.

An international treaty known as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal is an agreement designed to reduce the movements of hazardous waste between nations, and specifically to prevent the export of hazardous waste from developed to less-developed countries. To date, 86 countries, including the entire European Union, have implemented the treaty.

But there are loopholes, Ogunseitan notes. Cellphones, or e-waste in general, can be labeled as refurbishable or charitable donations and shipped to other countries without violating the treaty. "It's how you label the used electronics," he says.

Raw materials needed to manufacture electronics are often mined in areas prone to conflict. Political unrest leads to soaring costs for raw materials, human rights concerns and resource scarcity. One example is cobalt, used in lithium-ion rechargeable batteries.

More than 60% of the world's supply of cobalt comes from the Democratic Republic of the Congo, where children labor to mine heterogenite – a cobalt-containing stone. The rocks are sold to international processors, who then pass the cobalt on to multiple companies and supply chains. Last year the battery industry used about 48,000 tons of cobalt, and projections indicate more than double that amount will be needed by 2025 to meet global demand.

Even if manufacturers try to avoid purchasing cobalt mined by children, tracing supply chains is complex and costly. In January, international natural resources producer Eurasian Resources Group (ERG) launched a pilot program in its Congo-based plant to track the origin of cobalt. ERG is relying on blockchain – a record-keeping technology that uses a network of computers to share data about every transaction and participant – to confirm that its cobalt was sourced responsibly.

"But ultimately I think the solution is learning to recover cobalt from e-waste so we don't have to go through the rocks in Republic of Congo," Ogunseitan says.

An advanced e-waste recycling method known as urban mining can recover staggering amounts of valuable materials from e-waste. The four largest urban mining facilities are located in Belgium, Germany, Sweden and Canada.

Umicore, based in Brussels, is the world's largest precious metals recycling factory. The operation processes 1,000 tons of e-waste each day, and annually recovers 25 tons of platinum, 100 tons of gold and 2,400 tons of silver. E-waste comes into the factory and is separated, shredded or magnetically sorted, then continues a multistep process of smelting, leaching and electrowinning. In the final step, precious metals are collected from a residue – a bit like panning for gold along a riverbed. Toxic

Open burning of plastic-encased electronics and sheathed cables to recover copper and other valuable metals at the Agbogbloshie e-waste landfill in Ghana. The young men inhale dangerous levels of toxins during the process.

gases are monitored during the smelting process to guarantee emissions meet European and Flemish environmental control requirements.

Umicore sees itself as a leader in the circular economy movement. Unlike the linear economy model – described as take, make, dispose – a circular economy aims to recover and reuse resources. According to Umicore, more gold is recovered from one ton of e-waste than is found in 17 tons of gold ore.

Building a factory like Umicore in California would be almost impossible due to environmental regulations, according to Ogunseitan. Mishaps and cleanup from previous lead recycling efforts have cost the state nearly $200 million. "I'm all for environmental regulations," Ogunseitan says, "but [today] you can't establish a new incinerator for hazardous waste in California."

In 2017, UCI partnered with 25 universities, 44 companies, seven national labs, 26 industry trade associations and foundations, and three state governments (New York, Colorado and Utah) to establish the Reducing Embodied-Energy & Decreasing Emissions (REMADE) Institute.

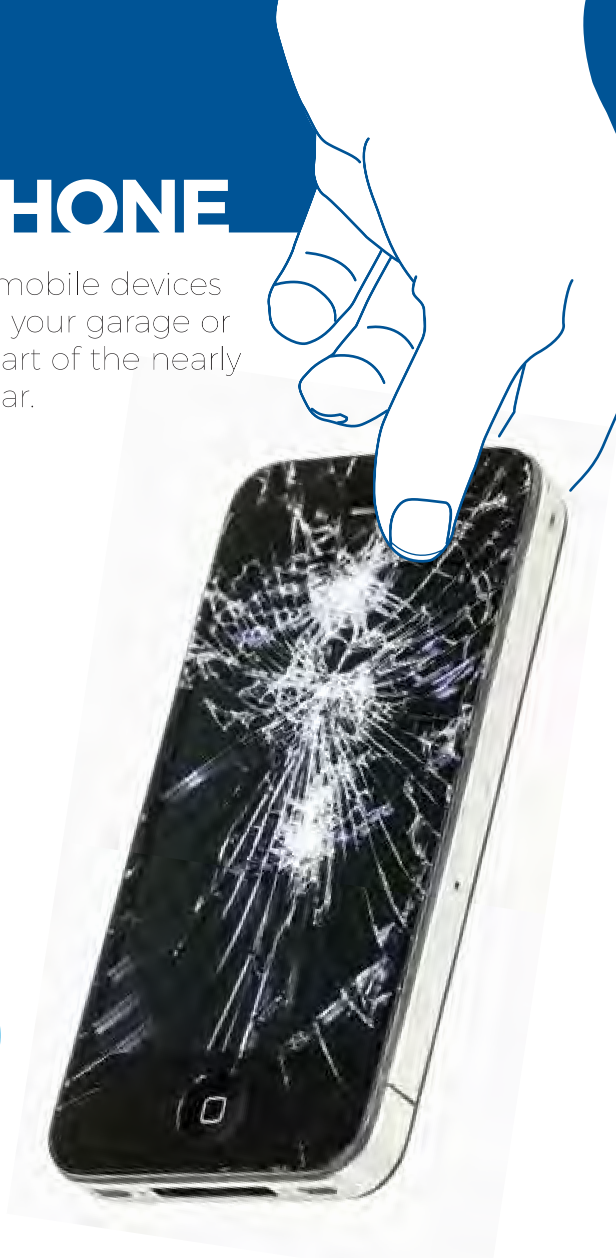
REMADE's primary focus is to understand the steps needed to retool remanufacturing processes for the circular economy. Ambitious research could discover new materials that could replace lead, cobalt and other hazardous metals in electronics. UCI researchers also are looking at ways to create products intended for reuse, recycling and remanufacturing.

Ogunseitan believes the REMADE collaboration can produce results. "Combining efforts could go a long way to minimizing the risks from e-waste – from mining cobalt, to worker safety, to the end-of-product life or to being thrown into a landfill in Accra, Ghana," he says. "There's a lot of waste in e-waste that shouldn't be waste. We need to take it back."

WHAT HAPPENS TO YOUR OLD CELLPHONE

According to the EPA, Americans get rid of 416,000 mobile devices every day (not counting those old phones stashed in your garage or junk drawer). Discarded cellphones make up a big part of the nearly 50 million metric tons of e-waste generated each year.

Here's what happens to discarded devices:



15-20% RECYCLED

Only 15-20% of e-waste is properly recycled. Of this, 40% of cellphones collected for recycling are refurbished.

APPETITE FOR INNOVATION

The average U.S. mobile phone owner upgrades to a new model every 22 months.

UP TO 80% EXPORTED

As much as 80% of e-waste generated in the U.S. is exported to Asia.

RECOVERING TREASURES

Recycling from 1 million cellphones can recover:

Copper: **20,000 lbs.**

Silver: **550 lbs.**

Palladium: **20 lbs.**

Gold: **50 lbs.**

3-5% DISPOSED

3-5% of e-waste ends up in landfills or is incinerated.

Incineration

Burning e-waste greatly reduces the volume, however it releases harmful mercury and cadmium gases into the environment.

Landfills

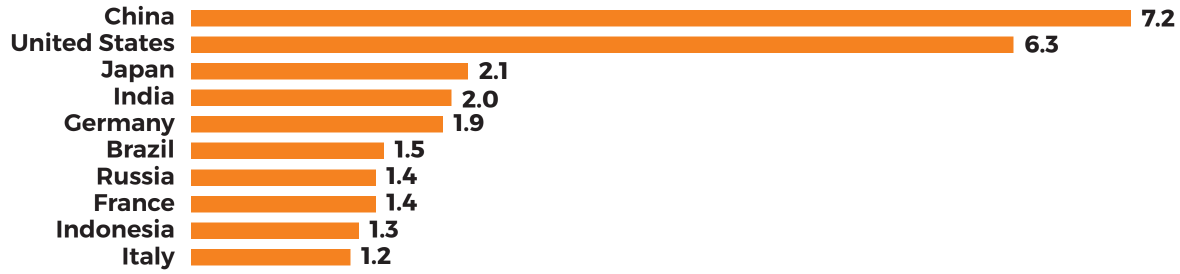
The most common form of e-waste disposal, landfills also have environmental impacts. Toxic substances like cadmium, lead and mercury can be released and contaminate soil and groundwater. Trace materials from e-waste account for 70% of toxic material in landfills, but only 2% of the trash by volume.

While e-waste makes up a mere **2%** of landfill volume, it accounts for **70%** of landfills' toxic waste.

Sources: The U.S. Environmental Protection Agency, "E-waste management as a Global Challenge" (2016) by Florin-Constatin Mihai and Maria-Grazia Gnoni, The Global E-waste Monitor 2017, United Nations University, the International Telecommunication Union, the International Solid Waste Association, BASEL Action Network, Greenpeace.

TOTAL E-WASTE GENERATED BY COUNTRY

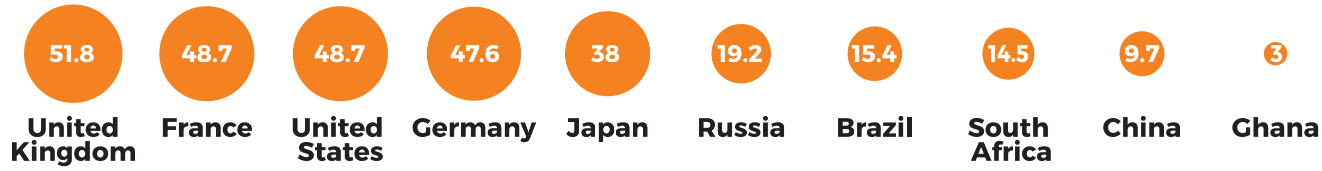
Top 10 countries by amount of e-waste* generated (In millions of tons)



*2016, includes devices with batteries or plugs, including mobile phones, laptops, TVs, refrigerators, electrical toys and electronic equipment.

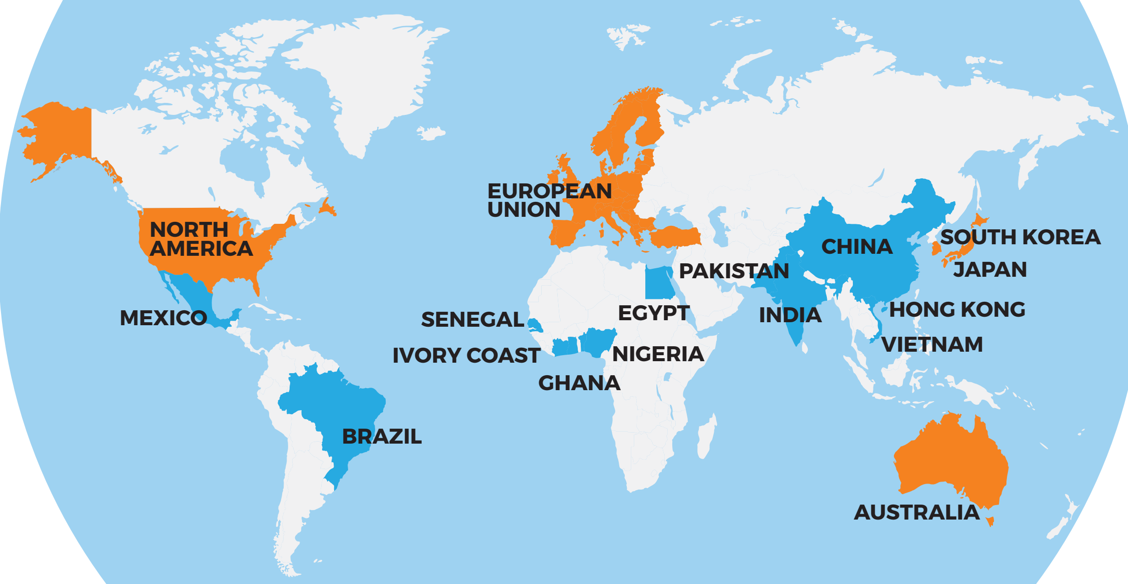
E-WASTE GENERATED ANNUALLY PER PERSON

(By country, in pounds)



WHERE E-WASTE ENDS UP

There is no established system for tracking e-waste shipments. This map is based on reports from Basel Action Network, Silicon Valley Toxics Coalition, Toxic Link India, SCOPE and Greenpeace.



E-waste original source

E-waste final destination

WORKERS

Workers often dismantle e-waste with their bare hands and are exposed to harmful chemicals such as beryllium, barium, arsenic, lead and mercury.

AIR

To harvest precious metals, e-waste is burned, releasing toxic fumes that are harmful to humans and the environment.

WATER

Wastewater from acid washes used to recover precious metals contaminates soil and waterways.

A Parting Shot

The environment, specifically water-related issues, is a focal point for UC Irvine researchers and an important CALIT2 priority as well. Last year, two CALIT2-affiliated researchers were part of a fact-finding mission to Paraguay to tour flood-ravaged areas and open dialogue with local residents. The team is working with Paraguayan civilian and government officials to address challenges created by flooding, deforestation and wetlands degradation. Brett Sanders, professor of civil and environmental engineering, and Richard Matthew, professor of urban planning and public policy, were among those on the UCI RISE team who made the trip, which was sponsored by UCI's Blum Center for Poverty Alleviation and its Resilient Infrastructure and Sustainable Environments program. RISE addresses extreme environmental impacts through research that makes powerful data and technology accessible to a wide range of decision-makers, using advanced computer simulations and visualizations that enable anyone to understand risks based on familiar reference points. "Our goal is to work collaboratively with our counterparts to gain a deeper understanding of the interconnections and trade-offs between climate, the environment, agriculture, trade and the displacement of populations," says Sanders, the project's research lead. "With that, we can hope to get a better handle on problems related to health, the environment, the economy and society as a whole."

Under the direction of Professor G.P. Li, CALIT2@UCI develops IoT technology-based innovations in a multidisciplinary research environment. By integrating academic research with industry experience, the institute seeks to benefit society, incubate new technology companies and ignite economic development. CALIT2 focuses on the digital transformation of health care, energy, the environment and culture.

UCI CALIT2
California Institute for Telecommunications and Information Technology

4100 CALIT2 Building
Irvine, CA 92697-2800