FALL 2019

# CONVERGENCE

The magazine of engineering and the sciences at UC Santa Barbara

FOCUS ON:

## HOT TOPICS

FIVE IMPORTANT AREAS WHERE UCSB RESEARCHERS ARE MAKING STRIDES

## UCSB'S QUANTUM LEAP

CAMPUS SELECTED AS SITE OF FIRST NSF-FUNDED QUANTUM FOUNDRY

## EXPANDING THE PALETTE

DISCOVERING A NEW PHASE IN BLOCK COPOLYMERS

## DUAL INTELLIGENCE

TEAM LINKS TWO TYPES OF MACHINE LEARNING ON ONE CHIP

UC SANTA BARBARA

# MESSAGE FROM THE DEANS

ROD ALFERNESS
*Dean and Richard A. Auhll Professor, College of Engineering*

PIERRE WILTZIUS
*Susan & Bruce Worster Dean of Science, College of Letters & Science*

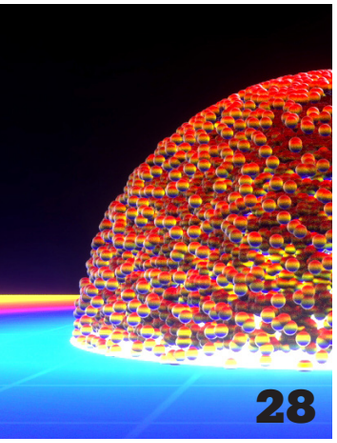
Thanks to decades of technological innovation, computer micro-processing speeds today are forty million times faster than they were just forty years ago, and the smallest transistors on a chip are about ten nanometers wide, or one ten-thousandth the width of a human hair.

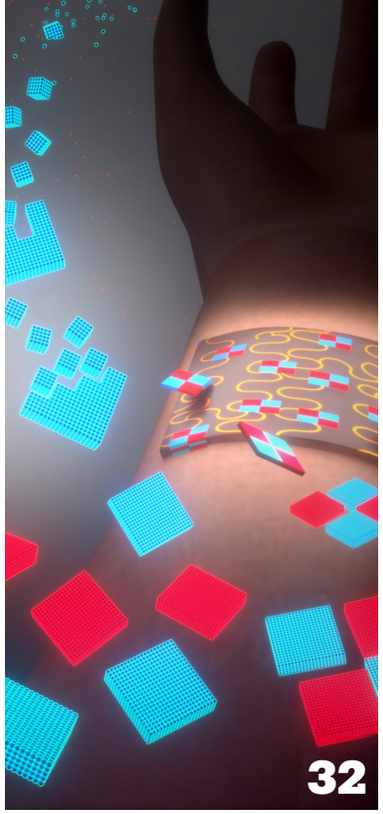
While computer engineers continue to eke out yet more efficiency from even smaller chips, the limit to how many transistors can be packed onto a silicon chip is rapidly approaching. Beyond that limit lies the next revolution, which may be quantum information systems. It is a revolution that will be made possible, however, only by developing new materials exhibiting quantum states that can, eventually, be harnessed to enable a vast realm of faster, more-efficient technologies.

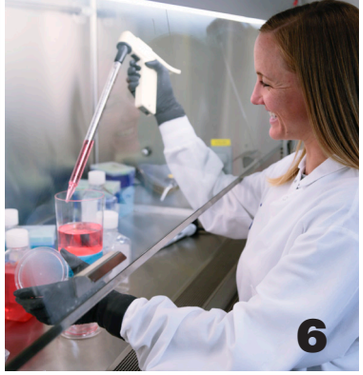
This past September, UC Santa Barbara received the high honor of being named the site of the nation's first National Science Foundation Quantum Foundry. UCSB's proposal was selected from among 37 submitted by the nation's top universities. The six-year, $25-million award is a striking example of the value that has accrued organically from UCSB's highly collaborative, extensively interdisciplinary orientation. That all-for-one approach has allowed us to assemble tremendous faculty expertise in relevant disciplines, as well as state-of-the-art equipment, for example, academia's largest collection of growth chambers for molecular beam epitaxy, essential for creating new materials. See page 8 to read about what this major award means for the university and the future of materials to enable quantum technologies.

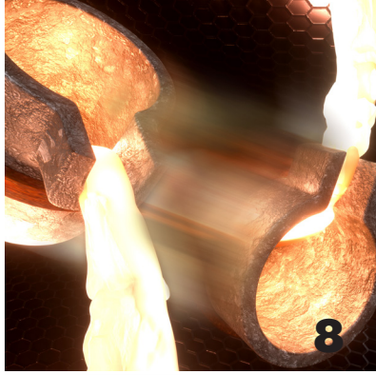
That same innovative, collaborative approach to problem-solving is evident all across engineering and the sciences, as shown in this issue's eleven-page "FOCUS ON: Hot Topics" section, beginning on page 17. Here, we introduce twenty-three research thrusts in five departments representing the leading edge of some of the most compelling topics of the day: machine learning, the control of dynamical systems, materials for quantum applications, systems biology and bioengineering, and a materials approach to new water-filtration membranes.

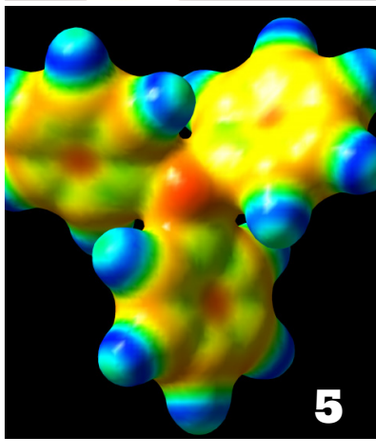
These articles represent only the tip of the engineering-and-science iceberg, of course, and this issue includes much more about the exciting work that continues to distinguish this university. We hope you find it as inspiring as we do.









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UC **SANTA BARBARA**
College of Engineering

# NEWS BRIEFS

## HYDROGEN'S NEGATIVE EFFECT ON BATTERIES

Batteries power our lives. We rely on them to keep our cell phones and laptops buzzing and our hybrid and electric cars on the road. But ever-increasing adoption of the most commonly used lithium-ion batteries may actually lead to increased cost and potential shortages of lithium — which is why sodium-ion batteries are being researched intensely as a possible replacement. They perform well, and sodium, an alkali metal closely related to lithium, is cheap and abundant. The challenge is that sodium-ion batteries have shorter lifetimes than their lithum-based siblings.

UC Santa Barbara computational materials scientist **Chris Van de Walle** and colleagues have now uncovered a reason for the loss of capacity that occurs over time in sodium batteries: the unintended presence of hydrogen, which leads to degradation of the battery electrode. Van de Walle and co-authors **Zhen Zhu** and **Hartwin Peelaers** published their findings in the journal *Chemistry of Materials.*

"Hydrogen is commonly present during the fabrication of the cathode material, or it can be incorporated from the environment or from the electrolyte," said Zhu, who is now at Google. "Hydrogen is known to strongly affect the properties of electronic materials, so we were curious about its effect on $NaMnO_2$ (sodium manganese dioxide), a material commonly used as a cathode in sodium-ion batteries."

To study this, the researchers used computational techniques capable of predicting the structural and chemical effects that arise from the presence of impurities.

Professor Peelaers (now at the University of Kansas) describes the key findings: "We quickly realized that hydrogen can easily penetrate the material, and that its presence enables the manganese atoms to break loose from the manganese-oxide backbone that holds the material together. This removal of manganese is irreversible and leads to a decrease in capacity and, ultimately, degradation of the battery."

"Earlier research had shown that loss of manganese could take place at the interface with the electrolyte or could be associated with a phase transition, but it did not really identify a trigger," said Van de Walle, in whose Computational Materials Group the studies were performed. "Our new results show that the loss of manganese can occur anywhere in the material, if hydrogen is present. Because hydrogen atoms are so small and reactive, it is a common contaminant in materials. Now that its detrimental impact has been flagged, measures can be taken during fabrication and encapsulation of the batteries to suppress incorporation of hydrogen, which should lead to better performance."

In fact, the researchers suspect that even ubiquitous lithium-ion batteries may suffer from the ill effects of unintended hydrogen incorporation. Whether fewer problems result because fabrication methods are more advanced in this mature materials system, or because there is a more fundamental reason for lithium batteries to be more resistant to hydrogen is not clear at present but will be an area of future research.

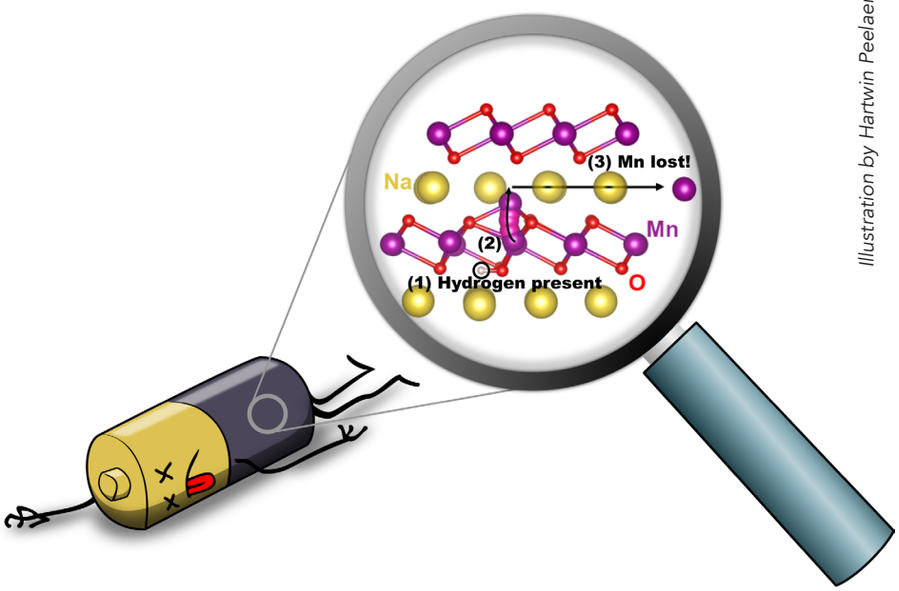



Illustration by Hartwin Peelaers

*An illustration depicting hydrogen-induced degradation of a sodium-ion battery: (1) When hydrogen is present (circled in black), (2) an Mn atom (purple) can move from the $MnO_2$ layer to the Na layer (yellow). (3) Mn can then move within the Na layer, and will be lost.*

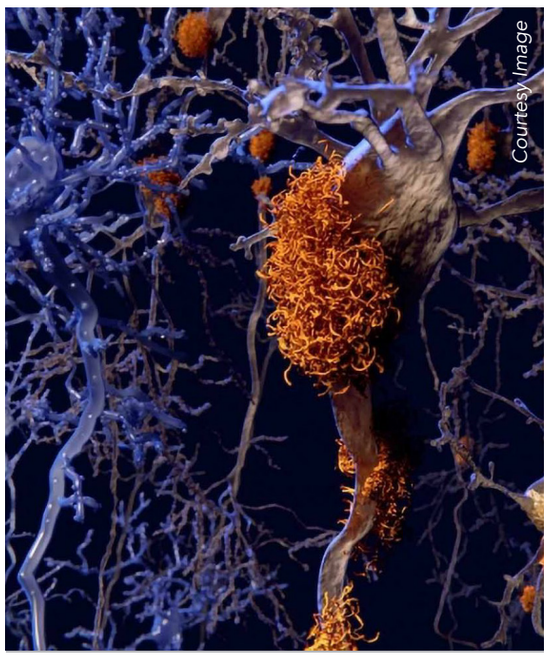
# NEW HOPE FOR TREATING DEMENTIA

In a great stride toward finding an effective treatment for early-stage neurodegenerative diseases, **Kenneth S. Kosik,** professor in the Department of Mollecular, Cellular and Developmental Biology, and collaborators have uncovered a "druggable" mechanism of pathological tau protein aggregation.

For the millions of people at risk for frontotemporal dementia and a host of other such conditions including Alzheimer's, this could signal a shift toward significant management of symptoms or outright prevention of some of our most devastating diseases.

"We're super excited about this," said Kosik, the UCSB Harriman Professor of Neuroscience and co-director of the campus's Neuroscience Research Institute. While there is much more work to be done, promising evidence for this treatable mechanism is mounting and the stage is set for future investigations.

In the wake of the recent halting of clinical trials for Aducanumab, a drug that once looked to be a promising Alzheimer's treatment, this development is a ray of hope. The team's paper, "A Farnesyl Transferase Inhibitor that Targets Rhes Reduces Tau Pathology in Mice with Tauopathy," was published in the journal *Science Translational Medicine.*

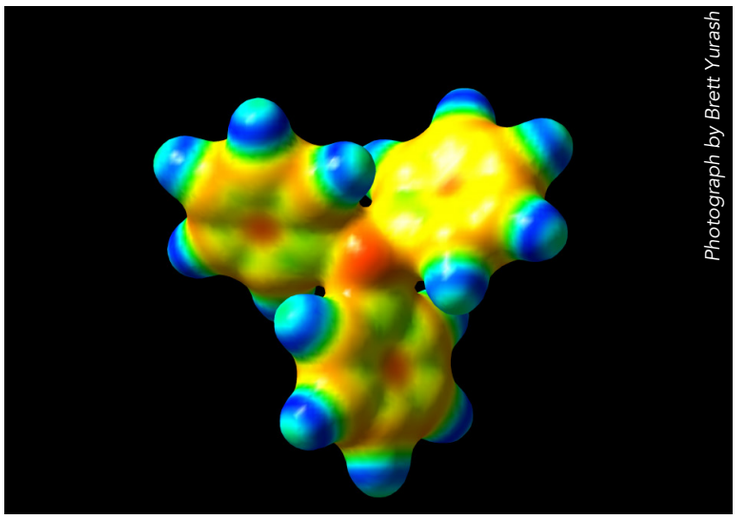



*Artist's concept illustration of a neuron (gray) with an abnormal protein deposition.*

# DOPING AN ORGANIC SEMICONDUCTOR? JUST ADD WATER.

The electrical conductance of semiconductors — those materials that make so much of modern life possible — falls between that of insulators, like rubber, and conductors, like copper. By doping the materials with various impurities, scientists can control a semiconductor's electrical properties, which is what makes them so useful in electronics. One class of new materials under investigation is organic semiconductors (OSCs), which are based on carbon rather than silicon. OSCs are lighter and more flexible than their conventional counterparts, expanding their potential applications.

In 2014, UC Santa Barbara chemistry professor **Thuc-Quyen Nguyen** and her lab first reported on doping of OSCs using Lewis acids; however, until now, no one knew why conductivity increased as a result. Now the group has collaborated with an international team of scientists to parse this mechanism, and their unexpected discovery promises to grant greater control over these materials.




*This Lewis acid changes the electrical properties of certain organic semiconductors when added in the presence of water.*

"People thought it was just the Lewis acid acting on the organic semiconductor," explained lead author **Brett Yurash**, a doctoral candidate in Nguyen's lab. "Now they know that water plays a key role in the process."

The Lewis acid grabs a hydrogen atom from the water and passes it over to the OSC. The extra positive charge makes the OSC molecule unstable, so an electron from a neighboring molecule migrates over to cancel out the charge. This leaves a positively charged "hole" that then contributes to the material's conductivity.

"The fact that water was having any role at all was really unexpected," said Yurash. In fact, the water that mediated the reaction was not even supposed to be there. Most of these reactions are performed in controlled, humidity-free environments, but clearly, some moisture had made it into the box with the other materials. And, as Yurash noted, "Just a tiny amount of water is all it took to have this doping effect."

Scientists, engineers, and technicians need to be able to dope a semiconductor controllably for it to be practical. "We've mastered silicon," Yurash said. "We can dope it the exact amount we want, and it's very stable. In contrast, controllably doping OSCs has been a huge challenge."

Lewis acids are fairly stable dopants, and the team's findings apply quite broadly, beyond simply the few OSCs and acids they tested. In most previous OSC doping work, molecular dopants were used, which don't dissolve readily in many solvents. "Lewis acids, on the other hand, are soluble in common organic solvents. They're also cheap and available in various structures," Nguyen explained.

Understanding the mechanism at work should enable researchers to design even better dopants. "This is hopefully going to be the springboard for launching more ideas," Yurash said. Ultimately, the team hopes these insights will help to push organic semiconductors toward broader commercial realization.

# BANKING PLURIPOTENT STEM CELLS

Stem cells are important to a great deal of research about a vast array of topics. Now, researchers can easily access more than 25 lines of stem cells in the recently opened Biobank within the Center for Stem Cell Biology and Engineering at UC Santa Barbara. The lab is housed in Biological Sciences 2.

The idea of mechanical engineering professor and director of the UCSB Center for BioEngineering, **Beth Pruitt,** the facility is located in a lab begun by **Dennis Clegg,** professor in the Department of Molecular, Cellular and Developmental Biology, who has used stem cells in research on macular degeneration, which can cause blindness. The bank holds cells derived from those engineered at the Allen Institute for Cell Science in Seattle, started by the late Microsoft co-founder, Paul Allen.

"The Cell Science group has engineered a collection of stem cell lines that have different fluorescent markers in them to indicate different structures within the cell," says associate laboratory director, **Cassidy Arnold.** "UCSB has systematically purchased the lines as they've been released."

Arnold and **Sam Feinstein,** who manages Pruitt's lab, oversee lab processes, which include expanding the cells by reproducing them under ultra-sterile conditions, and freezing them for distribution to researchers who want to purchase them. They also train other scientists and lab technologists in the care and processing of the cells and proper lab techniques to ensure sterile conditions for growth and propagation.

All of the cells come from the same parent cell, which is from what Arnold describes as, "essentially, a perfect human genome."

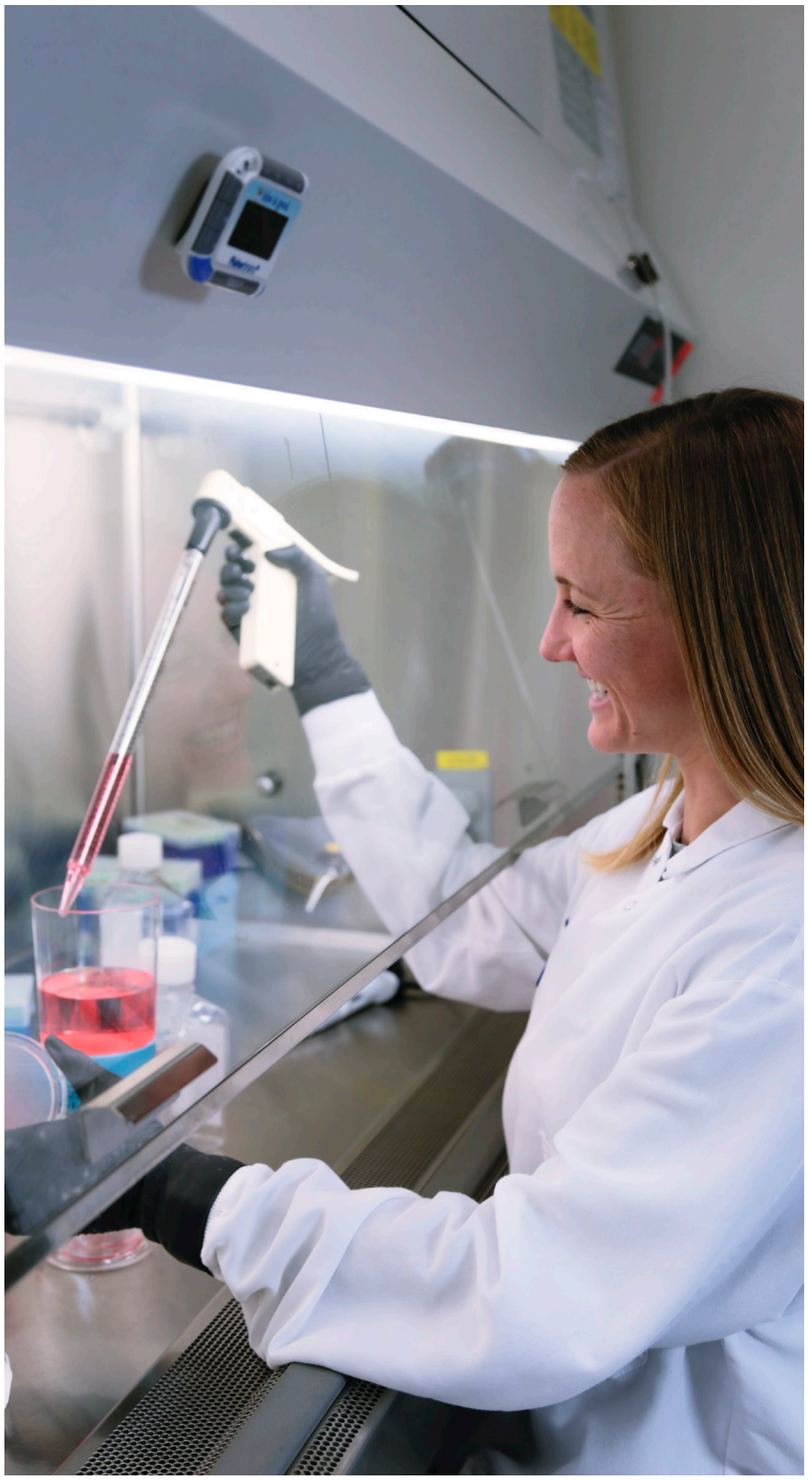
"The Allen Institute did a deep analysis of this person's genome and found that it had no mutations, so the institute decided to use the cell line as the basis for their fluorescent-tagging project," she says.

The original cell was not a stem cell but was transformed into one through a process called *induced pluripotency,* which makes it possible to take any tissue sample, even a tiny amount of skin, and revert it into a pluripotent stem cell. The process makes many more stem cells available and circumvents the ethical concerns around embryonic stem cells.

"The Allen cell bank is a tremendous resource for basic inquiry into cellular function," says Clegg. "Because they are pluripotent, these human cells can be coaxed to become practically any cell type in the body — in unlimited numbers!"

"Having visited the Allen Institute and hearing their researchers talk about the potential impact of these cells on biology research, I was convinced that they could really advance science," Pruitt says in describing her initial motivation for the cell bank. "By using these model cells, I wanted to elevate our campus capabilities and help leverage UCSB's great expertise in bioengineering and quantitative biology to emerge as a leader in reproducible, quantitative stem cell research.

"We hope, further, that by having easy local access to these lines, researchers can more readily deploy them in their research and exchange information with other labs using standard cells and methods to visualize and learn about living biological processes."

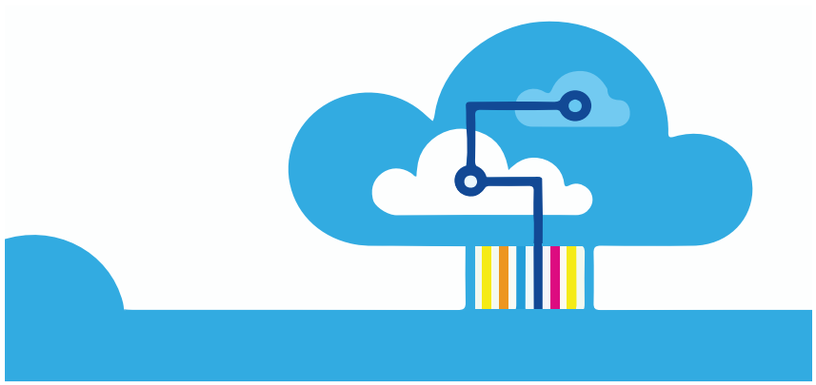


*Stem Cell Biobank associate laboratory director, Cassidy Arnold, prepares medium in which to propagate stem cell lines developed at the Allen Institute for Cell Science.*

# UCSB AND MICROSOFT PARTNER FOR NEXT-GENERATION CLOUD COMPUTING

The cloud — a globally distributed internet-based computer network system — is increasingly being used by entities of all kinds to store, access, and process data, enabling computing beyond the bounds of local computers and hard drives. While the cloud today is built with a sophisticated infrastructure of data centers connected by fiber optic networks, it is evolving. With an eye to growing the cloud further, Microsoft Research has assembled a cross-disciplinary team of scientists to explore how optics can be used not just to transmit data, but also to encode it, enhancing speed and energy efficiency.

UC Santa Barbara is one of six universities in the world and the only institution in the United States to be selected as an inaugural member of Microsoft's Optics for the Cloud Research Alliance. The other five are in Europe.



"It's a great opportunity to be a part of this important initiative and to work with world-class researchers on the critical optics research problems for the cloud of the future," said **Daniel Blumenthal,** a professor in the Department of Electrical and Computer Engineering who also serves as director of the Terabit Optical Ethernet Center and represents UCSB in the alliance. "It is a tremendous honor to be the only U.S. university involved."

"As our first U.S. partner, UC Santa Barbara brings a wealth of knowledge in the area of optical integration and devices and a long history of impactful research. We look forward to working together with them and our other partners to rethink cloud infrastructure and further this field of research," said Hitesh Ballani, senior principal research manager at Microsoft Research.

The alliance focuses on three major cloud resources — storage, networking, and computing — with projects intended to build upon the latest optical advancements to support them. In Blumenthal's project, he is investigating how ultra-fast optical switching and communications within the cloud's data centers can provide better and more predictable performance with higher reliability at lower cost. The challenge, he says, will be met by integrated photonics solutions, complex photonic circuits that reduce box-sized systems responsible for processing and transferring light down to the size of a microchip.

# HIRING THE BEST AND BRIGHTEST

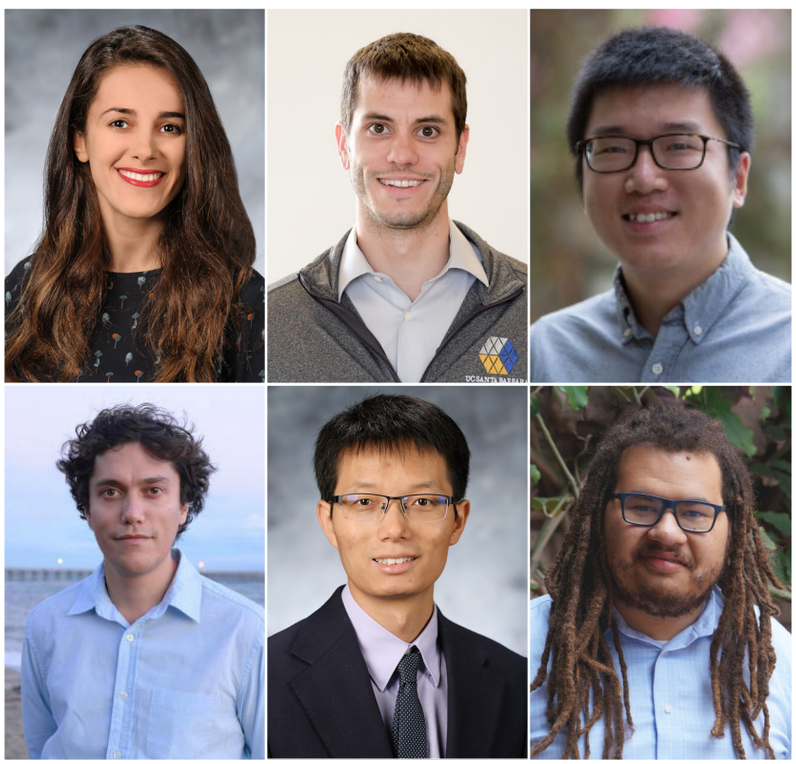
UC Santa Barbara administrators continue to succeed in their mission to hire the best and brightest young faculty in engineering and the sciences. According to UCSB's Office of Research, a higher percentage of assistant professors received a Faculty Early Career Development (CAREER) Award from the National Science Foundation (NSF) from 2007-2017 than did young faculty at any other public university.

UCSB ranked first among public universities, and third overall, behind only the Massachusetts Institute of Technology and Cornell University. The office compiled data provided by NSF and the Association of American Universities (AAU), in which a university's total number of NSF awards from 2007-2017 is divided by its annual average number of assistant professors.

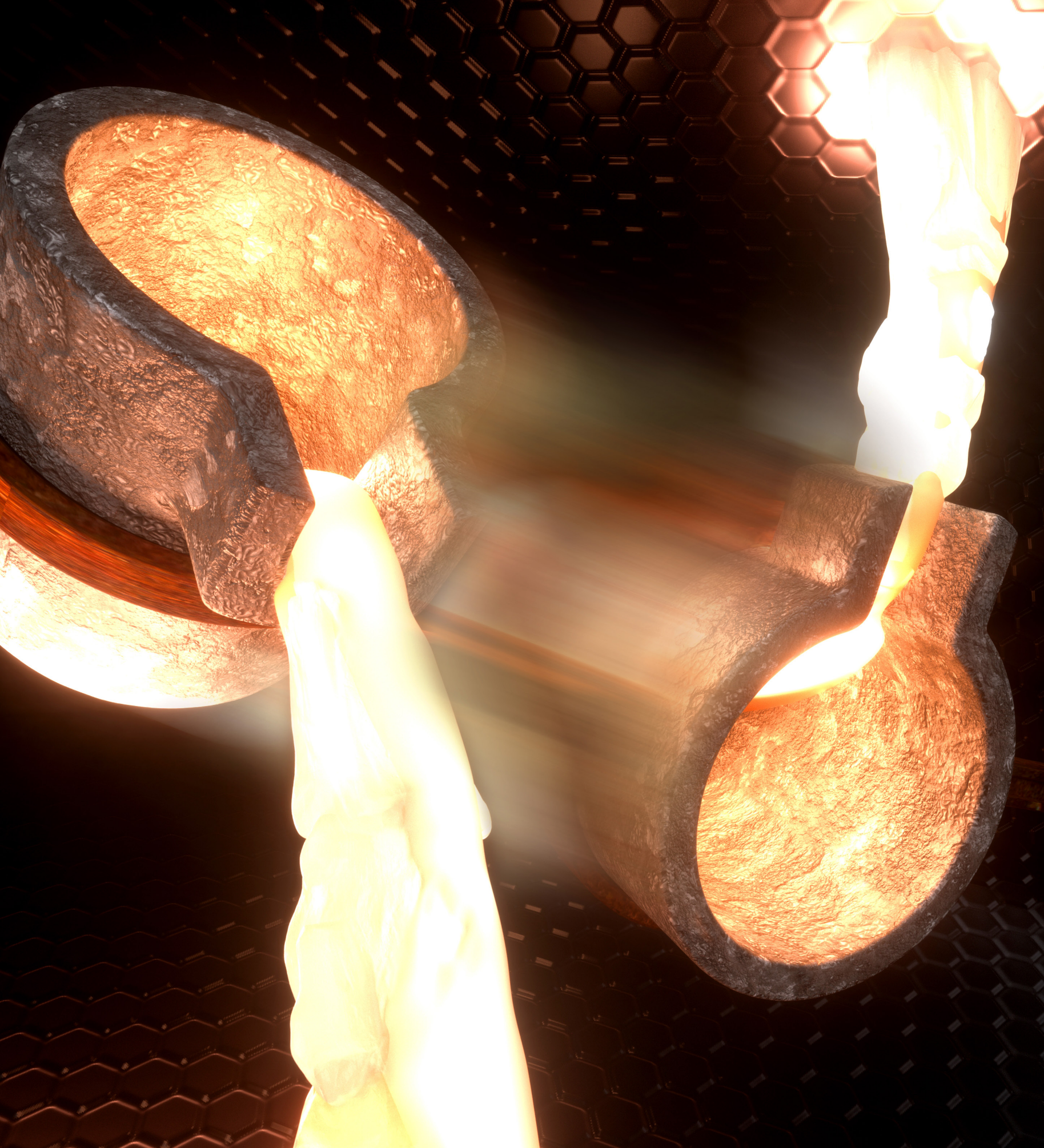
The NSF CAREER Award is the foundation's most prestigious honor for junior faculty, providing each winner with up to $500,000 to pursue cutting-edge research and tackle real-world challenges.

Recent hires are doing their part to maintain UCSB's position in the upper echelon of universities. Among public universities in 2019, UCSB had the highest percentage of NSF CAREER awards received by eligible assistant professors in the engineering and sciences. Only three private universities, Harvard (28%), Columbia (17%), and Vanderbilt (16%) ranked higher than UCSB (15%).

The six associate professors at UCSB who received awards in 2019 are **Mahnoosh Alizadeh** (electrical and computer engineering), **Chris Bates** (materials), **Daniel Conroy-Beam** (psychology and brain sciences), **Bolin Liao** (mechanical engineering), **Robin Matoza** (earth science), and **Zheng Zhang** (electrical and computer engineering).



*2019 NSF CAREER Award winners (clockwise from top left) Mahnoosh Alizadeh, Chris Bates, Bolin Liao, Daniel Conroy-Beam, Zheng Zhang, and Robin Matoza.*



# UCSB'S QUANTUM LEAP

The university is selected as the site of the nation's first NSF-funded Quantum Foundry, a center for the development of materials for quantum information–based technologies

We hear a lot these days about the coming quantum revolution. Efforts to understand, develop, and characterize quantum materials — defined broadly as those displaying characteristics that can be explained only by quantum mechanics and not by classical physics — are intensifying. Researchers around the world are racing to understand these materials and harness their unique qualities to develop revolutionary quantum technologies for quantum computing, communications, sensing, simulation, and other quantum technologies not yet imaginable.

In September, UC Santa Barbara stepped to the front of that worldwide research race by being named the site of the nation's first Quantum Foundry. Funded by an initial six-year, $25-million grant from the National Science Foundation (NSF), the project, known officially as the UC Santa Barbara NSF Quantum Foundry, will involve twenty faculty members from the campus's materials, physics, chemistry, mechanical engineering and computer science departments, plus myriad collaborating partners. The new center will be anchored within the California Nanosystems Institute (CNSI) in Elings Hall.

The grant provides substantial funding to build equipment and develop tools necessary to the effort. It also supports a multi-front research mission comprising collaborative interdisciplinary projects within a network of university, industry, and national-laboratory partners to create, process, and characterize materials for quantum information science. The foundry will also develop outreach and educational programs aimed at familiarizing students at all levels with quantum science, creating a new paradigm for training students in the rapidly evolving field of quantum information science, and engaging with industrial partners to accelerate development of the coming quantum workforce.

"We are extremely proud that the National Science Foundation has chosen UC Santa Barbara as the home of the nation's first NSF-funded Quantum Foundry," said **Chancellor Henry T. Yang.** "The award is a testament to the strength of our university's interdisciplinary science, particularly in materials, physics, and chemistry, which lie at the core of quantum endeavors.

"Under the direction of physics professor **Ania Bleszynski Jayich** and materials professor **Stephen Wilson,** the foundry will provide a collaborative environment for researchers to continue exploring quantum phenomena, designing quantum materials, and building instruments and computers based on the basic principles of quantum mechanics," Yang added.

> "IT RECOGNIZES THE VISION AND THE DECADES OF WORK THAT HAVE MADE UC SANTA BARBARA A TRULY WORLD-LEADING INSTITUTION."

"Being selected to build and host the nation's first Quantum Foundry is tremendously exciting and extremely important," said **Rod Alferness,** dean of the College of Engineering. "It recognizes the vision and the decades of work that have made UC Santa Barbara a truly world-leading institution worthy of assuming a leadership role in a mission as important as advancing quantum science and the transformative technologies it promises to enable."

"Advances in quantum science require a highly integrated

interdisciplinary approach, because there are many hard challenges that need to be solved on many fronts," said Bleszynski Jayich. "One of the big ideas behind the foundry is to take these early theoretical ideas that are just beginning to be experimentally viable and use quantum mechanics to produce technologies that can outperform classical technologies."

Doing so, however, will require new materials. "Quantum technologies are fundamentally materials-limited, and there needs to be some sort of leap or evolution of the types of materials we can harness," noted Wilson. "The foundry is where we will try to identify and create those materials."

**Research Areas and Infrastructure**

Quantum Foundry research will be pursued in three main areas, called "thrusts":

• *Natively Entangled Materials,* which relates to identifying and characterizing materials that intrinsically host anyon excitations and long-range entangled states with topological, or structural, protection against decoherence. These include new intrinsic topological superconductors and quantum spin liquids, as well as materials that enable topological quantum computing.

• *Interfaced Topological States*, in which researchers will seek to create and control protected quantum states in hybrid materials.

• *Coherent Quantum Interfaces*, where the focus will be on engineering materials having localized quantum states that can be interfaced with various other quantum degrees of freedom (e.g. photons or phonons) for distributing quantum information while retaining robust coherence.

"Developing these new materials and assessing their potential for hosting the needed coherent quantum state requires specialized equipment, much of which does not exist yet," Wilson said. "A significant portion of the NSF grant is designated to develop such infrastructure, both to purchase required tools and equipment and to fabricate new tools necessary both to grow the materials and characterize their quantum states."

UCSB's deep well of shared materials growth and characterization infrastructure was also a factor in securing the grant. The foundry will leverage existing facilities, such as the large suite of instrumentation shared via the Materials Research Lab and the California Nanosystems Institute, multiple molecular beam epitaxy (MBE) growth chambers (the university has the largest number of MBE apparatuses in academia), unique optical facilities such as the Terahertz Facility, state-of-the-art clean rooms, and others among the more than 300 shared instruments on campus.


*NSF Quantum Foundry co-directors Stephen Wilson and Ania Bleszynski Jayich.*

**Data Science**

NSF is keenly interested in both generating and sharing data from materials experiments. "We are going to capture foundry data and harness it to facilitate discovery," said Wilson. "The idea is to curate and share data to accelerate discovery at this new frontier of quantum information science."

**Industrial Partners**

Industry collaborations are an important part of the foundry project. UC Santa Barbara's well-established history of industrial collaboration — it is among the leading universities in the U.S. in terms of industrial research dollars per capita — and the application focus that allows it to to transition ideas into materials,

and materials into technologies, was important in receiving the foundry grant.

Another value of industrial collaboration, Wilson explained, is that often, faculty might be looking at something interesting without being able to visualize how it might be useful in a scaled-up commercial application. "If you have an array of directions you could go, it is essential to have partners to help you visualize those having near-term potential," he said.

"This is a unique case where industry is highly interested while we are still at the basic-science level," said Bleszynski Jayich. "There's a huge industry partnership component to this."

Among the ten inaugural industrial partners are Microsoft, Google, IBM, Hewlett Packard Enterprises, HRL, Northrop Grumman, Bruker, SomaLogic, NVision, and Anstrom Science. Microsoft and Google already have substantial campus presences; Microsoft's Quantum Station Q lab is here, and UC Santa Barbara professor and Google chief scientist **John Martinis** and a team of his PhD student researchers are working with Google at its office, adjacent to campus, to develop Google's version of a quantum computer.

**Undergraduate Education**

In addition, with approximatelys seven hundred students, UC Santa Barbara's undergraduate physics program is the largest in the U.S. "Many of these students, as well as many undergraduate engineering and chemistry students, are hungry for an education in quantum science, because it's a fascinating subject that defies our classical intuition, and on top of that, it offers career opportunities. It can't get much better than that," Bleszynski Jayich said.

**Graduate Education Program**

Another major goal of the foundry project is to integrate quantum science into education and to develop the quantum workforce. The traditional approach to quantum education at the university level has been for students to take physics classes focused on the foundational theory of quantum mechanics.

"But there is an emerging interdisciplinary component of quantum information that people are not being exposed to in that approach," Wilson explained. "Having input from many overlapping disciplines in both hard science and engineering is required, as are experimental touchstones for trying to understand these phenomena. Student involvement in industry internships and collaborative research with partner companies is important in addressing that."

"We want to introduce a more practical quantum education," Bleszynski Jayich added. "Normally, you learn quantum mechanics by learning about hydrogen atoms and harmonic oscillators, and it's all theoretical. We want to supplement that by leveraging our abilities gained in the past twenty to thirty years to control a quantum system on the single-atom, single-quantum-system level. Students will take lab classes where they can manipulate quantum systems and observe the highly counterintuitive phenomena that don't make sense in our classical world. And, importantly, they will learn various cutting-edge techniques for maintaining quantum coherence.

"That's particularly important," she continued, "because quantum technologies rely on the success of the beautiful, elegant theory of quantum mechanics, but in practice we need unprecedented control over our experimental systems in order to observe and utilize their delicate quantum behavior."

# AUHLL IN FOR UCSB

A conversation with CoE Dean's Cabinet member and key donor **Richard Auhll**

Richard Auhll majored in aerospace engineering at the University of Michigan, then landed his "dream job" as a rocket engineer in the Advanced Design Group of United Technologies Corporation's Rocket Division in the San Francisco Bay Area. While there, he earned a master's in aerospace engineering from Stanford. Later, he left to pursue an MBA at Harvard Business School, where a new goal came into focus: "heading a high-tech company on the West Coast." He moved to California and was hired by UCSB benefactor **Harold Frank** to lead one of his companies, Circon Corporation, which made ultra-miniature tools for microscope work on computer memories.

Auhll eventually purchased Circon and refocused it, based on his own market intelligence gathering, to manufacture the world's smallest surgical instruments. That led to developing the world's smallest color video-camera systems, which were connected to video monitors and used for teaching and to conduct micro-surgical eye and brain procedures. The micro-video system revolutionized endoscopy by allowing surgeons to use both eyes to view their procedures through ultra-small incisions magnified on color video screens, rather than squinting into a single eyepiece.

Auhll is a longtime member of the CoE's Deans Cabinet. He funded the Auhll Professor and Dean of Engineering Endowed Chair and the Auhll Engineering Student Center. He participated in the UC President's Engineering Advisory Council for all UC campuses, is a UCSB Gold Circle donor, and was the chairman of the UCSB Foundation. *Convergence* spoke with him in September.

**C:** *You never attended the UCSB College of Engineering but have contributed greatly to it over the years, in terms of both time and financial support. Why?*

**RA:** I am a true believer in higher education because of the very substantial benefits I have derived from it, especially as I am the first in my family to attend college. I believe that my success has been grounded in the knowledge, analytical thinking, and self-confidence I developed during my university education. I support the universities where I earned my degrees, and I also support UCSB due to the intellectual stimulation and the warm friendships I've developed with professors and staff over time. I believe in what they're doing here.

**C:** *You support not only the College of Engineering, but also Arts & Lectures and other programs. What motivates your philanthropy?*

**RA:** I believe that a well-educated person should have some positive impact upon the community where he resides. UCSB provides more than eighty cultural programs throughout the year. These events are a unique addition to one's life in Santa Barbara.

**C:** *After earning your BS and MS in aerospace engineering and working in that field, you earned your MBA at Harvard. What led you to the more entrepreneurial path you took?*

**RA:** At the time, most Harvard Business School graduates went on to Wall Street, product management, or management consulting. Entrepreneurism was not a hot topic then, as Silicon Valley was in early development. I wanted to be in charge of all corporate activities as soon as possible, instead of waiting thirty years! During my employment search while at Harvard, I encountered Harold Frank and persuaded him to hire me as president and chairman of Circon Corporation, a small eight-person manufacturer of ultra-miniature tools. A few years later, I secured financing to purchase the company. From there, major opportunities arose to expand and diversify.

**C:** *What stands out to you as an important point of difference at UCSB?*

**RA:** One thing is the cross-pollination among departments and labs. I've been involved with other universities where people were not nearly as cross-disciplinary and were very secretive and defensive about what they were doing. UCSB is noticeably open. The College of Engineering is small in some ways compared to competitor programs, but because of that spirit of collaboration, we have been able to work very well together and spread the advantages of any one area to benefit all the other areas. Another strength is that we're in a beautiful place where people like to live — on the ocean, not in a big metropolitan center. There's more to living than just working on your computer.

**C:** *Can you speak to the specific areas of strength where UCSB has chosen to invest its time, money, and energy?*

**RA:** UCSB has been very good at choosing areas to focus on. For instance, there is no aerospace program here, because they decided that the department couldn't be a major leader within a reasonable time. Likewise, it was decided not to develop an across-industry business school program and, instead, to create the more focused Technology Management Program. UCSB concentrates on fields where it can make substantial advances, rather than just copying what other people are doing in the areas.

For instance, our strength in materials, chemistry, physics, mechanical engineering, and computer science, plus the collegiality and collaborative approach to conducting science and engineering, were surely important in earning the $25 million grant from NSF to build the nation's first Quantum Foundry. We are poised to lead in developing materials needed to enable quantum computing and other quantum technologies. UCSB has been a great research university for a long time and is finally getting the recognition it deserves.

**C:** *How do you see alumni support for the College?*

**RA:** I think it's extremely important to inculcate in students from the day they are admitted that, as graduates, they should *want* to give back to the university, rather than thinking that the university owes them their education and when they leave, it's over. Only twenty percent of the entire university budget comes from the state. We need the support of our graduates who live good lives based on their professional success, which began here.

*Students at work in the Richard A. Auhll Student Center.*

# EXPANDING THE PALETTE

## UCSB RESEARCHERS DISCOVER A NEW PHASE OF BLOCK COPOLYMERS

All matter consists of one or more phases — regions of space with uniform structure and physical properties. Everyone is familiar with the common phases of $H_2O$ (solid, liquid, and gas), also known as ice, water, and steam. Similarly, polymeric materials can form a variety of different solid or liquid phases that determine their properties and ultimate utility. This is especially true of block copolymers, the highly useful self-assembling macromolecules created when a polymer chain of one type (call it "Block A") is chemically connected with a polymer chain of a different type ("Block B").

"If you want a block copolymer that has a certain property, you pick the right phase for a given application of interest," says **Chris Bates,** assistant professor in the Materials Department at the UC Santa Barbara College of Engineering. "For the rubber in shoes, you want one phase; to make a membrane, you want a different one."

Only about five phases have been discovered in the simplest block copolymers. Finding a new phase is rare, but Bates and a team of UCSB researchers including **Professor Glenn Fredrickson** (chemical engineering), **Professor Craig Hawker** (materials), **Morgan Bates,** a staff scientist and the assistant director for technology at the Dow Materials Institute at UCSB, and **Joshua Lequieu,** a postdoctoral researcher with Fredrickson, have done just that.

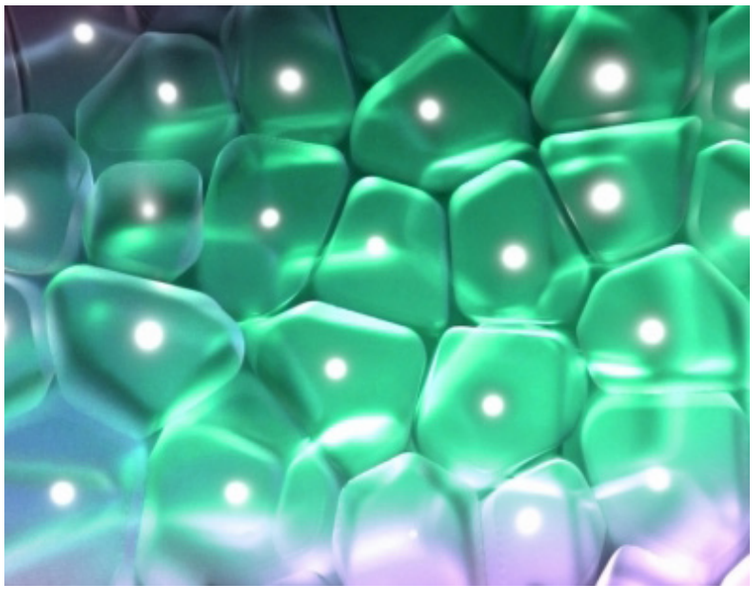
A little more than a year ago, Morgan Bates was doing some experimental work on polymers she had synthesized in the lab. "We wanted to understand the fundamental parameters that govern self-assembly of block copolymers by examining what happens when you tweak block chemistry," she notes.

Chris Bates explains that there are endless possibilities for the chemistry of "A" and "B" blocks. "Modern synthetic chemistry allows us to pick basically any type of A polymer and connect it with a different B block," he says. "Given this vast design space, the real challenge is figuring out the most crucial knobs to turn that control self-assembly. Morgan was trying to understand that relationship between chemistry and structure."

She recalls the process that led to the discovery: "I had chemically tweaked a parameter related to what is called 'conformational asymmetry,' which describes how the two blocks fill space. We weren't necessarily trying to find a new phase but thought that maybe we'd uncover some new behavior. In this case, the A and B blocks

that are covalently tied together fill space very differently, and that seems to be the underlying parameter that gives rise to some unique self-assembly."

After creating the block copolymers, she took them to the Advanced Photon Source at Argonne National Laboratory, located in Lemont, Illinois, where a technique called "small-angle X-ray scattering" was used to characterize them. The process yields a two-dimensional signature of scattered X-rays arranged in concentric rings. The relative placement and intensity of the rings indicate a particular phase. Morgan needed to travel to a national lab, because the process requires X-rays more powerful than what can be produced on campus.



*Artist's concept depicting block polymers packed together to form, in this case, a new phase of diblock co-polymer.*

After that work, says Chris, "Using knowledge of crystallography, you can interpret the scattering data and produce an image as if you were looking at the structure with your eye. And in this case, the data was of such high quality that we were able to do that unambiguously."

Morgan recalls that when she examined the X-ray pattern, one thing was unmistakably clear: "It looked different. I thought, 'What is that?'"

It was, of course, their newly discovered phase, known as A15. "With these types of AB block copolymers, there are only a handful of phases that people have observed previously, and we've found another one, which adds to the palette of possible options from a design standpoint," Chris says.

"Among the ways of categorizing structures, this phase belongs to a class known as 'tetrahedrally close-packed'," adds Lequieu, an expert in computer simulations who modeled the phase behavior of polymers. "The phase we've found in block copolymers was actually first observed in 1931 with an allotrope [or form] of tungsten. But in that case, A15 forms from metal atoms, which create a very small structure at the atomic length scale. Our block copolymers adopt the same structure but at a length scale two orders of magnitude larger, and, of course, no metal atoms are involved.

"If you were to look at both with a microscope, their structures would look the same, but just at different sizes . It's fascinating that nature chooses to use the same structural motifs for completely different materials having entirely unrelated chemistry and physics."

The project demonstrates the ease of, and proclivity for, collaboration among UCSB researchers. It began with new chemistry developed by Hawker and Chris Bates to tune the properties of materials, which was followed by Morgan's unexpected characterization results. "From there, we went to Josh and told him there's something strange in the experiments that we didn't expect and asked him why," Chris says. Lequieu then worked with Fredrickson to develop the computer simulations.

"There was a really nice back and forth on this project," Lequieu says. "An experiment was done that was challenging to understand, so we performed simulations to explain it. Morgan then did more experiments, informed by the results of the initial simulations, and observed that the computations were actually predictive. The phases observed experimentally showed up right where the simulations said they would. In some places, however the experiments and simulations disagreed, so we iterated multiple times to improve the models and really understand the subtleties involved."

"Moving forward," Chris adds, "our team continues to integrate materials synthesis and theory in a search for more unique phase behavior."

Lequieu describes the feedback loop from experiment to simulation to theory and back around as "sort of the dream of modern materials science. It takes a lot of work for Morgan to make these samples. It's much easier if someone predicts outcomes on a computer and can say, 'Here's a subset of polymers to synthesize that should form the desired structure.' This so-called 'inverse design' approach saves her a lot of time and effort."

In terms of nature falling back on preferred designs for otherwise unrelated materials, a bit of history is worth noting. In 1887, Lord Kelvin — he of the eponymous units of absolute temperature — was working on what later came to be known as the "Kelvin problem." It was an effort to determine how space could be partitioned into cells of equal volume with the least surface area between them. His proposed solution, which indicated the most efficient bubble foam, became known as the "Kelvin structure."

It held for about a hundred years, but in 1994 was shown to be incorrect. Kelvin had chosen what could be called "Structure A," but a team of British scientists showed that "Structure B" was even better. Since then, Structure B has gained fame in scientific circles and even well beyond, appearing, for instance, in the form of giant bubbles that serve as both functional architectural elements and design elements on the roof of the Beijing National Aquatics Center, built for the 2008 Olympics.

It turns out that the new phase, A15, discovered by the researchers in this project is Structure B, confirming once again that nature likes a previously successful design.

# Faculty Q&A

# JESSICA SANTANA

Jessica Santana joins award-winning faculty in advancing the practice of **Technology Management** at UCSB. She earned her PhD and MA in sociology from Stanford University after receiving a Master of Information Management and Systems degree at UC Berkeley, with certification in the Management of Technology from the Haas School of Business. She has also worked in industry, as a strategy and management consultant, entrepreneur, and product manager. *Convergence* spoke with Santana in October.

**C:** Welcome to UCSB. *What attracted you to UCSB and the Technology Management Department?*

**JS:** UCSB plays a significant role in advancing research across the fields that fascinate me, including quantum computing, social-network theory, digital gaming, and artificial intelligence. Part of what attracted me to the university is the interdisciplinarity of these fields on campus. Technology Management is especially poised to bridge these communities and contribute a novel perspective to the theory and application of Technology Management through curriculum and research in organizational behavior and theory, entrepreneurship, technology strategy, and other critical fields.

*C*: Why did you choose to conduct your research within Tech*nology Management, and how do you think your research will complement current faculty efforts?*

**JS:** *My background is in sociology, with expertise* in organizational theory, economic sociology, and network science. Sociology helps inform Technology Management by accounting for the relationality of technology, that is, evaluating the impact technology has on society and society has on technology, and considering the role of social structure and agency in technology. Along with my research and teaching in entrepreneurship, I am eager to build out the computational social science (including data science) program. This includes network science and text analytics, as well as machine learning, computational modeling, online experimentation, and other emerging methods.

**C:** *What is t*he focus of your research, and what are you working on right now? What are the potential implications on Technology Management and society?

**JS:** I primarily research the role of networks in innovation and entrepreneurship using computational social science and other methods. My current research focuses on how entrepreneurs use rhetoric and their virtual peer network to recover from failure. Most entrepreneurs fail, and they need to know how to deal with failure when it happens.

From a sociological perspective, entrepreneurship can be a powerful channel for mobility. However, there are privileges inherent in entrepreneurship, including who is allowed to fail and what types of failure are considered acceptable. Management science, which describes how people can learn skills to manage their organization effectively, often distinguishes successful entrepreneurs and executives from flashes in the pan.

**C:** *How did you become interested in this area of research, and where do you see it going in the future?*

**JS:** My interest in entrepreneurship grew out of my own experience as an entrepreneur. While studying information management and systems at UC Berkeley, I built a company that used mobile augmented reality to unveil hidden information about retail products. I became interested in computational social science after I joined Electronic Arts, where I was the core product manager for social and mobile games. Part of my role was to identify, track, and test game metrics to acquire, retain, and monetize users. It frustrated me how throttled access to this data was, and how precariously the analytic system was thrown together. This experience gave me valuable perspective on how to use social psychology and data science to build and test theories, as well as the limits to these methods and datasets.

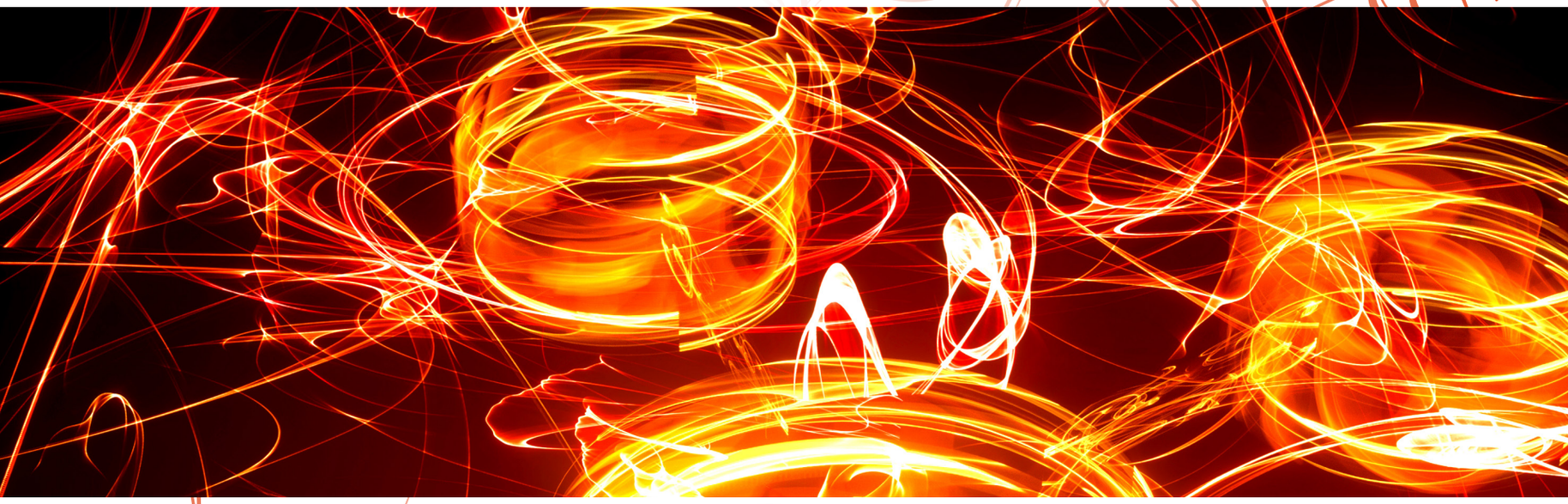
I believe that the next stage of research in management and organizational theory will be *people analytics* —using internal big data to study employees and make better management decisions. The next stage of research in computational social science will be ethical design and, perhaps, a new field of quantum information science that addresses topics like data anonymization, blockchain, and security in a quantum era. And the next stage of research in entrepreneurship will be virtual entrepreneurship, including distributed teams, peer learning, and crowdfunding.

*C: What other areas of study or advocacy are important to you, and why?*

**JS:** In a new program of research, I investigate the relationship between innovation and ethics in contexts such as synthetic biology, clinical trials, and cryptocurrency investment. In one project involving an international team of interdisciplinary scholars, we use text, network, biological innovation, and judging data from an international genetic-engineering competition to identify the relationship between innovation and ethical boundaries, and to predict the emergence of ethical codes and violations in innovative communities. Innovations, including gene-editing technology, high-frequency trading, and artificial intelligence, are often initially denounced by society as unwieldy and unethical. It is important to understand the conditions in which innovative deviance can benefit or harm society.

It is especially important for women and students of color to study and apply to technology management. Much of the bias reflected in AI and other technology today is the result of poor representation in the field. Addressing this underrepresentation requires studying the science behind technology management, including social psychology and organizational theory.

# FOCUS ON: HOT TOPICS



In popular culture, hot topics come and go. Celebrities, athletes, styles, hit shows, music, movies, design, and diets of all kinds pass into and out of our attention at breakneck speed.

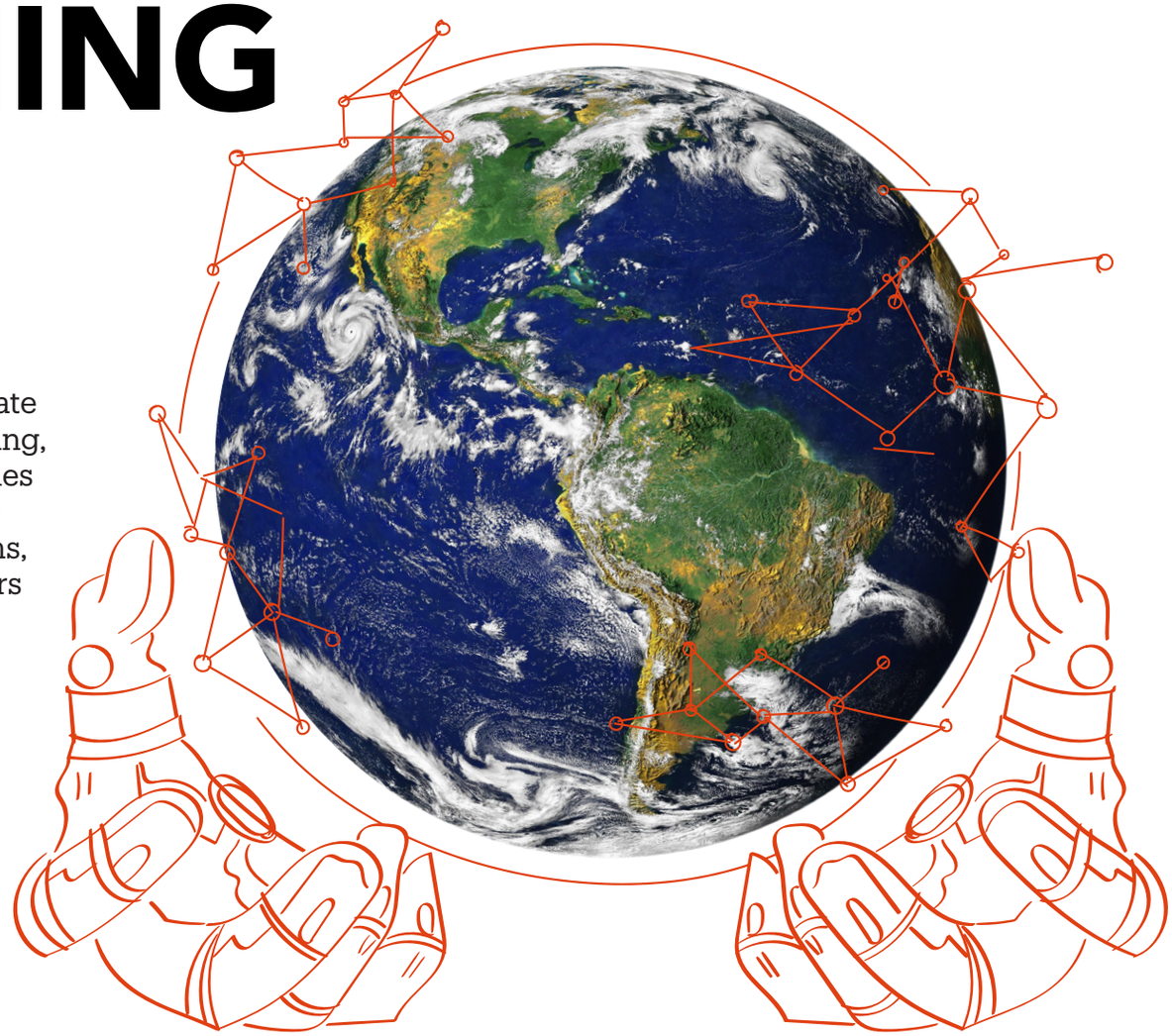
It's different in engineering and science. Important subjects for study emerge slowly, establishing the relevant fundamental science and theory can take years, and transforming the science into market-ready applications can add another decade or (much) more. Still, once important ideas gain traction, those "hot" areas of research attract tremendous attention and research funding and occupy the time of researchers around the world, including many at UCSB.

In this special section, we look at five areas where campus researchers have a leadership role: machine learning, systems biology and bioengineering, the control of dynamical systems, materials for quantum information, and the science behind improved membranes for water filtration.

We hope you'll come away understanding that, if the topic is hot, UCSB researchers are on it.

# MACHINE LEARNING

From data-intensive applications that include voice, image, and facial recognition, to using deep neural networks and natural-language processing software to root out hate speech and democratize computing, to developing software that enables machine-learning (ML) models to operate across hardware platforms, UCSB computer-science engineers are at the forefront of this AI-intensive moment.



## *PUSHING GROUP DYNAMICS*

Team projects are rife with group dynamics, which can affect outcomes and determine a group's success. In some of his work, computer science professor **Ambuj Singh** uses machine learning to model the cascading events occurring in what he refers to as "structured information networks," like those formed when humans (and AI agents) work together in teams. "We're trying to understand how information evolves and cascades over these networks to arrive at a certain outcome," he says.

That involves developing machine-learning models that can predict such things as how the group will perform based on how they are interconnected and how they reach a decision on the task at hand.

If a group is trying to make a distinction, Singh wants to know, "Is there some information related to the structure and how the individuals are connected and who is talking to whom that allows me to infer something at the higher level about the entire system, such as whether the group sentiment has changed, or if the group will achieve a good outcome? Or, can I predict that in the future, this structure will evolve into some other structure? In other words, can I model how this group is going to evolve over time and determine the right intervention?"

## KEEPING IT PRIVATE

Gmail users are familiar with the AI-enabled function that completes commonly used phrases after a few characters are typed. It's handy, but, as UC Santa Barbara computer science **Yu-Xiang Wang** explains, the way it works raises a security/privacy concern.

"The training data to complete your sentence comes from your own e-mails and from e-mails written in Gmail by people all over the world," says Wang, who works in the area of statistical machine learning, examining such issues as how algorithms make decisions and how much data is necessary for a given application to work well and, in the case of something like an automated medical procedure, ensure the patient's safety. "Sometimes, to suit your taste, Gmail personalizes e-mail suggestions by matching your language to that of people who write very much like you."

It can occur, however, that Person A writes a highly sensitive sentence specific to the context of an email and it gets picked up by the machine-learning system, which then recommends that exact phrasing to Person B. "If the two people know each other, that's a big privacy/security issue," Wang says.

One of his missions is to "prevent that from happening by training machine learning models that don't have that artifact. That's by integrating differential privacy, a cryptographic definition that it is the de facto gold standard that people use to prevent such privacy breaches."

## COMPILING TRADEOFFS

Like any software, machine-learning models run on devices, and devices vary in their available computing resources. That's why the same ML model that runs on your desktop computer, with its abundant energy and powerful graphics processing unit (GPU), can drain the battery of a smartphone, which has far fewer resources, in less than a half-hour.

UCSB computer science assistant professor **Yufei Ding** designs the lynchpin software — called a *high-performance compiler system for machine learning* — that makes it possible to run an ML model on any device "We want to deploy all kinds of ML models efficiently on devices having diverse computing resources," she says, "and we want both high processing speed and low energy consumption."

Her compiler system takes into consideration the device provided and the ML models written in a domain-specific language, say, one for bird watching. The compiler automatically optimizes the ML model to run on the device.

"It may change your model a bit, eliminating redundant computation to reduce energy consumption," Ding explains. "So, while, the full model running on a desktop might achieve 95-percent accuracy, it can be made ten times more energy efficient to run on your phone, at the negligible cost of less than 1-percent accuracy degradation."

> "WE WANT TO DEPLOY ALL KINDS OF ML MODELS EFFICIENTLY ON DEVICES HAVING DIVERSE RESOURCES."

## SPEAK NATURALLY

"Natural language processing [NLP] is about teaching machines to understand human language, and to communicate with humans," says UCSB computer science assistant professor **William Wang.** "It is considered one of the crown jewels in artificial intelligence."

Successfully implemented NLP can enable robots and voice assistants to perform increasingly sophisticated tasks and skillfully address problems that plague computer-mediated communications, such as misinformation and hate speech. Wang has been a driving force in establishing UCSB's NLP research group as one of the world's most prolific NLP labs.

In his current research, Wang focuses on the propagation of misinformation on the internet, revealing the network dynamics of propaganda, hoaxes, clickbait, and false articles on sites such as Twitter and Reddit. But he has an eye on broader problems as well.

"There are some emerging ethical issues with AI and data science," Wang says. "If you don't think about consequences when you're designing the systems, a lot of terrible things can happen. We need to go beyond accuracy and optimize also for fairness, privacy, transparency, and accountability."

The newly established Center for Responsible Machine Learning at UCSB is designed to do just that. "There are many challenges ahead," Wang says, "but with the new center, I believe that UCSB will take the lead in machine learning, NLP, and computer vision innovation."

## JUST-IN-TIME AI

In one of his multiple projects, computer science professor **Xifeng Yan** employs machine learning to create what he refers to as a "natural language interface to data," so that combining multiple Excel files to aggregate information or accessing more analytics can be done using a "natural-language interface that you can plug into the original data or into the Excel program itself. You ask a question in natural language and get the results directly from the data with no programming," he says.

He recently started another project for VISA, Inc., to answer questions related to forecasting various kinds of time series in such areas as transactions, demand, inventory, and workload. Initially, he says, "I was a bit concerned, since this area has been studied for more than one hundred years and I had published only one time-series paper before." He took on the project knowing that time-series data will grow exponentially in the era of AI and the Internet of Things.

By leveraging the newest deep-learning techniques, his lab needed only a year to achieve state-of-the-art performance in time-series forecasting. "Both understocking and overstocking of inventory hurt businesses, and getting the right balance can be extremely challenging and sometimes impossible," he says. "Machine learning can integrate big data to take uncertainty into consideration and make the most-informed prediction to help people."

# SYSTEMS BIOLOGY & BIOENGINEERING

Systems biology, which is closely related to bioengineering, involves understanding the evolution, dynamics, and causes of change in biological systems, as well as any feedback loops that maintain systems' stability. Here are a few of the several UCSB mechanical engineers who pursue compelling research in this area.

## *ON THE MOLECULAR CIRCUIT*

"My lab studies the molecular circuits that allow cells to make decisions about responding to physical cues in their environment," says UCSB mechanical engineering assistant professor **Adele Doyle.** "That is, how do mechanical forces, material properties, and electrical cues impact how the cell behaves? We want to understand how cells act like computers to convert cues from their physical environment into biological outcomes."

To do that, Doyle's lab develops data-driven simulations, work, she says, that is enabled by big data and new computational tools, and by "being in an engineering college in a university that also values quantitative biology. We can design new tools that help us identify which genes are affected by biomechanical forces and electrical properties, and then predict the effect on cell function," she says.

The research involves a three-fold effort to develop measurement techniques to detect cell signals more accurately, computational techniques to push progress on the data-analysis side, and experiment systems that provide greater control of the environment around living cells.

The idea, she says, is to "create a loop that allows us to make predictions from the simulations, test them in the lab, obtain more accurate measurements during the tests, and then use the experimental results to improve the simulations. Long term, we aim to understand how mechanosensitive molecular circuits promote cardiovascular and nervous system health."

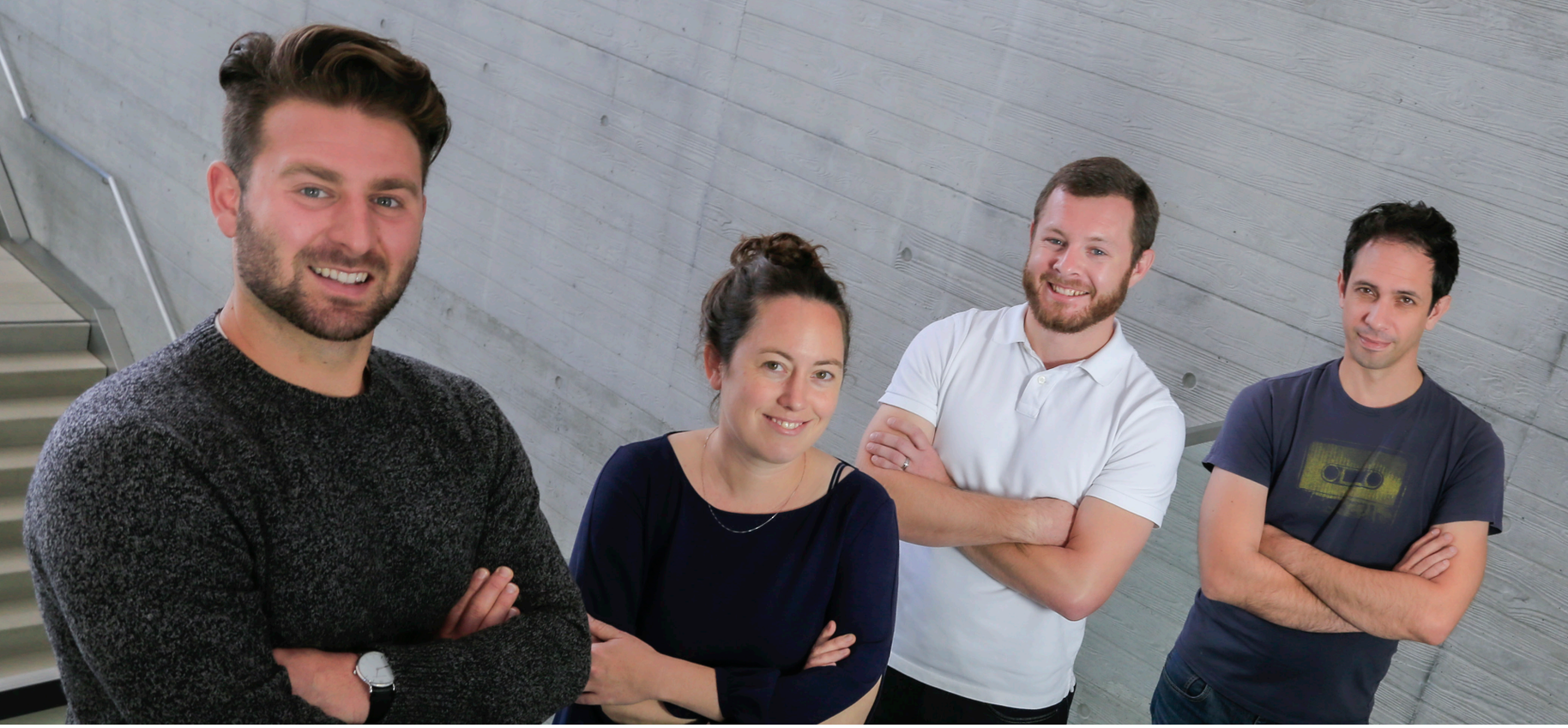
> "TINY OIL DROPLETS ABOUT THE SIZE OF A SINGLE CELL CONTAIN MILLIONS OF FERRO-MAGNETIC NANOPARTI-CLES."

## *THE MECHANICS BEHIND BIOLOGICAL STRUCTURES*

We know that DNA carries the genetic information to turn a simple egg into an organism. However, we do not know how the complex structures that make up our bodies, including our organs, are built. Mechanical engineering associate professor **Otger Campàs** wants to understand how it is done, how cells mechanically sculpt tissues and organs during embryonic development.

Campàs's interdisciplinary team has developed several groundbreaking technologies to answer this question. In one, they use tiny oil droplets about the size of a single cell that contain millions of ferromagnetic nanoparticles. "We inject the droplets into a tissue in a fish embryo and actuate them with magnetic fields," he says. "This tells us what kind of material forms the tissue of the embryo, and from the droplet deformations, we can measure the forces generated by the cells. We can track all of the cells in an organ as it is being formed and understand how the mechanics are shaping it."

Essentially, he notes, "We're trying to understand how the genetic rules are translated to the physical world to build a structure. One application is to understand how mutations translate into developmental defects that affect children. If you can understand the relationship between genetics and building the structure, you can start to see where gene therapy might be effective."



*Decoding nature's engineered systems (from left): Orlando Chirikian, Adele Doyle, Ryan Stowers, Otger Campàs*

## BIOMECHANICS: HARD-HEARTED RESEARCH

Mechanical engineering professor and director of the UC Santa Barbara Center of BioEngineering, **Beth Pruitt,** works in multiple fields within bioengineering: mechanobiology, stem cells, tissue engineering, and microfabrication. The goal in one of her current projects is to understand the mechanical drivers of heart disease.

"We know that the hearts of mice and men are different, so by using heart muscle cells engineered from human cell lines, we can create better models for understanding the biophysics of human disease processes," says Pruitt.

"We're trying to identify the molecular processes of cardiac diseases by mimicking the mechanical properties commonly found in diseased hearts, for example, increased stiffness," says **Orlando Chirikian,** a biologist and second-year PhD student working in Pruitt's lab. "We want to know how internal mutations and external cues interact in the progression of disease."

To that end, he and colleagues in Pruitt's lab seed heart-tissue cells, called cardiomyocytes, in specific patterns onto an inert polyacrylamide gel substrate that is meant to replicate the body's internal environment. The substrate can be made stiffer or softer "to achieve a cellular environment that is seen in disease states," Chirikian notes and enables the researchers to acquire force measurements.

"We force the cells into a rectangular form reflecting the highly organized, brick-like arrangement required for them to produce synchronized force generation," says **Kerry Lane,** a third-year PhD student on the project. "We grow cells on a normal substrate and a very stiff substrate and then compare them to understand how stiffness disrupts force production."

## STIFFENING RESISTANCE TO CANCER

Until recently, it was thought that the stiffness of a cancerous tumor was a byproduct of the disease, "but as engineers and physicists started looking into this, it became clear that the stiffness of the tumor can actually drive progression of the cancer," says UCSB mechanical engineering assistant professor **Ryan Stowers,** describing research that has a lot of overlap with that of his bioegnineering colleagues.

Stowers wants to understand how that happens biochemically.

For his research, biopsied tumors from human patients or mice do not provide enough control to know whether the tumor stiffness is a key determinant in this progression."You need a way to tune the mechanical property you're interested in and then see what the cellular outcome is," Stowers says.

To that end, he says, "What we do is develop artificial tumor environments that mimic the condition or characteristic we're interested in studying in humans or animals. We can control them pretty exquisitely based on their material properties. We encapsulate the cells inside these 3D structures and observe the effects of relatively more or less stiffness on cell morphology, migration, or proliferation. Downstream, we can assay the biochemical pathways that were implicated, and image the cells to see what occurred."

His hope is that "down the road, we'll be able to drug certain pathways to turn off that aspect of the cancer progression."

# *DYNAMICAL SYSTEMS:* **CHANGE** IS THE **CONSTANT**

More than thirty UCSB faculty are connected with the inherently interdisciplinary Center for Control, Dynamical Systems, and Computation (CCDC), with strong representation from electrical engineering and mechanical engineering, and additional affiliates from mathematics, computer science, and chemical engineering. It is an area where, says center director, **Andrew Teel,** junior faculty are making significant contributions in a variety of areas. Here, we summarize projects from several of those rising stars.

## *THE AUTONOMOUS FLEET*

In the future, fleets of autonomous ride-sharing vehicles — think Lyft and Uber without drivers — will become reality. So how will they work?

**Mahnoosh Alizadeh** and **Ramtin Pedarsani,** assistant professors in the Department of Electrical and Computer Engineering, are working on it. They are applying mathematical analysis to develop algorithms for controlling dynamical systems, which are rife with constantly changing variables. In this case, they are developing an optimized system for a fleet of driverless ride-sharing vehicles.

"Autonomous vehicles [AVs] are going to be the future," says Pedarsani. As such, adds Alizadeh, "We're working at the macroscale on how to control them and price rides to maximize either social welfare or the platform operator's profit."

An AV ride-sharing system presents an opportunity to optimize efficiency, because, while human drivers have their own agendas, Pedarsani notes, "AVs can be altruistic."

But modeling and implementing such a system is an enormously complex challenge. For instance, Alizadeh says, "After dropping off a rider, should a car wait in place for another ride request or for demand to increase at that location? Should it go pick up another customer or go to a location that has higher demand? If it's an electric vehicle, should it go to a solar charging station?"

"That's the dynamical system," Pedarsani says. "Demand and traffic change constantly throughout the day, and human drivers sharing the road are also involved. The dynamics are highly volatile. But you can address all that and simultaneously adjust the price according to demand," while ensuring, Alizadeh notes, that "enough cars are available so that the price for riders is reasonable, but not so low that too many rides are requested and long waits ensue."

To design a control algorithm for such a complicated problem, the first step is to develop a mathematical model that represents the key features of the system. "We try to abstract out the important parts," Alizadeh says. "We can't capture everything, but we capture what matters in terms of such important properties as system stability and efficiency."

To develop a computationally efficient and near-optimal solution, the researchers are applying a new tool from machine learning called *deep reinforcement learning*.

"Reinforcement learning can solve large-scale dynamical control problems without the need to know every detail of the dynamics," Pedarsani says. "This has not been done yet, but we have some promising preliminary findings."

> "WE CAN'T CAPTURE EVERYTHING, BUT WE CAN CAPTURE WHAT MATTERS FOR SYSTEM STABILITY."

## *GENETIC CIRCUITS*

In one of his main projects, mechanical engineering assistant professor **Enoch Yeung** is investigating control mechanisms located inside natural biological organisms that are the critical points for influencing synthetic gene circuitry. The work involves introducing genetic circuits, often designed to have some kind of logic-gate function or switching behavior, into bacteria and observing how the circuits impact the host and how the host organism influences the circuits.

"We are trying to model the interface between a host's intrinsic dynamics and the dynamics in synthetic genetic circuits," Yeung says. "We're building genetic circuits, from the bottom-up, that the cell has not seen before. We then model the progressive response and track emergent behaviors while evaluating the ability of the cells to enact a computational program, such as a logic gate or toggle switch."

Yeung says that the long-term goal of the research is to develop data-driven design algorithms for engineering genetic circuits with a minimal footprint on the organism. "We look at high-throughput experimental data from transcriptomics [the complete set of RNA transcripts produced by the genome], proteomics [proteins and their functions], and single-cell behavior, and from that, we identify genetic-circuit components that we should tune or refactor in order to minimize the impact."


## *HUMANS AND ENGINEERED SYSTEMS*

A great deal of ECE professor **Jason Marden**'s research emanates from the simple observation that "humans are complicated."

"If you're thinking about an engineered system that will be utilized by people, it's fundamentally important to understand how people make decisions," says Marden, whose research integrates engineering, control theory, and economics theory.

In one example of how humans impact systems, he describes two versions of a traffic-flow system leading from point A to point B — the baseline system and a duplicate of it that differs only in having one additional route.

"So, you take the new route because it helps you out," he says. "But it also helps out other people, and they gravitate to it. Suddenly, we're all using the new way, and the traffic on it is worse than on the old way. People trying to minimize their own congestion does not equate to the system operating desirably."

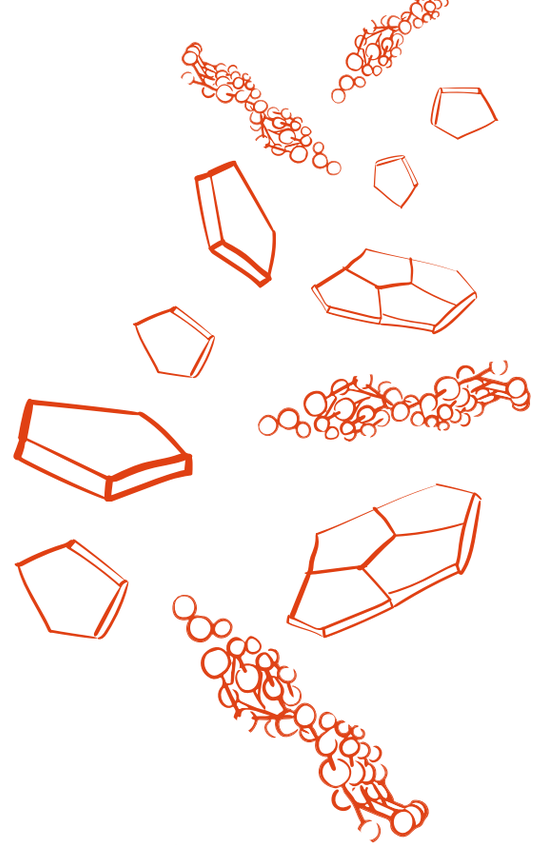
One way to address such system breakdown is through incentives, perhaps in the form of a tax or a subsidy, but different groups of people differ widely in their responses to various incentives.

The question for Marden becomes how to design incentives that will effectively influence users — i.e. encouraging them to use the various routes in ways that minimize congestion — and also be very robust to such variation but not make the situation worse.

Achieving that, he says, "is fundamentally hard."

> "PEOPLE TRYING TO MINIMIZE CONGESTION DOES NOT EQUATE TO THE SYSTEM OPERATING DESIRABLY."

# QUANTUM'S **MATERIAL PATH**



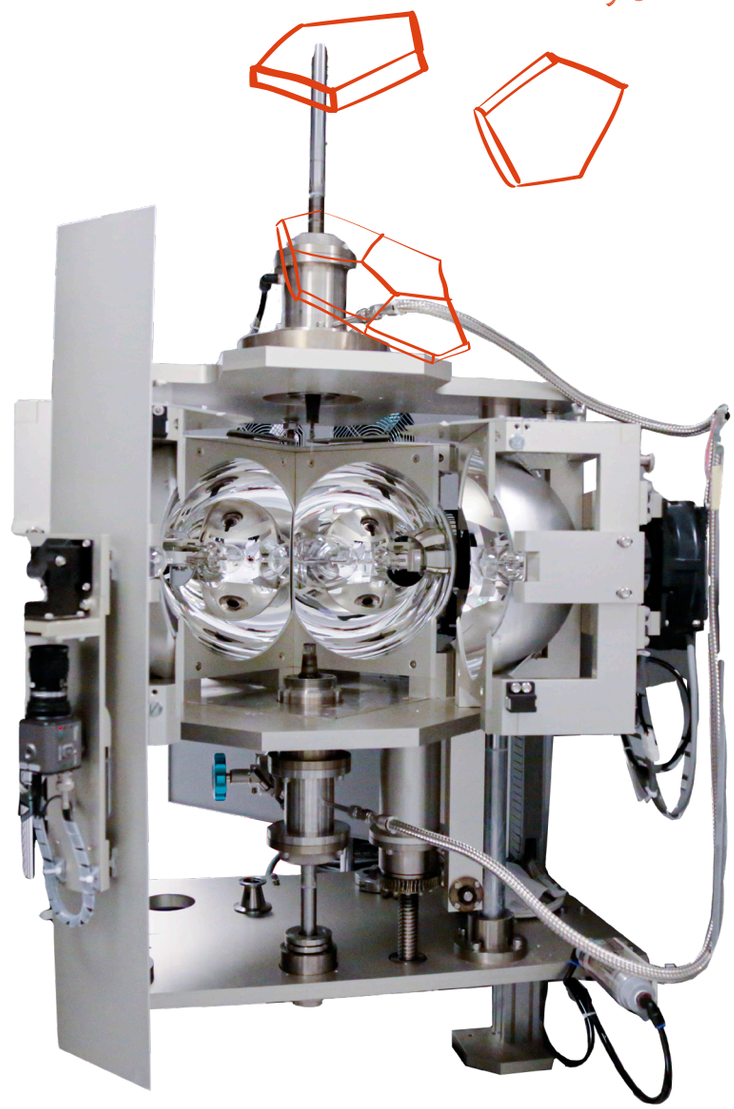
With the end of Moore's Law in sight, researchers are looking for the next silicon chip to drive future technologies. Materials for quantum information hold promise, and UCSB materials scientists and engineers are hard at work to develop and understand them.

## *UNCOVERING QUANTUM CAPACITY*

"UC Santa Barbara has a long history of leadership in developing the theory of quantum phenomena in materials, both in the Physics Department and at the Kavli Institute for Theoretical Physics [KITP},," says physics professor and KITP member **Leon Balents.** "KITP runs major research programs that attract twenty to thirty visitors at a time for approximately three-month visits often centered on quantum materials. This, in addition to a strong postdoctoral program at the KITP, local faculty in quantum materials, and the theorists at Microsoft station Q, make UCSB one of the largest presences in quantum materials theory in the world."

Balents's group studies the emergence of new phases of matter and of long-range quantum entanglement in quantum materials. "We are working on two-dimensional conductors like graphene, studied here on campus in the experimental group of [physics professor] **Andrea Young,**" Balents says. "We are also studying quantum magnetism, the phenomena in which electron spins spontaneously align or form quantum superposition states in crystalline solids.

"Our overarching goal is to uncover the remarkable new capabilities created by the quantum mechanics of many electrons, which eventually may help to harness energy more efficiently and convert it from one form to another, and to enable new types of information processing."



## *BULK MATERIALS SECRETS*

Materials associate professor **Stephen Wilson**'s lab develops ultra-high-purity crystalline materials in bulk form, with an eye toward discovering new electronic states that can be useful in advanced electronic applications or, more recently, in quantum information applications. "This is typically the frontier where you first discover new electronic states," he says.

He also works with fellow materials professor **Susanne Stemmer** and physics professors Leon Balents and Andrea Young to look for new topological superconductors, which have been hypothesized as a possible far-term material for quantum information and computing. Topological materials are those in which specific states are protected by the symmetries of the bulk material itself. "For instance, the crystal structure guarantees that certain properties exist, and it protects those properties," Wilson says.

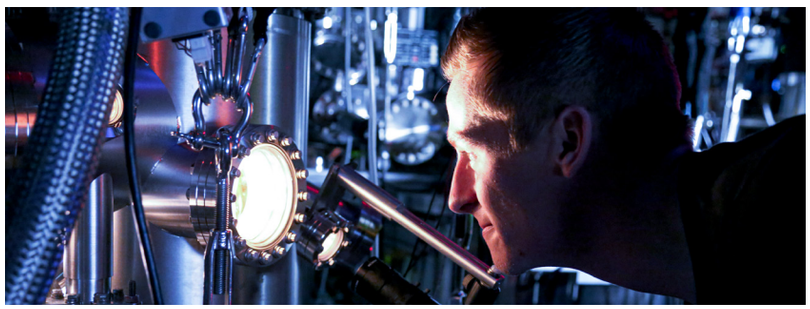
It is possible, he explains, to use the ideas of topological protections provided by certain materials to protect and store quantum information. For example, he says, "You can generate a special topologically protected state — the so-called Majorana fermion [a fermion that is its own anti-particle], which can be used for resilient quantum computing. That's the long-term vision for those materials."

## THE TOPOLOGICAL QUBIT

In his extensive UCSB lab, Professor **Chris Palmstrøm** (electrical and computer engineering, and materials) uses molecular beam epitaxy to combine elements to grow single-crystal compounds on single-crystal wafers, what he describes as "making designer materials with novel properties." He also makes thin films of materials that have been found, in bulk form, to have interesting and potentially useful characteristics.

"We're interested in what happens at the interface when different materials are put together," he says. "It may be that electrons behave in some novel way at the surface of a new bulk material, so, if we interface that with something else, maybe we can use the combined states to do novel things. Or, we can combine two more-normal materials to produce an interesting effect."

Currently, his lab team is attempting to put a superconducting material — one that conducts with 100-percent efficiency because it has no electrical resistance and no electronic field — onto a semiconductor material to see if the semiconductor can be made into a superconductor and create a novel electronic state called a Majorana fermion. It's related to Microsoft's approach for creating a topological quantum computer, but, says Palmstrøm, as is always the case at the leading edge of material science, "There are always plenty of challenges."



## DIAMOND PROTECTION

"One approach to developing materials for quantum information is to grow materials that will exhibit some kind of emergent property," says UCSB physics professor **Ania Bleszynski Jayich.** "You're trying to engineer the interactions within the material to cause new states of matter to arise."

Bleszynski Jayich, on the other hand, works on diamond as a material system for quantum information science, where the diamond lattice hosts localized quantum states in the form of atomic-scale defects. "Our choice defect is the nitrogen-vacancy [NV] center, where we replace one carbon atom with a nitrogen and then remove a carbon atom right next to it and leave it void," she explains. "The hardness that makes diamond good for use in grinding tips also makes it a very good protector of quantum phenomena, such as those exhibited by the NV center."

The NV center is currently the gold standard for solid-state spin systems for quantum information, in particular quantum sensing. But there is no lack of opportunities for even greater quantum control of the NV, which would speed the integration into useful quantum technologies, Bleszynski Jayich notes.

Further, guided by UCSB materials professor **Chris Van de Walle**'s seminal work predicting which material hosts and defect combinations will have properties useful for quantum technologies, Bleszynski Jayich says, "We're beginning to look at the quantum properties of altogether new defect systems that may, ultimately, surpass the NV center."

## THE CHEMISTRY OF MATERIALS FOR QUANTUM INFORMATION

In working with materials for quantum information systems, professor of materials and chemistry **Ram Seshadri** focuses on topological quantum materials, that is, materials whose electronic structure can protect a coherent state essential to quantum operations. "The starting point for everyone in this area is, typically, to perform an electronic structure calculation using the formalism developed by the late UCSB professor **Walter Kohn.**" (Kohn shared the Nobel Prize for this work.)

From there, he says, "When we find some interesting new-material candidates, and we try to make them in the lab and measure some of their properties. Then, ideally, we hand the material off to someone like [materials associate professor] Stephen Wilson, who can develop it further."

For some quantum materials, he adds, "We ask, what are the chemical origins of their particular properties, because we think that by learning the chemistry, we can develop some predictive control. The physics is the useful outcome; the chemistry is how you get there."

Seshadri also believes that, by understanding materials for quantum information systems, it is possible to gain insights into materials for energy conversion and storage systems, such as photovoltaics, magnets, and thermoelectrics. There have already been some suggestions that a certain class of materials for quantum information systems could also perform well as thermoelectric materials, and vice versa."

## ON THE THIN-FILM FRONT

When it comes to materials for quantum communication, says UCSB materials professor **Susanne Stemmer**, "I'm new to it, as many people are," adding, "in many cases, the theoretical framework exists. It's a question of which material will work."

In developing quantum materials, she focuses on thin-films and heterostructures of them grown by molecular beam epitaxy (MBE), which have extremely high purity, higher than can be achieved in bulk materials. "I'm interested in understanding new phenomena in new materials and how to manipulate them in thin-film nanostructures, with a view to room-temperature electrical applications.

"There is a class of quantum materials, called *strongly correlated materials,* which I've worked on for some time but are not well understood. They have a whole set of phenomena, such as transitioning from being a metal [conductor] to an insulator as a function of temperature or other parameters," she explains. "A theory one might use to calculate the properties of a semiconductor often fails for these materials, and not for known reasons."

In terms of quantum applications, her work is more aligned with the needs of quantum computing; however, she says, "I'm always interested in materials that might be useful for quantum computing but might also be very interesting for conventional electrical applications, say, for high-frequency field-effect transistors.

"The nice thing about working with new materials is that you often encounter unexpected behaviors and properties in them and realize that they might be good for something you had never thought about."

> "YOU'RE TRYING TO CAUSE NEW STATES OF MATTER TO ARISE."

# NEXT-GENERATION FILTERING MEMBRANES

Synthetic polymer membranes are widely used to purify water, but currently available membranes are ineffective when it comes to cleaning water, such as that used in oil and gas production, that is heavily contaminated with diverse pollutants and toxins. Better membranes are needed, but gaps in scientific understanding stand in the way.

In 2018, the U.S. Department of Energy provided a four-year, $10.75 million grant to fund the Center for Materials for Water and Energy Systems (M-WET) as one of its Energy Frontiers Research Centers. Involving teams at UCSB, the University of Texas Austin (UT), and the UC Berkeley National Lab, the highly collaborative center is intended to address those gaps and develop transformative polymer materials for energy-water applications.

UCSB M-WET researchers include nine UCSB professors and numerous graduate students and postdoctoral researchers working in four collaborative research units — three "Gap Attack Platforms" (GAPs) and an Integrating Framework group. Here, three graduate students and a postdoc share what each GAP is doing.

## *GAP 1: EMERGENT PROPERTIES OF FLUIDS AND INTERFACES*

Second-year PhD student **Sally Jiao** says that the challenge for her GAP 1 colleagues is to use simulations, while working closely with experimentalists, to understand "how to engineer, or 'decorate,' a membrane surface so that it resists gunk sticking to it and fouling it, which impairs performance."

Jiao explains that the entire M-WET Center is focused on studying a single nanoscale membrane platform called "*the universal membrane chemistry platform* (UMCP). "It is a specific triblock copolymer used to create the membrane," she says. "The polymer is composed of three different blocks, and you get a bunch of the self-assembling blocks together to create a porous structure. You can remove single blocks to create pores that allow solute to pass through, and other blocks can be functionalized with polymers called peptoids, to modulate the hydrophobicity and hydrophillicity of the surface.

"Another person in GAP 1 is working on modeling the part of the t-block copolymer that forms the surface adjacent to the water, and I'm working on testing models for the peptoids," Jiao adds. "In both cases, we're validating our models by comparing our results to those from experimentalists. Eventually, we'll put those models together and simulate the actual realistic surface that the water is going to see."

## *GAP 2: DESIGNING SPECIFIC INTERACTIONS*

"In M-WET, we want to design membranes for the specific water and the specific purpose we're interested in," says **Sam Warnock,** a second-year PhD student on GAP 2. The group is working to design a thin separation layer that has selected chemical functionalities incorporated into it to target specific solutes that the researchers either want to remove from the water and save for use, such as lithium for batteries, or remove and discard, such as pollutants. "In this case, we hope to change the membrane's transport

characteristics so that it will interact specifically with lithium, ignoring other ions, such as sodium and magnesium," Warnock says.

The work requires he and his postdoctoral research partner, **Shou Zhao,** to examine various aspects of the polymer, especially water uptake, which is the mass of water inside the membrane divided by the mass of the membrane itself. That ratio dictates the amount of free volume inside a membrane.

"Too much free volume and things can pass right through, because they won't meet any resistance," Warnock notes. "Too little, and not enough water goes through the membrane, resulting in lower throughput."

Gap 2 researchers would like to mimic natural, biological membranes, which achieve both rapid transport and high selectivity. Says Warnock, "There's an optimum value, and we're trying to find that balance by adding these selective interactants."

## *GAP 3: MESOSCALE STRUCTURES TO TAILOR FLUID FLOW*

"The membranes commonly used in the water-purification industry look a lot like Swiss cheese or a sponge, with the holes, called *pores,* having different sizes and shapes at the nanometer scale" says **Ségolène Antoine,** a postdoctoral researcher on GAP 3.

"Understanding the relationship between the membrane's pore structure and the flow of solvent versus solute [dissolved particles] is crucial for developing next-generation membranes," she explains. "Our mission consists of understanding the relationship between the structure of a membrane and its properties."

GAP 3 researchers seek to develop membranes having controllable and tunable pores with known and optimized geometry and pore-wall chemistry, in order to establish a relationship between the membrane architecture and the resulting transport of water and solute through the membrane. "In this project, we employ multiple experimental and computational tools, both to generate membranes of varying geometrical parameters and to characterize their performance," Antoine says.

The team is also developing a model for the transport of fluids in moderately sized, moderately complex cylindrical pores to understand how these parameters depend on pore geometry and on the chemistry of both pore wall and fluid. "After comparison with experimental results, this model will serve as the training set for the design of the 'best' pore," says Antoine.

## *THE INTEGRATING FRAMEWORK*

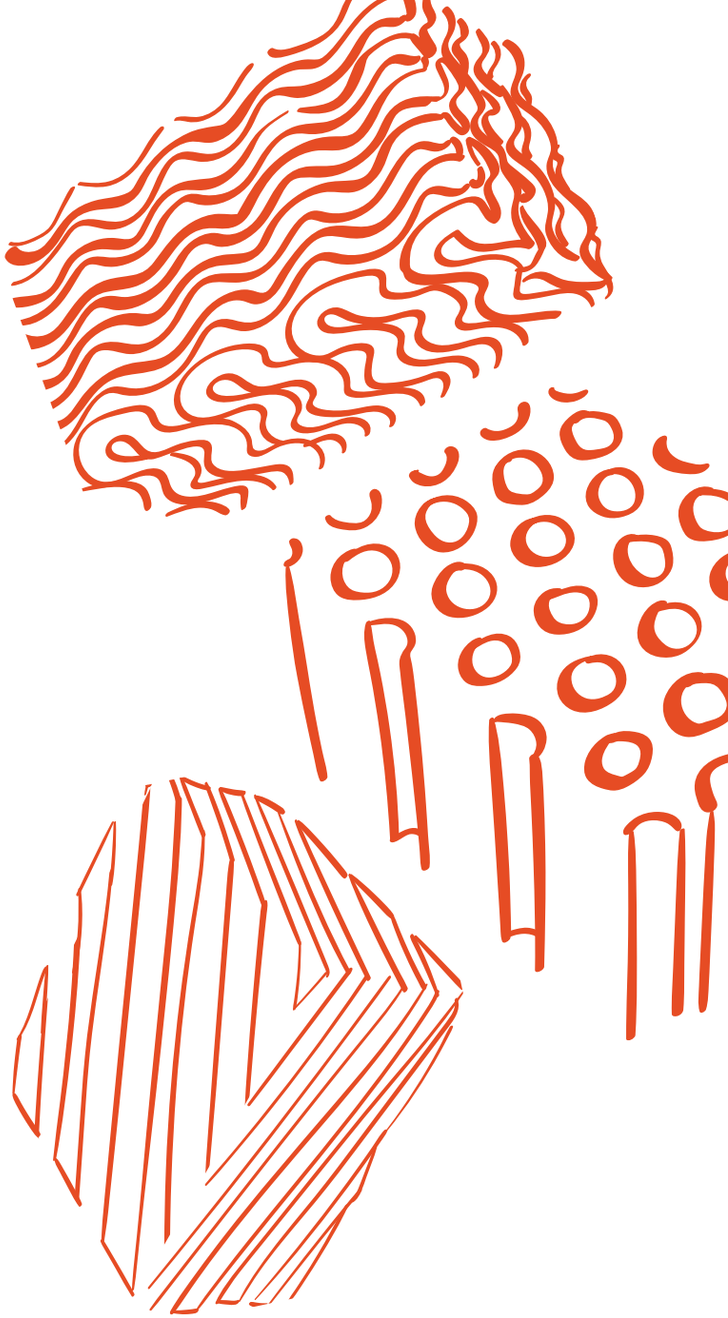
According to second-year PhD student **Varun Hegde,** the main job for him, his UCSB faculty colleagues in the mathematically oriented Integrating Framework Group — professors **Michael Doherty** and **Todd Squires** — and their University of Texas collaborators is twofold: "to make sure that all the groups can relate to each other's work, and to help direct future research."

In the former effort, standardization of an important central value is key. "When we look at a membrane, we want to know what its permeability is, and that is often dominated by the *diffusion coefficient* of the solvent that is moving through it," Hegde says. "All the different GAPs, through all their different experiments, interact with this value in some way."

Various important processes — simulations, macroscopic flux measurements, microscopic interferometry measurements, and nuclear magnetic resonance measurements to study water molecules moving in polymer membranes — can be used to determine diffusion coefficient values that are not necessarily the same.

"You can get a different form of the value depending on whether conditions change or you factor out a variable for a given experiment or simulation," Hegde notes. "It is important that the value is either always the same or, if it isn't, that everyone knows why not, so that the theoretical transport framework is standardized."

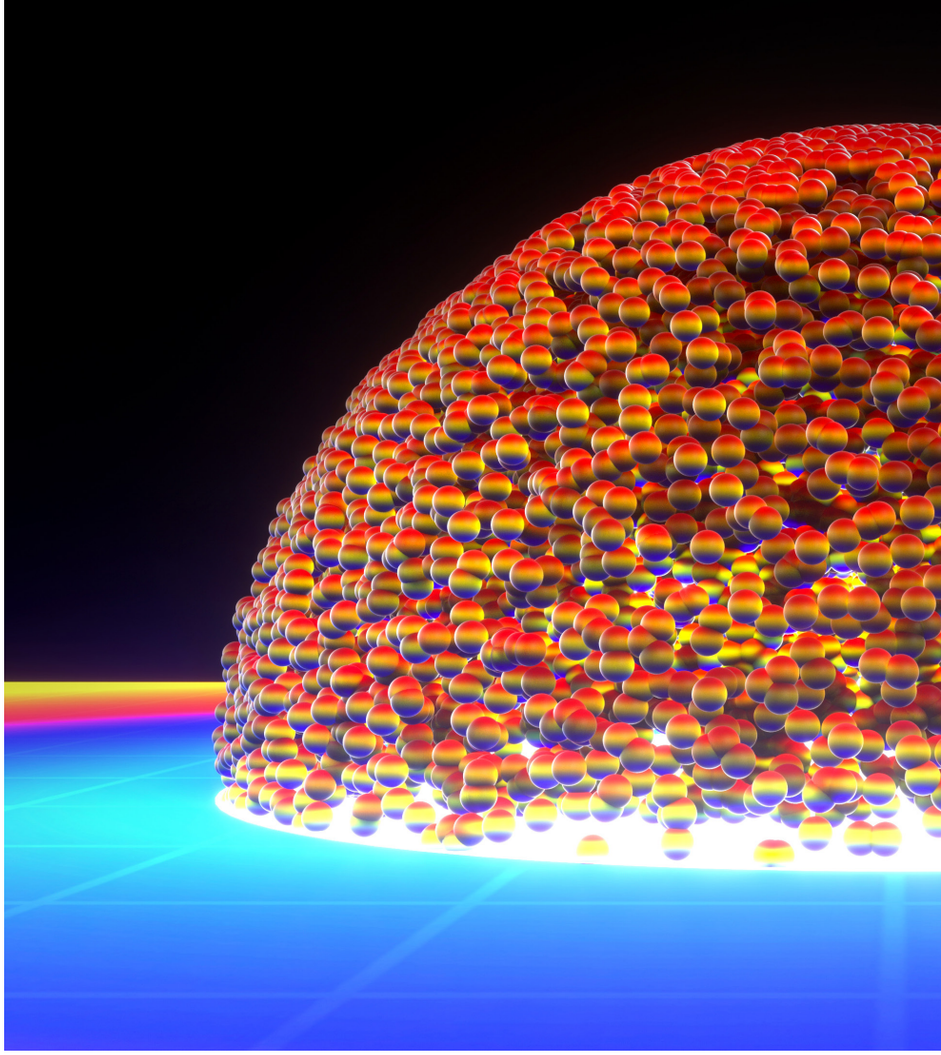
That standardization is critical for allowing other researchers to use the right value in the context of their own research.



"UNDERSTANDING THE RELATIONSHIP BETWEEN THE MEMBRANE'S PORE STRUCTURE AND THE FLOW OF SOLVENT VERSUS SOLUTE IS CRUCIAL FOR DEVELOPING NEXT-GENERATION MEMBRANES."

# A LARGE COMPUTATIONAL STEP TOWARD FASTER HEALING & BETTER DRUG DELIVERY

## Professor Frederic Gibou's lab creates the first large-scale simulation of cells' response to electrical pulses.



*Artist's rendering from a simulation of a large, spherical cluster of cells responding to an electric pulse. Cells in the aggregate are color-coded by their transmembrane potential (hotter colors imply highter potential). The equatorial slice is to illustrate some of the computational techniques used for solving bioelectric interactions on the cell membranes.*

It is likely that, in the not-distant future, wounds will heal faster with the help of an electrical pulse that promotes rapid cell growth. The same type of pulse may be used for more efficient and effective delivery of drugs to fight disease. Such treatments rely on a process known as "electroporation," in which an electrical field is applied to cells to increase the permeability of the cell membrane. Already, electroporation is being used experimentally to deliver chemotherapy into cancerous cells, but such treatments are in their infancy and involve a great deal of trial and error.

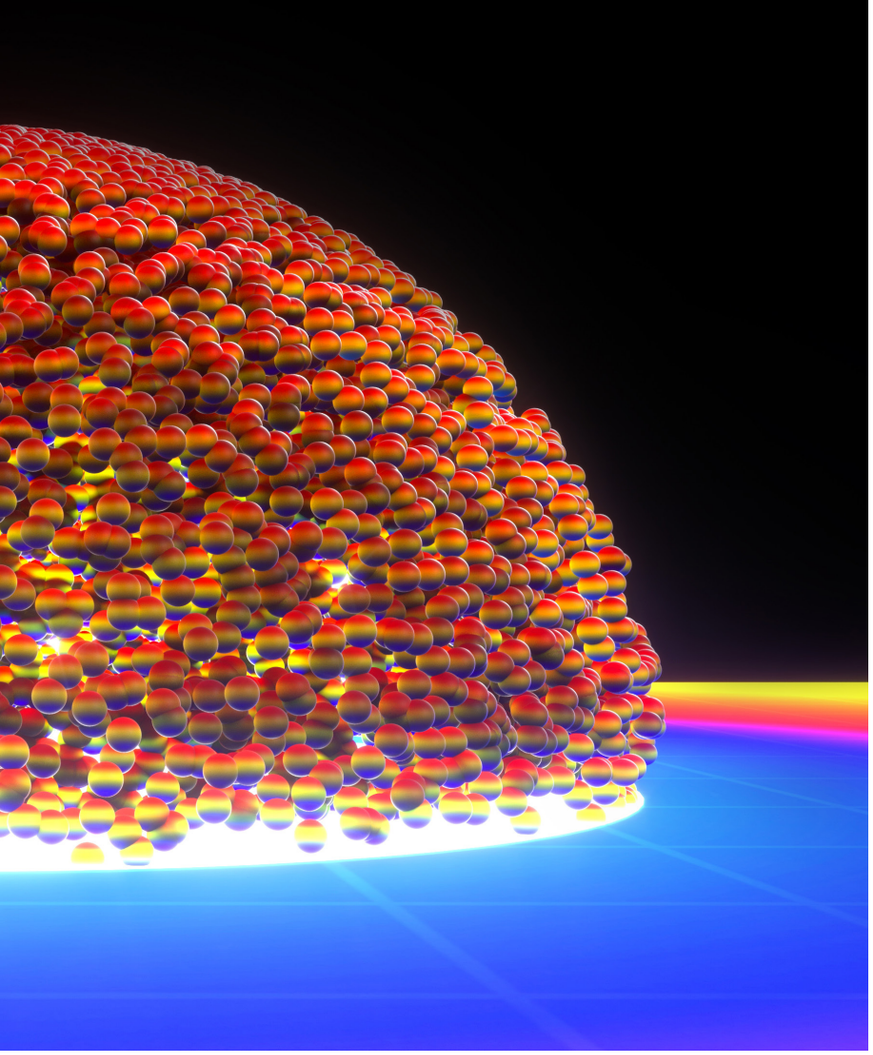
In a paper that has received widespread attention since being published in a 2019 issue of the *Journal of Computational Physics,* **Frederic Gibou,** chair of the Mechanical Engineering Department at the UC Santa Barbara College of Engineering, and a team of UCSB colleagues described research in which they developed the first computational models to study electroporation at the tissue scale. The research was funded by the U.S. Army Research Office's (ARO) Combat Capabilities Development Command Army Research Lab.

ARO mathematical sciences division chief, Joseph Myers, underscores the application of such simulations. "Mathematical research enables us to study the bioelectric effects of cells in order to develop new anti-cancer strategies," he says. "This new research will enable more accurate and capable virtual experiments of the evolution and treatment of cells — cancerous or healthy — in response to a variety of candidate drugs. Eventually, electric pulsation might also be used to accelerate the healing of combat wounds.

"This is an exciting but mainly unexplored area that stems from a deeper discussion at the frontier of developmental biology, namely how electricity influences morphogenesis, the biological process that causes an organism to develop its shape," says Gibou.

Until now, simulations of the effects of electroporation have been conducted on, at most, a few individual cells at a time. But an entire collective system of cells functions much differently than simply the sum of its cellular parts. Not only is it currently not possible to observe the cells as a system in situ, but variables such as environmental temperature and pressure as well as the strength, duration, and pattern of an introduced electrical field affect the behavior not only of individual cells but, more importantly, of the system as a whole.

"When you consider a large number of cells together, the aggregate exhibits novel coherent behaviors," said **Pouria Mistani,** a



PhD student in Gibou's group and first author of the paper. "It is this emergent phenomenon — novel behaviors that emerge from the coupling of many individual elements — that is crucial for developing effective theories at the tissue-scale."

What has been missing to arrive at such a system-scale understanding are the computational algorithms that Gibou's group created. "There is quite a lot of computational science that goes into the design of algorithms that can consider tens of thousands of well-resolved cells," Gibou notes. "We devised the parallel algorithms for describing the physics at the cell membranes and then implemented them into a super computer at the Texas Advanced Computing Center. The simulations gave us the data from the summation of the individual cells, and that data gave us access to the emergent phenomenon of the cluster, which we can now mine to develop a theory."

The team began with a phenomenological model for a single cell developed by the research group of Gibou's longtime colleague, Dr. Clair Poignard, at the Université de Bordeaux, in France. "This model, which describes the evolution of the transmembrane potential on an isolated cell, had been compared and validated with the response of a single cell in experiments," Gibou says. "We were then able to do a similar simulation for a substantial cluster of cells, applying a large electric field around the entire ball of cells. You can imagine that the cells at the surface are going to get a lot of the current and will shadow what the cells further from the surface get."

According to Gibou and Mistani, one of the main reasons for the absence of an effective theory at the tissue scale is a lack of data. Specifically, the missing data in the case of electroporation have to so with the temporal evolution of the transmembrane potential of each individual cell in a tissue environment. Experiments are not able to make those measurements.

"Currently, experimental limitations prevent the development of an effective tissue-level electroporation theory," Mistani said. "Our work has developed a computational approach that can simulate the response to an electric field of each individual cell in a spheroid comprising tens of thousands of cells, as well as their millions of mutual interactions. This has been, by far, the largest simulation of cell-aggregate electroporation to date. It has successfully provided terabytes of high-fidelity measurements of electroporation processes on tens of thousands of highly resolved cells in a 3D multi-cellular spheroid configuration."

"This work could result in an effective theory that helps us understand the tissue response to these parameters and thus optimize treatments," Mistani adds. "Previously, the largest simulations of cell-aggregate electroporation considered only about one hundred cells in 3D, or were limited to 2D simulations. Those simulations either ignored the real 3D nature of spheroids or considered too few cells for tissue-scale emergent behaviors to manifest."

> "THIS IS NOT MERELY A 'CHEAPER WAY' TO DO AN EXPERIMENT. RATHER, IT DELIVERS INFORMATION YOU CANNOT GET FROM AN EXPERIMENT."

"Our simulation provides the kind of data you need to build a theory," Gibou explains. "This is not merely a 'cheaper way' to do an experiment. Rather, it delivers information you cannot get from an experiment, because using current experimental techniques, it is not possible to measure the relevant physical features of each and every individual cell. And if you try to perform some measurement by placing an electrode or whatever, you change the entire system.

In their research, Gibou adds, "We mine the data within the framework of statistical physics, a theoretical tool that has been used successfully to describe the simulation results of materials. That allows us to view the cluster as a material and develop the theory. The theory will then give us a simpler equation for how the cluster behaves and, thus, a tool to understand and control bioelectricity.

"We did the simulation, we are building the framework of the theory to understand the system, and then we're going to add some complexity to the model to get closer and closer to the behavior of, perhaps, cancer cells," he adds. "And at the end, when the experiments that can probe average behaviors are performed, they will be more directed because they're informed by the model."

This work has received widespread coverage, including on the websites of two national supercomputing facilities — the Texas Advanced Computing Center (TACC) and the Extreme Science and Engineering Discovery Environment (XSEDE) — as well as in several specialized high-performance computing magazines and multiple popular science outlets.

# COMBINED INTELLIGENCE:

## TWO AI MODELS ON ONE CHIP

In its rapid rise to prominence, artificial intelligence (AI) has developed, so far, along two main paths: the machine-learning path and the neuroscience path.

The machine-learning (ML) path is aimed at bringing a high degree of accuracy to practical tasks — with the help of big data, high-performance processors, effective models, and easy-to-use programming tools. It has achieved human-level (or better) performance in a broad spectrum of AI tasks, from image and speech recognition, to language processing and autonomous driving, etc.

The neuroscience approach is meant to harness what we know about the brain's neural dynamics, circuits, coding, and learning to develop efficient "brain-like" computing capable of solving complex problems that are not exclusively data-driven and may involve noisy data, incomplete information and highly dynamic systems.

The two types of AI use different approaches to solving these different types of problems, and, not surprisingly, both are based on different and wholly incompatible software models, or platforms. Neuroscience AI takes place in what are referred to as spiking neural networks (SNNs), while machine learning occurs in the slightly misleadingly named (because of the word "neural") artificial neural networks (ANNs).

*The researchers developed a riderless bicycle as a proof-of-concept for the Tianjic chip, which combines the two main types of machine-learning approaches.*

> *OUR BIG IDEA IS THAT IF WE WANT TO GO A STEP FURTHER AT THIS STAGE, WE SHOULD BUILD A CROSS-PARADIGM COMPUTING MODEL.*

"The Neuroscience [NS] approach mimics the behavior of our brain circuits," says **Lei Deng**, a postdoctoral researcher in the laboratory of UCSB computer science professor **Yuan Xie** and a co-author of a recent paper in *Nature* titled "Towards artificial general intelligence with hybrid Tianjic chip architecture."

He adds, "We know that our brain can perform many tasks better than a computer can. The problem in terms of NS-oriented AI is that so many details of how our brain works are still unclear. As a result of those gaps in knowledge, we can say that the CS approach is very successful now, but the NS model will be the future."

In the human brain, the inputs for one neuron come from the firing activities of previous neurons, "So, it builds," says Deng. "A time factor is involved, so the historical states of a neuron will affect its future.

The CS model, on the other hand, does not build upon prior knowledge over time. Rather, it has a database and uses strong computing power to search through the data at high speed to refine matches. But it cannot accumulate knowledge to "learn as it goes."

"Sometimes, in the human brain, if a neuron accumulates information and the membrane potential crosses a threshold, the neuron will fire," Deng says. "But if the stimulus information is not strong, it will not cross the threshold and will be leaked; the membrane potential will decay if no other inputs are received. This process can help to denoise very noisy data. Our brain is a noisy system that receives many partial, 'noisy,' signals but is very good at filtering out that noise to extract only what is useful."

At this stage, and until the brain is better understood and computer scientists can achieve a blended artificial general intelligence (AGI), Deng says, "We believe that combining these two approaches is a promising path. Our big idea is that if we want to go a step further at this stage, we should build a cross-paradigm computing model."

It is a challenging proposition, as, usually, ANNs and SNNs have different modeling paradigms in terms of information representation, computation philosophy, and memory organization. Deng and his colleagues have addressed those issues to some extent for the first time on their Tianjic chip, which, as the authors write, "integrates the two approaches — computer-science-oriented and neuroscience-oriented neural networks — to provide a hybrid, synergistic platform."

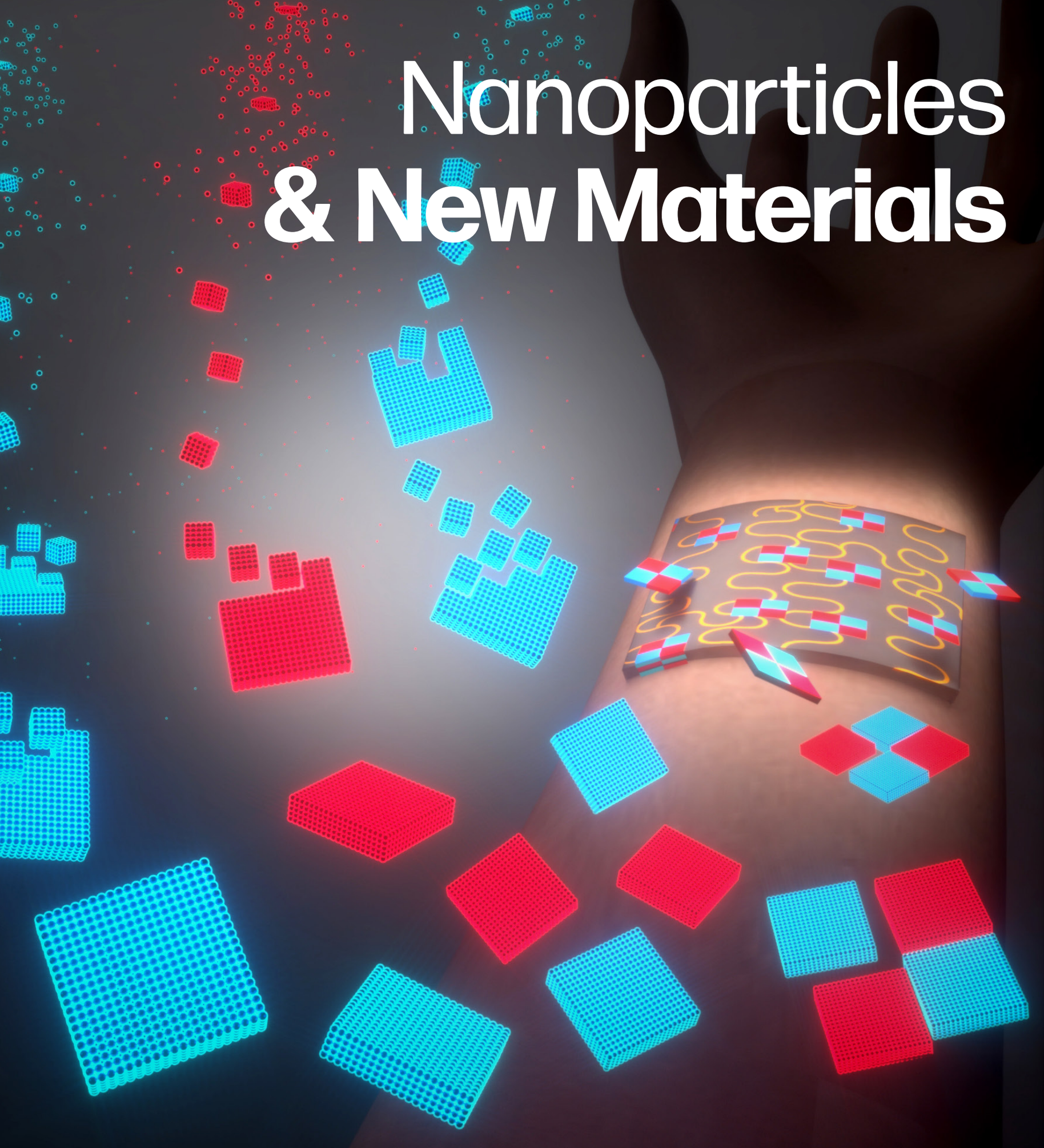
The authors add: "By compiling various neural network models in both domains, we were able to carry out a detailed comparison to align the model dataflow, with one-to-one correspondence, to relevant building blocks — namely axon [making up the input/output storage], synapse [indicating connections between neurons], dendrite [integrating inputs], soma [accumulating the integrated inputs onto the membrane potential and firing output signals], and router [implementing synaptic connections in hardware]. On the basis of this unified abstraction, we built a cross-paradigm neural scheme."

"The new chip is more flexible, so that it can do some of both types of AI," Deng says. As a proof-of-concept experiment, the team installed a single Tianjic chip into a riderless bicycle in China, deploying multiple specialized networks in parallel.

Deng explains that the Tianjic chip overcomes several drawbacks of the approach using heterogeneous architecture with separate chips for different types of AI. For instance, the heterogeneous model has limited flexibility in determining the optimal ratio of ANN chips to SNN chips to adapt to diverse real-world workload. Further, building extra inter-chip circuits for signal conversion results in inefficiencies, and, finally, the heterogeneous system has poor programmability for managing heterogeneous chips that have different languages.

The authors' unified architecture addresses those concerns, and in the future, the team plans to wire together hundreds of the chips (the bicycle has only one) to form a brain-like computer. They are currently developing a new chip for the job. "The first chip optimized function, not performance," Deng says. "For the new chip, there is a significantly higher emphasis on performance."

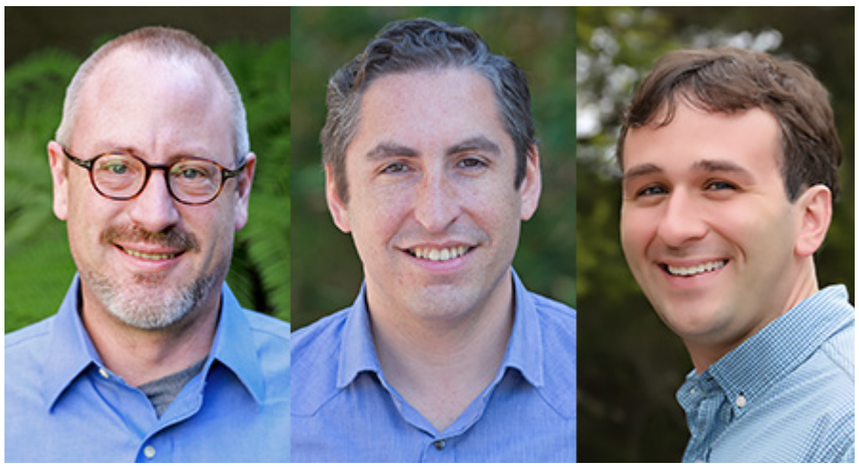
# Nanoparticles & New Materials



## A review in SCIENCE describes the state of the field and where it's going, while identifying obstacles ahead and important research that addresses them.

Materials made from nanoscale particles, which are less than 1 percent of the width of a human hair, create exciting opportunities to design new functional materials having unique responses to external stimuli, such as light, electrical and magnetic fields, and mechanical deformation. Embedding such particles in a "matrix" (here referring to a surrounding medium or structure) composed of a different material makes it possible to create nanocomposites that enable entirely new kinds of wearable sensors, highly efficient catalytic devices, and flexible displays.

The central challenges in developing such transformative devices have recently been summarized in an insightful review article co-authored by two professors in UC Santa Barbara's College of Engineering — materials scientists **Matthew Begley** and **Daniel Gianola** — and their long-time collaborator **Tyler Ray,** a UCSB alumnus and professor at the University of Hawaii. This timely review, published in a recent issue of *SCIENCE,* describes the current state of the field, maps out future research directions, identifies challenges to progress, and highlights more than thirty projects that represent important directions and approaches going forward.



*Co-authors (from left) Matthew Begley, Daniel Gianola, Tyler Ray.*

The review illustrates that a central need for tomorrow's materials scientists and engineers is to gain sufficient control during processing at multiple size scales to ensure that new materials not only have the necessary functional properties, but are also sufficiently robust to survive the stress of manufacturing techniques used to make macroscale devices.

"In a nutshell, we're interested in understanding, from a composite-materials standpoint, how nanoparticles and the surrounding material can be integrated, not just to make interesting materials, but also to allow for patterning and integration of nanocomposites into actual commercially viable devices" Begley says.

"A key point is mechanical robustness," Ray adds. "If we're extruding a material and it is very fragile or cannot be patterned to connect to other materials effectively, it will likely not find its way into a device for widespread use."

Despite the challenges, Gianola notes that there is strong motivation for addressing these integration challenges, saying, "The ability to make interesting nanoscale particles has simply exploded over the past decade; nanocrystals having various shapes, sizes, and compositions have created an incredible materials 'palette' that can be used to design entirely new types of functionality."

This palette is just the first stage, because, ultimately, nanoparticles must be arranged in useful ways at larger length scales. The authors illustrate that the coupling between stimuli and response is strongly enhanced by having deterministic control of multiple length scales in a hierarchical structure, such as the ordering of crystalline nanoscale particles having a prescribed shape to form "superlattices" in materials exhibiting emergent collective behavior not hosted in the individual particles. As Begley puts it, "We need to pull nanocomposites out of the beaker and put them into actual devices." To do this requires researchers to connect the novel synthesis techniques that have enabled this materials palette to fabrication at larger length scales.

According to the review, the challenge of using ordered nanocomposites in applications stems from several related factors: "the limited availability of pathways for synthesizing and patterning such materials over length scales required for devices; the need to develop fabrication techniques that make it possible to integrate nanocomposites with other materials required to connect or protect functional components; and the limited understanding of the thermomechanical stability of nanocomposites, both as isolated materials and as embedded components."

The authors highlight the critical roles multiple types of research have in making progress, from scalable nanoparticle synthesis and self-assembly methods used to bind particles together in organized patterns, to acoustic assembly for organizing particle aggregates, and 3D printing of nanocomposites to facilitate patterning in actual devices.

By integrating many different materials and perspectives on devices, the review provides keen insight into research that will lead to more widespread use of nanocomposites

"Our hope is that by taking a holistic view of the field, we can help to identify sticking points in developing technology," says Gianola. "That, in turn, should allow us to more quickly identify material systems that exhibit both desirable properties and clear pathways to integration in devices. We are optimistic that the review will, at the very least, stimulate many interesting discussions among our colleagues, which is always the first step to inspiring advances."

> *"IF A MATERIAL IS VERY FRAGILE OR CANNOT BE PATTERNED TO CONNECT TO OTHER MATERIALS EFFECTIVELY, IT WILL LIKELY NOT FIND ITS WAY INTO A DEVICE FOR WIDESPREAD USE."*

# UCSB College of Engineering
## Matters of Fact

**#1** **Among Public Universities**
in % of eligible assistant professors who received NSF CAREER Awards in 2019

**#2** **Among Public Universities**
in research expenditures per faculty (*U.S. News and World Report*'s 2020 Graduate School Rankings)

**3** **Nobel Prizes**

**5** **Straight Years**
ranked #1 public university in world for engineering research impact
(Leiden Rankings, 2015-19)

**5:1** **Graduate Student-to-Faculty Ratio**

**10:1** **Undergrad Student-to-Faculty Ratio**

**1,575** **Undergraduate Students**

**783** **Graduate Students**

**150** **Collaborative Faculty**

**4.49** **High School GPA**
of admitted CoE freshmen in 2019

**65%** **of UCSB's new invention portfolio involved CoE**
(Fiscal Year 2018)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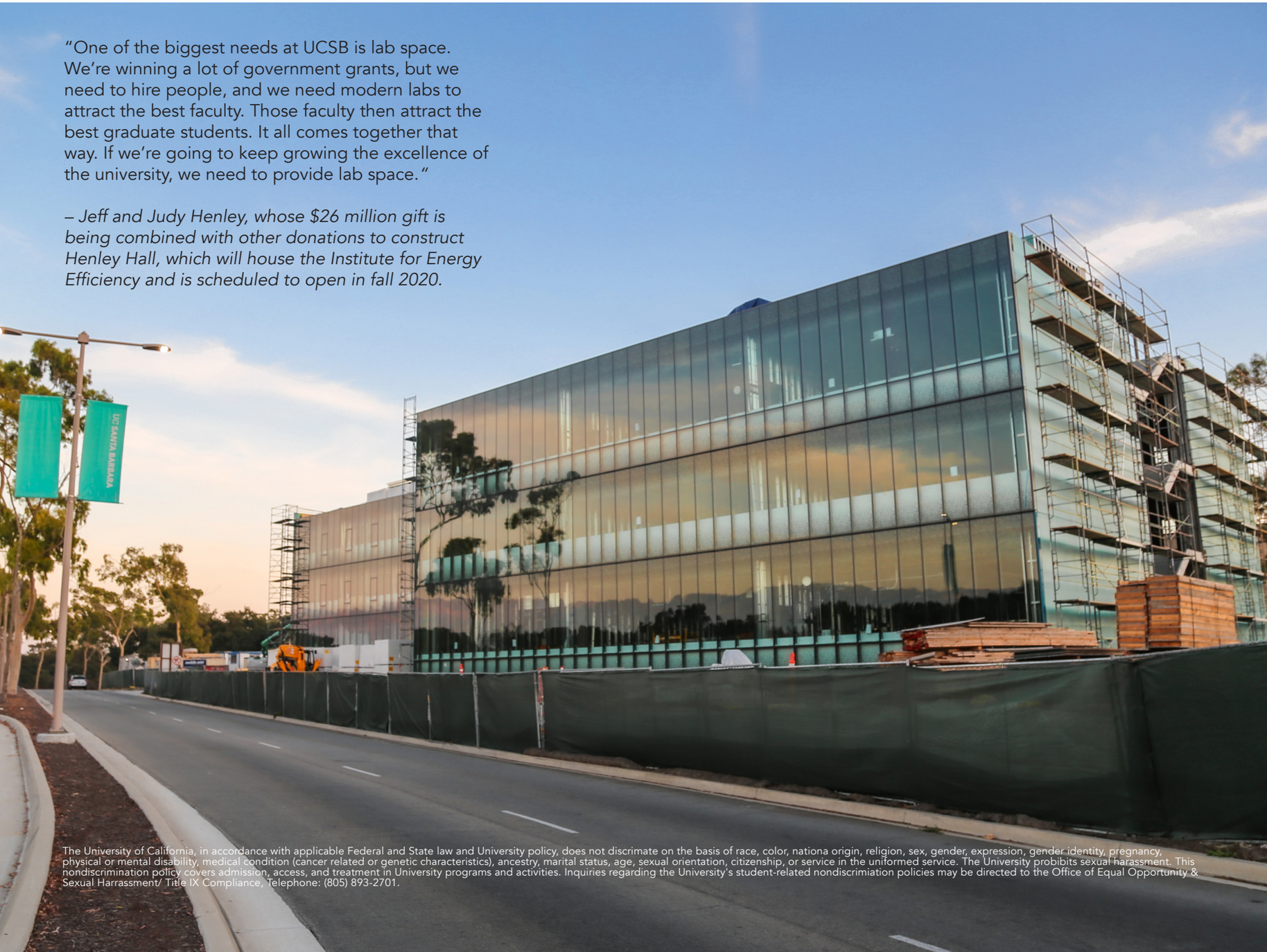


"One of the biggest needs at UCSB is lab space. We're winning a lot of government grants, but we need to hire people, and we need modern labs to attract the best faculty. Those faculty then attract the best graduate students. It all comes together that way. If we're going to keep growing the excellence of the university, we need to provide lab space."

*– Jeff and Judy Henley, whose $26 million gift is being combined with other donations to construct Henley Hall, which will house the Institute for Energy Efficiency and is scheduled to open in fall 2020.*