SUMMER 2024

CONVERGENCE

The magazine of engineering and the sciences at UC Santa Barbara

FOCUS ON: BATTERIES

RESEARCHERS FROM DIVERSE FIELDS AIM FOR THE ULTIMATE "POWER LIFT"

THE IEE AT 15

A MILESTONE FOR THE PIONEERING INSTITUTE FOR ENERGY EFFICIENCY

A STARTUP WITH SOLE

TWO COE FACULTY CREATE A SHOE TO ADDRESS A CONDITION AFFECTING MILLIONS

IN MEMORIAM: HERB KROEMER

THE NOBEL LAUREATE CHANGED THE WORLD AND LEFT A MULTI-LAYERED LEGACY

UC SANTA BARBARA

MESSAGE FROM THE DEANS

Umesh Mishra

Dean and Richard A. Auhll Professor, College of Engineering

Pierre Wiltzius

Susan & Bruce Worster Dean of Science, College of Letters & Science

Greetings to all our colleagues and friends in the UC Santa Barbara family.

Another academic year has flown by, a year filled with many more impressive achievements in the form of major grants, groundbreaking scientific findings published in distinguished journals, and recognitions and awards received.

Meanwhile, new challenges have arisen, and grand challenges continue to demand our best to address them. We in the College of Engineering and the Division of Mathematical, Life and Physical Sciences can take great pride in the accomplishments of UCSB faculty, professional researchers, graduate students, and undergraduate researchers, and the diligence they demonstrate in classrooms and labs to make a positive difference in the world.

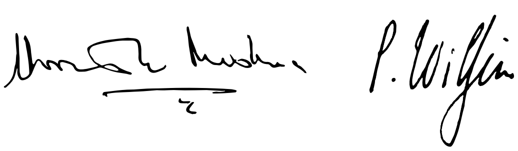
The cover story of this issue (“Power Lift,” P. 18) is a case in point, demonstrating once again the effectiveness of a collaborative multidisciplinary approach to research. The work involves faculty from the Materials, Chemical Engineering, Chemistry, Physics, and Electrical and Computer Engineering Departments, who are combining their expertise to design and produce new batteries that will be safer, more powerful, and more efficient. Their efforts are part of a worldwide push to combat climate change by weaning humanity from fossil fuels and creating sustainable electrified economies.

Closely related to that objective is the mission of UCSB’s Institute for Energy Efficiency (IEE), which celebrated its fifteenth anniversary last November. This issue’s article about the IEE (P. 12) provides just a glimpse of the diverse collaborative research being undertaken by several of the roughly one hundred faculty researchers who are affiliated with the center, many of whom are based in its LEED Platinum Henley Hall headquarters.

In this issue, we also remember UCSB professor and Nobel Laureate **Herb Kroemer** (P. 30), who died in March and is credited with developing the semiconductor heterostructures that enabled the modern era of microelectronics and information technology. You’ll also read (P. 26) about a startup created by mechanical engineering professors **Elliot Hawkes** and **Tyler Susko** to produce a carefully engineered walking shoe that addresses the specific needs of those who experience foot-drop syndrome. You’ll meet our Champion of Engineering (P. 28), UCSB alumnus, serial entrepreneur, and COE donor **Yulun Wang** (PhD ’88), who invented the surgical robotic arm, is a pioneer in telemedicine, and now works to deliver healthcare remotely to patients in underserved parts of the world. You’ll also read about two dynamic new faculty members (P. 11) and (P. 8) catch up on the many prestigious awards UCSB faculty received over the past year.

We hope you enjoy the issue and have a rewarding and relaxing summer.

Sincerely,



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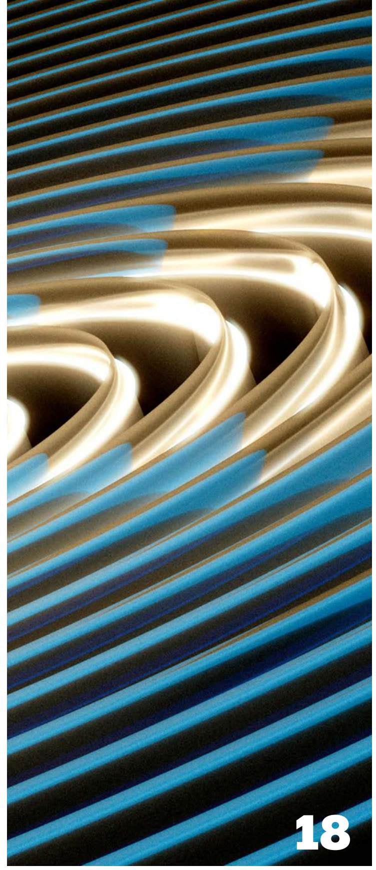

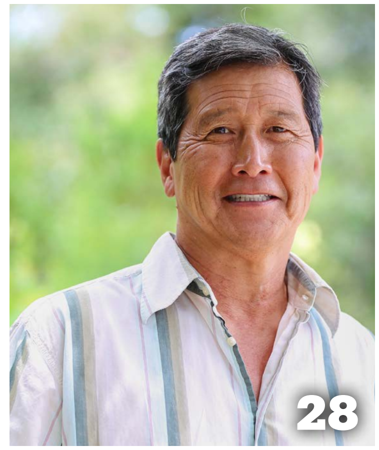

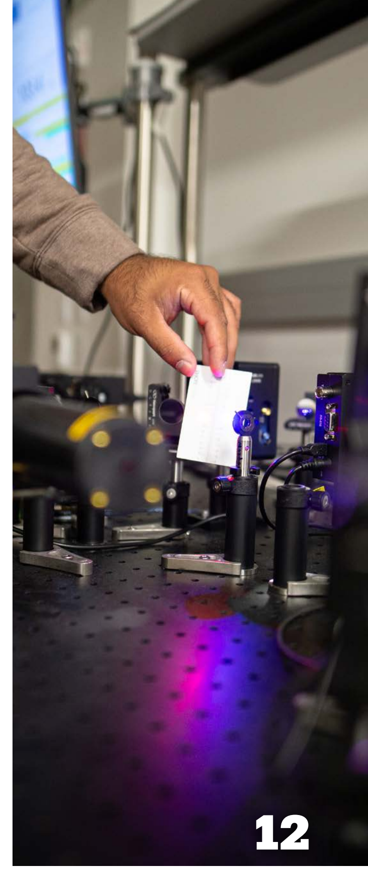

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UC SANTA BARBARA
College of Engineering

NEWS BRIEFS

PARA-POWER: RORY COOPER KEEPS ROLLING

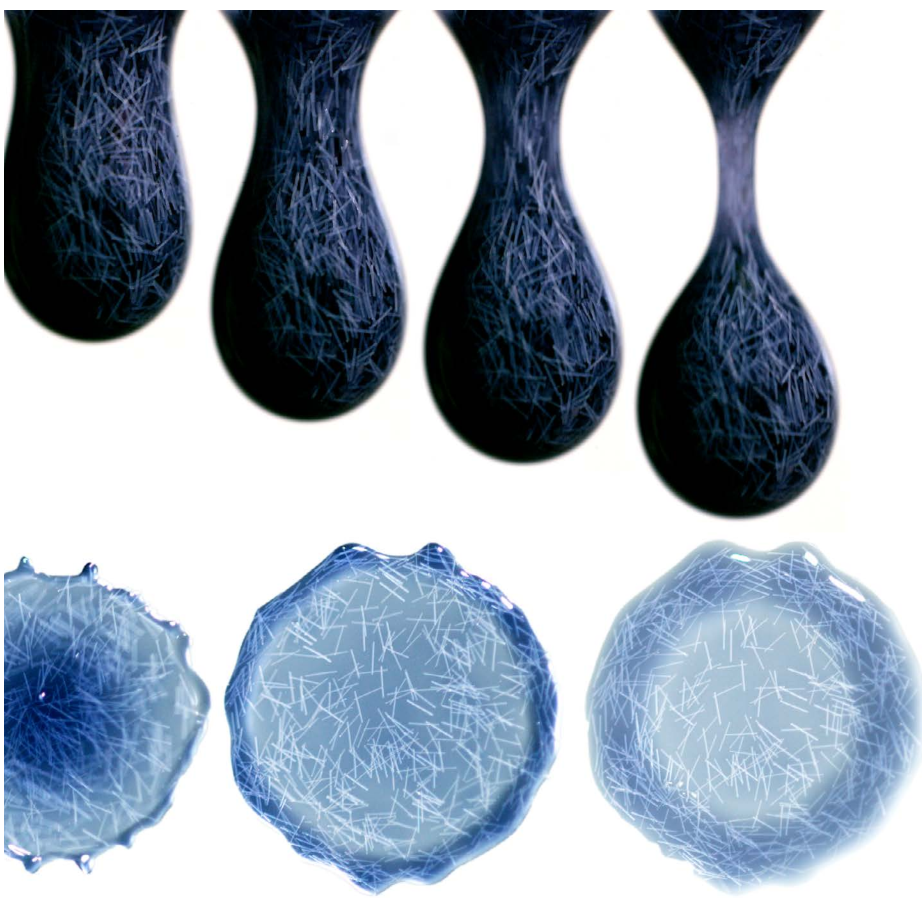
UC Santa Barbara alumnus **Rory Cooper,** known globally for his pioneering work in researching, conceiving, designing, and building adaptive technology for those who, like him, navigate the world in a wheelchair, returned to the UCSB campus on April 19 for the first time since receiving his PhD in Electrical and Computer Engineering in 1989. He delivered a wide-ranging talk about the seemingly limitless avenues of research and engineering under way at the University of Pittsburgh's Human Engineering Research Labs (HERL), which Cooper directs. A longtime para athlete who has won medals in the Paraympics and the World Para Athletic Championships, Cooper has been instrumental in numerous breakthrough technologies, including adapting the lightweight, ergonomic, injury-reducing designs of racing wheelchairs for everyday use.

Inventor, para athlete, and UC Santa Barbara alumnus Rory Cooper (right) shown during his wide-ranging talk at the College of Engineering.

A DROP OF RECOGNITION AT APS MEETING

A PhD student in the laboratory of **Alban Sauret,** associate professor in the Mechanical Engineering Department at UC Santa Barbara, was one of three presenters to win an award for their posters, which were featured in the Gallery of Soft Matter at the annual meeting of the American Physical Society, held in Minneapolis in March. Third-year student **Sreeram Rajesh**'s poster illustrated the release of suspended droplets containing agglomerations of fibers. Such suspensions could be useful in additive manufacturing (3D printing) by allowing the printing of fiber-reinforced composite materials having desirable mechanical qualities.

The image was made using high-speed photography and optical microscopy to capture the dynamics of a water-glycerol mixture containing nylon fibers of various lengths and at various concentrations. The poster shows images of the droplets dangling from a syringe before they are released (top row at left) and then spreading out on a hydrophilic surface after being released (bottom row at left). In his doctoral research, Rajesh is investigating the factors that influence the final orientations of the fibers in the liquid, which could affect the properties of the printed material.



The award-winning poster produced by Sreeram Rajesh shows the dynamics of fiber-containing droplets for 3D printing.

Photograph by Ram Seshadri

Ram Seshadri (left) and Anthony Cheetham have questions regarding big claims about AI and new materials discovery.

WILL AI IDENTIFY 2 MILLION NEW MATERIALS? OUR FACULTY HAVE QUESTIONS.

Every day we hear new claims about all the amazing things that AI will do for us. Are they valid? UC Santa Barbara faculty members — emeritus materials professor **Sir Anthony Cheetham** and materials professor and Materials Research Laboratory director and College of Engineering associate dean, **Ram Seshadri** — wondered that upon reading a paper by a group of Google DeepMind researchers published in *NATURE* last November.

The paper's authors suggested that AI would "enable the discovery of 2.2 million new stable materials...representing an order-of-magnitude expansion in stable materials known to humanity." Cheetham and Seshadri did some diligence and then followed with a jointly authored perspective piece casting a critical eye on the claims. Their article was published April 8 in *Chemistry Materials*.

Cheetham and Seshadri cite numerous technical questions about the means of classifying materials, but one point stands out. Materials scientists tend to agree, they say, that, in order to be considered new materials, novel compounds should demonstrate three key characteristics: . they should be "experimentally realizable, novel in the sense of being more than a trivial extension of known compounds, and able to display evidence of utility."

In the vast majority of the new materials hypothesized to arise thanks to AI and machine learning, they write, "We find scant evidence for compounds that fulfill the trifecta of novelty, credibility, and utility. "While the methods…hold promise, there is clearly a great need to incorporate domain expertise in materials synthesis and crystallography."

SHELLPHISH HACKERS TAKE $1 MILLION IN DARPA COMPETITION

The Shellphish Support Syndicate, a team comprising UC Santa Barbara computer science faculty and students, as well as UCSB alumni who are now professors at Arizona State University and Purdue University, has earned a $1 million award as one of seven funded teams that will participate in the DARPA Artificial Intelligence Cyber Challenge (AIxCC) Small Business Track Competition.

The prize money will support the team as it prepares for the next AIxCC event. For that competition, Shellphish team members will build a cyber-reasoning system that leverages advanced AI techniques to automatically identify vulnerabilities in software and propose software patches that fix them.

The team, with faculty support from UCSB computer science professors and cyber-defense experts **Christopher Kruegel, Giovanni Vigna,** and **Wenbo Guo,** also includes ASU professors **Adam Doupé, Yan Shoshitaishvili,** and **Fish Wang,** and Purdue professors **Antonio Bianchi** and **Aravind Machiry,** all of whom are UCSB alumni affiliated with the Computer Security Group (SecLab) and also members of Shellphish.

The next step in the AIxCC will be the Semifinal Competition (ASC), which will be held this coming August. Each of the top-seven-finishing teams in that competition will receive an additional $2 million and advance to the Final Competition (AFC), to be held in August 2025, with the top three teams each earning a portion of the $8.5 million in total prize money.

Cyberdefense is familiar terrain for all of the participants, and Kruegel and Vigna are key researchers in the new $20 million UCSB-led, NSF-funded ACTION Institute, which was established with the goal of teaming humans and AI agents in uprecedented ways to protect mission-critical cyberconnected systems and infrastructure, such as banks, hospitals, government organizations, etc.) Vigna is the director of the ACTION Institute, and Kruegel is a co-PI on that project.

Center of Engineering Innovation and Design donors Virgil Elings (left) and Alistair Wynn unveil a plaque to honor them and their fellow donors, as Mechanical Engineering Department chair, Jeff Moehlis, looks on.

EVENT HONORS COE MACHINE SHOP RENOVATION DONORS

Donors joined UC Santa Barbara faculty and staff in March for a ceremonial unveiling of a plaque dedicated to the donors who made possible the renovation of the College of Engineering (COE) Machine Shop, officially called the Center of Engineering Innovation and Design (CEID).

Long the first stop for COE faculty and students needing something built for a lab or an experiment, the shop is especially important to undergraduate students in the Mechanical Engineering (ME) Department. About twenty teams of such students each year use the shop to build and test their senior capstone projects.

On hand for the event were donors **Virgil Elings, Alistair Wynn,** and **Jim Frank.** Elings spent twenty years on the UCSB physics faculty and co-founded Digital Instruments, a pioneer in developing and manufacturing the scanning probe electron microscope.

When Wynn, who founded seven successful companies in the biomedical field, joined the Industrial Advisory Board ten years ago, he said, "We realized that the machine shop was outdated. With this project, I think we've fixed that."

Frank is a longtime COE donor for whose father Harold Frank Hall is named.

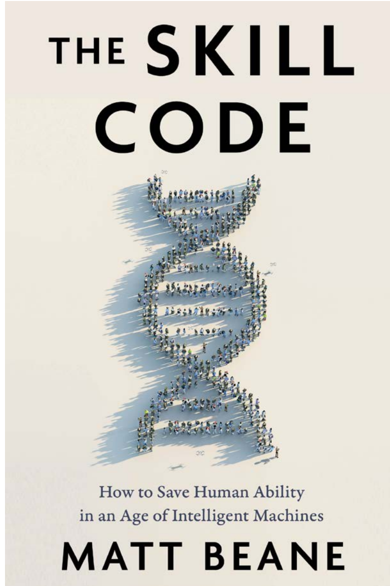
"The most important thing about the machine shop, I believe, is the possibility if offers for developing potential," said COE dean, **Umesh Mishra**. "It's a place for expression that can bring out the genius in a person."

ADDRESSING THE THREAT TO EXPERTISE IN AN AI WORLD

Matt Beane studies how humans build skill at work, and how that's changing with the introduction of intelligent technologies such as AI and robotics. The assistant professor in the Technology Management Department at UC Santa Barbara gave a TED talk on the subject (it has received nearly 2 million views), discussing how using these tools to pursue productivity can weaken the essential bond between expert and learner, with valuable skills being lost in the process. "We are separating junior workers from experts in workplaces around the world," says Beane. "It's a looming multi-trillion-dollar problem that few have been addressing until now."

Beane has written a book on the subject, titled *The Skill Code: How to Save Human Ability in an Age of Intelligent Machines* (Harper Business, 2024). In it, Beane reveals what he calls the "hidden code" that undergirds every successful expert-novice relationship. After spending the past decade examining this unique bond in a variety of settings, from warehouses to surgical suites, he identified the basic components of how we develop our most valuable skill. He calls them "the three C's" — challenge, complexity, and connection.

"When it comes to the three C's and how society is handling advanced automation right now, the novices and trainees have become optional, or have even been removed from the equation," explained Beane. "Raising awareness of that disconnect is an initial step in flipping the script so that technology can help make skill building easier than it was before."



The cover of Matt Beane's book about "the three C's" of human skill building in the age of artificial intelligence.

ECE AND META ALUMNA NAMED VP AT NVIDIA

Last November, **Alexis Black Bjorlin** (PhD '00) was named vice president/general manager of DG/X cloud services at Nvidia. She joined Nvidia from Meta, where she served as VP, Infrastructure, leading the development of compute, network, and storage infrastructure for general compute and AI systems.

"I'm thrilled to be here and to have worked at two of the most impactful companies in the world," she said. "I think it is the result of just focusing on where one can have an impact."

Bjorlin earned her PhD in the lab of electrical and computer engineering professor **John Bowers,** planning to become a professor, but the entrepreneurial activity in the department at the time," she says, "changed the course of my career."

At UCSB, she says, "I learned that you find the most value not when one lab is pitted against another, but when you're working together across disciplines or fields. UCSB had the most collaborative and interdisciplinary program. It's something I've tried to find and foster ever since and have carried with me into building teams and in looking for environments where innovation can thrive."

Bjorlin has hired many Gaucho graduates during her career, and she keeps going back to that well, describing UCSB, and optoelectronics in particular, as "an innovation center where so much of the research is just world-class. It has really helped set an ambitious goal of striving for maximum impact."

Nvidia vice president Alexis Black Bjorlin (PhD '00)

Photograph by Tony Mastres

A new $500,000 NSF grant is aimed at student retention.

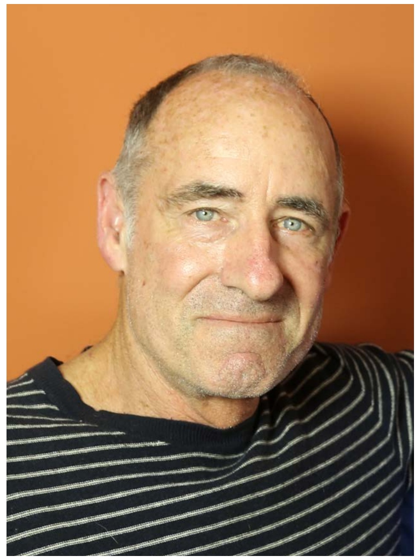
NEW GRANT TO BUILD STUDENT RETENTION

Freshman students in the UC Santa Barbara College of Engineering (COE) who are first-generation college students, are from low-income families or an underrepresented minority, or fit more than one of those descriptions stand to benefit from a $500,000 National Science Foundation (NSF) Hispanic-Serving Institution (HSI) grant. The proposal was written by computer science (CS) professor and Associate Dean of Diversity, Equity and Inclusion, **Elizabeth Belding,** CS associate teaching professor **Diba Mirza,** chemical engineering assistant teaching professor **Joe Chada,** and technology management assistant professor **Jessica Santana.** The new program, which will pilot in fall, is intended to increase retention and graduation rates of students in these communities by better supporting their academic success and sense of belonging in their major. UCSB is an HSI, defined as having at least 25-percent Hispanic full-time-equivalent undergraduate students.

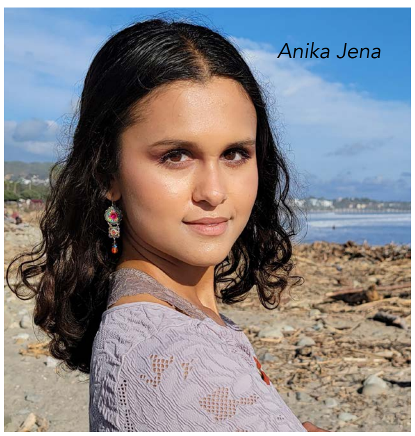
Students from the communities identified above face numerous challenges that can make it disproportionately difficult for them to graduate in engineering majors. The new Integrated Networking, Scholarship, and Peer Interaction for freshmen Engineers (INSPIRE) project is intended to fundamentally transform how such students experience their first year in the COE. By increasing retention and graduation rates of targeted students, INSPIRE is aimed at expanding the pipeline of diverse engineering and CS graduates, who can then pursue graduate degrees, join the workforce, and serve as role models for future engineering and computer science students reflecting the diversity of California and the nation.

ENTREPRENEURIAL FACULTY RECEIVE INNOVATION AWARDS

Two companies co-founded by professors from the UC Santa Barbara College of Engineering received 2024 Central Coast Innovation Awards from the *Pacific Coast Business Times.* Transphorm, a global semiconductor company co-founded by COE dean, **Umesh Mishra,** and **Primit Parikh** ('98), who earned his PhD in electrical and computer engineering from UCSB, received the University Partner Award. C-Zero, a company co-founded by chemical engineering professor **Eric McFarland**, received the Breaking New Ground — Energy Award. C-Zero, which is aimed at "unlocking the zero-emission [hydrogen] energy embedded in natural gas," was also recognized by *TIME,* placing at No. 24 on its list of 250 Top Greentech Companies in America for 2024.



Kudos in green (from left): Pacific Coast Business Times *publisher, Henry Dubroff (left) congratulates Umesh Mishra (blue jacket) and his Transphorm partner, Primit Parikh; C-Zero founder, Eric McFarland; C-Zero senior manager for R&D, Brett Parkinson (left), and senior materials scientist, Andrew Caldwell.*



Anika Jena

SOLID GOLD SCHOLARSHIP FOR CHEM-E UNDERGRAD

Second-year UC Santa Barbara chemical engineering student **Anika Jena** is one of 438 students nationwide who received 2024 Goldwater Scholarships, among the most prestigious national scholarships for undergraduate students planning research careers in mathematics, the natural sciences, or engineering. Each scholarship, awarded in honor of the late U.S. senator from Arizona, provides as much as $7,500 per year for up to two years of undergraduate study.

"Research can be tough. There are a lot of setbacks, and you often don't see results even after hours of work," Jena said. "This award reinforces my career aspirations and further motivates me to continue conducting impactful research."

Jena is currently working as an undergraduate student researcher in the lab of **Sho Takatori,** whose research Jena became aware of while still in high school. "Anika will become an exceptional scientist and future researcher," Takatori said. "I look forward to seeing what she will achieve during her undergraduate training, doctoral studies, and beyond."

UNSTICKING TAU TO FIGHT ALZHEIMER'S

UC Santa Barbara researchers continue to unravel the mysteries of folded tau proteins in the brain, the proliferation of which lead to several neurodegenerative diseases, including frontotemporal dementia, progressive supranuclear palsy, and corticobasal degeneration. In an article published in the April 3 issue of the *Proceedings of the National Academy of Sciences,* an interdisciplinary team comprising UCSB neuroscientist **Kenneth S. Kosik,** chemistry professors **Songi Han** and **Joan-Emma Shea,** and chemical engineering professor **M. Scott Shell** describes potential ways to interrupt this process. Their findings demonstrate the possibility of targeting "sticky" sites along the extended form of mutated tau to prevent misfolding of the protein and the ensuing spread of such neurofibrillary tangles. The team's tactic was to induce tau aggregation in a cell culture and use the system to introduce an amino acid that interfered with aggregation of misfolded tau.

The study presents molecular-level insights into how pathological tau spreads, a hopeful advance toward what the researchers describe as "a therapeutic intervention potentially capable of disaggregating tau or preventing its aggregation" in the long form. Any such therapy is still a long way off, but the findings present exciting potential pathways in that direction.

Faculty Awards
2023-’24

Each year, UC Santa Barbara College of Engineering faculty receive many of the most prestigious honors awarded by academic and professional societies in recognition of their innovative research and their discovery of new scientific knowledge. Here is a sampling of the honors bestowed upon our faculty by their peers since July 1, 2023.

Shuji Nakamura
Professor, Electrical and Computer Engineering and Materials
LpS Digital Innovation Award, LpS Digital Summit
The premier digital-lighting conference honored Nakamura, who received the 2014 Nobel Prize in Physics for inventing the blue LED, for impactful contributions to energy and lighting, and for his dedication to global sustainability.

Raphaële Clément
Assistant Professor, Materials
Rising Star Award, *Materials Today*; ISE Prize for Electrochemical Materials Science, International Society of Electrochemistry; Camille Dreyfus Teacher-Scholar Award
Clément recently received three significant junior-faculty awards in recognition of her work in the field of electrochemical materials science and her research group’s efforts to relate materials synthesis, atomic structure, and performance in battery devices (see P. 18), using, mostly, magnetism and magnetic-resonance probes.

Beth Pruitt
Professor, Bioengineering and Mechanical Engineering; Chair, Bioengineering
Elected Fellow, American Association for the Advancement of Science
Pruitt, the Mehrabian Chancellor’s Chair, was elected a Fellow by her peers in the American Association for the Advancement of Science for her “seminal contributions to developing custom measurements and analysis systems for cell-level studies of biomechanics, mechanotransduction, and pathways in cell-cell adhesion and subcellular organization, and exceptional sponsorship for bioengineering.”

Prabhanjan Ananth
Assistant Professor, Computer Science
Early CAREER Award, National Science Foundation
Ananth, who is the Glenn and Susanne Culler Chair, will receive more than $660,000 over five years from the National Science Foundation to develop the foundations of unclonable cryptography and algorithms that could be secure against an attack by a quantum computer.

Irene Beyerlein
Mehrabian Interdisciplinary Professor, Mechanical Engineering and Materials
Elected Member, National Academy of Engineering
Election to the NAE is one of the highest distinctions accorded to an engineer. Beyerlein was recognized for her “methodologies predicting the mechanics of complex engineering materials to improve their stability and strength.”

Yangying Zhu
Assistant Professor, Mechanical Engineering
Young Investigator Award, Office of Naval Research; Faculty Fellowship, Hellman Foundation
Zhu will receive $750,000 over three years to investigate a promising method for cooling high-performance devices. Knowledge gained from her work could be applied to solar thermal desalination, thermal management of data centers, and robotics that might be actuated by liquid-vapor phase change.

Haewon Jeong
Assistant Professor, Electrical and Computer Engineering
Early CAREER Award, National Science Foundation
Jeong received a five-year, nearly $600,000 grant to analyze the data-preparation pipeline in order to make end-to-end equitable machine learning possible. She will examine real-world dataset problems, such as missing values and data imbalance, to determine how bias can be either amplified or mitigated during the process of preparing data.

Paul Leonardi
Duca Family Professor and Chair, Technology Management
Distinguished Scholar Award, Communication, Technology, and Organizing Division of the Academy of Management
Leonardi received the award in recognition of his sustained body of high-impact work. An expert on the digital transformation in the workplace, Leonardi studies how companies that implement new technologies are affected and how they can use them to their advantage.

James Marden
Professor, Electrical and Computer Engineering
Fellow, Institute of Electrical and Electronics Engineers
Marden was elevated by his peers to the status of Fellow in recognition of his "contributions to game theory for distributed control systems." His work focuses on engineering desired behavior in sociotechnical systems, which are systems comprising both engineered and social components.

Robert McMeeking
Distinguished Professor, Materials and Mechanical Engineering
Platinum Medal, Institute for Materials, Minerals, and Mining
McMeeking, who has a distinguished career as a computational materials scientist, received the medal for his "wide-ranging contributions to micromechanics that have inspired a new generation of mechanics researchers in both the United States and the United Kingdom."

Enoch Yeung
Assistant Professor, Mechanical Engineering
Early CAREER Award, National Science Foundation
Yeung received a $640,000 Early CAREER Award from the National Science Foundation to conduct research on the dynamics of DNA structure and how it affects genetic programs in living cells.

Christopher Kruegel
Professor, Computer Science
Elected Fellow, Association for Computing Machinery
Kruegel, who is an expert on computer security, was elected as a Fellow by his peers in the Association for Computing Machinery in recognition of his significant "contributions to systems security, malware detection, and vulnerability analysis."

Larry A. Coldren
Emeritus Professor, Materials and Electrical and Computer Engineering
Heinrich Welker Award, International Symposium on Compound Semiconductors
The Welker Award recognizes Coldren for high achievement in materials technology, resulting in seminal contributions to tunable lasers, vertical cavity lasers, and photonic integrated circuits.

Siddarth Dey
Assistant Professor, Chemical Engineering and Bioengineering
Early CAREER Award, National Science Foundation
Dey received a five-year, nearly $1 million Early CAREER Award for his research, aimed at understanding how spatial and epigenetic factors in cells regulate gene expression during human development.

Michael Gordon
Professor and Chair, Chemical Engineering
Elected Fellow, American Vacuum Society
Gordon, the Warren G. and Kathleen S. Schlinger Professor of Chemical Engineering, was cited for "advances in synthesis, characterization, engineering, and simulation of nanostructured materials for applications in optoelectronics, energy, chemical conversion, and biology."

Tresa Pollock
Alcoa Distinguished Professor, Materials
William D. Nix Award, The Minerals, Metals & Materials Society
As a testament to her impact as a researcher and a mentor, Pollock was recognized for her "seminal contributions to the creep and fatigue behavior of structural alloys and underlying deformation mechanisms," and for "inexhaustible devotion to the mentoring of early-career scientists."

#4

COE ranks fourth among public universities in percentage of faculty (10%) who are elected members of the National Academy of Engineering.

Faculty Awards

Michelle O'Malley
Professor, Chemical Engineering and Bioengineering
Biotechnology Progress Award for Excellence in Biological Engineering Publication, American Institute of Chemical Engineers
O'Malley, the Scholle Chair in Chemical Engineering, was recognized by the Society for Biological Engineering for her outstanding contributions to the literature in the field.

John Bowers
Distinguished Professor, Electrical and Computer Engineering and Materials
Jun-ichi Nishizawa Prize, Institute of Electrical and Electronics Engineers
Bowers, the Fred Kavli Chair in Nanotechnology and the director of UCSB's Institute for Energy Efficiency (see P. 12), was honored for his "contributions to photonic integrated circuit technologies." The award recognizes Bowers for the impact his innovations have made on his profession and the world.

Philip Christopher
Professor and Vice Chair, Chemical Engineering
Guiseppe Parravano Award for Excellence in Catalysis Research, Michigan Chapter of the North American Catalysis Society
The biennial award recognized the Mellichamp Chair of Sustainable Manufacturing for "outstanding achievement in the conduct of clever, productive, and influential research on problems of central interest and importance in catalysis and related fields."

Misha Sra
Assistant Professor, Computer Science
Early CAREER Award, NSF; Faculty Fellowship, Hellman Foundation
Sra, the John and Eileen Gerngross Chair, received a five-year, nearly $600,000 Early CAREER Award to harness artificial intelligence, virtual reality, and augmented reality to enhance a human's physical abilities to learn and recover motor skills.

Chris Van de Walle
Professor, Materials
Materials Theory Award, Materials Research Society
The leading professional society dedicated to advancing materials science honored Van de Walle for his contributions in developing first-principles methodologies for understanding how point defects affect light emissions in wide-bandgap semiconductors.

7 The number of COE faculty **NSF CAREER Awards** received in 2023-'24, tying the record for most in an academic year

Nina Miolane
Assistant Professor, Electrical and Computer Engineering
Early CAREER Award, National Science Foundation; Faculty Fellowship, Hellman Foundation
Miolane received a five-year, nearly $500,000 Early CAREER Award to further develop methods to precisely quantify every nuance of geometries captured in live 3D images, an accomplishment that could enable breakthroughs in data-driven biomedicine.

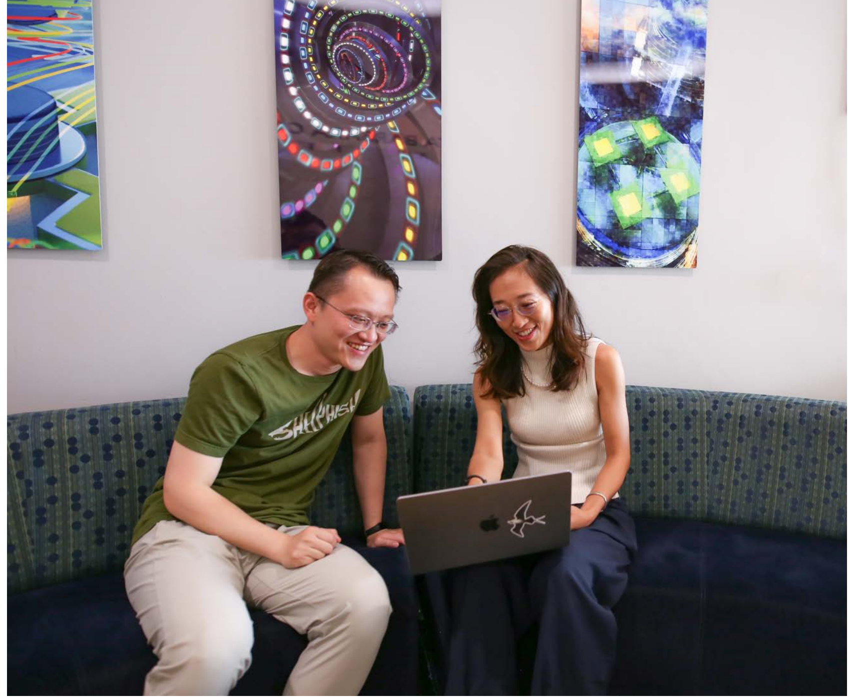
M. Scott Shell
Professor, Chemical Engineering
Elected Fellow, American Association for the Advancement of Science
Shell, the John Myers Founder's Chair, was elected a Fellow by his peers in the American Association for the Advancement of Science in recognition of his "creative contributions to molecular simulations in the chemical sciences, including powerful methods for coarse-graining and free-energy estimation."

William Wang
Mellichamp Professor of Artificial Intelligence, Computer Science
Pierre-Simon Laplace Early Career Technical Achievement Award, Institute for Electrical and Electronics Engineers
IEEE's Signal Processing Society recognized Wang for his "contributions to the development of scalable algorithms in natural language processing."

New COE Faculty

Two new computer science faculty members are thrilled to work with "giants" in their fields

UC Santa Barbara's Computer Science (CS) Department welcomed two assistant professors this spring, each of whom further strengthens areas of research in which College of Engineering faculty have already established themselves as pioneers: quantum computing and computer security. **Divyakant Agrawal**, professor and chair of the CS Department, says that the additions of **Murphy Niu** and **Wenbo Guo** will ensure that the department "remains at the forefront of research" in those two specialty fields.



Wenbo Guo (left) and Murphy Niu.

MURPHY NIU

UCSB and the surrounding area have become a hot spot for quantum research and breakthroughs. Led by UCSB physics professor **John Martinis,** a team of Google and university scientists made history in 2019 by achieving "quantum supremacy." Google has since opened a Quantum AI Campus in Santa Barbara. UCSB is also home to Station Q, Microsoft's headquarters for quantum-computing research, and the Quantum Foundry, the National Science Foundation's first quantum center, where researchers are developing next-generation materials to power quantum-based electronics. Niu, who joined the university's CS Department this spring as an assistant professor, is thrilled to collaborate with the vibrant quantum-research communities at UCSB and to play a key role in helping the CS Department define its unique strengths in quantum computing.

"Google and the Quantum Foundry, which is one of the top fabrication facilities that focuses on the material-science side of quantum research, were two of the biggest draws to UCSB," said Niu, who received her PhD in theoretical and mathematical physics from MIT in 2018. "But I'm also very honored to be the first quantum-focused faculty member in the Computer Science Department."

Niu takes a theoretical approach to everything having to do with real, rather than conceptual, quantum technology. She works from the bottom up, trying first to understand what a particular quantum-computing system does and does not do. She then uses that information to develop quantum algorithms covering the full stack of error corrections, quantum control, quantum measurements, and application design. Now that she is a UCSB faculty member, she has access to plenty of actual devices on campus on which to translate her theory-based work.

"I'm a physicist by training, so I focus on understanding the novel physics of the system, and I'm also a computer scientist who is passionate about machine learning. So, my research deals with harnessing both the imperfections and the unique advantages of different quantum hardware through machine learning and algorithm designs," explained Niu, who previously worked as a senior research scientist on the Google Quantum AI team. "My research sits at the intersection of experiments and theory, as well as of physics and computer science."

Her ultimate research goal is to develop quantum-computing models for how to better program, control, characterize, measure, and error-correct a large-scale quantum computer without making various unrealistic demands on the quantum hardware that prevent scalability. Niu also investigates how to use machine learning with and for quantum computers.

Niu has an additional goal, which is to cultivate the next generation of quantum researchers, which she hopes to do by developing and teaching undergraduate and graduate-level quantum-computing classes at UCSB.

"I became interested in quantum computing when I was an undergraduate student," said Niu. "I think that having early exposure across all engineering departments, and even physics and mathematics, will foster students' interest and could inspire more of them to pursue quantum research and, in turn, computer science at the graduate level."

WENBO GUO

To say that Wenbo Guo was excited to join UCSB's CS Department as an assistant professor this spring would be a big understatement.

"It feels like a dream come true, because the CS Department has a long history of success in computer security. I've admired UCSB's SecLab ever since I started graduate school," said Guo, referring to the Computer Security Lab, which is run by professors **Giovanni Vigna** and **Christopher Kruegel**. "SecLab has been a leader in computer-security research and has produced the top computer-security researchers for decades. Now, I get to work with the great researchers in that lab and many other talented members of the department. I'm incredibly lucky."

Guo's research blends cybersecurity with machine learning (ML). He works to design effective and trustworthy ML-based solutions for a wide range of security problems, including for software security and large-language models like ChatGPT. A self-described life-long learner, he says that his research endeavors are driven by real-world problems that he encounters on his own. For example, while learning about software security, he found himself wondering if ML models could be applied to security applications. This novel approach became the subject of a paper that received the ACM CCS Outstanding Paper Award at one the top security conferences in the world.

"I look at myself as an outcome-driven researcher who is motivated by tackling novel and difficult research challenges," explained Guo, who received his PhD from Pennsylvania State University and completed his postdoctoral research at UC Berkeley. "I work to solve a real-world issue by developing new and more practical techniques."

Most recently, he pivoted his research in response to the emergence of ChatGPT, investigating how to make it and other similar models safe and secure, while at the same time studying how those models can help solve security problems. "For instance," he noted, "people may turn to ChatGPT to generate a code, but how do they know if the code is secure or not?"

Guo says that his appetite for learning new things is not limited to computer-related topics. Since moving to UCSB, he has ventured into that most idiosyncratic of Santa Barbara pursuits: learning how to surf.

IEE at 15

Relentlessly pursuing the goal of using less to do more

Since it was established in 2008, the Institute for Energy Efficiency (IEE) at UC Santa Barbara has become a juggernaut of collaborative interdisciplinary innovation. The nearly one hundred current affiliated faculty and their predecessors, in disciplines ranging from economics and electrical engineering to physics, biochemistry, materials, and environmental policy, have made dozens of groundbreaking discoveries and developed important technologies and strategies related to three interdisciplinary pillars, or themes: Smart Societal Infrastructure (SSI), Energy Efficient Computing and Communications (EECC), and the Food-Energy-Water Nexus (FEWN). Here, we offer just a glimpse of *some* of the much larger universe of research being undertaken by IEE affiliates.

The IEE was created as existentially significant questions about environmental sustainability were coming into sharper focus and becoming a larger part of the global conversation. The challenge presented by those questions has only deepened in the years between the institute's founding and its fifteenth anniversary, celebrated last November, two years after it moved into LEED Platinum–certified Henley Hall.

"We have a problem, and it is becoming increasingly clear to all of us that, as a society, as a university, as a college of engineering, as an institute, we need to fix it," says UCSB professor and IEE director, **John Bowers,** whose research on laser-based photonics has been key to many major gains in energy-efficient data transmission, including the fact that, as he says, "Computing is perhaps a thousand times more efficient than it was fifteen years ago."

The problem Bowers is referring to, which is also closely related to the subject of this issue's cover story on battery research (see page 18), is climate change and the increasingly urgent need it presents to wean ourselves from reliance on the fossil fuels that drive it and also cause a host of other related environmental and health problems.

During its first fifteen years, the IEE has more than lived up to the promise of making meaningful contributions to an energy-efficient, clean-energy future. While most projects fit within one of the three main research pillars, many others closely relate to, complement, or overlap with another pillar, or even two other pillars.

The pillars are a useful organizational tool, but, as you will see by reading on, they never prevent a project from being taken on because it doesn't altogether "fit" into one or another broad theme. That is what makes it possible for Nobel laureate and professor of materials and electrical and computer engineering **Shuji Nakamura** to collaborate with his fellow materials professor and co-director of the UCSB Solid State Lighting and Energy Electronics Center (SSLEEC), **Steven DenBaars,** and chemical engineering professor and catalysis expert **Phillip**

Christopher to design new LED lasers expressly to enhance faster, more energy-efficient catalytic processes. At many universities, such a project might never happen at all, much less receive a $50,000 IEE seed grant to begin the work.

Such overlapping interests, coupled with an eager willingness to embrace broad — and broadly interdisciplinary — themes reflects UCSB at its most effective and goes a long way toward explaining IEE's tremendous impact and outstanding worldwide reputation.

"Thanks to the generosity of [lead Henley Hall donors] **Jeff** and **Judy Henley** and others, IEE has grown to become a campus lightning rod in the best sense, getting people together to address the efficiency side of sustainability," says COE dean, **Umesh Mishra,** who is also a leading researcher and entrepreneur in gallium nitride-power electronics. "If you waste less energy, you have to generate and store less energy from renewables, so efficiency is what takes the pressure off the system. At UCSB, we are naturally collaborative, and what Henley Hall and IEE did was to create a home for people to sit alongside each other and have the kind of cross-disciplinary collaborations required to address energy efficiency at large. The building creates a kind of tornado effect, if you will, whipping all the collective energy into a nice strong Force 5 effort."

While Bowers and his fellow IEE researchers in photonics-based electronics have achieved enormous gains, Bowers, the Fred Kavli Chair in Nanotechnology, remains keenly aware of a conundrum. He explains: "Every efficiency gain is made in the context of the ever-increasing need for power and computing. So, if you are a thousand times more efficient, but you are doing five-thousand times more computing, that's a net loss, not a gain. We need to treat that."

"In the short term, say, the next ten to twenty years, energy efficiency will still be the biggest thing you can do to reduce a carbon footprint," says Jeff Henley, who is also vice chairman of Oracle and a member of the COE Dean's Cabinet. "At IEE, we're doing a lot of basic research and working closely with companies like Google, Microsoft, Facebook, and others, which allows us to educate people who can work for those companies, as well as people who will stay in the research role in universities. So, IEE is assuming a very prominent role in what UCSB science and engineering do. And we have to keep getting better, because you never want to stand still."

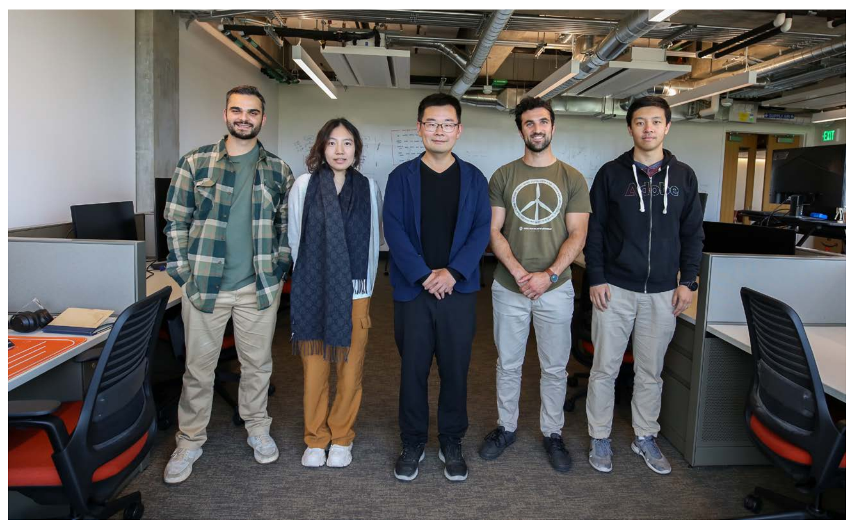
IEE director, John Bowers

AI and Energy

With artificial intelligence (AI) and the enormous cloud data centers, or "server farms," that provide the computing power for it dramatically increasing electricity demand, the efficiency of computing is more important than ever. "One thing a lot of people around here work on is making computers talk to each other more efficiently, so that they're not sitting around waiting for data," Bowers notes. IEE researchers have worked on that challenge in many ways, including as part of a strong multi-year partnership with Meta, which has provided substantial funding to the institute. And while AI plays an ever-increasing role in communication, it is also increasingly important in systems evolved within the Smart Social Infrastructure pillar and is, as you'll read shortly, also connected to the FEWN pillar.

The efficiency of data centers is a key research focus. "Data centers are revolutionizing our society, and they can make us all much more productive," says Bowers. "The problem is that very advanced chips require a kilowatt of power each, and a data center has a million of them linked together. Using optics — photonics specifically — rather than wire is a much more efficient way to move data throughout those kilometer-long facilities."

Today, all long-distance data transmission is fiber-optic based, which is faster, more efficient (thanks to much lower loss than traditional copper wiring), and much higher-capacity, but that efficiency ends at the rack of electronics in the data center, Bowers explains. "Our goal, by integrating photonics and silicon together, is to get that transition point down to the chip itself. So, now, we're making lasers, modulators, and detectors on silicon with these very advanced processing chips. The world is going to move in this direction, and I think it will have a great impact on data-center evolution.



AI and natural-language-processing expert William Wang (center) with graduate students (from left): Antonis Antoniades, Yuxi Xie, Alfonso Amayuelas, and Weixi Feng.

"If we can get ten times the interconnectivity, we can get nearly ten times the efficiency, and that's a big win," Bowers says, adding, "In terms of moving data, we now have photonic chips that generate laser *combs* capable of transporting 3.2 *terabits* [Tb] of data per second" [a terabit being one million

Chandra Krintz and Rich Wolski with their robot, Gort, which they hope will gather data in agricultural fields that can be used to support farmers.

"A big part of what we do is to bring the very cutting edge of technology to people who have not previously had access to it in a way they can use."

megabits, roughly the amount of an average household's monthly internet data use]. At press time, a paper about to be published from the Bowers lab described a 12-Tb/s source.

Reducing AI's energy footprint is the work of many researchers in Henley Hall, the entire second floor of which is "basically AI," Bowers says. Among them is computer science professor and Mellichamp Chair in AI, **William Wang,** a world expert on natural-language processing — the discipline that focuses on human-machine interaction — and the director of the Center for Responsible Machine Learning at UCSB.

In his 15th-anniversary IEE talk, titled "Towards Efficient Learning-Free Inference for Generative AI," Wang explored the development of *generative large-language models*, the era of which was ushered in by Chat GPT. Previously, each AI model would have to be trained individually for a selected task. Data would be provided to programmers, who would train the model specifically for *only* that task. Because the latest LLMs have such a huge vocabulary of English, however, they are able to, essentially, train themselves, such that one model can now perform numerous different tasks based on "fine-tuning" instructions for each one. That saves a lot of computing time and associated energy, but the tradeoff, as we hear about almost daily even in the mainstream media, is that the ever-larger data sets used to train the self-training models require ever more electricity.

Cloud over Agriculture

Computer science (CS) professors **Chandra Krintz** and **Rich Wolski** both had academic careers at UCSB, left to start their own respective tech companies in the cloud space when it was just getting started, then returned to UCSB. They conduct some of their research within IEE's Food-Energy-Water Nexus focus, which has the mission of enabling renewable energy to account for fifty percent of U.S. energy production by 2030 and one hundred percent by 2050.

To that end, IEE researchers develop novel techniques and approaches for enhancing and expediting safe, high-quality food production and water purification while reducing energy, water, and other inputs.

Seeing an opportunity to apply cloud computing innovations focused on e-commerce to what Wolski refers to as "a whole raft of societal problems that were not benefiting from this amazing technology revolution," he and Krintz joined forces. They created a lab, and a project called SmartFarm, aimed at "allowing technology to benefit some underserved parts of society," Krintz says. "Rural communities and agriculture were prime application domains that were so in need of some of these advances that would enable them to use cell phones, data analytics, and other technologies to enhance their agricultural efficiency."

SmartFarm became, Wolski says, "a guiding framework for everything we do today," all of which relates to the IEE mission of enhancing efficiency to protect and preserve resources. They work along three main thrusts: agriculture, ecology, and climate change. "We have found that all of them can benefit from the same kind of unified approach to adopting cloud-based technological inputs that have revolutionized e-commerce, social networking, and entertainment," Wolski says.

Krintz and Wolski routinely collaborate with farming practitioners, literally *in* the field. "It is unusual for computer scientists to work with professional growers as research collaborators," Wolski points out, "but that is how we know our research will have an immediate impact."

Krintz adds, "A big part of what we do is to bring the very cutting edge of technology to people who could not previously access it in a way they can use. Growers manage their crops by hand, relying on a lifetime of accumulated expertise. They say *I'm going to spray on Tuesday,* and now we can say, 'Here's how much moisture is in the soil now. Do you [still] want to spray on Tuesday, or maybe on Friday, when conditions will be more favorable?"

Data analysis is a crucial SmartFarm input. Krintz and Wolski have worked with one consultant in California's Central Valley, a retired farmer who has a business helping growers with their irrigation strategies. His practice has been based on using a great deal of instrumentation and some chemical assays to assess the soil composition of a given plot, and then to prescribe various watering strategies.

"The issue we saw was that, while he was using data to inform his recommendations, he could use it in a better, more scientifically defensible way," Wolski explains. "We built a service and then back-tested it against about twenty-five years of his analysis, and the benefits to be gained were astonishing. It's an example of someone who was highly competent, but not necessarily competent with the technology. The impact was instantaneous, and now there's a bunch of people who have much better irrigation scheduling today because of a system that is rigorous as opposed to ad hoc."

In this and other work that Krintz and Wolski did with the consultant, they had to be sure, Wolski says, "that our suggestions fit his *mental* model, or he wouldn't trust them. This is his living, right? We were able to do that and help him improve his outcomes."

Krintz says that they would have failed had they simply said, "Listen to us; here is how to improve your efficiency. You should do this." Rather, it's important to start where people are, communicate in language they understand, respect what they are already doing, and "make it clear that their interests are at the center of our interests. We're learning how to cross these tremendous communication gaps and experience gaps to bring data science and data-driven thinking to rural communities, in particular. It's extremely challenging; it requires new training and new thinking, and that's part of why we do this research."

Ahead for Krintz and Wolski is further development of the robot they created and named Gort (after the humanoid character designed to protect the universe in the 1951 film *The Day the Earth Stood Still*). The original Gort had a laser as a weapon; this latter-day version incorporates a laser to use as a networking technology for gathering and distributing data, that could also power batteries. Gort has not yet been put to work in agricultural fields. That, as Krintz and Wolski say, "is on the horizon."

Beyond LEDs

Light-emitting diodes (LEDs) occupy an important place in the IEE. UCSB materials professor Shuji Nakamura won his Nobel Prize for inventing the blue LED, which enabled the white LED and the ensuing world-wide revolution in lighting efficiency. LEDs also led to lasers, which are now being used to generate all sorts of efficiency gains.

DenBaars and Nakamura have worked steadily since the 1990s to increase the efficiency of LED lighting, which is projected to have prevented approximately 200 million tons of CO_2 from entering the atmosphere by 2030. Their collaboration with Phillip Christopher to develop lasers is the kind of interdisciplinary project that would occur in only a few places, where no silos separate research that, on first glance, might appear unrelated.

While light-powered catalysis is not new, until now it has been done using off-the-shelf lasers that are not designed for catalysis and, therefore, do not achieve optimal efficiency. DenBaars and Nakamura, co-directors of SLEEC, a consortium linking industry and academia and dedicated to developing powerful energy-savings through technology, are designing new LEDs expressly suited to laser-powered catalysis in terms of wavelength, on-off modulation rate, and directional control of emitted light.

"Chemical processes take a lot of energy," Bowers notes. "You can cook

In a novel project funded with an IEE seed grant, (from left) Phillip Christopher, Steven DenBaars, and Shuji Nakamura are collaborating to make LED lights specifically for catalysis.

As the home of the Institute for Energy Efficiency, LEED Platinum–certified Henley Hall is brimming with energy-saving features.

an egg by boiling water, but that's really inefficient. But if I shine the right-wavelength of light at the egg, it will absorb one hundred percent of the light and cook in no time. That's kind of what Phil, Steve, and Shuji are doing. It could have huge implications in terms of making an energy-intensive process much more efficient."

One possible application of that research is in making hydrogen without releasing emissions. Christopher explains that some people do that by cracking ammonia (NH_3) to release hydrogen and benign nitrogen gas. An immediate goal of the research is "to tailor the LED laser operation to promote the energy efficiency of this reaction."

"Hydrogen has the potential to be a great emission-free transportation fuel," Bowers notes, "and if you can make it efficiently, that could have a huge impact on our society and on the world."

Making Infrastructure "Smart"

Mahnoosh Alizadeh aims to reshape how people consume electricity in their homes. An associate professor in UCSB's Electrical & Computer Engineering Department, Alizadeh's research is focused primarily on shifting demand behavior by designing data-driven incentives. With the increasing integration of renewable energy, especially at the grid edge, the electric grid faces significant stress in order to incorporate the additional uncertainty renewable energy brings in terms of generation outputs, posing serious risks to grid stability. Alizadeh says that addressing that challenge requires "re-imagining the end-use experience of how electricity delivery markets operate."

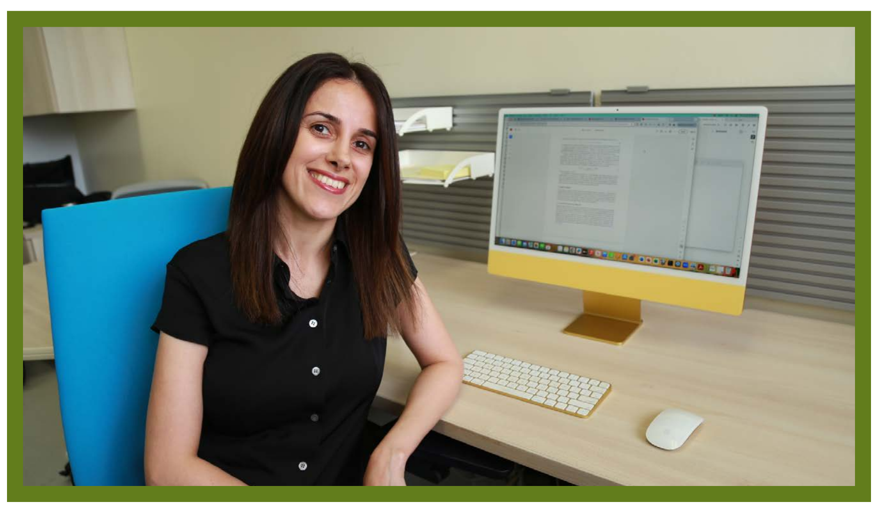
Her work, as well as that of fellow mechanical engineering professor **Igor Mezić** falls within the Smart Societal Infrastructure (SSI) research pillar, but is very much related and complementary to concepts underlying research in the FEWN pillar. SSI research is focused on the operations of the power grid, the components it comprises, and the interplay of the grid with the wide variety of societal systems that attach to it, such as electric transportation networks. IEE's research programs in the SSI pillar explore a variety of approaches to improving the power grid and its components.

Alizadeh employs a variety of tools including optimization, data-driven learning, machine learning, and game theory in trying to understand how to motivate human beings to make decisions aligned with sustainability. "For instance, how might we coordinate users to be more flexible, so that they consume more solar energy or wind energy as it is produced in the grid, since those types of energy are hard to control, and it is expensive to store the energy they produce," she queries. "Or, how can we get consumers to charge their electric vehicles at the right time and location in terms of energy availability? That is clearly a highly interdisciplinary problem, because it involves human behavior and decision-making, how we operate the power system, real-time data streaming, and so on, and, thus, a variety of tools are required to model and address it."

Alizadeh is also involved in examining how to use data-driven machine learning to understand customer behavior and fine-tune operations for supplying power and other critical infrastructure services. Off-the-shelf tools lack the safety-critical constraints necessary in operating the power system, which she describes as "basically a very large circuit with hard physical constraints that have to be met at every instant."

Since data-driven learning and control algorithms essentially learn by trying things and then seeing the outcome and can't know what will happen until they do, "The major problem," Alizadeh says, "is what if the 'trial' outcome violates the safety-critical constraints of the power system? Developing machine-learning algorithms dedicated to systems that have hard physical constraints has been my group's major focus for the past two years."

Also working within the SSI pillar, Mezić has produced groundbreaking work in the area of learning algorithms, often with the goal of operating buildings at optimal efficiency. That can mean removing unreliable human behavior from the energy-saving equation by relying on sensors and smart systems to run HVAC and lighting systems, which account for most of the energy use in commercial buildings. Through his startup company, EcoRithm, Mezić has developed software that manages energy usage in more than fifty million square feet of commercial buildings worldwide. A number of buildings on the UCSB campus also benefit, including Henley Hall, which includes an array of energy-saving elements, from abundant natural light to natural cooling, that earned it the U.S. Green Building Council's highest level of certification.



Mahnoosh Alizadeh focuses on running the grid more efficiently.

Chasing Quantum

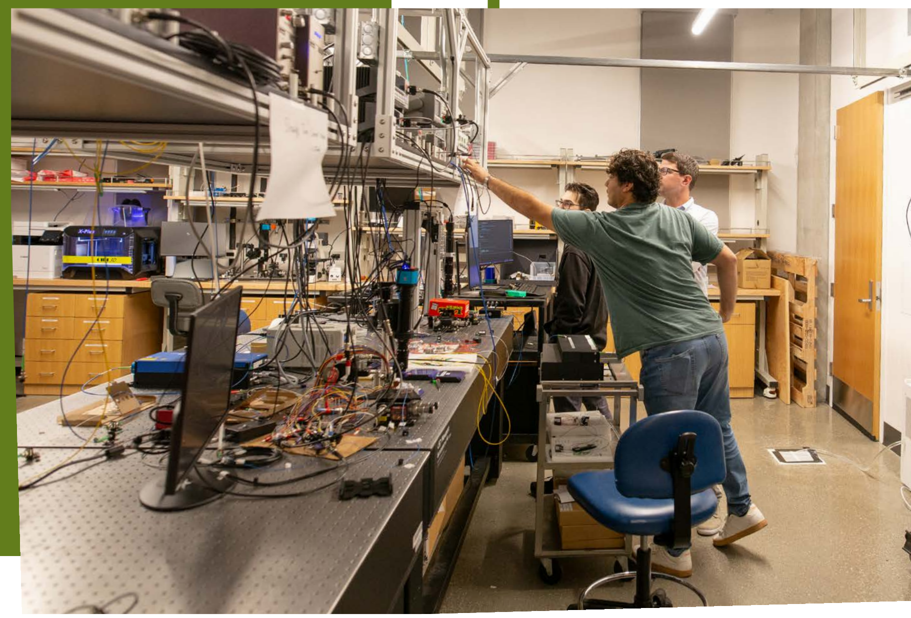
While many technologies are aimed at achieving gains in energy efficiency, some, like those in the quantum realm, must be energy-efficient even to function at all. "Quantum and efficiency go hand in hand," says electrical and computer engineering associate professor **Galan Moody,** who is working to develop hardware for photon-based quantum computers and networks, noting the extreme fragility of particles entangled in the quantum state of interrelatedness, in which anything done to one of two entangled particles instantaneously affects the other, regardless of the distance between them.

Quantum bits, known as *q-bits,* are the quantum-mechanical analog of classical bits, which power all of our electronics (the 0's and 1's corresponding to transistor off and on states). But unlike classical bits, q-bits can be in superpositions — *simultaneously* 0 and 1 — that are sensitive to every kind of environmental disturbance: vibration, temperature, humidity, etc. Anything can disrupt whatever quantum mechanical process a q-bit was a part of. "You can't just dump more power in or amplify the signals when you're dealing with q-bits, because it introduces too much noise," Moody says, "so you have to think about system efficiencies from the beginning."

A worldwide race is currently underway to determine which of several competing quantum platforms will emerge as the most promising upon which to build the quantum future. Google, working with UCSB physics professor **John Martinis** at a lab in Goleta, used one of those platforms to achieve so-called *quantum supremacy* in 2019. With its 53 q-bits, the cryo-cooled Sycamore machine was able to solve a benchmarking series of computations much faster than IBM's Summit supercomputer. Just how much faster has been a subject of debate ever since, but quantum computing hardware has become increasingly faster at certain tasks. More importantly, Moody notes, quantum systems can have tremendous energy advantages. Moody estimates that Google's hardware did its work using "tens of kilowatts of power," while the Summit configuration probably required tens of *megawatts* of power. And faster computation reduces run time, Moody notes, providing huge energy savings.

UCSB's major presence in materials and quantum physics played a key role in the National Science Foundation's decision to locate its first NSF Quantum Foundry at UCSB, with physics professor **Ania Jayich** and materials professor **Stephen Wilson** as co-directors and some twenty-five affiliated UCSB faculty conducting related research.

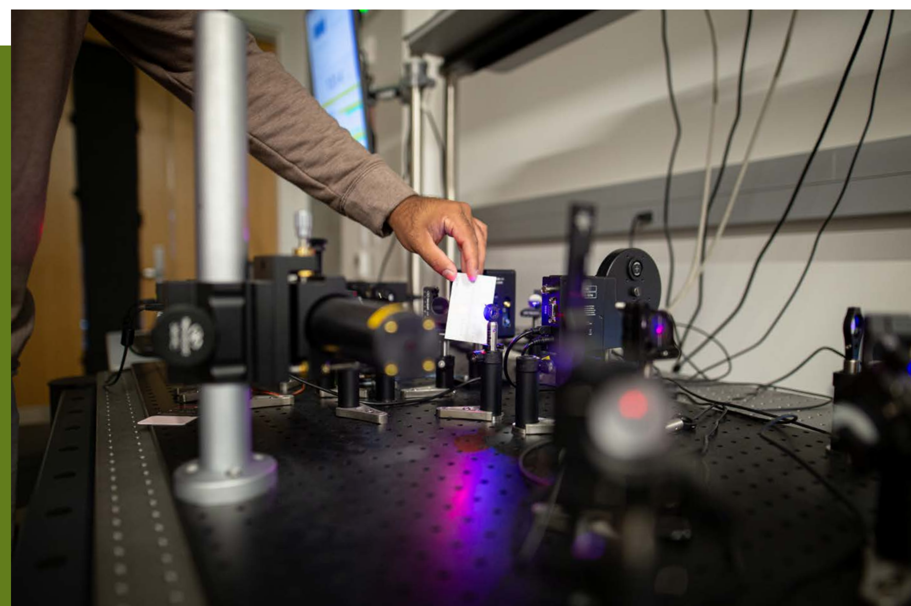
As mentioned at the top of this article, IEE encompasses a vast realm of complementary and sometimes overlapping research that spans disciplines and departments, all of it aimed at addressing grand challenges related to energy efficiency and environmental sustainability. The unparalleled combination of expertise, collaboration, and interaction that characterizes the institute has thrust it, in its first fifteen years, to the forefront of the effort to re-create our energy future.

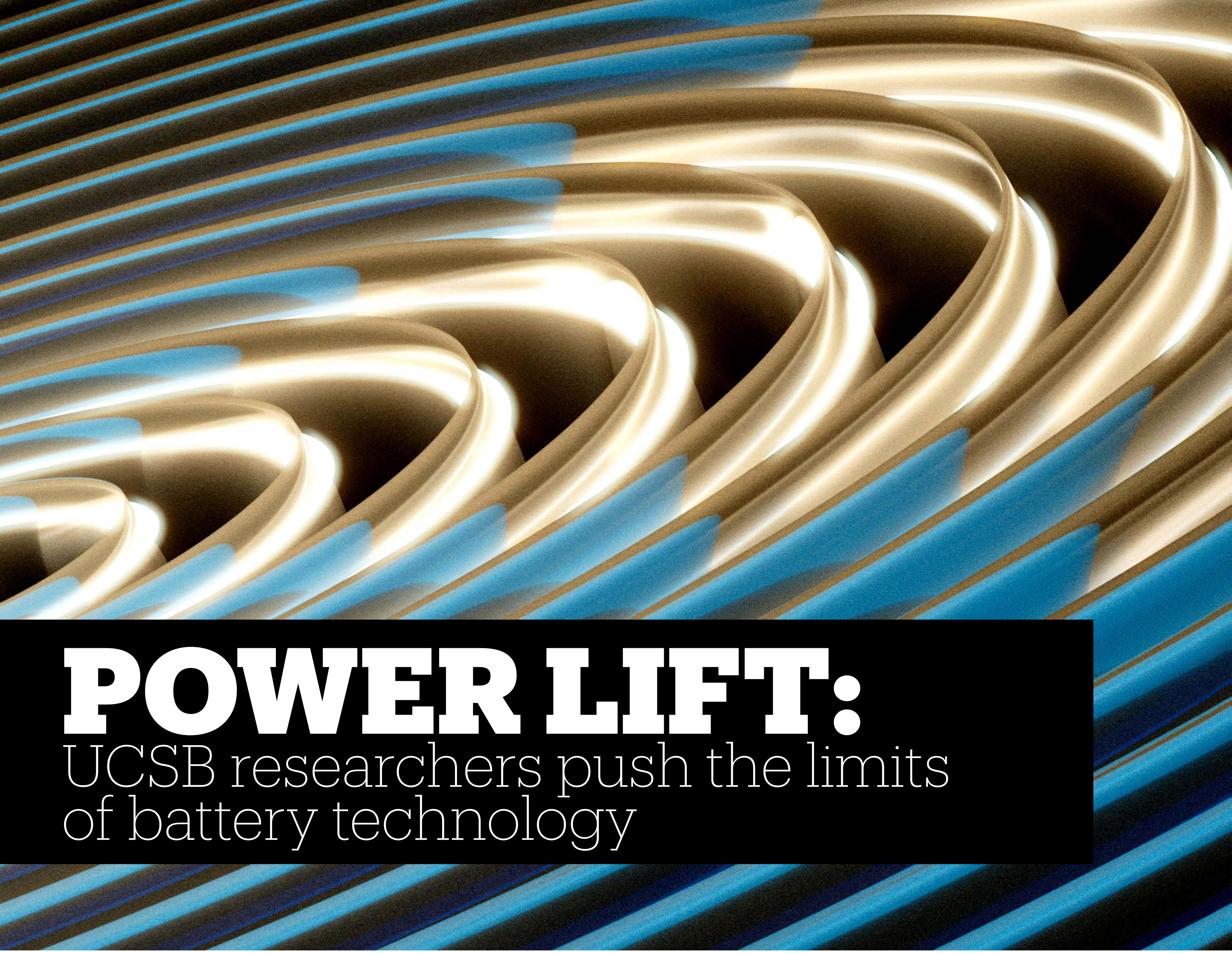


Galan Moody (right) looks on as PhD students (from left) Nick Lewis and Josh Castro make adjustments to optimize the chip-scale entangled-photon-pair source in the Moody lab in Henley Hall.

"More importantly, quantum systems can have tremendous energy advantages, using tens of kilowatts of power to do their work, rather than tens of megawatts."

In Henley Hall, a researchers adjusts an optical setup in the quantum photonics learning lab, where students gain important quantum knowledge by creating photons that are entangled in a quantum state.





POWER LIFT:
UCSB researchers push the limits of battery technology

Now more than at any other time in human history, batteries are a big deal, and no wonder; we will need billions of new and better batteries to power our imagined carbon-neutral future, most notably for electric vehicles (EVs), handheld electronic devices, and battery "farms" for storing energy produced intermittently by renewable energy sources such as the sun and wind. Visions for — and prototypes of — electric big-rig trucks, airliners, and almost anything else that currently runs on fossil fuel are in the offing.

There is work ahead. "We're still very far from being a carbon-neutral society," says **Raphaële Clément,** an assistant professor in the Materials Department at UC Santa Barbara and an expert in using nuclear magnetic resonance (NMR) spectroscopy to characterize materials, including those being developed as battery materials. "Achieving a fifty-percent reduction in U.S. greenhouse gas pollution from 2005 levels by 2030, a goal that was announced by President Biden at the Leaders Summit on Climate in 2021, will require building enough storage facilities [farms], and diversifying the chemistry portfolio of batteries to make it possible to build such storage units at the necessary scale."

Additionally, she notes, at least some of those new technologies will need to be made from earth-abundant elements that are, perhaps, less energy dense but adequate for grid storage, where having a high energy-to-weight ratio is not as much of a concern as it is for, say, EVs, since the batteries are stored in one place. The important concerns are, rather, low cost, sustainability, and durability to keep maintenance costs down. On the EV front, better batteries are needed that will last longer, extend driving ranges, charge in a few minutes, and incorporate elements that are abundant, cheap, and mined in ethical and sustainable ways.

Clément is one of some twenty faculty members, most of them in the College of Engineering (COE), who conduct battery research at UCSB. Having won a National Science Foundation Early CAREER Award in 2022, Clément is working on materials that could be used in a sodium-ion battery, an alternative to the lithium (Li)-ion battery. She works with numerous colleagues who are developing theoretical models, creating computer simulations to test theory, advancing new technologies, and planning pathways to large-scale production.

Among that group is one of the COE's newest faculty members, **Jeff Sakamoto,** a world-leading battery expert whose research is focused entirely on batteries and who helped to build a battery pilot and test plant during his ten years at the University of Michigan (UM). He came to UCSB last November with appointments in both the Materials and Mechanical Engineering Departments and is ideally positioned to anchor the university's strong team of battery researchers.

> **"The migrating electrons can do work. It's a genius invention from two hundred years ago."**

(Not) a Simple Thing

A battery may seem a relatively simple thing, consisting of an anode, a cathode, a liquid electrolyte, and current collectors made of aluminum on the cathode side and copper on the anode side (for a Li-ion cell). Enabling batteries that are energy-dense, powerful, safe, and environmentally sustainable, however, requires operating at the cusp of material stability and instability, and changing the materials chemistry of one battery component often requires changes to one or more — or even all — of the other components.

At a basic level, all batteries function in the same way, by separating electrons from atoms and shuttling the resulting ions inside a cell between the cathode and the anode — electrodes that store chemical energy — while the freed electrons flow through an external circuit to power a device or allow charging. The electrolyte, interposed between the electrodes, has the single function of transporting ions.

"The migrating electrons can do work," notes materials and chemistry professor **Ram Seshadri,** who is also the associate dean for research at the COE and the director of the UCSB Materials Research Laboratory. "It's a genius invention from two hundred years ago that allows chemistry to be separated by transporting the ion through one channel and the electron through another."

Lithium has only one electron and the highest *electrochemical oxidation* potential — the tendency to lose an electron — of any element on the periodic table. That is what makes it such a valuable battery element. When a Li-ion battery is charged, the cathode — the higher-voltage of the two electrodes —simultaneously releases a Li-ion and an electron. The Li-ions then flow through the liquid electrolyte and are inserted into the anode material, where they recombine with an electron released from the cathode. Essentially, the charging process involves changing the Li-ion concentration in the electrodes to increase the chemical energy stored in the battery.

In the discharged state, Li-ions prefer to be in the cathode material rather than in the anode. The charging process overrides that affinity, forcing Li-ions to flow in a direction opposite the natural flow, to the anode. The anode is typically made of graphite, which consists of layers of carbon atoms, the carbon layers being held together by weak bonds. That unique bonding in graphite makes it easy for Li to be inserted between and extracted from the rows of carbon atoms. Once the graphite is full and cannot intercalate (absorb) more Li, the battery is fully charged.

The chemical potential energy accumulated in the electrodes has now been maximized and can be converted to electrical energy during discharge, which repeats the process of transporting Li-ions and electrons, but in the opposite direction. As the electrons travel through the external circuit back to the cathode, they convert the chemical energy stored during charging into electrical energy to power an EV, a cell phone, or any other battery-enabled device.

Li-ion batteries, currently the world's leading battery technology, the power of which Tesla and other EV companies demonstrated by employing them in massive arrays of more than seven thousand cells to power each of their vehicles, are a well-developed technology, but they have limitations.

Some of the highly collaborative faculty researchers who are pursuing new battery technologies at UCSB (from left): Ananya Balakrishna, Yangying Zhu, Rachel Segalman, Glenn Fredrickson, Robert McMeeking, Ram Seshadri, Anton Van der Ven.

For instance, ideally, the anode could be made of pure metallic lithium, which would increase the energy density of the battery, defined as "energy per given unit of battery size. "But, practically speaking, you can't do that," says UCSB materials professor **Anton Van der Ven,** who is known for his work building computational models of materials at the atomic scale. "That's because lithium is highly reactive and deposits non-uniformly at the anode." Those deposits are highly problematic, sometimes growing as fingers — called *dendrites* — that penetrate back through the electrolyte, short-circuiting the battery when one of them makes contact with the cathode." The fires in EVs we hear about on the news are sometimes the result of such short-circuits.

The UCSB Research Mix

To address those and other issues, a group of COE faculty from the Materials, Chemical Engineering, and Mechanical Engineering Departments are working together on every aspect of batteries, including new chemistries and recycling.

Through various collaborations, Ram Seshadri has demonstrated that calcium can be employed effectively as an anode in primary cells (defined as able to be discharged only once), has contributed a better understanding of sulfur redox in lithium sulfur batteries, and has conducted research to develop new cathode materials. His group is known for its anomalous use of household microwave ovens to prepare battery materials in a rapid, efficient method that takes minutes rather than hours.

More recently, Seshadri has also focused on recycling, and specifically the structures and compositions of products that are obtained while reclaiming components from used and dismantled batteries. He is interested, for example, in recovering lithium, nickel, cobalt, and graphite from cathodes and anode mixtures. "Heat treatment [used to eliminate certain chemicals at end of life] results in all sorts of new chemistry," he says. "We are trying to decipher those chemical changes as a step to developing efficient recovery techniques."

Clément complements her investigations of new materials for a possible sodium-ion battery — sodium being much cheaper and more abundant than lithium — by contributing her expertise in NMR spectroscopy to study new materials for lithium-based batteries. This powerful technique, which requires expensive instrumentation and a high level of expertise, makes it possible to analyze the atomic structure of a material by tracking interactions between nuclear and electronic spins, allowing Clément to study the charge-discharge processes in battery materials at the most fundamental level.

Sakamoto, an expert in fabricating ceramics for energy technologies, is continuing work he began at UM to develop a solid-state Li-ion conducting ceramic electrolyte, which would replace the liquid electrolyte in current Li-ion batteries. That effort involves advancing not only fundamental materials

science, but also the understanding of processes — how chemistry and electrochemistry affect the actual mechanical properties of a battery — with further considerations regarding how to manufacture such a battery.

"Making solid electrolytes work is a huge challenge, primarily because there are so many complicated reactions at the anode and cathode side, as well as complex chemomechanical reactions that can cause [the above-mentioned] lithium dendrites to penetrate and cause a short-circuit," he says.

Because Li metal is significantly softer than a typical ceramic electrolyte, scientists initially thought that Li dendrites would not penetrate solid-state electrolytes, but it turns out that they can. There is still a healthy debate within the scientific community as to how that is physically possible, but the prevailing theory is related to the imperfections or defects in the ceramic electrolytes. According to that view, Li metal deposition causes localized build-up of pressure sufficient to cause the ceramic to crack. Once a crack forms, it is quickly filled by Li metal and the crack or Li metal dendrite grows toward the cathode, eventually contacting it and causing short-circuiting to occur.

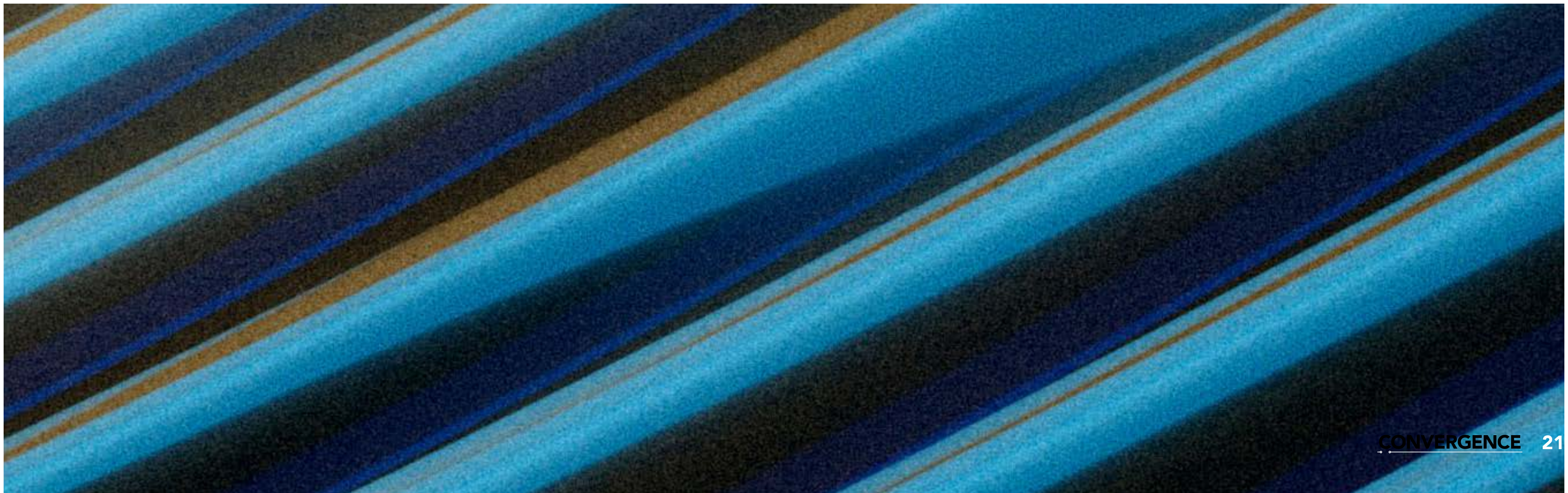
"In principle, if you can get rid of those defects, then that ceramic membrane — or other solid-state electrolyte — is physically hard enough, has adequate conductivity, and is stable enough to flatten the dendrites," Sakamoto says. This would enable uniform, dendrite-free plating and stripping of lithium metal, an improvement that would dramatically extend battery life.

> **"If there is one thing he knew, and that others who work on ceramics know, it is that they are inherently brittle....That has been the Achilles heel for ceramic solid-state battery technologies."**

Another key challenge of making a ceramic electrolyte is evidenced by what happens if you drop your coffee cup onto the kitchen floor: it shatters. The late UCSB materials professor **Tony Evans,** who wrote the proposal for the first of seven rounds of NSF funding for the MRL at UCSB, the latest commencing in 2023, did a lot of work on ceramic coatings used in extreme environments. "If there is one thing he knew, and that others who work on ceramics know, it is that they are inherently brittle," says Sakamoto, who has spent fifteen years studying ceramics as a possible solid-state battery electrolyte. That has been the Achilles heel for ceramic solid-state battery technologies, because to prevent fracture, they have to be thick, and that makes them heavy — not an option for, say, the batteries in an EV or an aircraft.

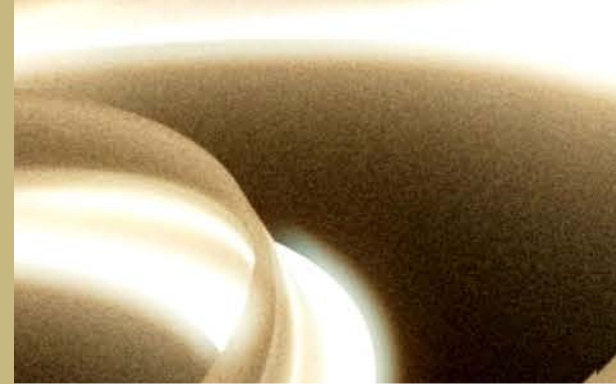
In the 1980s Evans, UCSB computational materials scientist **Robert McMeeking,** who is able to model the growth of dendrites in lithium-ion liquid and solid-state batteries, and other colleagues made a great deal of progress on that problem, which, says Van der Ven, "is exactly the same problem that arises in trying to make a ceramic electrolyte."

In batteries, the brittleness of ceramics creates a challenge related not to performance, but to making the battery at scale. "If you have an intrinsically brittle material, how do you get it into batteries without it breaking during the manufacturing process?" Sakamoto says.



Faculty Q&A

JEFF SAKAMOTO



Materials professor and Mehrabian Chancellor's Chair **Jeff Sakamoto,** who also has a partial appointment in mechanical engineering, came to UCSB last November with a reputation as a world expert on batteries, and focuses ranging from fundamental research through manufacturing. Having grown up in Silicon Valley when fruit trees dominated the pre-microprocessor landscape, Sakamoto earned his bachelor of engineering degree at Cal Poly San Luis Obispo and his PhD at UC Los Angeles. An expert in high-performance ceramics, he worked at the Jet Propulsion Laboratory in Pasadena before spending ten years at the University of Michigan, where he engaged with auto makers to develop new battery technologies. We caught up with him in February. His expertise is reflected throughout the main article as well.

What brought you to UCSB?

I was born and raised in California, and it has always been home for me. It's great to be back where I'm close to my extended family. With my kids finishing high school in Ann Arbor, I thought it was a good time to consider transitioning to a university that has a history in advanced ceramic research and, more broadly, strong fundamental materials research and materials characterization. Advanced ceramic research has been part of the UCSB Materials Department DNA since it was founded. Moreover, the College of Engineering at UCSB is recognized as a world leader in engineering studies. When I considered how well aligned my career goals and personal connections were with the opportunity, I accepted the position immediately. I also need to emphasize that the people and the collaborative environment equally contributed to my excitement at becoming a part of UCSB. This is a dream come true!

What are some of the main considerations when you think about manufacturing and commercialization of batteries?

That's the area of techno-economic analysis, and it involves big-picture thinking: before lifting a finger in the laboratory, you have to figure out if it's viable at scale, because if you're going to make a battery for EVs, you will eventually need billions of them. If we're considering using a certain material, we have to think about whether there is enough of it in the Earth's crust, where it will come from, and whether the material extraction and processing are sustainable. Public policy and environmental and social studies are integral to that kind of analysis, so it can attract the interest and contributions of faculty from across campus.

Looking at the possible trajectory for battery research at UCSB, would you like to do something here similar to the battery lab you started at the University of Michigan?

Yes, but it would be different. One mission could be to make state-of-the-art lithium-ion batteries. The students — and especially graduate students — could complement their course work by learning how to design, fabricate, and test batteries, do post mortem analyses, and so on. That would prepare them to hit the ground running when they graduate. Companies need battery experts, and companies that can benefit from this program will likely want to invest in fellowships or buy a piece of equipment that they're interested in using and that also grows our capabilities. That's a way to bring in industry, connecting its needs with the students we graduate. We would be advancing battery research while focusing on workforce development.

There's great value in fundamental research at UCSB, as well as a broad and deep technology pool. I will endeavor to bring these strengths to bear in our collaborative efforts to commercialize technologies that will help create a sustainable energy future.

"Ceramic electrolytes can be promising in prototype cells made in the laboratory, where they are handled very gingerly, but can we make them tougher and stronger, so that they can survive a high-speed manufacturing process? That's another branch of research that this [materials] department is well poised to examine."

The brittleness of ceramics derives from the nature of their bonding and how they are made. Some (usually small-scale) materials systems are fabricated from the bottom up by depositing atoms via processes such as chemical or physical vapor deposition, but, Sakamoto says, "For more of the recently discovered breakthroughs in ceramic electrolytes, you take a batch of powders and squish them together. That more-scalable process also produces microstructural defects, little pores that, in a battery, cause pressure build-up from localized deposits of Li metal, which crack the ceramic [as mentioned above]. The defects are the enemy, and we need either to get rid of them or discover ways to enable tougher ceramics."

A further challenge in solid-state batteries results from having a solid interface between both of the electrodes and the electrolyte. For example, if a Li-metal electrode is used, each charge and discharge of the battery causes a thirty-percent change in volume as a result of deposition and dissolution of lithium. "Depending on the battery-pack design, this can change the cell pressure during operation, which may change the battery behavior," Sakamoto explains. "On the other side of the cell, the cathode particles may also expand and contract during cycling, causing stress at the cathode-electrolyte interface. Whether at the cathode or the anode, these pressure changes during operation result in mechano-electrochemical phenomena that are still not fully understood. If these knowledge gaps could be closed, solid-state battery technology would advance significantly toward commercialization."

Many battery scientists, including Clément, also think a lot about the "tremendous amount of pressure that must be applied during solid-state battery fabrication to create good interfacial contact between the components." Beyond fabrication, solid-state batteries work well only if pressure is also applied *during* electrochemical cycling; i.e. during charge and discharge. "That is possible by packaging the cell in a very thick casing, but by doing that, you're defeating the purpose of a high-energy-density battery, which must be lightweight, because a casing that can contain so much pressure will be heavy," Clément notes, making it impractical for use in a car, a plane, or a cellphone we carry in our pocket, where weight matters.

Further, she adds, "We also don't know how applying so much pressure to these materials might affect their properties or how they behave. What does the pressure do to the materials at the interfaces of different components? There are still a lot of unanswered fundamental questions."

"We don't know how applying so much pressure to these materials might affect their properties or how they behave. There are still a lot of unanswered fundamental questions."

Clément's research on materials for a sodium (Na) battery are driven, to some degree, by the fact that sodium is about 1,200 times more plentiful in the world and much cheaper than lithium. "Once we get it working," Sakamoto says, "it is probably the answer to enable batteries for low-cost, sustainable grid or long-duration energy storage." But even for large, heavy batteries that can be stored underground, Sakamoto says, circling back to a point of constant focus, "Once a suitable electrolyte or materials for electrolytes are identified for a sodium battery, you then have to think about *manufacturing*. If you get to the point of having new chemistry to move sodium ions through a ceramic electrolyte, and new water-based liquid electrodes, then you have to figure out how to make it affordably, safely, and at scale. So, our sodium-battery team includes a cathode team, an anode team, an electrolyte team, a cell-characterization team, and a manufacturing team."

As with so much about batteries, however, "getting it working" is the trick. The deployment of Na-ion batteries has been hampered by a lack of cathode materials that are capable of storing large amounts of charge reversibly, as occurs in a Li-ion battery. "Viable sodium alternatives to current lithium-based batteries have proven elusive," says Clément, who is studying a class of candidate Na-ion cathode materials called *weberites*. "We are curious as to whether we can make new chemistries for sodium-ion cathodes that are different from those used for lithium. A lot of research is being done on swapping out lithium for sodium and using the same

Raphäele Clément prepares an NMR rotor sample holder, which is rotated at high speed in the instrument to provide views of the material's atomic structure.

chemistry, but sodium has problems that lithium doesn't have, so we're looking at completely different structures.

"The weberite are fluorides — highly electronically insulating materials," she notes, "but the composite electrode we prepare must be reasonably conductive. We are currently optimizing the electrode formulation to achieve that."

The Polymer Picture

Chemical engineering professor **Rachel Segalman** and chemistry professor **Javier Read de Alaniz**, in collaboration with Clément and materials and chemical engineering professor **Glenn Fredrickson,** an expert on simulating polymers, are collaborating to develop a polymer electrolyte for a solid-state battery. Segalman, an expert in ion and electron conductivity in polymers, and Read de Alaniz, a synthesis expert, design and synthesize new polymer electrolytes. Clément's expertise in NMR plays a major role in helping them to understand how the lithium and its counterion (produced when an ion is) move through devices.

Fredrickson conducts multiscale modeling studies of zwitterionic polymers — polymers that bear a pair of oppositely charged groups in their repeating units — which Segalman, Read de Alaniz, and Clément are investigating. His work encompasses atomistic molecular dynamics (MD), coarse-grained MD, and field-theoretic simulations to probe the dissociation, structure, and dynamics

> **"In an ideal world, before any new battery material or component was produced it would be modeled computationally to indicate promising directions."**

of dissolved lithium salts within the solid-matrix polymer. His findings are being used to guide the design of next-generation of polyzwitterions, the aim being to optimize ionic conductivity while maintaining desirable mechanical properties, such as processability, and ignition (fire) resistance.

Segalman describes their work as developing organic molecules that both help to dissolve the lithium salts (separating the positively charged lithium from its negatively charged counterion) in the system and also enable the lithium to move through the device quickly. This is difficult, because the lithium generally ends up coordinated (stuck) to the polymer, but only the lithium (not its counterion) matters in terms of battery performance.

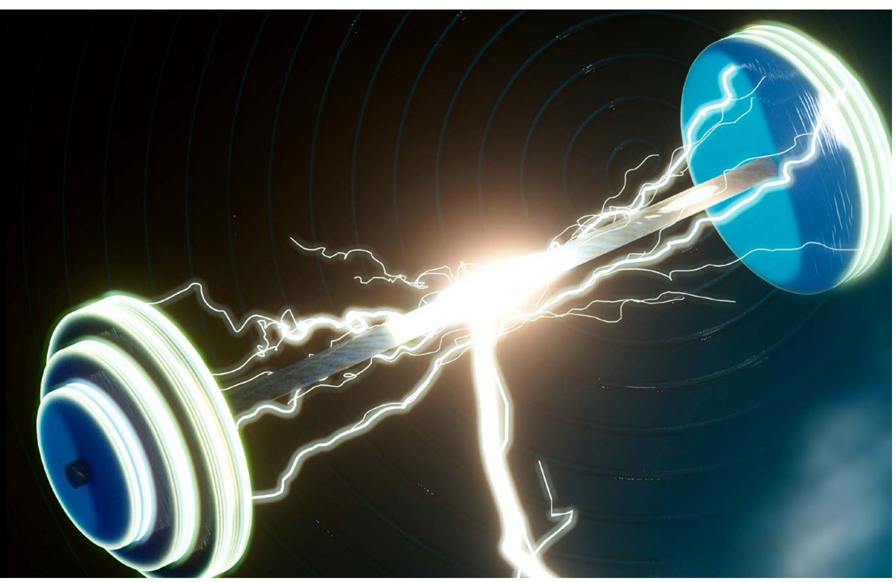
Read de Alaniz describes the research from the synthesis side as addressing a delicate balance in terms of bonding the polymer to lithium. "If you're thinking about selective lithium-ion transport, you need molecules that can interact with the lithium-ion dynamically."

On the other hand, if the binding with the polymer isn't strong enough, all the ions [lithium and its counterion] will re-cluster (aggregate) and no longer be useful in the battery. "Solubilizing the Li by coordinating with units on the polymer makes it less likely that the Li will aggregate and helps to increase the total amount of Li in the polymeric system," he says. "The goal is to separate the lithium ion from its counterion so that only lithium moves but does not aggregate."

Thus, the question of balance. "That process must also be dynamic — i.e. intermittent — enough to promote movement of lithium through the battery," Read de Alaniz adds. "That is not easy, because binding often is designed to be more long-term and persistent."

He and Segalman rely on Clément to verify the results of experiments designed to understand how lithium interacts with the polymer matrix. "Raphäele is able to say, 'Oh, you have two types of lithium, one that is free-flowing and conducting, and one that's serving as a stationary point binding the materials together,'" Segalman says. "That's what we want to have happen. It's amazingly complicated, but we are making great progress."

> **"That's what we want to have happen. It's amazingly complicated, but we are making great progress."**



Theory First

In an ideal world, before any new battery material or component was produced, says Van der Ven, it would be modeled computationally to indicate promising directions for research and rule out likely dead ends. Mostly, however, that is not what happens.

"A long-term dream of computational materials scientists is that our theories and algorithms are able to model the behavior of a new material before it is ever synthesized," Van der Ven explains. "We can do this to some extent, and there are many examples where modeling has provided useful directions for experimental researchers. Even before we fully achieve that, however, an important role of computational materials science is to generate a deeper, mechanistic understanding of how battery materials behave and how that behavior depends on the underlying chemistry of the material."

Materials assistant professor **Ananya Balakrishna** performs computational modeling that complements Van der Ven's work, but at a larger scale and in a more predictive way. "Anton's group works from first principles — the material properties, and those findings feed into our model," Balakrishna says. "When we're thinking of battery materials, we're thinking of one part of it, so let's say it's the cathode. We take a slice of it and visualize how the microstructures appear as the battery is charged and discharged, and how certain microstructural design changes could have a big impact on reducing either volume changes or interfacial stresses, both of which can damage and degrade the battery. A distinguishing feature of our method is that it allows us to predict how microstructures evolve in situ and how these microstructures collectively govern material cyclability. One can use such insights to design materials so as to mitigate some of the challenges that manifest on the large scale."

Related Efforts

Assistant chemistry professor **Lior Sepunaru** is currently focusing his research efforts on what is called a *redox flow* battery. Appropriate for long-term energy storage, it works much as a liquid-ion battery does except that the transport of ions and electrons occurs between "huge tanks of liquids that carry energy in chemical form," Sepunaru says. Such batteries incorporate a membrane that prevents the liquids on either side of it from contacting each other and short-circuiting the battery. In a recent advance, researchers in Sepunaru's lab developed a concept design for such a battery using liquids that don't mix — much as water and oil don't — eliminating the need for a membrane and cutting the cost of the battery by thirty percent.

New COE chemical engineering assistant professor **Tyler Mefford** also researches electrochemical materials and devices that can provide long-term grid-scale stationary storage of renewable electricity at a fraction of the cost of Li-ion batteries. Candidate technologies include aqueous batteries, which utilize earth-abundant elements for the electrodes and water for the electrolyte, and liquid fuels that can be electrochemically charged and discharged. Elsewhere, UCSB mechanical engineering assistant professor **Yangying Zhu** is studying how batteries hold up through repeated cycling between extreme high and low temperatures, an area of study relevant to both space travel and, perhaps, EVs, which can suffer poor battery performance in very cold temperatures on Earth. "We know a lot about batteries at room temperature, but we know very little about battery behavior outside that room-temperature window, and that might be important for space applications, such as on the moon." (Zhu was recently the PI on a study of water-droplet behavior aboard the International Space Station.)

"The battery may be close to room temperature during the lunar day, but at night, the temperature ranges from 280 to 360 degrees below zero Fahrenheit," Zhu adds. "You cannot charge or discharge a battery at those temperatures, because the liquid electrolyte will freeze, rendering the battery unusable. We want to know whether the battery will be damaged by repeatedly cycling through freezing and thawing processes, and whether freezing might damage its structural integrity."

To find out, Zhu uses two types of spectroscopy. For one, she shines a laser light into the cell and then obtains information from the back-scattered light. In the other, she works with UCSB mechanical engineering associate professor **Bolin Lao,** who uses a laser to excite the sample, which provides an acoustic response. If there is a crack in a battery component, the acoustic signature is affected.

Silver Buckshot

The current state of battery research and the complexity of the related challenges can be understood in those associated with batteries for EVs and grid storage. The key requirements of EV batteries are high performance (low weight and small size), low cost, sustainability, and safety. Because lithium-based chemistries are a proven technology that, by and large, exhibit the highest performance, they are the most attractive in that setting and, accordingly, leading the path toward an electrified future. If, however, new technologies beyond Li-ion batteries are commercialized, such as solid-state batteries that are safer and provide double the performance, they could dramatically accelerate the widespread adoption of EVs.

For grid storage and light-duty vehicles that don't require the same high performance, the challenges are guided more by cost, the abundance of materials, and their sustainability and safety. Sodium or other non-lithium chemistries that use water-based electrochemistry are attractive batteries for grid storage, but, most such "beyond-Li-ion" technologies, such as sodium batteries, are nascent and, while promising, require more technological development before they can be widely implemented.

"Regardless of the battery type, it is becoming increasingly apparent that there is no silver bullet or universal battery chemistry or energy technology that will enable the transition to a sustainable energy future," Sakamoto says. "Instead, an electrified future will likely require 'silver buckshot' — multiple chemistries and types of batteries, with each filling a role."

While the possibilities for new battery materials and chemistries may not be endless, they can seem to be, as evidenced by the multiple interdependent variables. Finding the winners will require ample time and intensive coordinated efforts, both to narrow down the field of candidates and also to build up, in some cases, atom by atom or monomer by monomer, materials for batteries that will, one day, release society from its reliance on fossil fuels. As is often the case, UCSB researchers are at the forefront of that world-wide effort.

A Startup with Sole

UCSB researchers create a shoe to address a debilitating condition that affects millions

The variable-friction shoe (left) that (from left, opposite page) Tyler Susko and Elliot Hawkes created has the huge advantage of appearing to be a normal shoe, not an orthopedic device; vastly improves users ability to walk; and has additional therapeutic benefits that have resulted in a $2.3-million grant from the NIH.

Millions of people in the United States experience "foot drop" — an inability when walking to avoid scuffing the ground when bringing one foot forward through the air to take the next step. Foot drop can result from any number of causes, including spinal cord injuries, stroke, cerebral palsy, multiple sclerosis, Parkinson's disease, or even, simply, weakness associated with advancing age.

"It's a huge population," says **Tyler Susko,** associate teaching professor, undergraduate vice chair, and capstone instructor in the Mechanical Engineering Department at UC Santa Barbara. He worked on rehabilitative robots while pursuing his PhD at the Massachusetts Institute of Technology and, in 2015, began trying to find a way to help people who experience foot drop. Now, nine years later, he and associate mechanical engineering professor **Elliot Hawkes** have a startup company, called Cadense, Inc., which recently delivered its first shipment of a custom shoe that alleviates foot drop while providing multiple related benefits.

The two researchers call their invention a "variable friction shoe," a reference to the fact that the sole contains both high-friction and low-friction components. When the foot is moving forward during what's called the "swing phase" of walking, the low-friction component is elevated from the sole, so that if the foot contacts the ground, the shoe slides forward rather than stopping, which can lead to trips and falls. Once the foot reconnects with the ground as the step is completed and the weight shifts to that foot, the low-friction surface retracts, exposing the high-friction surface, which provides a stable, non-slip landing for the "stance phase" of the step, when the foot is on the ground.

The idea had its origins in Susko's PhD work, when he conducted a study in which multiple people who had walking disabilities walked on a treadmill customized so that, as their foot started to come forward, the track dropped away, allowing the leg to swing forward freely, without scuffing. After the study, one participant told Susko how good it felt to walk without worrying about scuffing and tripping and that she wished she could "take it outside of the lab." Susko started thinking about how to make that possible. It hinged on the question: *How can we do this complex thing — removing the floor of the treadmill — in the simplest way possible?* "I say so many times to my students that the one fundamental principle of mechanical design is to keep it simple," Susko notes. "Anything you design should be as simple as possible."

Getting to simplicity is, of course, a complex undertaking. The vision for a shoe became a mechanical engineering undergraduate capstone project in 2015, Susko's first year at UCSB, with students designing a robot shoe that was too complicated, too heavy, and too reliant on things that could fail to function. "The thing we learned from that was not to make a robot shoe," Susko laughs.

At that point, Susko was joined by Hawkes, an expert in soft-material robotics and biomechanics who had just been hired by UCSB. At the time, Hawkes was working to create a wearable device to improve running performance. He designed a simple, one-dollar rubber band tied between the legs that made runners seven-percent more efficient.

Creating it involved, first, carefully analyzing the forces runners applied to an instrumented track, then determining how to modify those forces ideally, and finally, designing the simplest device possible to achieve those modifications. Hawkes says that he brought a similar process to the walking project: "I remember vividly examining the forces that occur during impeded walking, and devising a variety of ways to modify them, all of which failed, before we identified the variable-friction concept."

But going from concept to a shoe that would work for hundreds of thousands of steps was not a straightforward task. The team continued to work on the project with a second set of students, one of whom, **Erinn Sloan** (BS '17, MS '18), continued the project as the subject area for her master's degree. They were buying shoes — HOKA eventually gave them some — cutting them up, and trying different things. "We could hack a shoe and get a new concept the next day," Susko recalls.

Eventually, Hawkes, Susko, and Sloan patented the variable-friction shoe. "In 2019, we had a preliminary shoe, and it looked promising," Susko said. "People using it walked faster, with no instruction. Some people walked twenty to sixty percent faster. We also looked at people's 'gait strategies,' such as swinging their foot wide to get it forward. With the shoe, they no longer did that, and because the leg was moving straighter, they went faster."

Susko's intention, however, was to "develop a rehabilitation device that people could use to repair and retrain their brains," so he was not satisfied with a shoe that simply assisted walking. A grant from the California NanoSystems Institute at UCSB made it possible to locate a shoe designer and find a manufacturing facility to produce the first prototypes, which were beta-tested in 2022.

Several people in the initial trial used the shoe as an assistive device and immediately improved their gaits. Then, in a longer trial, they discovered the shoe's rehabilitative effects."We found one man who had suffered a stroke eleven years before," Susko says. "Usually, there is no natural recovery at that point, but using the shoe, he ended up walking three times faster than when he started. His calf muscle got so big that he had trouble fitting it inside his AFO [ankle foot orthosis, the standard of care for foot drop]. We thought, *So, there's muscle contraction and increasing muscle tone*, which was really interesting evidence, so we presented that to the National Institutes of Health (NIH)."

"Assistance is one thing," Hawkes adds, "but rehab is a whole other level. It means that they could graduate out of the shoe eventually and no longer need assistance."

The result of sharing the results from their production prototype tests with NIH resulted in a $2.3-million NIH grant for a study with researchers at Northwestern University. Together, they will collaborate to run a four-year clinical trial studying the effects of using the variable-friction shoe compared to the AFO brace.

Now in production, the first order of 2,080 pairs of Cadense shoes were delivered this past March, 800 of which were pre-ordered and would be sent directly to customers. Made with standard running-shoe materials, they look like running shoes and cost $198, giving those who experience foot-drop an affordable opportunity to step into a brand-new world of possibility.

CHAMPION OF ENGINEERING

Yulun Wang

A Global Vision for Health Care

Yulun Wang (PhD ’88) has built multiple companies to provide care…everywhere

Remote surgery, telemedicine in all its forms, even international remote medical consultations and remotely supported surgeries in underserved areas of the world — **Yulun Wang** has played an instrumental role in making all of these important, often-life-saving, services possible.

After earning his BS, MS, and PhD (’88) in electrical and computer engineering at UC Santa Barbara — he wrote his dissertation on a novel high-performance computer for advanced robot control — Wang started founding companies to serve people’s medical needs. At his first, he invented the voice-controlled robotic arm, making Computer Motion, founded in 1990, the first company in the world to bring an FDA-approved surgical robot to market. Computer Motion IPO’d in 1997 and then merged with Intuitive Surgical in 2003. He founded InTouch Health in 2003, becoming a pioneer in remote medical consultation. The company sold to Teledoc for $1.1 billion in 2020. In 2017, he formed the nonprofit World Telehealth Initiative (WTI), leveraging a global network of tens of thousands of physicians to sustainably provide medical expertise to the world’s most vulnerable and underserved communities. His latest company, Sovato, is focused on using remote telesurgery to address the extreme shortage of surgeons in many parts of the U.S. and the world. *Convergence* spoke with him in May.

Convergence: *Did entrepreneurship come naturally to you?*
Yulun Wang: After completing my PhD, I had to decide between going into academics or industry. I decided that I wanted to build products as opposed to publishing papers. I became an entrepreneur because I wanted to build my own products rather than working on other people’s ideas. I can’t say entrepreneurship came naturally, as I’ve learned thousands of lessons along the way.

C: *What is some key advice you think aspiring entrepreneurs should know but might not know?*
YW: I always say to aspiring entrepreneurs that one can be at the leading edge of a new technology at a young age, but you can only acquire business skills through years of doing business. So, my

advice is to find some older, experienced mentors who can help them on their journey.

C: *What have been one or two of the most valuable lessons you've learned in overcoming challenges as an entrepreneur?*
YW: First, perseverance and patience are necessary qualities for an entrepreneur. Second, enjoy the journey, as opposed to being fixated on the destination; that is easier said than done. Finally, know that there will surely be twists and turns along the way.

C: *What were your biggest takeaways from your time at UCSB, aside from the knowledge and expertise you gained?*
YW: I think the most important benefit of education is not only gaining knowledge but rather, learning how to think and how to explore. It's about how curious you are about new ideas. I've now come to appreciate the fact that, usually, seventy to eighty percent of an intellectual pursuit lies in figuring out what the right problem is and framing it, as opposed to finding the solution — so, asking the right question. I have a phrase I use all the time that relates to an important specific skill set, which is *creating order out of chaos.* That, I find, is a very important skill set that applies not only to engineering, but to life in general.

C: *Tell us a little about InTouch, your company that launched the world's first medical robot, which conducted the first telesurgery.*
YW: After Computer Motion merged with Intuitive Surgical in 2003, I started InTouch Health. In 2001, while still at Computer Motion, I led a project in which a surgeon in New York City operated on a patient in France. That was the first telesurgery. The world wasn't ready for remote surgery in 2003, but it did seem ready for telemedicine, which is enabling a clinician to consult with a patient at a distance. That was the premise for InTouch. We built a robot that could move through the hospital the way a doctor does for patient rounds. It would go room to room and, with a bedside assistant, allow the remote doctor to see his or her patients throughout the day.

Yulun Wang delivers the keynote address at the 2024 UCSB COE Undergraduate Commencement.

"The first six months, people were not willing to invest. But if you keep going, eventually you'll find the person who says, 'Wow, that's great technology. I've been looking for something like that, and I'd like to support it.' Just don't give up."

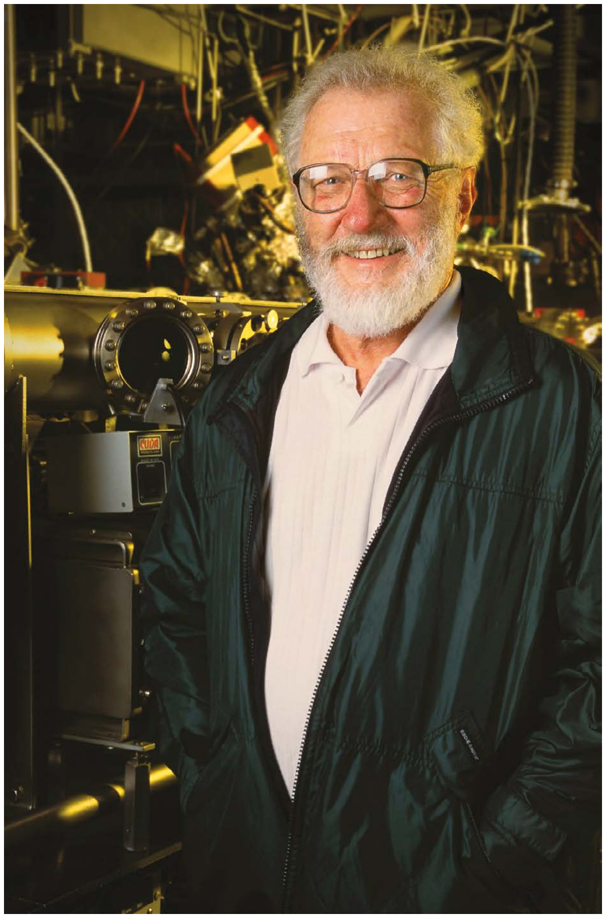
We really found our market in taking care of stroke patients**.** At the time, stroke was the third-leading cause of death [it now ranks fifth] and the leading cause of long-term disability. The main reason was that you couldn't get a stroke neurologist to the patient's bedside fast enough, and with strokes, they say "Time is brain," because during a stroke, up to 1.5 million brain cells die every minute in an untreated patient. Using telemedicine, we could get the remote stroke neurologist there fast to assess the patient and figure out the right treatment quickly. Today, InTouch, which is now a part of Teladoc Health, facilitates over two hundred thousand stroke assessments a year. Based on our periodic surveys of nurses who are helping patients, we estimate that about ten percent of those stroke interventions are life-saving — that's twenty thousand lives per year — and that roughly fifty percent of interventions reduce long-term negative outcomes, improving the outlook for another hundred thousand people per year.

C: *You say that one of the most important elements of the World Telehealth Initiative is that the model is scalable. What makes it so?*
YW: There are two big innovations we're bringing forward. One is telemedicine, which we've talked about. The other is that we're building a matching platform that takes into account multiple factors, such as medical expertise, time zones, provider availability, languages, existing relationships, diaspora, and so on, in order to connect the need to the provider. That is what is enabling us to scale while providing this capability at very little cost.

C: *You've talked about breaking a career into three phases: survival (the beginning), success (through middle career) and significance. You seem to have moved into the last phase. Can you tell us something about that?*
YW: In the significance phase, the focus is not about monetary gain anymore. Hopefully, you've got that kind of tucked away, and you can focus solely on how you think you can do good. For me, personally, I've mapped that into three main areas: I have the World Telehealth Initiative, a nonprofit that I work on a fair amount. I feel a tremendous debt of gratitude to, and affinity for, UCSB. I was educated there, and I think education is foundational for people being able to reach the significance phase. I have been connected to UCSB ever since. And I'm on the board of Cottage Hospital, so that's on the healthcare side. Those are the things that I keep putting energy into. It's nice, and necessary, for people to donate money to various causes, but I've tried to be more selective and to focus my effort in those three areas.

C: *How does the UCSB component of that show up for you?*
YW: I believe that you have to remember where you came from and who helped you along the way. UCSB was foundational in helping me to build what has been a very enjoyable and exciting career. I've been on the advisory board of both the Mechanical Engineering and Electrical and Computer Engineering Departments for a long, long time, and I speak there once or twice a year. I provide entrepreneurial advice. I'm contacted frequently by UCSB students, and even professors, who are interested in starting this or that, and I provide my input. I've also made financial contributions annually for decades. Again, rather than giving, say, one big gift, I prefer to maintain a long-term relationship, so I kind of couple my money and time together, and I intend to do that for the rest of my life.

C: *What strikes you about the progress or change you've seen in the College of Engineering since you graduated in 1988?*
YW: The College of Engineering has continually produced stellar graduates. I've hired well over one hundred of them over my career, and they do incredibly well. The other thing worth mentioning is the focus on interdisciplinary research. It really does shine through. I've interacted with people from all kinds of universities all over the country and around the world, and the collaboration that is part of the DNA and culture of the College of Engineering is unique. It's real; it's authentic, not just a bunch of talking points. I'm also what people might think of as a bioengineer, so I'm extremely interested to see how UCSB's newest department, the new Bioengineering Department, is going to move forward.



Herb Kroemer in the lab he built at UCSB, home to some of his seminal work in developing his theories of semiconductor heterostructures, for which he received the Nobel Prize.

Kroemer receives his Nobel Prize from King Carl Gustav XVI at the Stockholm Concert Hall in December 2000.

Herb Kroemer (1928-2024)

His heterostructures changed the world

UC Santa Barbara and the world lost one of the greatest technological visionaries of our time on March 8, when emeritus professor **Herb Kroemer,** who earned a Nobel Prize for his seminal work on compound semiconductors, died at the age of 95. Born August 25, 1928, in Weimar, Germany, Kroemer came to UCSB in 1976, where he held the Donald W. Whittier Chair in Electrical Engineering and joint faculty appointments in the Electrical and Computer Engineering Department (ECE) and the Materials Department. Kroemer received the Nobel Prize in Physics in 2000 in recognition of his work, which included developing semiconductor heterostructures that are used in high-speed- and opto-electronics and laid the foundation for the modern era of microchips, computers, and information technology.

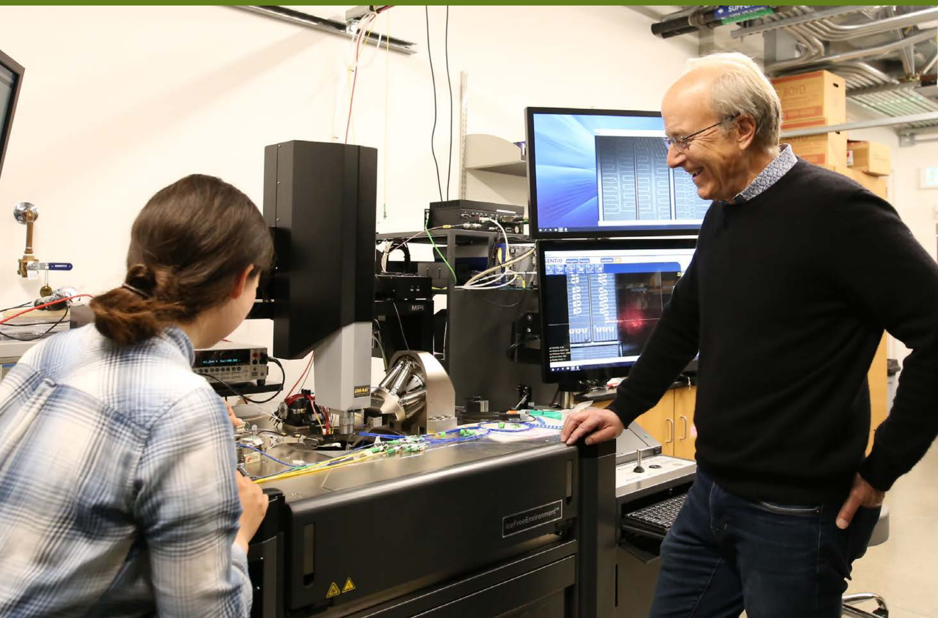
"In India, there is the concept of a guru, someone who is a teacher in the broadest sense, someone who teaches not only curriculum, facts, skills, and information, but also morals, ethics, leadership, graciousness, and generosity," said **Umesh Mishra,** dean of the UCSB College of Engineering, who was born and raised in India. "We have been fortunate to share time with Herb Kroemer, who embodies that broad ethos of the guru, who taught physics, materials science, and electrical engineering at the highest level, but also life and behavior. There are not many gurus, and we have lost one."

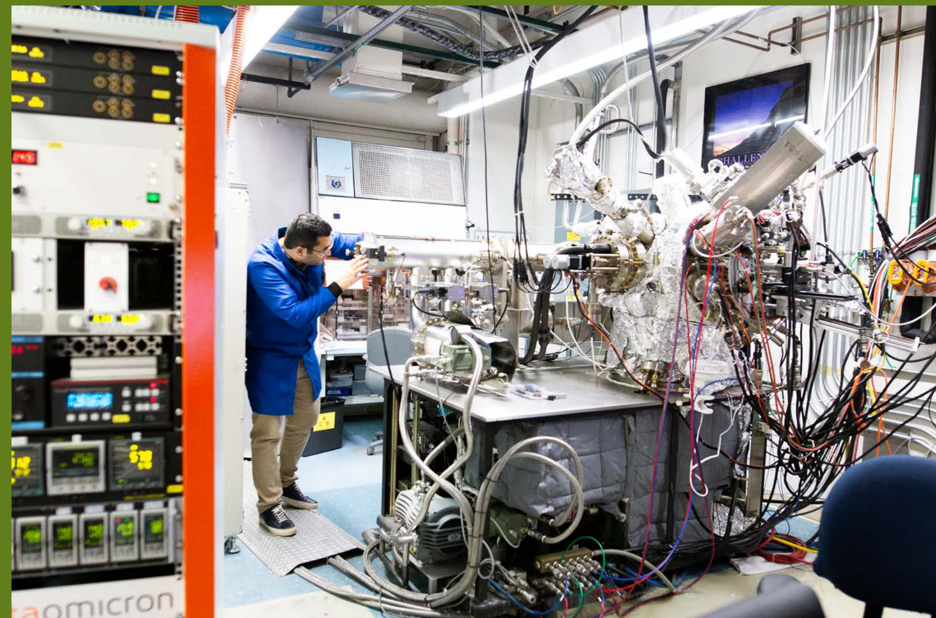
Following work in several research laboratories in Germany and the United States, in 1976 Kroemer persuaded the Electrical & Computer Engineering Department at UCSB to direct a substantial portion of its limited resources to expanding the department's small semiconductor research program, with a particular focus on the emerging field of compound semiconductor technology. Seeing an opportunity for UCSB to become a leading institution in that area, Kroemer himself became the first member of what would soon become one of the world's preeminent groups dedicated to the physics and technology of compound semiconductors and the many devices they enable. His discoveries provided the basis for numerous technological innovations we now use on a daily basis – from cell phone and satellite communications to high-speed transistors and solid-state lighting.

"Herb was an inspiration to everyone," said ECE and Materials professor **John Bowers,** a world expert on integrated lasers, the Fred Kavli Chair in Nanotechnology, and the director of the UCSB Institute for Energy Efficiency. (See P. 12) "He invented the double-heterostructure laser, which earned him a Nobel Prize, but also enabled the first commercial semiconductor lasers, which are used worldwide in fiber-optic networks and enabled the internet, transforming the world."

In addition to the Nobel Prize, Kroemer received the Grand Cross of the Order of Merit of the Federal Republic of Germany, the highest award given by the German government. He was a member of both the National Academy of Engineering and the National Academy of Sciences, and a fellow of the American Physical Society and the Institute of Electrical and Electronics Engineers

Scan the QR code at right to read what some other UCSB faculty members had to say upon Kroemer's passing.





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