FALL/WINTER 2024

CONVERGENCE

The magazine of engineering and the sciences at UC Santa Barbara

FOCUS ON:

UCSB BECOMES A QUANTUM COLONY

LEADING THE WAY IN RESEARCH AND EDUCATION FOR A NEW ERA

TECH EDGE: EXFAB

A MAJOR AWARD PUTS UCSB ON THE CUTTING EDGE OF BIOTECH

TWO BIG AWARDS FOR JIM SPECK

HE'LL STUDY LED EFFICIENCY AND A NEW GENERATION OF POWER SWITCHES

STUDYING RDS IN SPACE

EMILIE DRESSAIRE SENDS NINE EXPERIMENTS TO THE INTERNATIONAL SPACE STATION

UC SANTA BARBARA

MESSAGE FROM THE DEANS

Greetings, and welcome to the latest issue of *Convergence*. While it is hard these days to avoid noticing the worldwide race to harness quantum phenomena for use in computing, sensing, communications, and other important applications, less obvious to some might be UCSB's position of prominence in the emerging quantum realm.

Since 2019, when the campus was named the home of the National Science Foundation's first Quantum Foundry, UCSB faculty from multiple departments in engineering and STEM more broadly have been leading the way in many areas within the quantum field. Their work with their colleagues at UCSB and around the world, especially in materials science, physics, and photonics, have led to important gains in understanding and producing quantum phenomena required for advanced technologies. The article "Focus On: UCSB Becomes a Quantum Colony," (P. 18) serves as a primer on what's happening in the campus quantum realm.

Given UCSB's long-standing strength in materials science — a major factor in the Quantum Foundry's being sited here — this seemed a good time for a faculty Q&A with materials and chemistry professor and Materials Research Laboratory director, **Ram Seshadri.** You'll find his engaging, personable take on a mix of materials-related subjects on page 16.

This issue also includes coverage (P. 12) of another major new facility, the BioFoundry for Extreme and Exceptional Fungi, Archaea and Bacteria (ExFAB). Funded by a $22-million grant, the state-of-the-art laboratory, directed by chemical engineering and bioengineering professor **Michelle O'Malley,** is the nation's first NSF BioFoundry to be focused on largely untapped and unexplored microbes that live in extreme and unusual environments.

Space-based science has exploded in recent years, and mechanical engineering professor **Emily Dressaire** recently sent a series of experiments to the International Space Station in an effort to better understand the fluid dynamics of respiratory distress syndrome (RDS), a complication often associated with Covid 19. On page 10, read about what running experiments in near-zero gravity did to forward her reseach.

You'll also learn about materials scientist **Jim Speck**'s two major awards (P. 28), one, a Vannevar Bush Faculty Fellowship to continue his groundbreaking work on some little-understood physics related to efficiency loss in LEDs, the other an ARPA-E award to develop ultra-efficient next-generation power switches.

Another ARPA-E award went to assistant professor of mechanical engineering **Yangying Zhu** (P. 30), who is working on a new approach to water desalination that could cut the energy consumed in that process by half.

As always, News Briefs (P. 4) presents a collection of intriguing short items, including a follow-up to the Shellphish team's participation in the DARPA cyber-security challenge. They recently reached the final round, earning $2 million in the process. We hope you enjoy the issue!

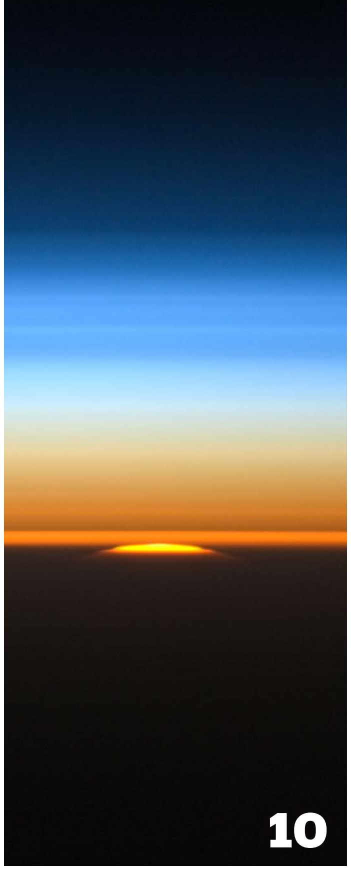
Umesh Mishra

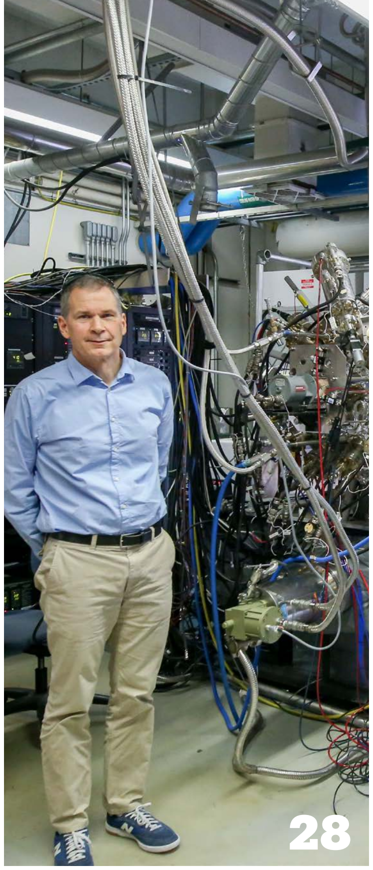
Dean and Richard A. Auhll Professor, College of Engineering

Shelly Gable

Interim Dean of Science, College of Letters & Science

Scan to read Convergence online





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UC **SANTA BARBARA**
College of Engineering

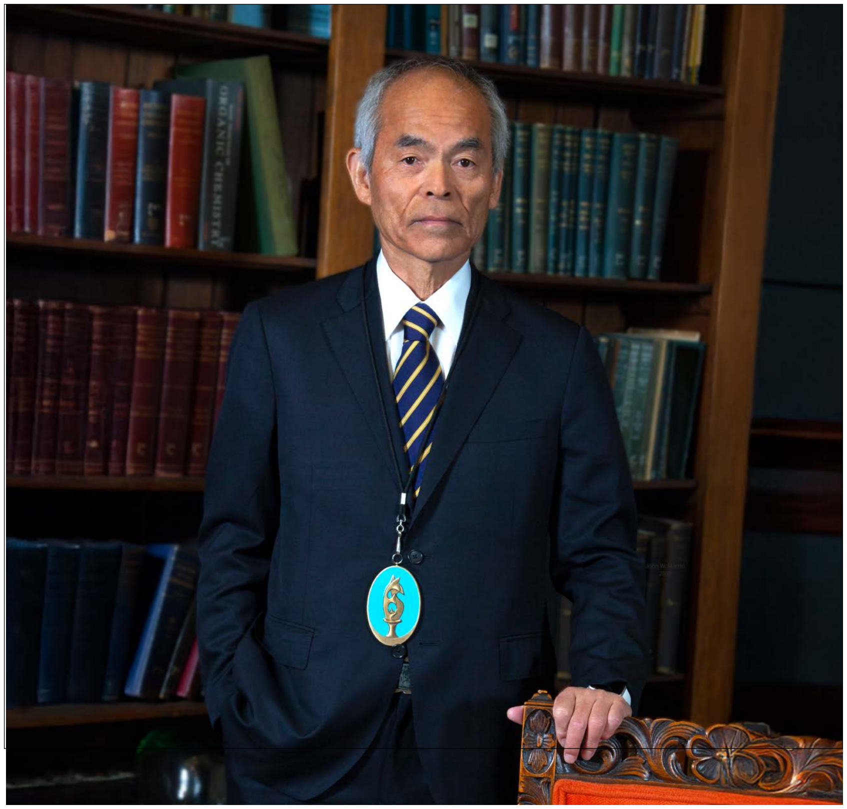
NEWS BRIEFS

ANOTHER HONOR FOR THE MAN WHO REVOLUTIONIZED LIGHTING

UC Santa Barbara engineering professor **Shuji Nakamura** was honored in Dayton, Ohio, on November 13 when he and two others were inducted into the Engineering and Science Hall of Fame. The professor of electrical and computer engineering and of materials was elected "for pioneering invention and development of the blue light emitting diode (LED), a breakthrough that made possible the energy-efficient white-light LED in global use today." The invention earned Nakamura the 2014 Nobel Prize for Physics. The other 2024 inductees were Carl Harry Knowles, inventor and developer of the first programmable barcode scanner and handheld laser scanner, and Clarence "Kelly" Johnson, a pioneer in designing jet fighter planes.

Nakamura joined others to light up Henley Hall on Dec. 4 as the Solid State Lighting and Energy Electronics Center at UCSB celebrated its 25th anniversary during the 2024 SSLEEC Annual Review Conference. Initially named the Solid State Lighting Display Center and part of the Materials Department, the center was renamed SSLEEC in 2013, expanding the goal of advancing new semiconductor-based energy-efficient lighting technologies through partnerships with key industry leaders.

The SSLEEC leadership team comprising Nakamura as director, **Steven Denbaars** (Materials; Electrical and Computer Engineering [ECE]) as co-director, **Jim Speck** (Materials), and College of Engineering dean, **Umesh Mishra** (ECE), has established a unique business model linking key industry partners with UCSB faculty and student researchers to collaborate across disciplines in addressing challenging problems in a range of important research areas.



Photograph by John Martin

Shuji Nakamura wears the medal he received as an inductee into the Hall of Fame.

Image courtesy Sphere Ent.

The surface of the Sphere in Las Vegas is covered with 1.2 million ultra-high-resolution LEDs that can display 256 million different colors.

LED UP YOUR WORLD

National LED Light Day was celebrated on October 7, as it has been since 2016. Here are a few quick facts about the tiny lights that changed the world.

1939 – Zoltán Bay and György Szigeti create and patent the first LED.
1968 – Hewlett Packard begins using LEDs in calculators, and experiments with LED colors.
1987 – LEDs are used in vehicle brake lights and signal lights, as well as in traffic lights.
2006 – UCSB professor of electrical and computer engineering **Shuji Nakamura** invents the white LED.
2012 – 49 million LED bulbs are in use in the U.S., accounting for roughly $675 million in energy savings.(The Department of Energy's current estimate is 2.3 billion LED bulbs)
2014 – Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura receive the Nobel Prize in Physics for developing a blue LED.

- Today's LEDs use 90-percent less energy than incandescent lights.
- LEDs can last up to 50,000 hours, compared to a maximum of 2,000 hours for an incandescent bulb. An LED bulb installed in a newborn baby's room today will last until that child is ready for college.
- LEDs don't attract bugs.
- The famous Time Square New Year's Eve crystal ball is illuminated by 32,256 LED lights; the Eiffel Tower has 20,000. But the largest LED display in the world, by far, is the Sphere at The Venetian Resort in Las Vegas (left), with 1.2 million lights covering 580,000 square feet of the Exosphere.

NSF FUNDS PARTNERSHIPS FOR ACCESS

As part of its Partnerships for Research and Education in Materials (PREM) program, the National Science Foundation (NSF) has awarded more than $5 million to support two collaborative research efforts involving UC Santa Barbara. The programs broaden access to materials-science-focused skills and opportunities by supporting partnerships between minority-serving institutions and NSF-funded research centers and facilities at research-intensive institutions.

A new round of funding was provided for the Partnership for Research and Education in Materials Science (PREMS). Since 2006, the UCSB Materials Research Laboratory (MRL), an NSF Materials Research Science and Engineering Center (MRSEC), and Jackson State University (JSU) in Mississippi, where Black students make up thirty-seven percent of the population, have collaborated to provide summer research internships for JSU students at UCSB, allowing them to work with faculty and spend time in the university's world-class facilities.

New for this round of funding is a partnership involving the NSF Quantum Foundry at UCSB (see article on page 18), the nation's first Quantum Foundry, established in 2019 with a six-year, $25-million NSF grant aimed at developing materials and devices for quantum-information-based technologies. Now, New Mexico State University (NMSU) — one of the largest minority-serving institutions in the U.S., with more than sixty percent of its students identifying as Hispanic or Native American — has partnered with the Quantum Foundry to launch the Partnership for Research and Education on Quantum Materials and Processes (PREQ). The PREQ is aimed at broadening participation of underrepresented minority students in materials research and education by providing them with opportunities to work on next-generation quantum materials and devices.

"It will be great to partner with NMSU and share expertise and students with them, enabling us to broaden our own research impact and to reach a wider network of minority-serving institutions," said **Stephen Wilson**, a UCSB materials professor and co-director of the Quantum Foundry. "Quantum science in particular has suffered from a lack of participation from researchers from minority communities, and the PREM program helps to narrow that divide."

UCSB researchers are also involved with a third active PREM, which partners New Mexico Highlands University and the NSF-supported BioPolymers, Automated Cellular Infrastructure, Flow, and Integrated Chemistry Materials Innovation Platform (BioPACIFIC MIP). Faculty from various departments at UCSB and UC Los Angeles received a five-year, $23.7-million grant from NSF in 2020 to operate the one-of-a-kind facility dedicated to revolutionizing high-performance polymers.

"For UC Santa Barbara to have three partnerships really speaks to our commitment to broadening participation in STEM disciplines," said materials professor **Ram Seshadri,** the College of Engineering's Associate Dean for Research and director of the MRL. (See the interview with him on page 16.) "The PREMs are a testament to the spirit on campus and within the College of Engineering."

Students present their summer research projects at the conclusion of their internships provided by the Partnership for Research and Education in Materials Science Program.

DENISE MONTELL WINS SECOND NIH PIONEER AWARD

It is extremely difficult to secure a highly competitive Pioneer Award, which the National Institutes of Health issue in support of high-risk, high-reward research. Now, UC Santa Barbara's **Denise Montell**, Duggan Professor and Distinguished Professor in the Department of Molecular, Cellular and Developmental Biology at UC Santa Barbara, has received her second Pioneer Award in ten years.

The honor comes with $5.5 million over five years for her to further develop her work on innovative immune therapy. She intends to use the funds to test a new treatment her group is developing to treat cancer and other diseases, and to combat antibiotic-resistant bacteria.

"I'm extremely excited about this project, because it's one that really started with my very first graduate student, **Anne Marie Murphy** [regarding the toxicity of a hyperactive form of a particular protein found in fruit flies] when I was a brand-new assistant professor," said Montell.

"The NIH High-Risk, High-Reward Research program champions exceptionally bold and innovative science that pushes the boundaries of biomedical and behavioral research…and is poised to have a broad impact on human health," said Tara A. Schwetz, NIH Deputy Director for Program Coordination, Planning, and Strategic Initiatives.

Chancellor Henry T. Yang said of the accomplishment, "It is truly incredible that, for the second time in a decade, Professor Montell has received this prestigious award, which highlights her groundbreaking research and her unwavering dedication to advancing biomedical science."

Professor Denise Montell will receive $5.5 million in funding to pursue her groundbreaking immune therapy research.

NEWS BRIEFS

UCSB's SciTrek educational program teaches students to think critically and work as part of a team by providing first-hand scientific experiences.

FEDERAL GRANT EXPANDS UCSB SCIENCE-EDUCATION OUTREACH PROGRAM

Learning to think like a scientist involves learning to design experiments, and since 2010, a program started by UC Santa Barbara Feldwinn and biochemistry professor **Norbert Reich** has been engaging enthusiastic UCSB undergraduate volunteers to help teach those skills to K-12 students.

Now, the SciTrek program is set to expand its scope and offerings thanks to a $1 million grant from Congress spearheaded by U.S. Representative Salud Carbajal. Through SciTrek, Carbajal said, "UCSB is providing firsthand scientific experiences to our next generation, sparking interest in STEM careers and ensuring that investments we are making in cutting-edge economies like space and science have the bright young minds to carry these fields forward."

Each SciTrek module involves five to eight days of experiments on a particular topic, such as sound waves or cellular respiration. A teacher or SciTrek staff member leads the module, and undergraduate mentors work directly with small groups of students.

"They do an experiment, they collect their own data, they come up with their own ideas. They make mistakes. They fail. They do it again," Reich said. "At the end, they come up with a poster and they argue about it, just like science in a research setting.

"I'm not necessarily interested in making little scientists out of students," he adds. "I'm interested in improving their understanding of how to think deliberately and critically about problem solving."

SHELL(PHISH) GAME

Shellphish, the hacker collective that began in UC Santa Barbara's Cyber Security Group (SecLab) under the direction of computer science professors **Giovanni Vigna** and **Christopher Kruegel,** and that now includes assistant professor **Wenbo Guo** and UCSB alumni who are professors at Arizona State University and Purdue University, has qualified for the finals of the AI Cyber Challenge (AIxCC), sponsored by the Defense Advanced Research Projects Agency (DARPA) and the Advanced Research Projects Agency for Health (ARPA-H). The competition unfolded at the DEF CON 32 Hacking Conference, one of the world's largest cybersecurity conferences, which was held in Las Vegas from August 9-11.

The finals, which will include seven teams remaining from an initial field of nearly forty, will be held in August 2025. The team's remarkable achievement, earned by the performance of its cutting-edge Cyber Reasoning System (CRS), earned a $2 million cash award.

The ARTIPHISHELL AI system succeeded in the semifinal round by demonstrating exceptional capabilities in autonomously identifying, analyzing, and patching complex vulnerabilities found in real-world software, and solving a problem that no other team did.

The Shellphish hacker collective won $2 million for advancing to the DARPA AI Cyber Challenge (AIxCC) finals.

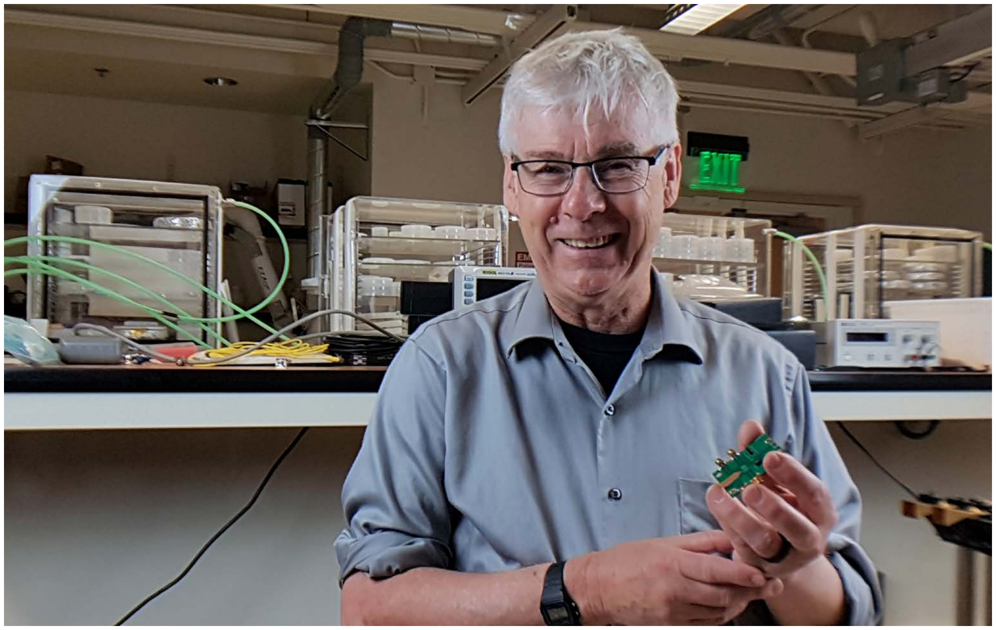
Students will gain hands-on experience inside the UC Santa Barbara NanoFabrication Facility, a state-of-the-art cleanroom with more than $60 million in equipment.

LOCAL PARTNERSHIP FOR SEMICONDUCTOR WORKFORCE TRAINING

UC Santa Barbara and Santa Barbara City College (SBCC) have joined forces to expand a National Science Foundation–funded program that provides critical workforce pathways for micro/nanotechnology and semiconductor manufacturing. The collaboration with NSF and Intel will help meet a demonstrated need in the high-tech-industry space by providing SBCC students and faculty access and training in the university's state-of-the-art NanoFabrication Facility.

"With increasing investment in semiconductor technologies in the U.S., it's really important that we also support a talented and diverse semiconductor workforce," said **Galan Moody,** an associate professor in electrical and computer engineering at UCSB and a co-PI on the proposal. "This partnership does exactly that by providing students with hands-on cleanroom training, certification, and pathways to industry jobs."

"With this new NSF-funded program we will be able to provide a pathway for the local population to enter the semiconductor industry," said UCSB NanoFab scientist **Demis D. John.** "Since 2022, NSF has already enabled SBCC students and others to get their foot in the door with our one-week cleanroom 'bootcamp,' hosted at UCSB. Over the next few years, we'll be able to expand that one-week experience into a full educational program powered by SBCC curriculum and the advanced facilities we have on campus.



UC Santa Barbara professor Mark Rodwell and collaborators are joining forces to develop next-generation semiconductor technologies.

DESIGNING NEW ARCHITECTURE FOR LIGHTNING-FAST CHIPS

Within the next decade, electronics will need to handle incredibly high data rates — up to terabits per second — to drive a range of data-intensive technologies. **Mark Rodwell,** professor in the UC Santa Barbara Electrical and Computer Engineering Department, is joining colleagues at Penn State University as part of a three-year, $2-million National Science Foundation grant to study the future of semiconductors, with an eye to making that possible.

The work will involve developing wireless communications and sensing platforms through advanced chips and packaging. The solution will require large transmitter and receiver arrays above 200 GHz, but implementing them using current semiconductor and packaging technologies presents significant thermal, electromagnetic, and mechanical challenges.

If successful, the work is expected to serve as the basis for next-generation wireless connectivity and sensors to drive the integration of digital, physical, and human worlds, thus enabling innovation across industries. In his part on the project, Rodwell will focus on developing an indium phosphide amplifier design, which is needed to generate sufficient power at such high frequencies. Together, the researchers will work to integrate the three technologies into a single device. Look for more on their progress in the future.

NEWS BRIEFS

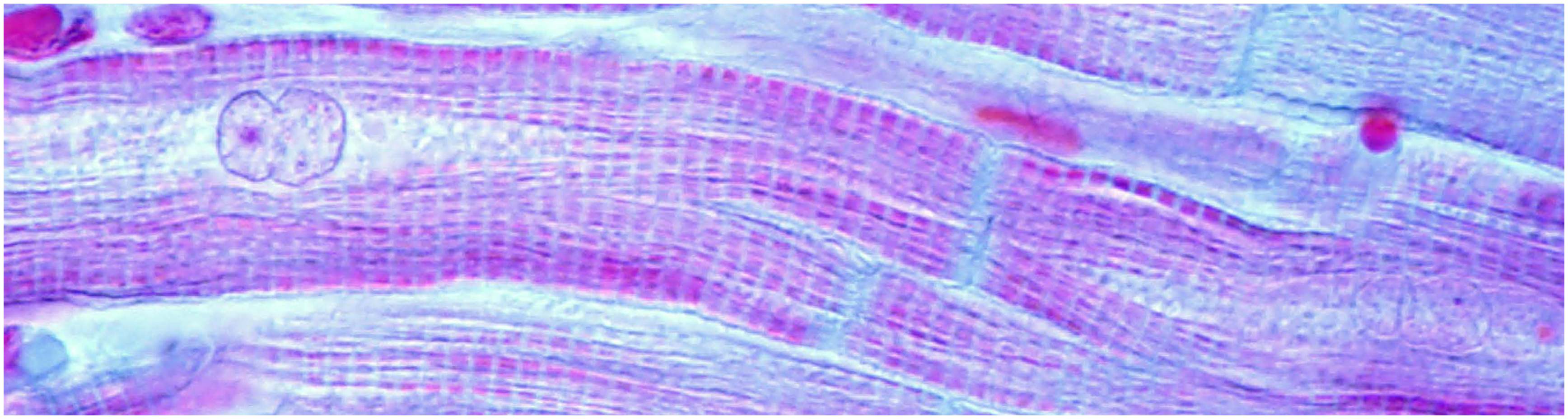
UCSB SCHOLAR EARNS AWARD GIVEN TO ONLY THREE PHD STUDENTS IN THE WORLD

The steady improvement in the performance and versatility of electronic systems is due largely to the scaling down of transistors and their derivatives, allowing for smaller, more powerful, more versatile electronics. These advancements have, however, introduced challenges, particularly in power dissipation, which directly impacts energy efficiency. As a result, electronics engineers, material scientists, and physicists worldwide are striving to address the degradation in energy efficiency of electronics caused by the continuous miniaturization and denser arrangements of components.

Among them is **Arnab Pal,** a recent UC Santa Barbara doctoral graduate in electrical and computer engineering. His doctoral research was recognized with a prestigious PhD Student Fellowship from the Institute of Electrical and Electronics Engineers (IEEE) Electron Devices Society (EDS), annually awarded to a single PhD student from the Americas and to a total of three PhD students worldwide.

Pal, who was advised by electrical and computer engineering professor **Kaustav Banerjee,** focused his doctoral research on exploring the fundamental physics of 2D materials in designing high-performance transistors and neuromorphic electronics exhibiting brain-like energy-efficiency. "As the only student from the Americas and the fourth from the Nanoelectronics Research Lab and UC Santa Barbara to earn this distinction, I am particularly grateful to Professor Banerjee," he said. "His unwavering support, invaluable insights, and inspirational guidance have been instrumental in shaping my research journey. His mentorship not only fueled my passion for discovery, but also empowered me to achieve the results that made this recognition possible."

Arnab Pal (right) and Professor Kaustav Banerjee hoist Pal's fellowship plaque.



A microscopy image showing muscle fibers of heart myocardium.

THE HEARTBEAT GOES ON

Researchers in the lab of UC Santa Barbara bioengineering professor and Bioengineering Department chair, **Beth Pruitt,** have worked with colleagues at Stanford University to develop software to enable high-throughput observations of the contractile dynamics of individual cardiomyocytes (heart cells responsible for heart expansion and contraction) derived from human induced pluripotent stem cells (hiPSC_CMs). The work appeared in the June 26 issue of the journal *Nature Communications*.

The software program, called CONTRAX, which the authors describe as a "versatile, streamlined, open-access pipeline," makes possible "quantitative tracking of the contractile dynamics of thousands of single hiPSC-CM over time," at a much-increased rate of throughput. That, in turn, makes it possible to "reveal converging maturation patterns, quantifiable drug response, and significant deficiencies in hiPSC-CMs that carry disease mutations."

CONTRAX comprises three modules that work in a complementary manner to: provide parameter-based cell identification according to user specifications; perform microscopy video of many cells in a streamlined fashion; and stitch together video images to quantify mechanical function and create a timed trace from the heartbeat in a dish, important in trying to figure out the peak force, as well as contraction and relaxation velocities.

From there, Pruitt says, "We can determine whether there are differences in response to our changing parameters we define for the different experimental treatments."

ELECTRONS IN ACTION: THE MOVIE

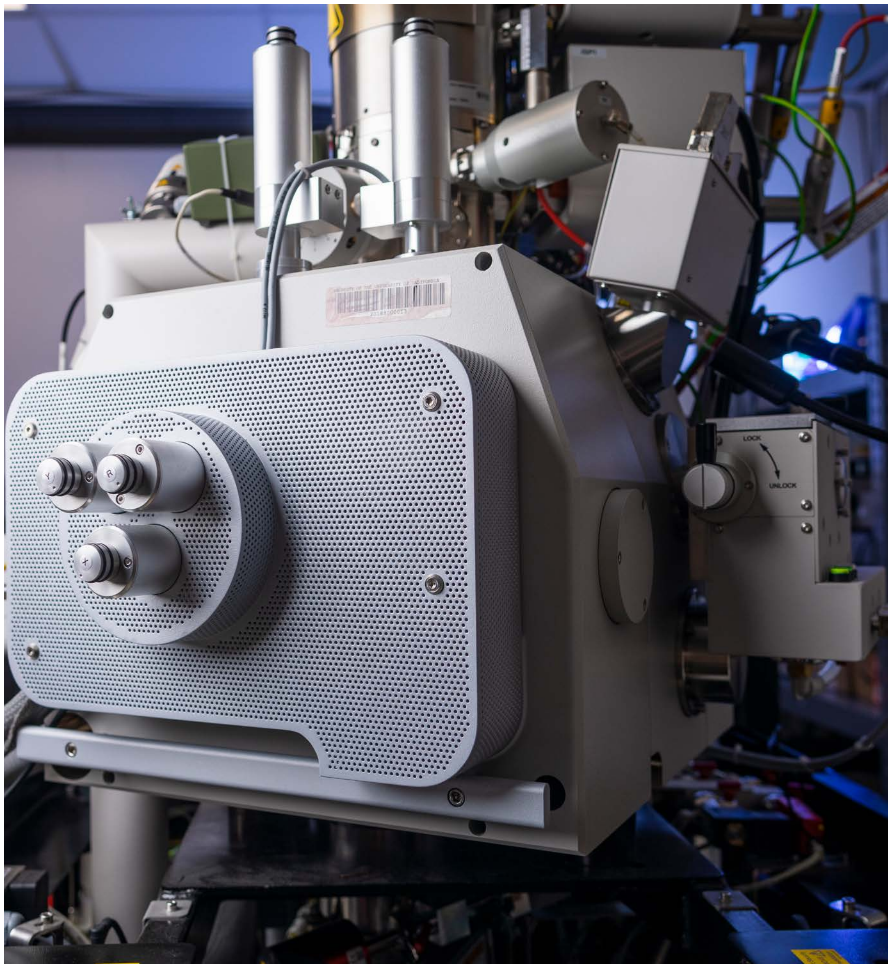
Electrons moving across the interface of different semiconductor materials drive all of our electronic devices, but no one had ever seen that process until **Bolin Liao,** an associate professor in the UC Santa Barbara Mechanical Engineering Department, used scanning ultrafast electron microscopy (SUEM) techniques developed in his lab to make a "movie" of the phenomenon.

Anyone who has used a solar cell has seen the result of *photocarriers* in action. Sunlight hits a semiconductor material, causing excited electrons to move and separate from their opposite-charged "holes," creating a current that can be harnessed to power electronic devices.

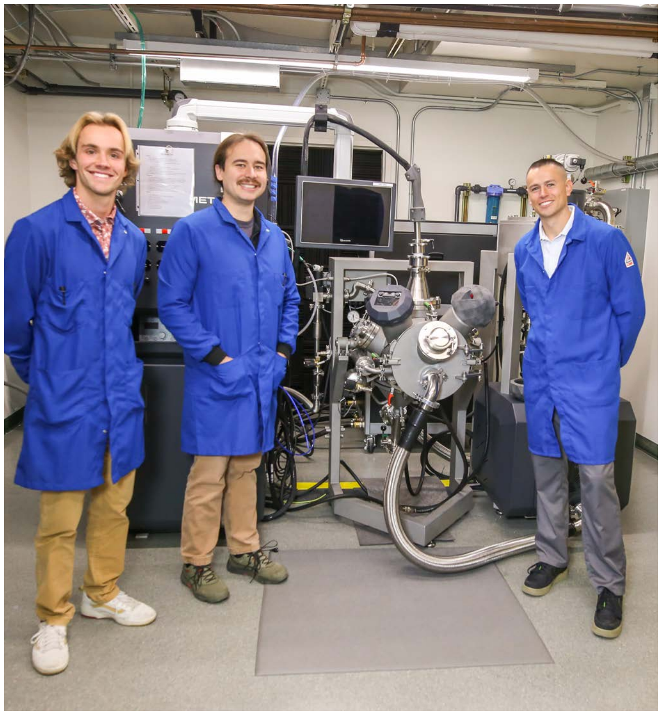
The majority of those photocarriers lose most of their energy within a few picoseconds (trillionths of a second), which is why photovoltaics harvest but a fraction of the carriers' energy in their "hot" state before they cool down and release the excess energy as waste heat. The hot state holds potential related to energy efficiency but also presents challenges within the semiconductor material. It is therefore important to understand how hot carriers behave as they move through semiconductor materials and, in particular, across the interface, or heterojunction, of two different materials.

"If you excite charges in the uniform silicon or germanium regions, the hot carriers move very, very fast, with a very high speed initially because of their high temperature," Liao explained. "But if you excite a charge near the junction, a fraction of the carriers are actually trapped by the junction potential, which slows them down." Such trapped hot charges result in reduced carrier mobility, which can negatively affect the performance of devices that separate and collect hot charges.

"The really exciting thing about this work is that we were able to visualize how the charges, once generated, actually transfer across the junction," Liao said.



The scanning ultrafast electron microscope in the Bolin Liao lab.



Lucas Erich (left) with (from left) second-year materials PhD student Logan Winston and materials assistant professor Daniel Oropeza, will use the ultrasonic atomizer (shown) to produce metal powders for 3D printing as part of his NASA project.

MATERIALS PHD STUDENT RECEIVES HIGHLY ACCLAIMED NASA FELLOWSHIP

Lucas Erich, a second-year materials PhD student at UC Santa Barbara, has received a prestigious NASA Space Technology Graduate Research Opportunities (NSTGRO) Fellowship. The NSTGRO program supports researchers who are pursuing ideas that could contribute to the agency's goal of creating innovative space technologies.

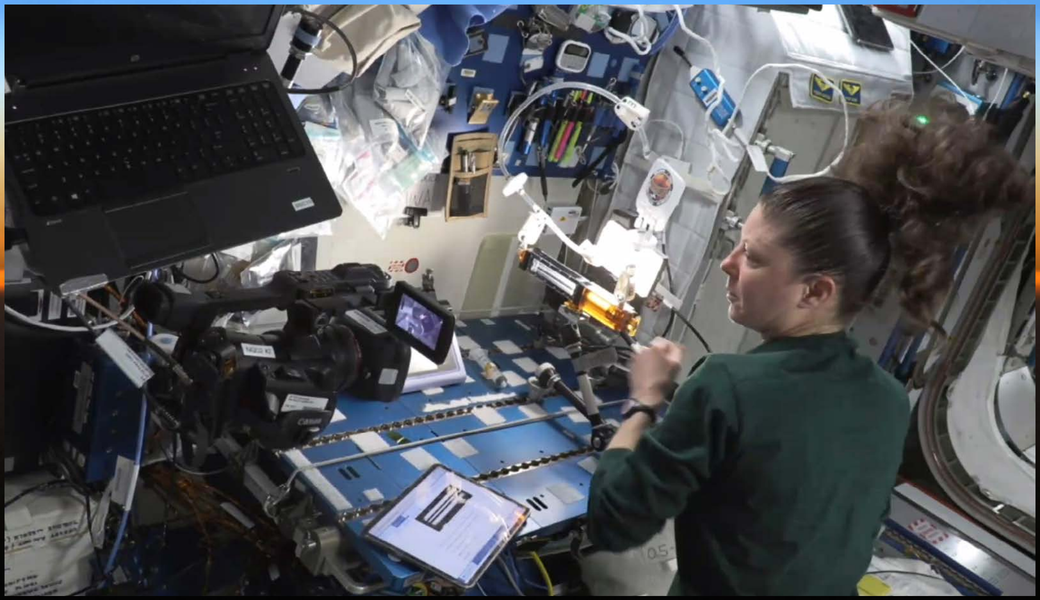
"I am extremely excited and grateful," said Erich. "I've been fascinated by space for a while, so I feel fortunate to receive an opportunity from NASA to merge my passions for powder metallurgy and nuclear propulsion with my interest in space."

As an NSTGRO Fellow, Erich will receive up to $84,000 annually to cover expenses for up to four years, and to pursue innovative, space-technology research at UCSB with his advisor, **Daniel Oropeza,** an assistant professor in UCSB's Materials Department. He will also complete internships every summer at a NASA Center, where he will be matched with a NASA Subject Matter Expert who will serve as his research collaborator and act as a conduit into the larger technical community.

"Lucas is an incredibly intelligent and passionate student," said Oropeza, who also received a NASA Space Technology Research Fellowship as a graduate student at the Massachusetts Institute of Technology in 2017. "This fellowship gives him the chance to work on exactly what he wants to do, complete summer rotations at up to four different NASA Centers, and develop deep connections at NASA. It's a unique, amazing, and well-deserved opportunity."

Erich's research project is related to NASA's pursuit of nuclear-thermal- and nuclear-electric-propulsion rocket-engine systems, technologies that draw energy from nuclear fission instead of traditional chemical reactions.

Studying Respiratory Distress Syndrome in Space



"Whoa" moment: astronaut Tracy Dyson conducts one of the nine experiments Dressaire sent to the ISS.

At night, far from any city, it's possible to spot the lights of the International Space Station (ISS) in its orbit 250 miles above Earth. Earlier this year, **Emilie Dressaire,** an assistant professor in the UC Santa Barbara Mechanical Engineering Department, had a much more intimate look at the 356-foot-long spacecraft, spending time *inside* it via Zoom as she worked with an astronaut to fix a problem with one of nine onboard experiments she had sent to the ISS last November.

"You're at home, and it's the middle of the night, because they work on European time," she recalls of the interaction. "You set your alarm for one AM, turn on Zoom, and start watching the experiment. You're talking to somebody who is in a crowded control room in Colorado, and they're talking to the astronaut in space. In one experiment, fluid was moving too quickly in a tube, so we were trying to fix it. My six-year-old daughter climbed into bed with me, saw this astronaut Tracy Dyson with her hair floating around, and said, 'Whoa.'"

Definitely not your average wilderness ISS sighting.

For Dressaire, the idea to send experiments into space had its roots in the Covid pandemic, when tens of thousands of people suffered — and many died — from respiratory distress syndrome (RDS). Dressaire, an expert in fluid dynamics who had been interested for some time in how fluids interact with gels, saw RDS as an expression of such dynamics.

"That's kind of the lens we looked through when we heard about this respiratory problem," she says. "There were lots of conversations about people, especially adults, who weren't getting a lot of relief from the traditional approach, called surfactant replacement therapy (SRT), in which liquid medication is administered through the trachea."

The treatments for RDS involve introducing a surfactant — a slippery medication that gets distributed throughout the respiratory system and is intended to provide relief by making things move. The liquid medication is the "fluid" in the fluid-gel interaction that interests Dressaire, while the "gel" is the mucus lining of the upper respiratory tract.

> "Many experiments aboard the ISS are fully automated, but Dressaire preferred to work with human beings, who, she says, 'can modify things if something goes wrong.' In fact, as Dressaire recounts the project, the human element recurs again and again."

Emilie Dressaire

Reading up, Hatching a Plan

As Dressaire and her lab group started digging into the literature, it appeared that a lot of work had been done to see if the difference between the efficacy of SRT in infants and adults could be due to the difference in size of the respiratory system.

The researchers read papers in which scientists concluded that the more extensive branching of the adult respiratory system compared to that of an infant played a role in how well surfactant replacement therapy worked. They also looked at the effect of gravity, which is greater in adults, because their lungs are bigger than those of babies, which leads to the surfactant ending up in the bottom of the lungs. They thought, however, that there was more to it, and that gravity probably did not account for the adults' reduced responsiveness to SRT.

The researchers found, too, that some of the surfactant gets stuck in the upper respiratory tract, where it isn't needed. "At that point, nobody had considered the role of mucus," Dressaire explains, "but we thought that maybe the more mucus is present, the more the medication accumulates in the upper respiratory tract. We thought that the mucus was probably affecting how, and how much of, a drug is being delivered to the respiratory system, where it needs to go."

Dressaire wanted to study that phenomenon, but doing so on Earth comes with big challenges. "If you want to look at small-scale effects that are most important deep in the lungs, then you have to make gel-coated channels in the micrometer range," she notes, "and it's really hard for us to make the gel-coated tube and then image the deformation caused by the motion of the fluid. Eventually, we thought, *What if we go into space, where we can have big tubes and not worry about gravity, making it possible to isolate the effects of surface tension?*"

They had a plan. To prepare to execute it, Dressaire hired an implementation partner, BioServe, based at the University of Colorado, Boulder, because, she says, "We had never built an experiment for space, and NASA has a lot of rules to make sure everybody is safe and things work right, and that we can communicate with astronauts and so on." BioServe worked with **Trinh Huynh,** a fourth-year PhD student in Dressaire's lab, to design the experiments and were in the communication loop when astronauts were working on them.

Experiments in Space

Many experiments aboard the ISS are fully automated, but Dressaire preferred to work with human beings, who, she says, "can modify things if something goes wrong." In fact, as Dressaire recounts the project, the human element recurs again and again.

One of the astronauts her team worked with was flight commander Butch Wilmore. He and mission pilot Sunita "Suni" Williams were launched into space June 5 as the first astronauts aboard the Boeing Starliner rocket, which would later return to Earth without them, when, following detection of helium leaks and other problems , it was deemed unsafe for human flight. While unfortunate for the crew, who now are expected to be back on Earth early in 2025, Dressaire says, "It also meant that we had more time with Butch, which was awesome. By the end of our experiments, he was saying, 'Oh, this is fun. If there's one more sample, sign me up.'" (Wilmore got his wish when he was scheduled to run the final experiment on October 17.)

While Dressaire sent nine samples for nine experiments to the ISS last November, with the intention of determining whether the mucus lining could slow down, speed up, or trap some of the liquid medication used in SRT, it wasn't until January that the first of them was run. They had to wait behind a collection of biological experiments that involved living cells or mice that had to be taken care of first. "Our gels are really stable, so we knew we would not be at the top of the pile," Dressaire says.

Each of the nine experiments was slightly different in terms of such variables as the thickness of the gel layer, the viscosity of the liquid, and the size of the tube. "If we were to run those experiments on Earth, we could have used water-based liquids and gel, but because they were going to space and wouldn't be run immediately, everything had to be oil-based so that it wouldn't dry out. We needed an analog for water, and oil was close enough."

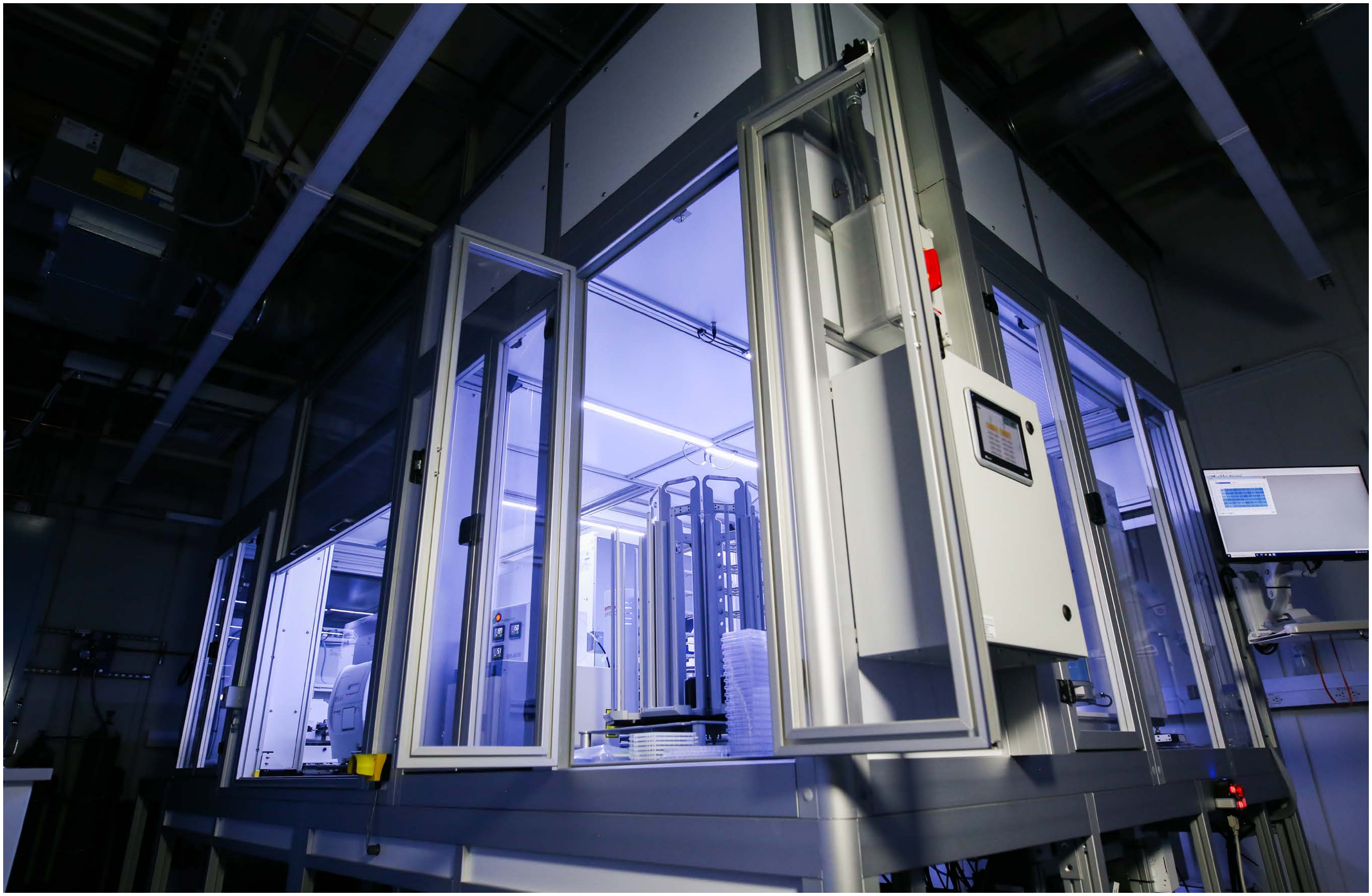
When astronaut Loral O'Hara started conducting the first experiments, things didn't go quite as planned, with some of the oil flowing in the wrong direction. "We had considered that something might go wrong, and it turned out that a solution was kind of built in," Dressaire explains. "We had the astronaut slightly blow up a little bag that was part of the experimental setup, and then just squeeze it to redirect the oil if she saw it going the wrong way again. It worked."

Throughout the interactions around the experiments, Dressaire was impressed with the astronauts' commitment to doing everything they could to get the science right. "They were always asking, 'Can I do something else' or 'Is this where I should be?'"

In July, Dressaire and the team were starting to see results, via video recordings of each experiment that they received from NASA. "We're looking at the plug or the fluid moving faster or slower. Initially we could see that when we have a thick mucus-like layer, more fluid appears to stick to it, which is what we hypothesized."

The next step will be to compare the results from the experiments conducted aboard the ISS with those previously done in the lab to quantify the difference gravity makes and solidify whether or not their hypothesis is true. If, at the end of it all, they do realize that thick mucus makes the treatment less effective, Dressaire notes, "Then maybe they can use a medicine to try to make the mucus thinner and more fluid. Once we've quantified the effect, that's something that other scientists could also put in their numerical simulations to combine different effects and study the transport in patient-specific lung geometries."

Undergraduate student researcher JP Raimondi (left) and fourth-year PhD student Trinh Huynh pause in the Dressaire lab while preparing the nine experiments for their journey to the International Space Station.



State-of-the-art instrumentation, including this automated and customized robotic assembly system, will be the centerpiece of UCSB's NSF ExFAB BioFoundry facility.

UCSB to Lead NSF-Funded Center on Exceptional Microorganisms

A SIX-YEAR, $22-MILLION GRANT INCLUDES PARTNERS UC RIVERSIDE AND CAL POLY POMONA. TOGETHER THEY WILL ESTABLISH A FIRST-OF-ITS-KIND BIOFOUNDRY.

Synthetic biology involves engineering the genetic material of organisms such as viruses, bacteria, plants, and yeast to have new desirable characteristics. The multidisciplinary field employs biological technology (*biotech*) techniques, such as DNA sequencing and genome editing, to modify or engineer new organisms with the aim of addressing challenges in medicine, agriculture, manufacturing, and the environment. For example, scientists are using synthetic biology to develop next-generation vaccines, to engineer organisms that capture carbon, and to create nutrients for crops to minimize the need for industrial fertilizers.

New robotic workflows and technology powered by machine learning have emerged to accelerate and prototype designs of microorganisms for applications in biotechnology. This infrastructure is housed in facilities, called *biofoundries,* most of which are privately owned and operated by pharmaceutical and biotech firms. In an effort to broaden access to state-of-the-art technology, workflows, processes, and knowledge, the National Science Foundation (NSF) created the BioFoundries Program. In August, NSF announced a six-year, $22-million award to UC Santa Barbara to establish the BioFoundry for Extreme and Exceptional Fungi, Archaea and Bacteria (ExFAB), a collaboration led by UCSB, together with UC Riverside (UCR) and Cal Poly Pomona (CPP). The NSF ExFAB BioFoundry establishes the nation’s first biofoundry focused on largely untapped and unexplored microbes that live in extreme and unusual environments.

“We are extremely excited, because this funding provides access to instrumentation and infrastructure that nobody, especially in academia, has had access to before,” says ExFAB director, **Michelle O’Malley,** a professor of chemical engineering and bioengineering at UCSB. “The facility will allow us to unlock the promise of a new generation of synthetic biology focused on extreme and unusual microorganisms isolated from nature.”

“UCSB is a world leader in promoting multidisciplinary, center-level science,” says **Umesh Mishra,** dean of the UCSB College of Engineering and a professor of electrical and computer engineering. “We are extremely proud to host the NSF ExFAB BioFoundry, because it unites several strengths across our campus for the first time — from marine science to chemical engineering and bioengineering. This sizable NSF award raises the profile of our campus and serves as a focus point for continued investment in biotechnology and bioengineering at UCSB.”

Foundry researchers will focus on developing techniques to learn from nature’s more unusual microorganisms, referred to as “extreme,” because they do not conform to standard growth habits and culture conditions in a lab. They may have unusual nutritional requirements or grow at extremely high or low temperatures — or even without oxygen — all of which makes them difficult to study with existing infrastructure.

“These extreme microorganisms defy our current understanding of biology, yet they still host traits and components that we want to harness for biotechnology, such as enzymes that chew up waste, or pathways that could be used to make valuable products and new medicines,” says O’Malley, who is pioneering a new research field by engineering anaerobes to turn plant waste into more sustainable fuels, chemicals, or bio-based materials.

> “The facility will allow us to unlock the promise of a new generation of synthetic biology focused on extreme and unusual microorganisms isolated from nature.”

ExFAB director, Michelle O’Malley

RESEARCH THEMES

By focusing on extreme microbes, ExFAB researchers are pushing the boundaries of biotechnology discovery and innovation within three central research themes: bioremediation, biosynthesis, and using extreme microbes to better understand the rules of life.

Bioremediation refers to the process of using microorganisms to break down hazardous materials and substances into less toxic or nontoxic products. Such ubiquitous microbes, including algae, fungi, and bacteria, are found in nature and thrive in their harsh environments by using the contaminants as a source of food and energy. ExFAB researchers will collect, identify, and categorize microbes that thrive in various extreme environments to unlock their secrets and engineer microorganisms that are able to degrade waste. In one project under the bioremediation pillar, researchers seek to address environmental contamination caused by per- and polyfluoroalkyl substances (PFAS), also known as “forever chemicals,” because they are nearly indestructible and resist breakdown in the environment and in our bodies. Another interdisciplinary team will study marine bacteria that host unique genes enabling them to remove chlorine molecules, via a process called *dehalogenation,* when a remaining amount of an insecticide, such as long-banned DDT, is discovered in soil.

Biosynthesis is a multi-step enzyme-driven process accomplished by the action of microorganisms and by which simple compounds are converted or combined to form more complex products that are valuable to society. Engineers already use biosynthesis to produce fuels, chemicals, medicines, and cosmetics. Examples of biosynthetic-themed research within ExFAB include work by O’Malley’s group to exploit the power of anaerobic gut fungi to secrete enzymes that degrade dry plant matter, as well as a collaboration aimed at harnessing the basidiomycete yeast Rhodotorula as a way to produce chemical precursors.

In pursuing both the biosynthesis and bioremediation themes, the ExFAB team will also uncover new *rules of life,* which the NSF defines as "elucidating the sets of rules that predict an organism's observable characteristics; its phenotype." Inspired by NSF's ten "Big Ideas," extreme and exceptional microbes offer clues into the surprising inner workings of microorganisms. Many of the microbes that will be studied in ExFAB have not been cultured or described previously, and they host highly unusual cellular traits and compartments. For example, ExFAB research led by **Jean-Marie Volland,** an assistant professor of molecular, cellular, and developmental biology (MCDB) at UCSB, is aimed at characterizing new nuclear compartments in exceptionally large sulfur bacteria, which could redefine textbook knowledge of bacteria. Finding and characterizing these surprising structures will help scientists predict how biology works, and also guide them in engineering desirable traits into microorganisms.

Researchers believe that the new high-throughput experimental workflows made possible by ExFAB will change how biology is discovered and engineered in microbes. Gene-to-gene function studies of extreme microbes in both anaerobic and aerobic environments will now be possible. As a result, researchers will be able to capture unique rules of life by performing genome editing from every type of extreme microorganism, ranging from gut fungi and bacteria found deep in the oceans, to large sulfur bacteria and microbes existing in outer space.

"The facility provides an exciting opportunity to open synthetic biology to the vast diversity of microbes that nature provides," explains ExFAB co-director Ian Wheeldon, a chemical environmental engineering professor at UCR and an expert in synthetic biology and engineering non-conventional microbes. "Until now, the focus of synthetic biology has been to develop new approaches to engineering a small number of commonly used microbes. This facility will dramatically broaden this approach by enabling synthetic biology in any microbe."

Research in the areas identified above will be aimed at achieving three major goals for the center that have been established by the interdisciplinary team: to enable basic science discoveries from extreme organisms, to pioneer new strategies using microbes to capture and convert carbon, and to fabricate novel workflows and infrastructure to advance biotechnology and translate it into the real world.

THE GROUNDWORK

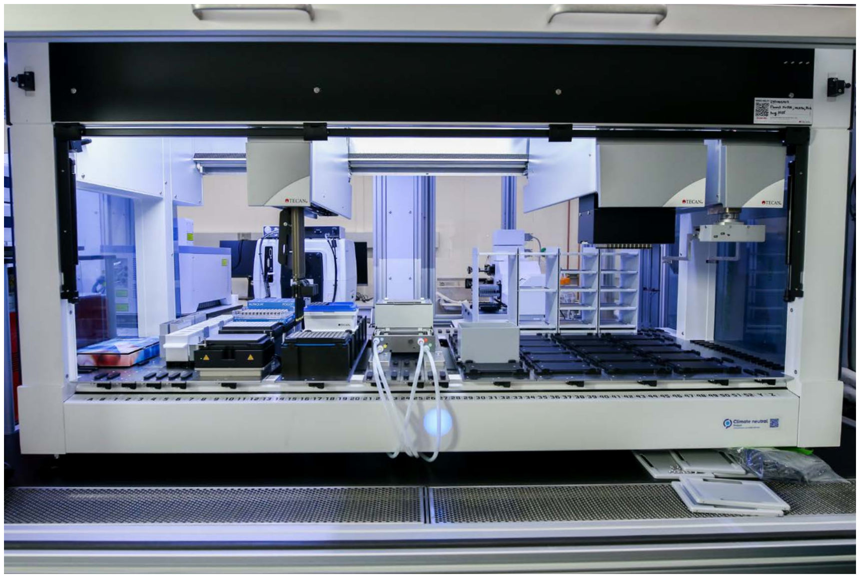
UCSB laid the foundation for the ExFAB months before applying to the NSF's BioFoundries Program when O'Malley received a $9.85-million grant through the Department of Defense's Defense University Research Instrumentation Program (DURIP). The grant, which followed twenty years of sustained funding from the U.S. Army Research Office for the Institute for Collaborative Biotechnologies (ICB), a large interdisciplinary research alliance led by UCSB, allowed the university to purchase a pair of workflow systems comprising robotic assembly and analytical tools to enable automated synthetic biology. The systems are major components of the NSF ExFab BioFoundry, complementing and extending each other for researchers embarking on this frontier of biological investigation.

One customized system was designed to handle mammalian cells — the type of cells that researchers use as platforms for drug discovery or to learn how human cell biology works. A second set allows for rapid screening and engineering of microbial cells and microbial communities.

"Automation eliminates the bottleneck and allows us to develop and analyze incredibly large datasets to find true breakthroughs," says O'Malley.

"This technology provides the kind of experimental firepower of a mid-size biotechnology or pharmaceutical company, but in such a way that we can be flexible in pursuing answers to many different problems," says **Max Wilson,** an assistant professor in UCSB's MCDB Department. "When you have robots that don't sleep and don't make mistakes, you can do extremely precise research at unprecedented scales."

"The exciting new investment from the NSF recognizes UCSB's growing research prominence in the field of synthetic biology and builds upon the recent investment from the Army Research Office," says chemical engineering professor **Brad Chmelka,** co-director of ICB. "This NSF award exponentially expands UCSB's interdisciplinary research culture in biology, materials science, physics, chemistry, and engineering, which will benefit from, and can be expected to catalyze, new innovations and applications in biotechnology."


A view of one of two Tecan Fluent 780 liquid handlers — this one is for the Mammalian system — that will be customized so that the filtration unit can be swapped out for a colony-picking robot, called the Pickolo. O'Malley lab project scientist Elaine Kirschke, who worked on customizing the liquid handler, which is just over seven feet wide and a yard deep, describes it as "a pretty serious piece of automation," complete with its own robotic gripper arm. Incredibly versatile, it can carry out complex liquid-handling tasks, such as magnetic bead separation and vacuum filtration. "It is the closest thing you can get to robotically mimicking human hands at the bench, but it is capable of throughputs that would break the human wrist," she says.

NEW FACILITIES

The transformative nature of the NSF award is especially evident when it comes to infrastructure and access to experimental facilities. All three campuses will house state-of-the-art equipment suites, and research activities will be supported by a team of project scientists, process engineers, and specialists.

Researchers are especially thrilled about the NSF's BioFoundry award, because it will enable them to leverage and expand the already-funded DURIP equipment, most of which has been installed, while the facilities at UCR and CPP make it possible for more researchers and students to access the technology there.

The funding allows CPP to establish its first shared-use facility that is open to outside industry and academics. CPP will lead ExFAB's efforts to identify and perform metagenomic analysis of microbes newly collected from the environment. The space will feature a high-throughput sequencer and additional equipment to support sequencing projects. Prior to such equipment becoming available on the three campuses, faculty had to send their sequences to be analyzed at third-party facilities.

"This is an amazing opportunity for our students, and I can't wait to get started," says ExFAB co-principal investigator Jamie Snyder, an associate professor of biological sciences at CPP who specializes in archaea and archaeal viruses. "Our students will be working on projects directly related to the research mission of ExFAB, and they will know that they are part of something that is unfolding on a grand scale."

UCR will build a new facility dedicated to high-throughput microbial phenotyping. The automated platform, which will feature liquid handlers and robots, will be able to process thousands of aerobic microbes at high-speed, characterizing how well various species grow in different environments, at different temperatures, and on different carbon sources.

"The UCR team brings expertise in engineering microbes, genomics, environmental microbiology, and synthetic biology," explains Wheeldon.

Unpacking the future of biotech: UCSB ExFAB BioFoundry staff and senior participants with a shipment of newly arrived equipment (from left): Oliver Vining, Elaine Kirschke, Jean-Marie Volland, Nathalie Elisabeth, Sherylle Mills Englander, Max Wilson, Michelle O'Malley, Joel Rothman, Niels Volkmann, Carolyn Mills.

> "The unique suite of cutting-edge instrumentation will enable technologies to address some of the nation's biggest challenges, and a workforce that is ready and able to put these innovations to use."

"These skill sets are critical to helping solve important biotechnology challenges, develop new biotechnologies, and discover new biology."

The state-of-the-art instrumentation will be the centerpiece of the UCSB facility, which will also be the first and only one of its kind in the United States. "The signature piece of UCSB's biofoundry will be the environmentally controlled preparation-and-analysis chamber, which can be completely anaerobic," says O'Malley. "The user community from industry and academia will finally have access to an anaerobic biofoundry dedicated to the study of exceptional microbes, one that can carry out genetic engineering and prototyping, and use imaging, sorting, and rapid chemical profiling to link that directly to microbe function."

The anaerobic workflows provided by the foundry will also allow researchers, such as UCSB bioengineering professors **Dorit Hanein** and **Niels Volkman,** to apply cryogenic electron microscopy and cryo-electron tomography to visualize the structure of the microorganisms with nearly atomic resolution. Those additional insights will allow scientists to better understand natural processes, knowledge that can inspire future applications in such areas as renewable energy and environmental remediation.

The California NanoSystems Institute (CNSI) at UCSB, which was established by the Governor's Office in 2002, will manage and coordinate ExFAB operations at all three campuses. CNSI is currently home to two $20-million-plus NSF-funded centers — the Quantum Foundry (see article on page 18) and the BioPACIFIC MIP (dedicated to scalable production of bio-derived building blocks and polymers), as well as the campus's only deep-computing center and seven specialized shared-instrumentation facilities dedicated to fields ranging from quantum to biotech.

"CNSI is proud to be the home of ExFAB and to provide foundational support that will increase the impact of ExFAB innovations," says CNSI co-director **Craig Hawker,** a professor of materials and of chemistry and biochemistry. "The unique suite of cutting-edge instrumentation will enable technologies to address some of the nation's biggest challenges, and a workforce that is ready and able to put these innovations to use."

External users from industry and academia can access the ExFAB BioFoundry in two ways: by directly shipping samples for complete handling by staff, and via on-site training and co-use of equipment with staff. Leadership aims to complete at least one hundred total user projects over the first six years of operation, estimating that more than half will be external projects.

TRAINING A DIVERSE WORKFORCE

The ExFAB will establish an educational program to train and attract the future biotechnology workforce by establishing a solid partnership between two UC campuses and a third university that is part of the California State University (CSU) System. All three are Hispanic-Serving Institutions (HSI) and Asian American Native American Pacific Islander Serving Institutions (AANAPISI). By creating shared-use facilities on three campuses, ExFAB will offer unprecedented access to cutting-edge instrumentation to members of industry and academia, including students and faculty from the 23 CSU campuses.

ExFAB will recruit CSU master's students to participate in a ten-week research internship at UCSB or UCR, during which they will receive professional development and work in a scientific community at an R1 (research-intensive) university. ExFAB will also offer one-quarter fellowships to PhD students at UCSB and UCR and host a summer school to train and recruit new users.

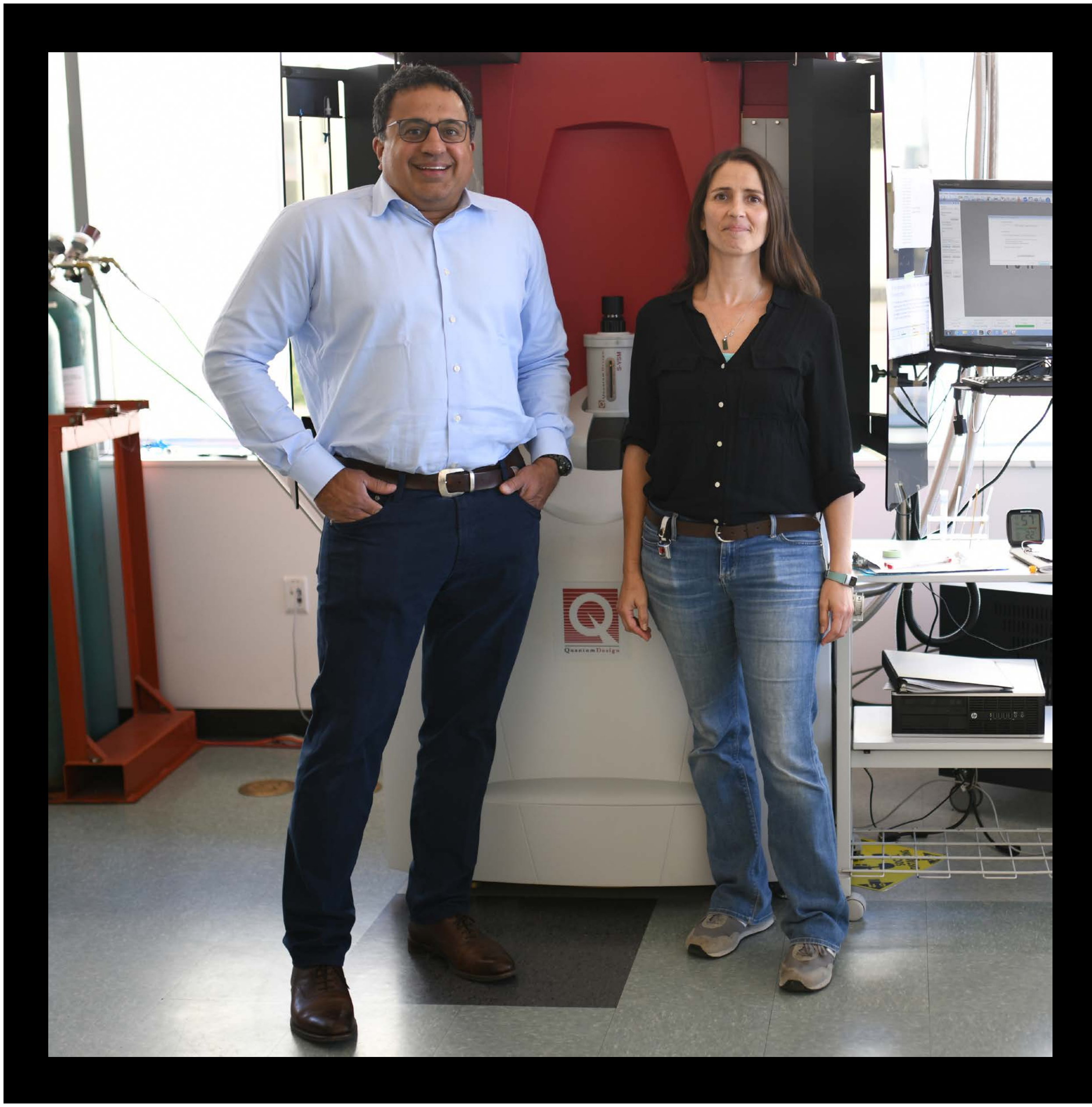
"Many CSU students want to enter industry or PhD programs but lack experience at an R1 university setting," says Snyder. "This opportunity will allow them to be trained on automated equipment they will likely find in industry, and to interact with PhD students, postdocs, lab technicians, and senior scientists in R1 labs. The facility will enable us to create more pathways into the biotechnology workforce for people who, currently, may not feel represented in the field."

Between the unique rapid-throughput equipment that can leverage machine learning to predict outcomes and perform hundreds of experiments in the time humans could do only a few, the singular focus on radical organisms, the interdisciplinary reach and multi-university involvement, and the opportunity to bring a wide range of students into this exciting area of research, the NSF ExFAB BioFoundry is set to dramatically expand the frontiers of biological understanding.

More information about the ExFAB BioFoundry can be found at exfab.org.

Faculty Q&A

A Conversation with Ram Seshadri



Ram Seshadri and Amanda Strom, technical director of the TEMPO Laboratory, one of eight staffed shared experimental facilities managed by or partnered with the MRL.

Ask **Ram Seshadri** about the UC Santa Barbara Materials Research Lab (MRL), one of the longest-running National Science Foundation (NSF) Materials Research and Science and Engineering Centers (MRSECs) in the nation, and he will talk first about the people involved with it. The MRL director and professor of materials and chemistry will mention the students who are educated there — from UCSB, from high schools in summer, and through exchange programs with universities that have no comparable facility. He'll talk about the faculty, whose research drives the enterprise. And he'll talk especially about the staff who make it all work and whom he considers close friends. "The people do not work for the enterprise," he says. "The people *are* the enterprise."

In his eleven years as MRL director, Seshadri has been involved in leading two rounds of MRSEC proposals, after having served on a third as co-PI when fellow materials and chemistry professor **Craig Hawker** was director. The current associate director (and associate professor of materials), **Christopher Bates,** describes Seshadri as, "an extremely good teacher, demonstrating how to stay proactive in managing a large research team and outreach program by balancing new events and continuously evolving MRL programs to meet the changing needs of the large MRSEC community."

We spoke with Seshadri in August, about a year after the lab received its seventh consecutive round of multi-year NSF funding since being established in 1993.

Convergence: *What do you see as the main focus areas for the MRL at this period of its history?*

Ram Seshadri: The MRL has always had three foundational legs, the first being education and outreach, and we are really happy about where we are with that. As just two examples, the University of California has an NSF grant we participate in called the Louis Stokes Alliance for Minority Participation, which was just renewed for five years, and our PREM (Partnership for Research and Education in Materials) with Jackson State University, in Mississippi, just received its fourth five-year cycle of NSF funding, continuing that long-standing relationship, which includes student exchanges. We have a successful undergraduate summer research program, and many other educational elements.

Another leg of the MRL is our emphasis on facilities. We serve the whole campus — actually, the whole world — by offering everyone access to our facilities, so we always find new challenges there, one of which, currently, is providing enough GPU servers to help our colleagues who work in artificial intelligence [AI] and rely on the affiliated Center for Scientific Computing.

The third leg, of course, is research, without which nothing else would exist. Our current round of funding supports two new interdisciplinary research groups [IRGs). Researchers in IRG One are working on the chemistry of polymers, to improve their recyclability, reusability, and processability. UCSB has been a leader in developing plastics for electronics, but those polymers are extremely hard to process. So, it turns out that determining how to reuse a polyethylene plastic bag and how to better process a conducting polymer are linked.

IRG Two is more about fundamental science, being focused on learning from biology how matter, particularly *active matter* [matter that uses energy to move on its own], is assembled and processed. A famous problem in materials science is how a bunch of M&Ms will pack in a jar. Now, imagine that the M&Ms are moving, like a school of fish. It turns out that these things assemble, pack, and coalesce in ways that obey some very deep fundamental physical laws. Learning from nature and from model systems helps us better understand a range of phenomena in cells, and in structures at larger length scales.

We also award annual seed grants, two of which typically go to early-career faculty. For example, materials assistant professor **Ananya Balakrishna** is using a seed grant to understand how certain crystals change into other kinds of crystals when they are hit with light. How does this happen on a macroscopic scale? How quickly does a change take place? Does it start from one end and go to the other, or does it start in the middle and go out? These are questions about physical phenomena that, again, have important implications in a whole range of applications.

C: *You recently became Associate Dean for Research in the COE. Can you tell us what that position involves?*

RS: Over the past few years, I have found myself willy-nilly advising a lot of groups on how to conduct team research and go after team funding. I was doing this informally but realized that it would be nice to do on a more formal footing so that I could try to point out, particularly to rising early-career faculty, that if they work in teams, they can access far more research dollars than they can in the single-PI mode. In recent years, I've also started pointing out that working in teams is far less lonely, compared to working on one's own as a single PI with a transient population of students and postdocs. Having colleagues gives you people to lean on, to talk to, to share with, to think with, and to secure funds with. Working together is a key strength at UCSB. I have seen places that lack this team spirit, where researchers work in individual silos, and it seems a far less satisfying arrangement.

C: *Are there instruments in the MRL that are more important than others?*

RS: There is a hierarchy of instrumentation that you need for material characterization. Some instruments don't cost very much, and some cost a lot, and if you don't use the inexpensive instruments, it's pointless to use the expensive ones, because no material is ever characterized by one technique. It's a symphony. You need the solo violinist with the Stradivarius, but you also need the triangle, otherwise the symphony doesn't work. (Of course, if you're talking about the *1812 Overture*, you also need the cannon!)

> **“It has always been clear to me that we are only as good as the people we have.”**

C: *How do you allot time to all of the various researchers who want to use MRL facilities?*

RS: Anyone can sign up. It's first come, first served, and everyone has equal access. If someone needs more time than was allotted to them or is at a critical point in their research and absolutely must use a certain instrument now, then it's basically a lot of horse-trading.

C: *What is perhaps the biggest challenge that the MRL faces?*

RS: NSF budgets that have been flat over the years, while the costs of students and postdocs and other things have shot up. Not surprisingly, a big priority for me is to ensure that our facilities keep getting renewed and reinvigorated in the face of that.

C: *You have said, "The* people are *the enterprise." Can you elaborate?*

RS: It has always been clear to me that we are only as good as the people we have. It isn't easy to find good facility staff, and we've been fortunate to have exceptional staff running our instruments. We have ten facility staff members, led by four *technical directors*, and making sure they are happy and not overworked so that we can continue this strong tradition is always foremost in our thinking about the health of the MRL. The longevity among our staff is a matter of great pride to me, and we think it reflects the climate that we strive to accomplish and the quality of leadership throughout the MRL.

We like to tell graduate students we are recruiting that the quality of our facility staff will probably accelerate their PhD by a year. We mean it, and our students know this, which is why at the end of their PhD defenses, they often spend time thanking people who run the facilities. There is not a moment when I'm not grateful for them, personally as well as professionally.

C: *Can you talk a bit about the relationship of the MRL to the Quantum Foundry (of which you are part) and the role the MRL plays in Quantum Foundry research? (See article on page 18.)*

RS: The Foundry does not actually have a general shared facility. They have specialized instrumentation, but they use MRL facilities, of course, as well as those in the Center for Scientific Computing. A main thrust of the Foundry is discovering materials that lend themselves to topological quantum computation, specific classes of materials that have been proposed as model platforms for hosting qubits. We don't know if they'll work, and devices have not yet been made. The field is somewhat futuristic at this point. But, as with so many other things, we're finding that as you study these materials, you learn a lot of very cool physics. Studies of fundamental physics have never gone to waste, and they can lead to very surprising outcomes that nobody anticipates.

C: *What are one or more of your own personality traits that you bring to your role as MRL director?*

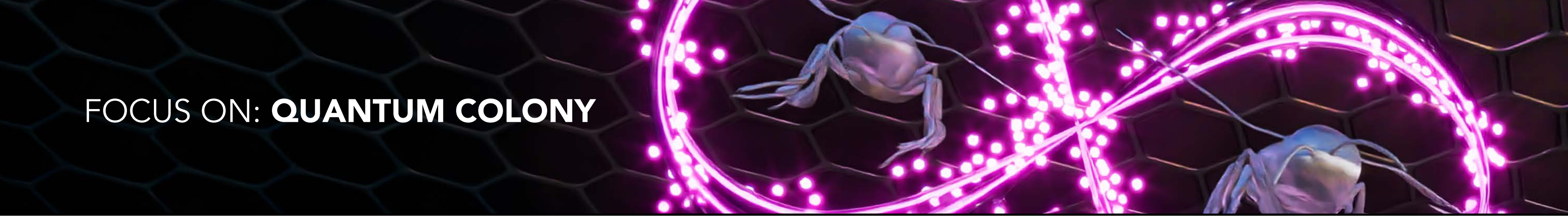
RS: When I came to UCSB, then Materials Department chair, **Fred Lange,** said something interesting to me about the MRL director at the time, **Tony [Sir Anthony] Cheetham.** He said, "Tony is a strange person; he'll help you even if he doesn't like you." And that has stuck with me as a trait of good leadership, that you want to see people doing well, and that you help people and are able to separate your ability to help them from whether you like them or not. That's what I strive for; it's up to other people to judge whether I've accomplished this well.

The other quality I think has helped me is that I love science. I'm very curious, and I'm not transactional about acquiring knowledge. I don't say, "Oh, this particular polymer chemistry has nothing to do with my research, so I won't find out about it." Whatever it is, I'm interested.

Last, I don't want to belabor this point, but good leaders should attend to the people in the enterprise, because it's always about the people. It's never about instrumentation. When I show students the great facilities we have in the MRL, for example, our NMR [nuclear magnetic resonance] facilities and our X-ray diffraction facility, I don't tell them that these are the best instruments in the world; I tell them that they are run by the best technical directors in the world, the best staff. I think that's a much more powerful message.

FOCUS ON: **QUANTUM COLONY**

In 2019, UC Santa Barbara took a major step in solidifying its standing as a hotspot of quantum research, securing a six-year, $25-million National Science Foundation (NSF) grant to establish the nation's first NSF Quantum Foundry (QF), with UCSB physics professor **Ania Jayich** and materials professor **Stephen Wilson** as co-directors. The foundry is aligned along three "pillars" of emphasis: developing materials that host unprecedented quantum coherence, training the next-generation quantum workforce, and partnering with industry to accelerate the development of quantum technologies. With leadership now moving toward its renewal period, we offer this glimpse into the thriving Quantum Foundry.



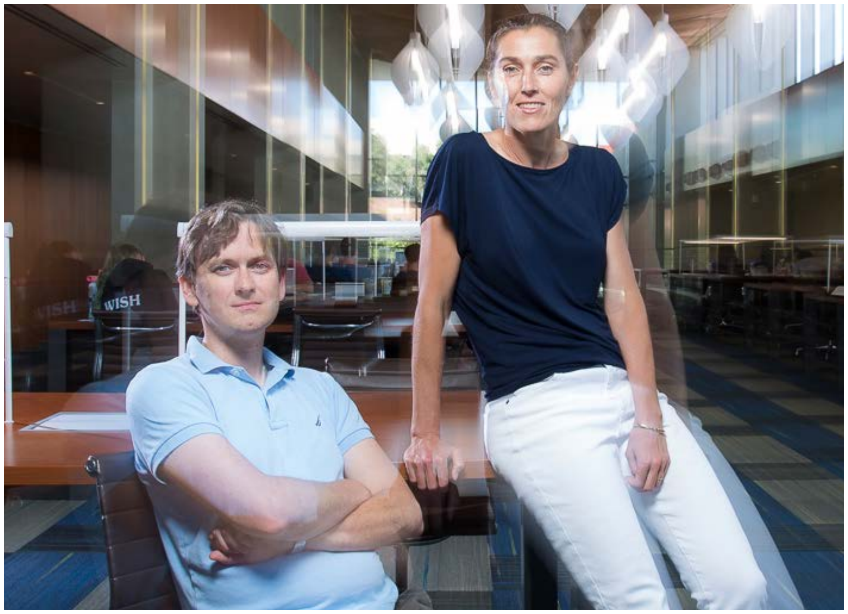
A Counterintuitive Road to….

The phrase q*uantum mechanics* can make a non-expert's eyes glaze over, so quantum sensing, quantum encryption — quantum *anything* — can be a lot to grasp. Take quantum computing, perhaps the Holy Grail of the quantum promise. Most of us can relate to a *bit* in a classical computer being either on or off — a one or a zero in binary-code language. We get that. But simultaneously one *and* zero is decidedly less intuitive. That is the realm of the quantum bit, or *qubit,* the abilities of which makes quantum computing such a powerful promise.

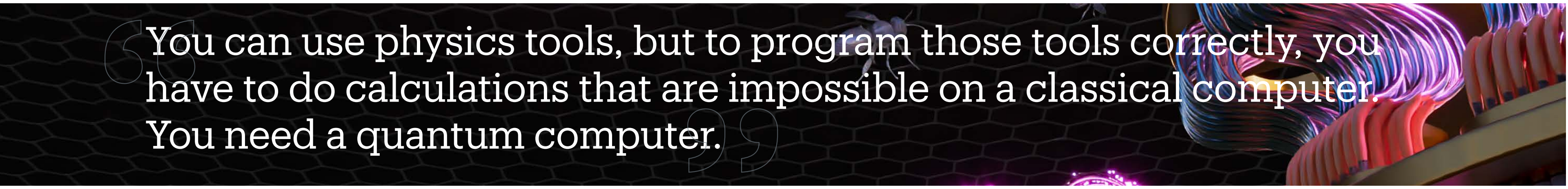
Qubits do a job similar to that of normal bits, but with a distinct quantum advantage. Qubits, and all other harnessed quantum functions, depend especially on two important and closely related quantum phenomena — *superposition* and *entanglement.*

In considering *superposition,* it can be helpful to imagine a tossed coin that is flipping in the air, not yet a "head" or a "tail," but in a state where both are equally likely. In the same way, a superpositioned quantum particle, whether a single photon or a subatomic entity, such as an electron — has the same counterintuitive ability to be two different possibilities *at once.*

Entanglement refers to the relationship between two quantum objects such that measuring the property of one of them, even if it's on the other side of the universe from its entangled partner, impacts the state of the other object *instantaneously,* what Einstein referred to as "spooky action at a distance."



Materials professor Stephen Wilson (left) and physics professor Ania Jayich have served as co-directors of the Quantum Foundry during its first five highly active years.



> "You can use physics tools, but to program those tools correctly, you have to do calculations that are impossible on a classical computer. You need a quantum computer."

Generating and controlling such states and their associated behavior add up to a grand challenge, which, if solved, holds the promise of enabling a wide range of new technologies. A quantum computer might make it possible to solve certain problems that are so complex as to be, currently, unsolvable, because doing so requires more computing power than the largest supercomputer can generate in many lifetimes.

UCSB Professor **Michel Devoret,** a world-renowned quantum physicist who recently arrived from Yale University to join the UCSB Physics Department and serve as chief scientist on the Google quantum computer project in UCSB-adjacent Goleta, recalls that the phrase *quantum computing* was coined by Richard Feynman to indicate that quantum mechanics operate in a space of such exponential vastness that computing their properies would itself require a quantum computer.

"For instance, when it comes to understanding what's involved in a molecule," Devoret says, "you can use a certain number of physics tools, but in order to program those tools correctly, you have to do some calculations that are impossible on a classical computer. You need a quantum computer even to figure out the right experiments to probe a molecule."

Clearny, there remain vast domains of unresolved quantum knowledge, knowledge that, without the help of marshaled quantum forces and effects, might remain foreever beyond human understanding. No wonder, then, that a quantum computer has caught the attention of scientists around the world.

That potential of a quantum computer has everything to do with how differently it operates compared to a classical computer. The latter solves a problem by sending out strings of binary-code queries on a linear exploration of all the possible paths to an answer. When the query encounters a dead end, it reverses course, then starts a new search from the beginning, wasting time and energy. A quantum computer, by contrast, explores every pathway option *simultaneously,* working with nearly incomprehensible speed and efficiency to sort through that vast data domain.

Siting the Foundry: Why UCSB Made Sense

It is not especially surprising that NSF selected UCSB as the site of the first Quantum Foundry, a decision that reflected some key UCSB strengths: strong Materials and Physics Departments and one of the longest continually funded (since 1993) NSF Materials Research Science and Engineering (MRSEC) laboratories (aka the Materials Research Lab), the brilliant scholars and experimentalists at the Kavli Institute for Theoretical Physics (KITP), one of the best nanofabrication facilities (cleanrooms) in the nation, a world-class suite of shared instrumentation, and, perhaps most important, a decades-old reputation for collegial collaboration across disciplines.

"On the logistical side, we have the groundwork laid at UCSB," says Jayich, whose own research is focused on leveraging the anomalous quantum properties that arise from defects in diamonds to produce quantum-enabled sensors. "Quantum science necessitates a collaborative approach, because

there are so many challenges to realizing useful quantum technologies: you have to make the materials that can protect quantum coherence, develop the algorithms, and design and make nanoscale devices that are clean enough and precise enough to to make it possible to manipulate, control, and preserve quantum coherence."

"The cleanroom is hugely enabling," says Wilson, whose own materials work is centered on investigating topological superconductors and other materials relevant to quantum information science. "Our people use the cleanroom. Industry people use it. As a result, we have lots of industry spin-offs. I think it's one of the reasons why we were so prepared to lead a lot of what's happening in quantum research."

Adds Jayich, "The ecosystem UCSB has in terms of its collaborative nature, its welcomeness to industry, its facilities, the expertise in the KITP, have made it a breeding ground for a lot of seminal work in quantum science and technology. It's a place where people in industry want to come."

Both Google and Microsoft have quantum-computer labs in Goleta, while Microsoft also has space in Elings Hall at UCSB, and has had a presence on campus since 2005. "That's an obvious testament to UCSB's willingness to work with industry partners," Jayich says.

The Microsoft quantum effort is distributed among locations in Redmond, Washington; Europe, and UCSB/Goleta, with their local presence, both on campus and in their local headquarters, being responsible primarily for device design and data analysis, once results come in following fabrication in Europe and testing in Redmond, and quantum error correction.

"It's helpful to be part of a research ecosystem where there's a lot of talent," says Chetan Nayak, Principal Research Manager of Microsoft Station Q. "You have so many people on site here and visitors, PhD students, and postdocs coming through CNSI, the MRL, and KITP. Especially in the early days, it was extremely valuable to be in that environment."

Currently, the Foundry has nearly thirty industry partners, including Microsoft, Google, CISCO, GE, Northrop Grumman, Hewlett-Packard, HRL, Honeywell, Intel, and many more. UCSB's strong materials and device-fabrication capabilities, Wilson says, "have allowed us to become a magnet for companies, because we have the ability to innovate around new materials and devices for quantum information."

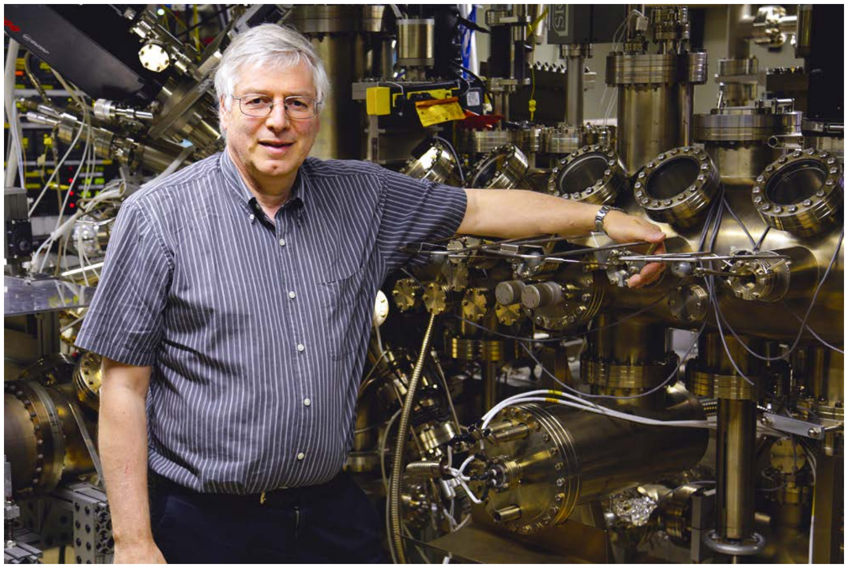
Wilson identifies a prolonged effort to "re-engage with industry" — one of the foundry's three pillars, the other two being to develop quantum materials and to educate the quantum workforce — as an important near-term quantum strategy. "On the fundamental-research front, academia has been increasingly decoupled from industry over the past several decades," he explains. "When I was graduating with my PhD, I didn't give a thought to going into industry, because the jobs just didn't exist. Now, however, industry and academic interests in quantum are somewhat aligned, so we're trying to re-couple and jointly push the field forward. A lot of companies — and not only Google and Microsoft, but other large companies like IBM, which has a huge quantum-computing effort, are returning to more basic research, and they're hiring theoretical physicists they wouldn't have hired twenty years ago. Students are coming into grad school saying, 'That's my goal in life; I want to work in the quantum industry.'

UCSB is educating students like those, who can contribute to what Wilson describes as "the kind of quantum-literate, quantum-motivated workforce that will allow people to translate some of these ideas to near-term applications or start building medium-term platforms or devices for quantum-based information. We don't yet have the answers for quantum technologies, so it's not as if we can take some existing idea or demonstration and improve it,"

Jayich adds. "Industry has become willing to take on that challenge, which is pretty exciting — and different. We've trained a lot of students who have gone on to a lot of high-profile positions in the quantum industry, and the foundry has strong industrial connections. Those industrial partners are interested. They're working with us. They collaborate with us."

Quantum 2.0

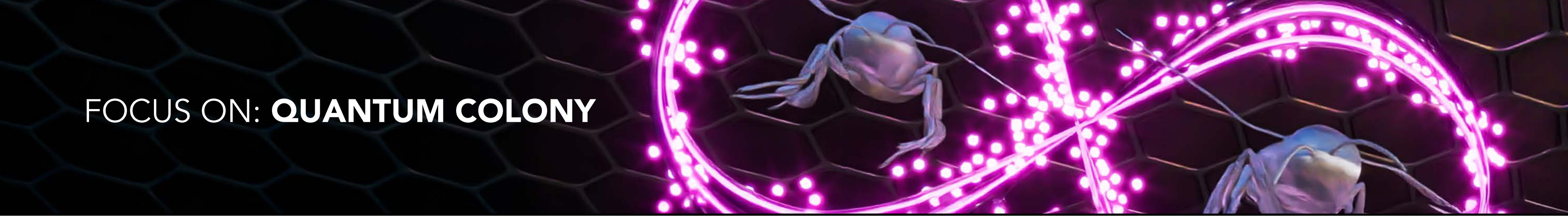
Current research toward new quantum applications is part of what some refer to as the second quantum revolution, or Quantum 2.0, which is still in its early stages and is, for now, focused primarily on fundamental science in both the physics and materials-science realms. In the long term, Wilson sees foundries becoming more oriented to making devices from the materials generated on the existing footprint, but for now, there is a lot to unravel. "Quantum is still a very counterintuitive phenomenon that's not very well understood in many realms, and how to best apply it is even less well understood," Wilson says.



Distinguished professor of Electrical and Computer Engineering and Materials Chris Palmstrøm in his lab, where he works to produce promising new quantum materials.

"The first quantum revolution yielded mostly classical technology — the transistor, the laser, atomic clocks — which gave us computers, LEDs, GPS navigation, and many other life-changing applications," says **Galan Moody,** associate professor in UCSB's Electrical and Computer Engineering Department, who has several quantum projects underway. "Those technologies require quantum mechanics to understand and predict their performance, but now we're in the second quantum revolution, and researchers are leveraging the full power of quantum mechanics — things like entanglement, superposition, and precisely controlling individual quantum objects — to achieve things that aren't possible with classical technologies."

How those efforts will play out, in terms of either the scale of any effects quantum-enabled technologies will have or which areas of endeavor will benefit most from them, UCSB distinguished professor of Electrical and Computer Engineering and Materials **Chris Palmstrøm,** whose current research is focused largely on identifying promising quantum materials, does not claim



to know. As someone with decades of experience developing new materials, sometimes with an application in mind, sometimes to see where something new might lead, he currently has his focus on locating materials that might contain elusive Majorana fermions.

"In the past, one was used to the vacuum tube, and then the transistor came out, and what was the drive for that?" Palmstrom asks rhetorically, noting that while vacuum tubes were, in fact, large, bulky, unreliable, and power hungry. "All people really wanted was a plug-in replacement. No one thought of an integrated circuit, which came incrementally, but that's what science does, and I would say that that is what we're doing now as we aim for the quantum computer, quantum encryption, and all of these other quantum technologies: we're moving incrementally toward recognized goals, but there may also be something we haven't thought of that this will enable us to do."

"As you study these materials, you learn a lot of very interesing physics, none of which will go to waste," says MRL director and professor of materials and chemistry, **Ram Seshadri.** (See Q&A with him on page 16.) Studies of fundamental physics have never gone to waste, and the outcomes of such research can be very surprising."

In considering the uncertainty of the quantum future, UCSB materials professor **Susanne Stemmer** refers to a comment by the late UCSB physics professor, Nobel Laureate, and father of the heterostructure, **Herb Kroemer,** who famously said, "Ultimately, progress in applications is not deterministic, but opportunistic, exploiting for new applications whatever new science and technology happen to be coming along." Adds Stemmer, "The types of questions being raised by these quantum materials will lead to new scientific insights, which will enable new applications to be created."

In her lab, Stemmer pursues such insights by using thin films to investigate possible superconducting materials — i.e., those in which electrical resistance disappears and magnetic fields are expelled from the materials such that they conduct electrons with one-hundred-percent efficiency. "Many of the kinds of characterizations you would want to do with these materials require thin films to identify what type of superconductors they are, because some of them exist only at interfaces between one film and another, and that's our area of specialization in my lab."

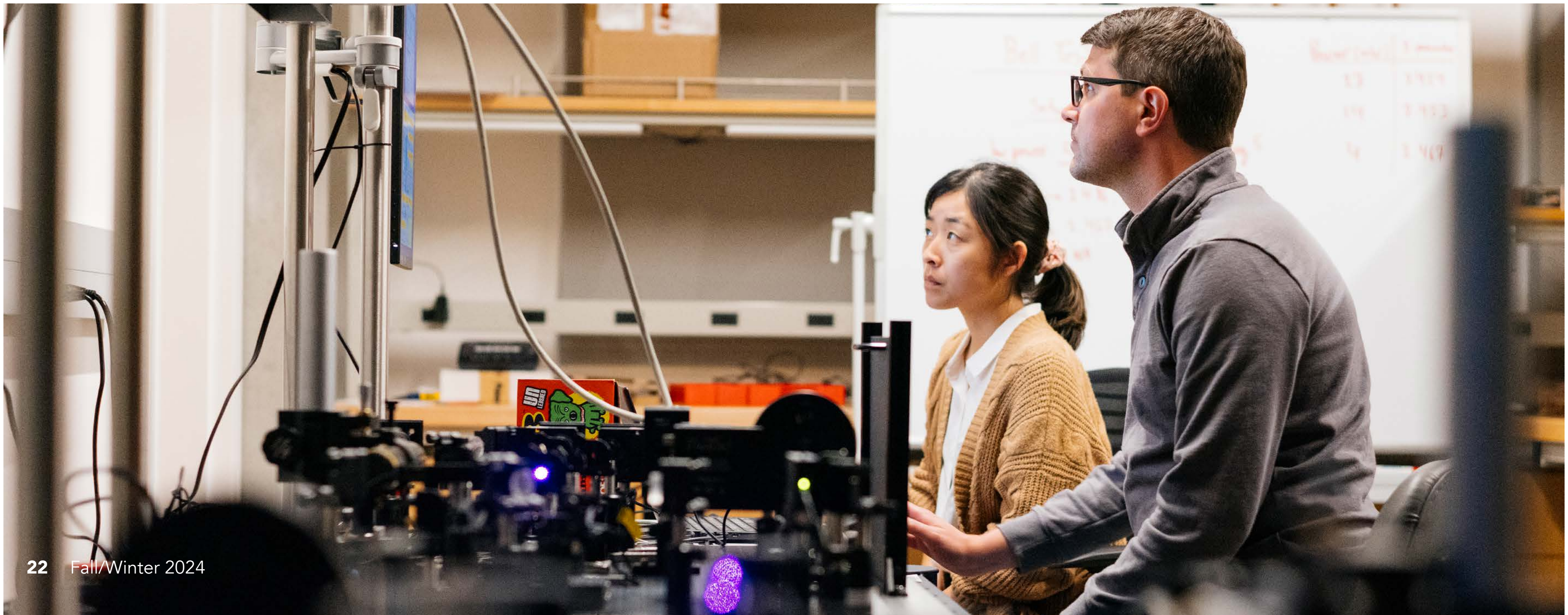
> "The thing about quantum mechanics is that it approaches the smallest physical length scales and energy scales, and those systems are extremely sensitive to the smallest perturbation."

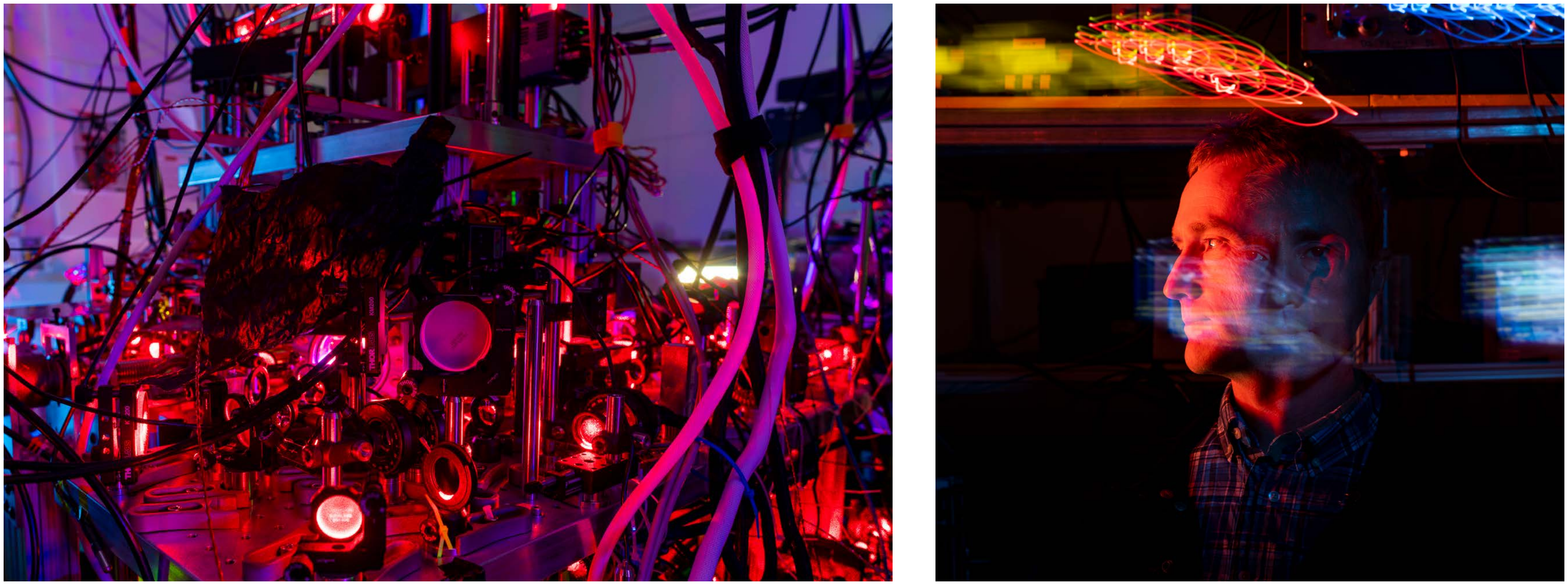
One major step on the quantum-computer path occurred in 2019, when Google's 53-bit Sycamore processor — built in Google's Goleta lab in a project led by UCSB physics professor (now emeritus) **John Martinis** — performed a complex calculation with a known outcome in record time, thus demonstrating so-called *quantum supremacy.*

While the margin of that supremacy has been hotly debated, the experiment served as a measure of how far quantum research had advanced. "The first qubit was put into action about twenty-five years ago," Moody said during a talk in 2023. "Now we have tens to hundreds of qubits and are gaining on a thousand."

Progress to be sure, but most experts believe that a quantum computer built on the Google platform would require something on the order of a million cryocooled qubits and would occupy a space similar to a cloud server farm in order to provide adequate error correction.

"Basically, the whole thing about quantum mechanics is that it is really approaching the smallest physical length scales and energy scales," Jayich notes, "and those systems [including all of those cryocooled qubits] are extremely sensitive to the smallest perturbation."


In the Quantum Photonics Lab in Henley Hall, associate professor Galan Moody (right) and his students, including third-year PhD student Amalu Shimamura (left), design, fabricate, and test integrated quantum photonic devices and quantum materials that are relevant for quantum information technologies.



Physicist David Weld (right) is intimately familiar with the quantum world. He uses the elaborate light table in his lab (left) to gradually slow and chill atoms to a temperarature ten-billionths of a degree above absolute zero. Once the atoms are in that well-understood state, he can hit them with various forces to elicit less-understood quantum phenomena.

The Materials-Physics Interface

Palmstrøm worked with Martinis in the early years of the research that led up to Google's Sycamore experiment, and more recently, has collaborated with researchers in Microsoft's Q Lab. Their approach relies on engineering a single material able to provide adequate stability, while Google relies on qubits that are powerful but have a high error rate, necessitating most of the many qubits thought to be needed to provide error correction.

Such research requires the kind of collaborative interdisciplinary research that is *the* foundation upon which UCSB has built its reputation, especially in STEM fields. "Our Materials Department is a little unconventional and very forward looking," Stemmer says. "UCSB is known for having effective synergies between different departments. It worked very well for optoelectronics, and it is working very nicely right now for quantum materials."

That exchange across disciplines is evident throughout foundry research. "As a physicist, I understand the quantum-information-science aspects really well, but being able to work with my materials colleagues, and having material students in the lab now, I can actually think about the materials science behind how to get there," Jayich observes. "That's a pretty unique combination that not a lot of places have."

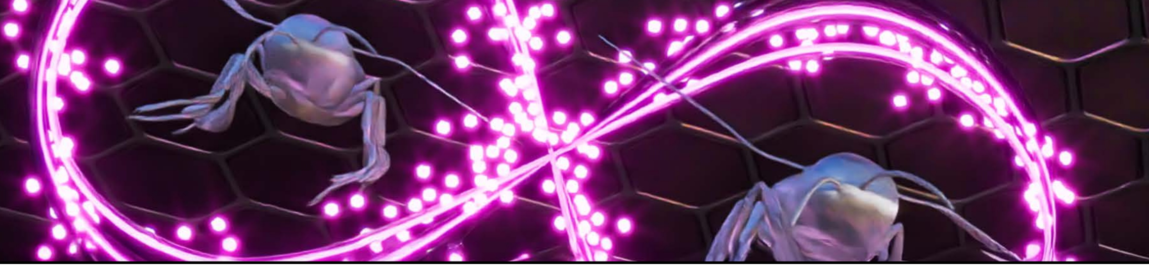
"The Foundry is developing nonlinear photonic materials and architectures that can generate entangled photon sources at much higher rates than has been possible previously," Wilson says. "**John Bowers** [distinguished professor of electrical and computer engineering and materials] and Galan Moody have really led in this area, developing a materials platform based on gallium arsenide, which has allowed them to achieve world-record rates of entanglement generation, enabling useful applications."

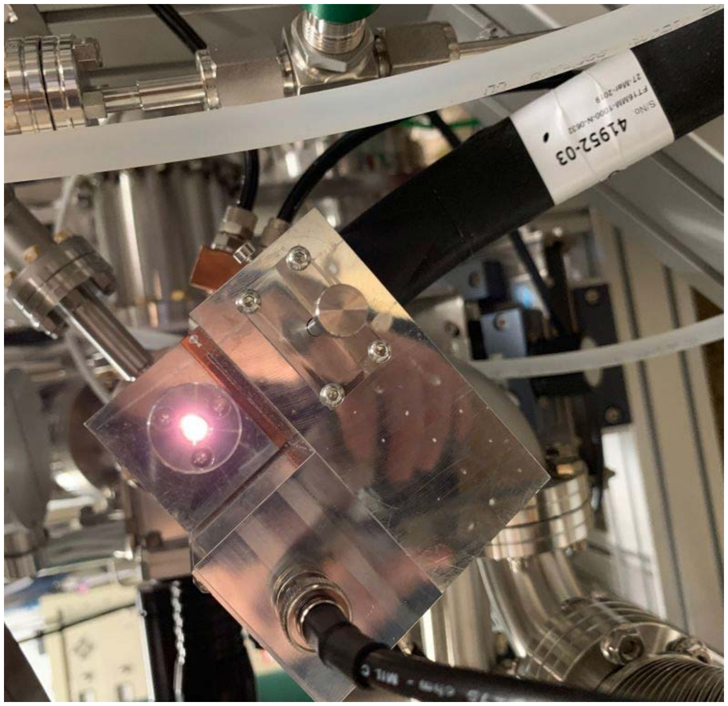
Jayich's research spans the intersection of physics and materials science. "We're now working toward actually utilizing quantum entanglement in the solid state to improve sensors, which has never been done before," she says. "That opens the door to developing materials specifically with these quantum information-science applications in mind."

Hypothesized Majorana fermions, thought to be key to error correction in a topological quantum computer, are perhaps the most-important particles under investigation, and another area of intersection between physics and materials science. "We need to determine whether these quasi-particles exist and can actually reduce the need for error correction," Jayich says. "It's a contentious area of research. Some groups claim to have observed them — or their signature — but it is not universally accepted that those observations were made, or that what the researchers saw was what they thought they saw."

That "debate" gets at another key point about the quantum realm: everything is so small and so susceptible to instantaneous change, that it is extremely difficult to observe quantum phenomena. "These quantum effects happen on such small length scales and involve such a small number of atoms at such small energy scales that you can't probe them with traditional bulk-materials characterization techniques, like scanning electron microscopy, atomic force microscopy, or materials characterization tools in the MRL," Jayich explains. "We're actually developing new ways to characterize these materials systems, basically by probing the defects themselves to see how they lose their quantumness, a probe of the materials that has a level of sensitivity unprecedented for classical systems."

"This effort involves researchers across the fields of condensed-matter physics and materials trying to understand quantum phenomena, but we're also beginning to build these simulators out of atoms or out of defects in solid-state materials so that we can begin to understand some of the new superconducting phases or magnetic-order phases that we find," Wilson explains. "We want to build up those systems from some more controllable building blocks to bridge the gap between what someone like [UCSB physics





Dan Blumenthal (left) performs pioneering research to shrink quantum devices from the table-top scale to the chip scale. (Below left): In this device in the Palmstrøm lab (previous page), helium plasma is used as a vacuum ultraviolet (VUV) source for angle-resolved photoemission spectroscopy.

professor] **David Weld** is doing, when he puts atoms into a controlled state to see what happens, and creating and controlling a real material system."

> *"With atoms and molecules in a gas moving at thousands of kilometers per hour, physicists have long sought a way to slow them down… to trap them."*
>
> *— The Institute of Physics, October*

Now, researchers around the world trap atoms every day. In Weld's experiments, conducted in a pair of large black boxes each about ten feet across, he superheats metal atoms in an oven to make a gas. He then transfers the atoms in their gaseous phase to a location where laser light that has undergone extensive refinement by way of a series of lenses, polarizers, and modulators is used to "trap" the atoms, slowing them and decreasing their energy. During a series of steps, the atoms are cooled to a temperature of about ten-billionths of a degree above absolute zero, far below the lowest naturally occurring temperature in the universe.

"These are complicated experiments requiring an array of electronics, optics, high vacuum, mechanics, and magnets," Weld says while standing next to one of the black boxes that enable him to run a broad range of experiments aimed at eliciting and understanding particular quantum phenomena. "It's hard to do, but, if you do it right, you can make something on the order of a million atoms attain exactly the same quantum state, then hit them in various ways to make them interact with each other, and see what happens. We can use these very well-defined, well-understood quantum mechanical starting states as a baseline for experiments exploring poorly-understood regimes of quantum dynamics."

Wilson describes Weld's work controlling single atoms in the gas phase as "providing foundational insights for the Quantum Foundry's materials work."

Seeing the Quantum Light

"There is an exciting overlap between the engineering and the quantum photonics aspects, with optics and photonics experts such as Electrical and Computer Engineering Department professors **Dan Blumenthal,** Bowers, and Moody, working with David Weld and [fellow UCSB physicist] **Dave Patterson,** making major contributions," says Jayich. "It's all coming out of the UCSB ecosystem."

In Blumenthal's lab, he says, "We use integrated lasers and optics on a chip that operate from the visible to the near-infrared, in order to prepare, manipulate, measure, and harness entangled atoms and ions or their quantum states, to perform sensing and computational operations."

A pioneer in ultra-low-loss integrated waveguides and low-linewidth lasers and a global leader in creating chip-scale devices having very high spectral purity and high power, in 2023, Blumenthal demonstrated the first photonics circuits for creating cold atoms of rubidium, and he and colleagues at the University of Massachusetts recently demonstrated the first photonic integrated circuits for strontium trapped-ion qubits.

Blumenthal and colleagues at the University of Texas, the University of Colorado, and Caltech University are collaborating on a NASA Quantum Pathways Institute (QPI)

project to integrate lasers and optics to create an orbiting network of satellite-deployed atom-interferometers, which can be used to precisely measure gravitational gradients related to climate science, such as subtle changes resulting from shifts in sea level or Earth's glaciers. "The portability enabled by moving such functionality to the chip scale," Blumenthal notes, "enables favorable new applications that can be used in space and other settings, where size is a constraint, while providing improved reliability and power at reduced cost."

Bowers, who is the Fred Kavli Chair in Nanotechnology and a pioneer in optical electronics and photonics, and Moody are investigating quantized light, including collaborating on a recently awarded $10-million grant from the U.S. Department of Defense DARPA (Defense Advanced Research Programs Agency) to design and build technology involving *squeezed light,* which can be harnessed for quantum technologies and make it possible to reduce the noise in an optical detector to below the so-called *quantum limit*.

Their project involves generating specialized quantum states of light that can be harnessed for quantum technologies, including building an integrated photonic chip that is more precise, more stable, and much smaller than existing technology. An extreme — and enormous —version of a sensitive optical detector is seen in the Laser Interferometer Gravitational-Wave Observatories (LIGOs). The few-kilometer-sized experiments (there are currently three such installations in the world) incorporate high-power lasers and optics to measure tiny stretching of space time resulting from cosmic gravitational waves that originated from high-energy events more than a billion light years away.

Photons have the advantage of being unaffected by environmental factors, such as motion or changes in temperature or pressure, making entanglement in photons much more stable than it is in atoms. Furthermore, because photons can be entangled at room temperature, an optical quantum computer would not need the exotic network of cryocooling elements that makes up the bulk of existing one-off quantum computers. The down side of photons is that they don't easily interact with each other, which makes it challenging to use them for quantum computing. Solid-state qubits, on the other hand, entangle comparatively easily, but if their fragile entanglement is lost during a calculation, the calculation ends.

"It's pretty clear that photonics is going to be an important part of the quantum effort, because photons can retain their entanglement for a long time," Wilson notes. "Of course, there is this kind of delicate balance in quantum technologies between, on the one hand, having particles, like photons, that are isolated and not interacting with things, and needing to be able to control the entanglement of particles that interact with some desired degree of freedom. Being able to walk the line between those two conflicting requirements starts with having really good control over the synthesis of the materials and over device fabrication, and that's something we're good at in an unprecedented way at UCSB."

"Photonics for quantum is huge, and it's another area where UCSB is so uniquely set up," Wilson adds. "Not only do we have excellent photonics, but we have the platforms of gallium nitride and other materials that support higher-energy colors in the blue ranges, which are really important for sensing for atomic quantum technologies."

The first photons were entangled over fifty years ago, in a famous experiment at UC Berkeley that earned John F. Clauser a share of the 2022 Nobel Prize in Physics. In 2023, Moody distributed entangled photons across campus and back to his lab via a fiber optic cable under Mesa Road to test how any perturbations — car motion, temperature, etc. — would affect the entangled photon pairs. Through the journey, entanglement remained perfectly intact. Moody's group is now using this entanglement for cryptography and quantum networking on campus.

Students, Education, and the Quantum Workforce

Major NSF grants always include an educational component, but education and workforce training are especially prominent parts of the foundry award, and UC Santa Barbara has developed a variety of programs to educate future leaders in the quantum field.

Home to 26 affiliated faculty, the QF currently supports 22 paid graduate student fellows, along with three funded postdoctoral researchers (and eight active postdocs in all). Since operations began in 2020, some 125 graduate students and postdocs have joined the QF, which also hosts eight

Graduate student Madeleine Bow Jun Leibovitch (center) leads a high school short course on the "art of physics" to give students a taste of how physicists tackle problems and use their creativity to perform interesting science.

Quantum Foundry Ambassador Lillian Hughes helps local junior high school students learn about resonance. The experiment shows that when sound passes through differently shaped objects, the resonant frequencies of the objects cause the pitch to alter.

PhD student Kamyar Parto (left) works in the Quantum Photonics Lab with Arjun Choudhri, a high school student he mentored during a previous summer internship. The light table in the lab give students like Choudhri and UCSB undraduates the opportunity to study light in ways not possible at most institutions.

undergraduate interns every summer, primarily from California community colleges. Annual high school short courses and family-inclusive junior high outreach have all been designed and are taught by foundry graduate students and postdoctoral researchers. The three programs are run by **Wendy Ibsen,** Associate Director of the Center for Science and Engineering Partnerships at UCSB, and Undergraduate Research and Outreach Coordinator for the QF.

"My time at UCSB and my involvement with the Foundry have equipped me with a comprehensive skill set essential for a career in quantum technologies," says **Sahil Patel,** a QF associate and fourth-year PhD student in the Moody lab. "World-class facilities have provided hands-on experience with instrumentation and experimental setups, allowing me to conduct cutting-edge research and troubleshoot complex technical challenges, while collaborative projects have enhanced my problem-solving abilities and prepared me to excel in any setting."

Patel has also mentored in several of the foundry's educational programs, saying, "Students in the courses gain tremendous insight and are introduced to topics they would not otherwise even hear about until the graduate level, making our mentorship efforts fun and highly engaging."

Faculty-student interaction is key to passing down generational knowledge and experience, but student-to-student interaction carries a particular value. "The most important thing is to get the students to talk to each other, and there is a huge amount of coordination among foundry students," Wilson says. "It happens through seminars, coordinated workshops, and other activities that allow them to find out what their peers are doing and to come up with interesting new ideas to try. If students are trained to be collaborative, then they'll naturally have more of that mindset."

"The quantum community at UCSB is exceptionally collaborative and welcoming," says Patel. "I receive tremendous mentorship and guidance tailored to my interests, and also have invaluable interactions with my fellow grad students. This

> "The foundry is full of amazing role models. Professors are truly committed to helping students and future quantum researchers."

spirit embodies the UCSB ethos, ensuring that collaboration is merely 'a walk away.'"

Madeleine Bow Jun Leibovitch, a Quantum Foundry associate and fourth-year PhD student in the Weld lab who says that atomic physics is "one of the coolest things I've ever done," began a foundry short course for high school students by telling them that they would be exploring "what an experimental physicist actually does." Artistically inclined, Leibovitch says, "I was always good at math but never saw myself as someone standing at a blackboard writing equations." She learned to solder for a stained-glass middle school art project and fell in love with physics when she saw how many "making" opportunities the lab provided, including plenty of soldering on circuit boards and machining equipment.

She told her students: "So much of experimental physics research is driven by creative thinking, problem solving, and making things with our hands, adding, "We'll explore some of the most common fundamental-physics research tools…and how they are harnessed to build things to answer deep questions about the universe." Finally, she told them, "This course will be about physics, but it will also be about art, creative expression, and expanding our physics explorations beyond calculations and math."

In her course, she says, "The students asked great questions. They were interested and engaged. We had so much fun together. When I asked at the end whether they thought physics was something they might be interested in, they overwhelmingly said yes."

Lillian Hughes is a sixth-year materials PhD student who has been a quantum fellow since 2021 and is advised by Jayich and Stanford professor Kunal Mukherjee. For her research, which involves engineering defects in diamond for quantum sensing and simulation, she studies diamond growth and how to controllably create defects having improved quantum properties. "The foundry is full of amazing role models," she says. "Professors, from my advisors to committee members and beyond, are always interested in discussing research and career development, even if my interests are not directly connected to their work. They are truly committed to helping students and future quantum researchers."

She says that a collection of new advanced instruments acquired for the foundry have served her critically, enabling her and her Jayich-lab colleagues to "develop and synthesize unique types of diamond, which has resulted in many collaborations and connections around the globe, since most research groups do not have this growth capability or expertise. The foundry has certainly made me a better scientist, and I feel very grateful to have been involved with it."

Recently, the foundry also received an NSF grant that will allow it to partner with New Mexico State University, one of the largest minority-serving institutions in the U.S. The grant will allow the foundry to launch the Partnership for Research and Education on Quantum Materials and Processes (PREQ), giveing PREM students the opportunity to work on next-generation quantum materials and devices, thus broadening participation of underrepresented minority students in materials research and education.

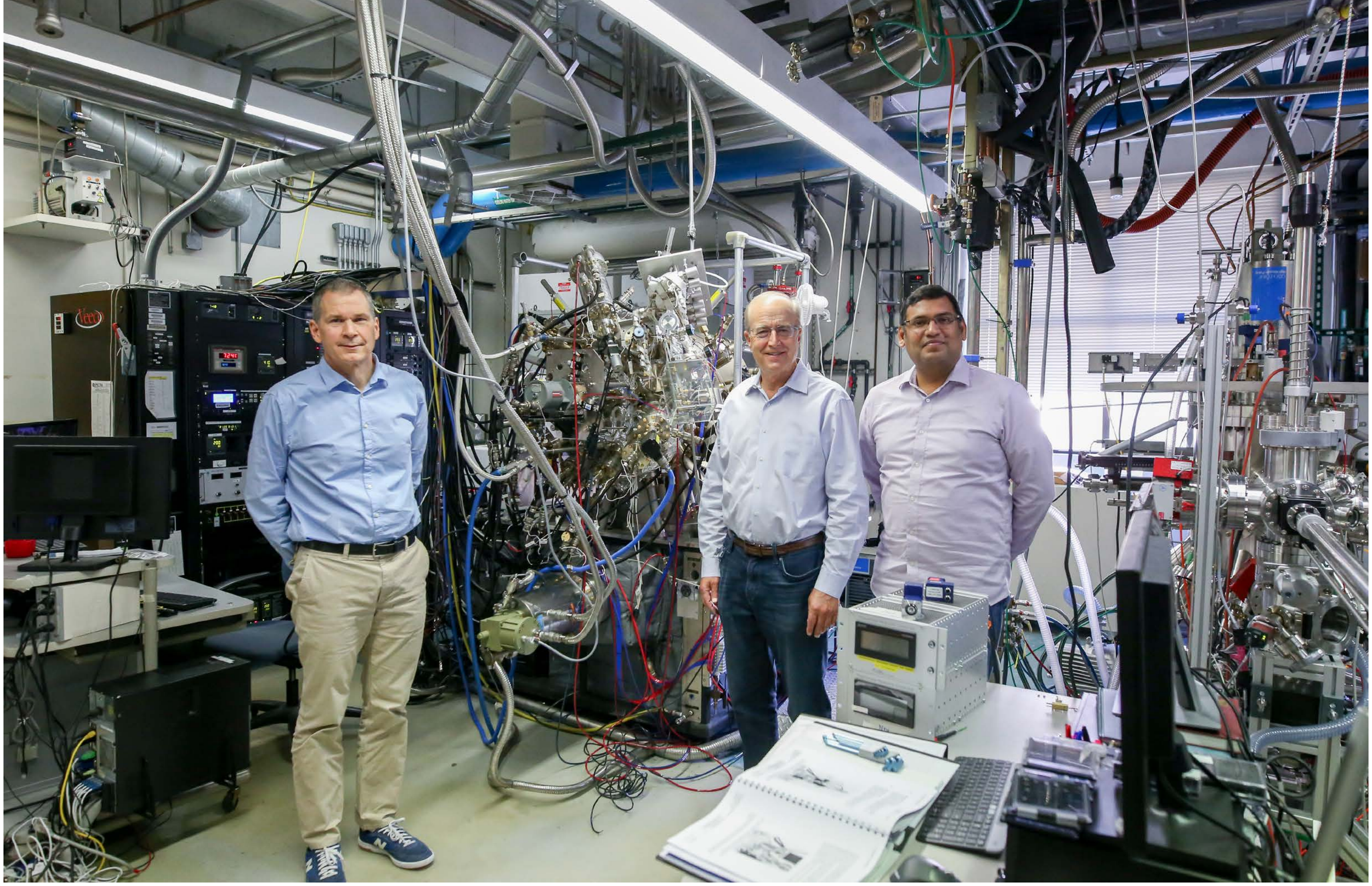
The Quantum Constellation

As industry plays a stronger role in research, it will require brigades of what Wilson refers to as "a new kind of scientist." Hiring those people strengthens industry's research capabilities, which, in turn, leads to further engagement with the university, which supports research on campus and increased collaborations between faculty and industry, smoothing the way for UCSB graduates to step into rewarding quantum careers.

Quantum research at UCSB has now achieved self-sustaining momentum, and since opening, the QF has been joined by other centers on campus. Many QF faculty are affiliated with those centers, as well as a network of centers at national labs and other locations. Weld, Jayich, Martinis, and UCSB physicist **Andrew Jayich** are all part of the NSF's Challenge Institute for Quantum Computing CIQC at UC Berkeley; Jayich, Weld, and Wilson are co-directors of the privately funded Eddleman Center for Quantum Innovation (ECQI) at UCSB, focused on quantum research and education; and UCSB recently received funding for a new Partnerships for Research and Education in Materials (PREM) program. The QF plays a role in coordinating joint events among those various centers. In addition, Weld says, "The Department of Energy has funded five $125-million quantum centers around the nation, and many of us are part of those." Weld is also the leader of a new NSF NRT grant on integrative quantum technology.

"Every time you have a paradigm shift in how humanity tries to organize and use information, a new age usually follows," Wilson says. "One can look at the digital information age. Before that, you had analog information storage, and before that, you didn't have any storage other than what was written; no electronic information at all. Quantum is a new way to collect, organize, and use information, and it is pushing a new paradigm in terms of how one actually thinks about collecting and storing information in ways that can contribute to human success in many fields."

Colony of collaborators: Some of the undergraduate and graduate students, postdoctoral researchers, and faculty members from nearly ten UCSB departments who conduct research in the Quantum Foundry.



UC Santa Barbara professors (left to right) Jim Speck, John Bowers, and Sriram Krishnamoorthy are collaborating to develop compact high-velocity switches.

TWO MAJOR GRANTS FOR THE JIM SPECK LAB

THE MATERIALS PROFESSOR WON BOTH A VANNEVAR BUSH AWARD AND AN ARPA-E GRANT

UC Santa Barbara materials professor **Jim Speck** received two major grants in 2024. The first was a Vannevar Bush Faculty Fellowship (VBFF), which will allow him to further investigate loss mechanisms in gallium nitride (GaN) light-emiting diodes (LEDs). GaN, of course, is the semiconductor material that **Shuji Nakamura,** before becoming Speck's colleague in the UCSB Materials Department, used to invent the blue LED, which enabled the white LED and a world revolution in lighting and would earn Nakamura the Nobel Prize in 2014. The other award Speck received is an ARPA-E grant to develop a new generation of optically controlled high-voltage power switches.

Vannevar Bush: Hot-Electron Physics

Speck received the highly prestigious Vannevar Bush Faculty Fellowship — only eleven were awarded in 2024 — from the U.S. Department of Defense to pursue high-risk, high-reward research, the kind, the DoD said in a release last summer, that has "transformed entire disciplines, birthed novel fields, and challenged established theories and perspectives." The five-year, $3-million award will enable Speck to build on research he has pursued for nearly fifteen years related to the little-understood physics behind a loss mechanism in GaN LEDs known as *current droop*.

Normally in an LED, electrons and holes combine in a quantum well, rise to a higher energy level, and then emit light as the extra energy is released. Sometimes, however, rather than an electron recombining with a hole to make a photon, *two* electrons recombine with a hole to make a "hot" electron, in a process aptly called *non-radiative*, because it does not emit light, only heat, and is therefore an element of efficiency loss. Speck will work closely with UCSB colleagues, such as materials professors **Chris Van de Walle,** an expert in modeling loss mechanisms in GaN semiconductors and

LEDs, and **Claude Weisbuch,** with whom Speck designed and ran experiments that enabled them to become the first to measure hot electrons arising from non-radiative recombination, called *Auger* recombination.

"We worked hard to design experiments that would enable us to extract the very-high-energy Auger electrons out of the semiconductor," Speck explains, adding that their desire for a better understanding of the Auger process was driven by a curious fact: "If we look at the science of the semiconductor and the way light-emitting diodes work, there are no processes that should generate *hot carriers*."

Releasing those hot electrons allowed them to measure the particles and their energy in vacuum in a spectrometer, and in 2013, Speck and Weisbuch published an important paper describing their research to achieve the world's first direct measurement of hot electrons. Thanks to work that Speck, Weisbuch, and Van de Walle have done together since then, Speck says, "All aspects of the technique have gone forward by leaps and bounds. It is still a very active area of our research, and is the foundation for our pursuits made possible by the Vannevar Bush Fellowship."

Much remains to be understood, however, about the complex physics behind Auger recombination and the resulting current droop. Speck's VBFF will allow him and his UCSB colleagues to spend the next five years diving deep into that knowledge frontier.

Compact High-Voltage Switching

Imagine that a utility needed to shut down some part of the electrical grid it manages in order to prevent an imminent cyber attack or avoid having power lines come down in a wind storm, possibly setting off fires. (The DoD says that power disruptions cost the U.S. more than $150 billion per year.)

That is the realm of power switching, and in August, Speck received a three-year, $3.1-million grant from the DoD's ARPA-E Program to develop more efficient power switches. Speck and his collaborating co-PIs, UCSB professor of electrical and computer engineering and Institute for Energy Efficiency director, **John Bowers,** materials associate professor **Sriram Krishnamoorthy,** and a colleague at Ohio State University, Jin Wang, intend to develop switches on a gallium oxide (Ga_2O_3) material platform that integrate optics to make them faster, simpler, smaller, and more powerful than their predecessors.

Currently, high-voltage direct-current (HVDC) power systems are used primarily to send power a relatively short distance, say, from an offshore wind farm to the mainland, because that is the fastest way to move the electricity. It is then switched to alternating current (AC) once it reaches a device on the other end, as is the case with the HVDC cable that crosses San Francisco Bay.

HVDC is too expensive, however, for long-range transmission and involves many elements that have to be combined to do the job. For instance, Krishnamoorthy explains,"If you're talking about moving, say, a megavolt or hundreds of kilovolts, and an individual power module is 6.5 or 8.5 kilovolts, then you need to stack hundreds of power converters in series and control them synchronously to switch very high powers at the grid scale.

"That requires sophisticated switches," he adds. "In one aspect of this program, which has three parts, we're exploring whether we can develop an individual power switch or, eventually, a module that can handle higher voltages, replacing the "stacks of modules and dramatically simplifying the system in many areas of power electronics."

The hardware in current switching systems is built with silicon technology, but the researchers would like to replace it with one requiring a smaller number of switches built on a platform of Ga_2O_3. Speck has been a longtime leader in gallium oxide research, having received a seed grant from the UCSB Materials Research Lab in the 2000s to work on it as a transparent conducting oxide. (The metals often used in semiconductors absorb light; transparency allows more light to be pulled from a heterostructure that incorporates the Ga_2O_3.) He was one of the first to grow gallium oxide crystals, and he ran the first U.S. Department of Defense Multidisciplinary University Research Initiative (MURI) program on the material. Van de Walle has also done extensive modeling of gallium oxide semiconductors.

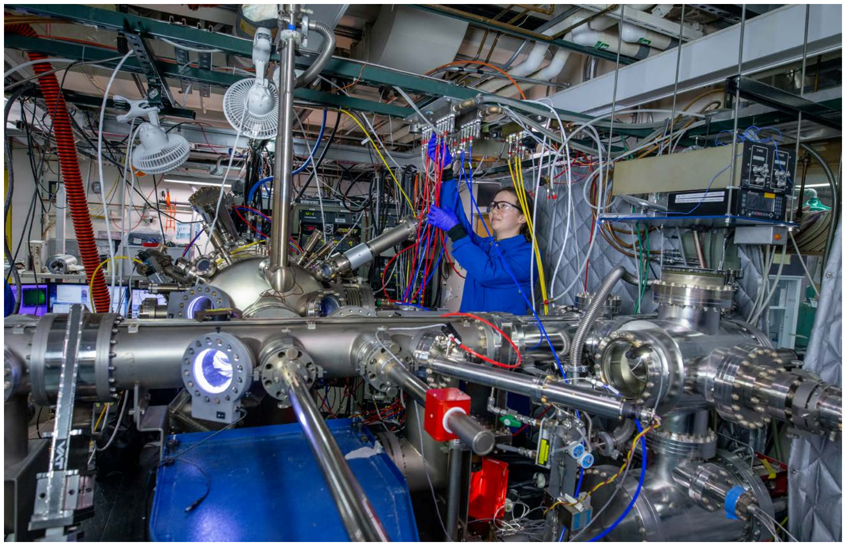
"A long sequence of activities has led to the kind of generational experience and the program we have now at UCSB," says Krishnamoorthy. "You need that kind of history of excellence to convince funding agencies to give you money."

The second aspect of the project is to make the new switch faster, and while questions remain as to the desirability of that approach *at the grid scale,* Krishnamoorthy explains that it has obvious benefits for consumer electronics. "At that scale, if you can make switches that can switch faster by increasing the power density, then your capacitors and inductors can be smaller while still managing the current," he says.

The third part involves figuring out how to control the new devices. Typically, stack modules and anything in the power system or power electronic circuit are controlled with electrical signals. But they have an inherent problem, knowns as *parasitics,* a type of loss mechanism that any wire has and that leads to issues of electromagnetic interference (EMI), which equates to inefficiency and creates feedback loops that can negatively affect the switch.

Seeking to address that shortcoming of wired systems, Bowers, with his expertise in photonics, is aiming to control the new high-voltage switches optically rather than electronically. "Typically, a transistor is controlled with a gate; we're planning to use John's opticals to control Jin Wang's circuit," explains Krishnamoorthy. "They will be like light-controlled high-voltage fast switches, and they'll be based on a high-speed gallium arsenide heterojunction photo transistor from John's lab."

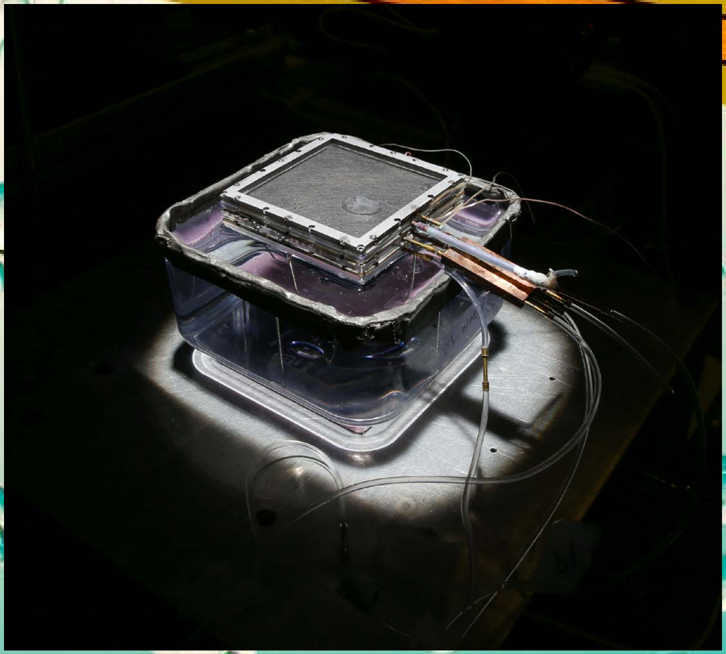
"This project is very exciting, especially since we will be scaling multiple levels of abstractions," Krishnamoorthy says. "We are doing cutting-edge material science, because we'll be using both metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) work to grow the gallium oxide crystals for the power devices. [Using those two systems allows the team to determine which method produces crystals that are best for the application.] I will build the high-voltage power switches, and John will build the fast-response optically controlled transistors, which will be part of the gate drive circuit, built by Jin Wang and incorporating Bowers's optics. We've built the first round of devices, and so far, everything seems to be working."



Rosalyn Koscica, a fifth-year PhD student in John Bowers's group, works in the Molecular Beam Epitaxy lab, attending to a setup required to grow gallium nitride.

A Major Award to Improve Desalination

Yangying Zhu is named one of the first 13 academics to receive a new IGNIITE grant



A prototype (inset, left) of the device for energy-efficient thermal-distillation desalination developed in Yangying Zhu's lab at UCSB.

With freshwater becoming scarce, desalination of ocean water is increasingly being employed to bridge the gap between the amount of freshwater that is needed and what's available. Desalination is an energy-intensive process, however, one often powered by fossil fuels, so meeting the need for freshwater can exacerbate the challenge of reducing atmospheric CO_2, the main driver of climate change.

Yangying Zhu, an assistant professor in the Mechanical Engineering Department at UC Santa Barbara, is addressing that conundrum thanks to a two-year, $500,000 seed grant from the Advanced Research Projects Agency-Energy (ARPA-E) within the U.S. Department of Energy (DOE). The grant was provided as part of Inspiring Generations of New Innovators to Impact Technologies in Energy (IGNIITE 2024) a new ARPA-E program supporting early-career scientists and engineers to convert disruptive ideas into impactful energy technologies and bringing them to market.

“This is the first time the agency has funded early-career single-investigator research,” Zhu says. “Instead of being solely focused on fundamental discoveries, as are NSF Early CAREER awards [which Zhu has also received previously], this one is focused on supporting ideas that align with the ARPA-E mission of improving energy efficiency and sustainability for the United States.” The agency received 400 applications for the highly competitive grants, selecting only 23 for funding. Of those, just 13 were from academia, with the rest in industry, startups, and national labs.

Zhu has two main objectives in her project: to improve the energy efficiency of the thermal distillation desalination process, and to use renewable energy — either solar or waste heat from industry, such as that from power plants and data centers — to power the process. “We are targeting both energy efficiency and reduced dependence on fossil fuels,” she says.

Zhu (left) and graduate students Emily Spitaleri (front) and Patrick Babb examine an evaporator membrane made in Zhu's lab for the ARPA-E project.

> “Zhu, who has expertise in heat and mass transfer, plans to develop a novel architecture to potentially reduce energy consumption of the desalination process by half.”

There is no shortage of available industry waste heat, but it is considered “low-grade,” because it has a relatively low temperature of around one hundred degrees Celsius. That is far below what's needed, says, to drive a power plant, so it gets wasted, but, Zhu notes, “It's fine for our purposes, since that is the boiling temperature for water.”

Conventional thermal distillation methods usually require more than one hundred kilowatt hours (kWh) of thermal energy to produce one cubic meter of fresh water. Zhu, who has expertise in heat and mass transfer, plans to develop a novel architecture that would potentially reduce energy consumption of that process by half.

Using thermal energy to evaporate water requires three things: liquid, solid, and vapor — called *a three-phase contact line,* along which all three phases occur. Evaporation and condensation are most efficient at or near the contact line, where the overall thermal resistance is low.

Zhu uses a cup of coffee to illustrate a heat-transferring context lacking such a three-phase contact line, because there is only the liquid-vapor interface. The cup is the solid, but the contact line, where the three phases meet, runs only along its perimeter. “If I were to have a membrane on top of the cup, within each pore of the membrane I would have liquid, vapor, and solid, providing the three-phase contact line that makes evaporation much easier,” Zhu explains. “When heat is provided to the porous-solid membrane, it transfers the heat to the liquid to evaporate it. That process is most efficient when the heated membrane is very close to the liquid-vapor interface.”

In the case of the cup of coffee, only the perimeter of the cup and the coffee near it receives the heat. It then has to pass through the liquid (not a good conductor of heat) to warm the rest of the coffee. “If you had a membrane, each pore would be like a tiny cup of coffee,” Zhu says. “The solid would receive the heat, which would then be carried to a very nearby microscopic vapor interface. That's what is meant by “thin film” in the title of the project — the liquid film is very thin and also very close to the solid. If each pore of the membrane is, say, one micron in diameter, then the heat from the solid has to travel only one micron to reach the liquid-vapor interface for evaporation.

“Ideally, the solid membrane would be made of a highly thermally conductive material, so that the heat will move through it easily, heating the whole membrane,” Zhu continues. “There is a range of materials — mostly metals — that are already used for this, or you can have a hybrid system consisting of polymers supported by a metal. We're using commercially available materials, because desalination is a practical process, so you can't create something that's very expensive or hard to get, like platinum.”

The other innovation in this project is that it involved not only thin-film evaporation, but also thin-film condensation. “It is really the same process, and equally as important as evaporation, but in reverse,” Zhu says, “so we also need lots of three-phase contact to release the heat that builds up during the process. You need to absorb heat during evaporation and release it during condensation. You want that to occur at the liquid-vapor interface and then to move easily to the membrane, which can conduct the heat away.”

In the above scenario, the solid will conduct the captured heat to another stage to evaporate more water, thus the phrase multi-stage desalination. “We're thinking of having ten to twenty stages,” Zhu notes. “We need to develop a model to predict what the right number is, because at some point, the efficiency decreases, and the amount of distilled water you collect after each stage will decrease. We have already built a two-stage prototype in the lab and done some very preliminary tests on it. So far, it's working well.”

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