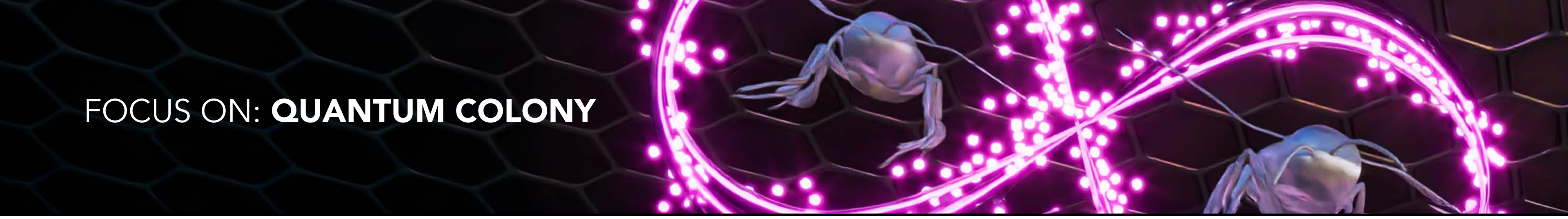
FOCUS ON: **QUANTUM COLONY**

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.



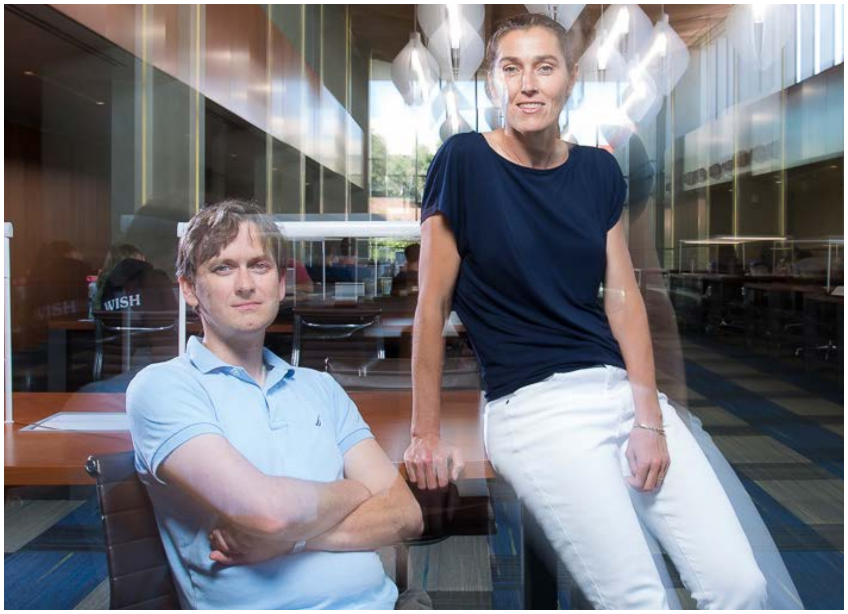
A Counterintuitive Road to….

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.

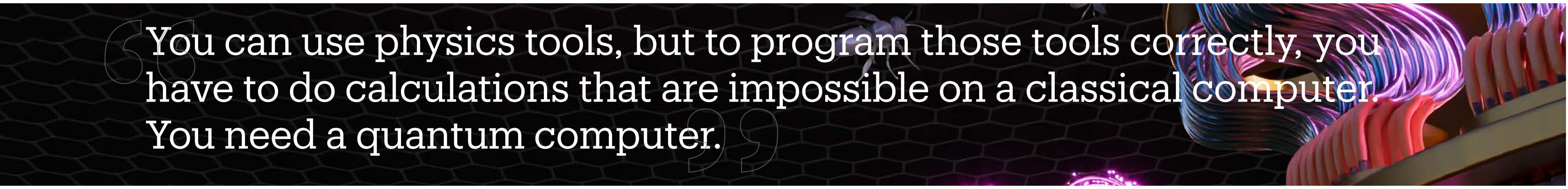
Qubits do a job similar to that of normal bits, but with a distinct quantum advantage. Qubits, and all other harnessed quantum functions, depend especially on two important and closely related quantum phenomena — *superposition* and *entanglement.*

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."

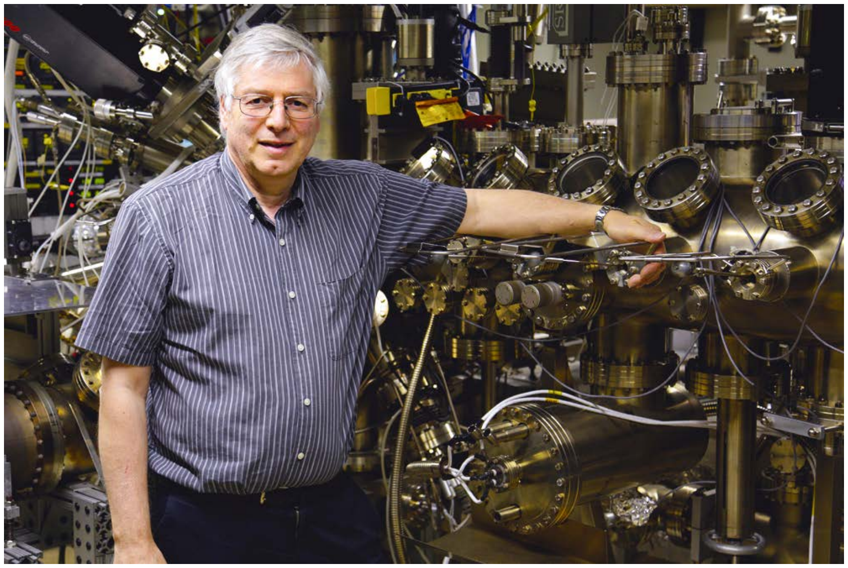
Wilson identifies a prolonged effort to "re-engage with industry" — one of the foundry's three pillars, the other two being to develop quantum materials and to educate the quantum workforce — as an important near-term quantum strategy. "On the fundamental-research front, academia has been increasingly 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."

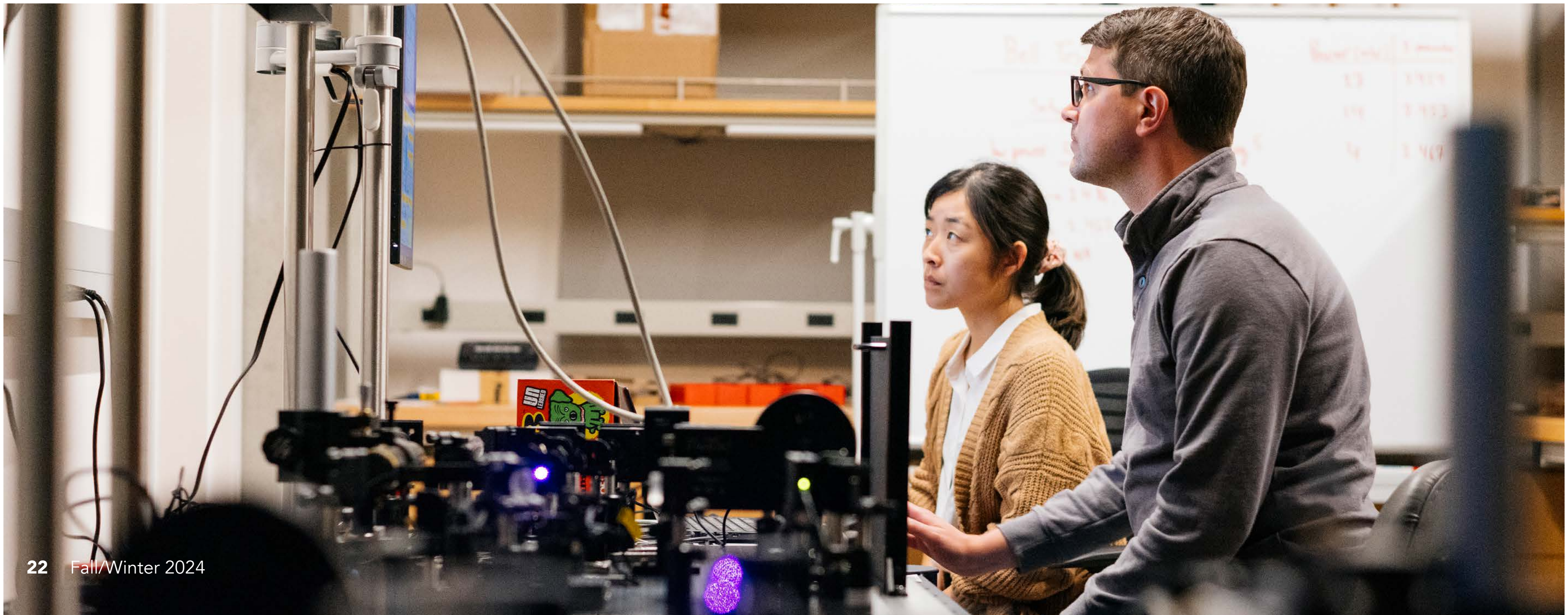
One major step on the quantum-computer path occurred in 2019, when Google's 53-bit Sycamore processor — built in Google's Goleta lab in a project led by UCSB physics professor (now emeritus) **John Martinis** — performed a complex calculation with a known outcome in record time, thus demonstrating so-called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

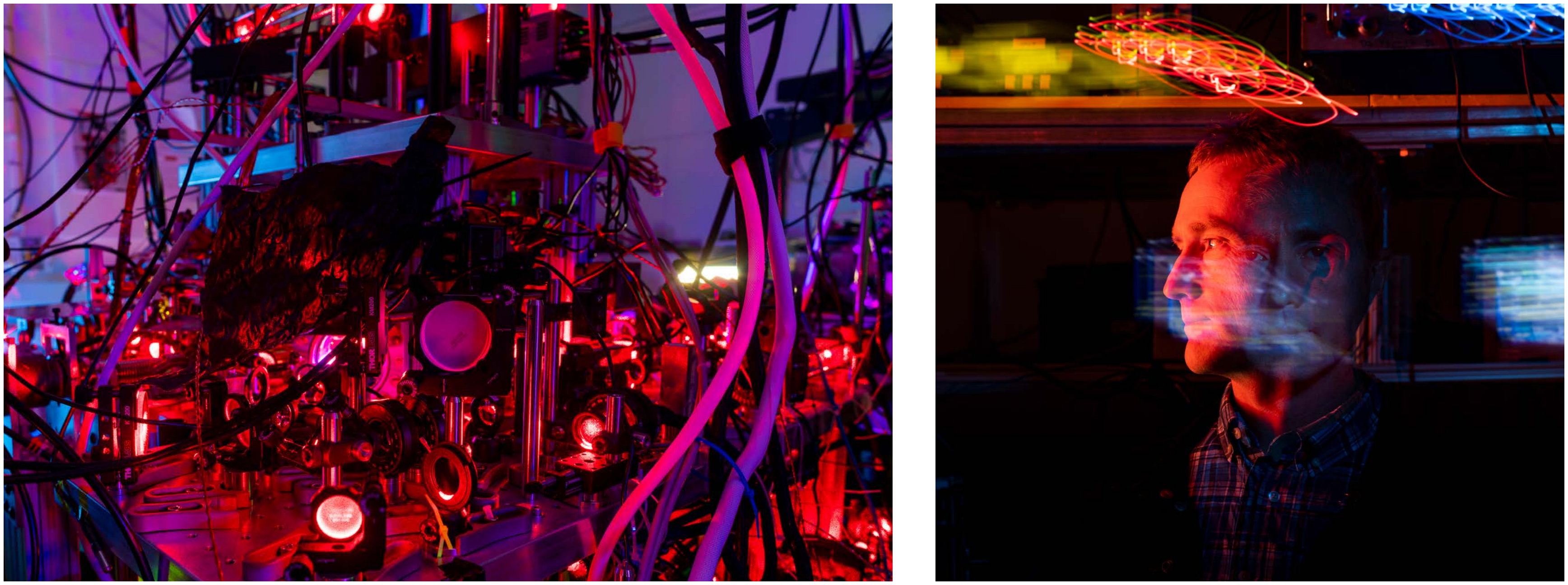
While the margin of that supremacy has been hotly debated, the experiment served as a measure of how far quantum research had advanced. "The first qubit was put into action about twenty-five years ago," Moody said during a talk in 2023. "Now we have tens to hundreds of qubits and are gaining on a thousand."

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."

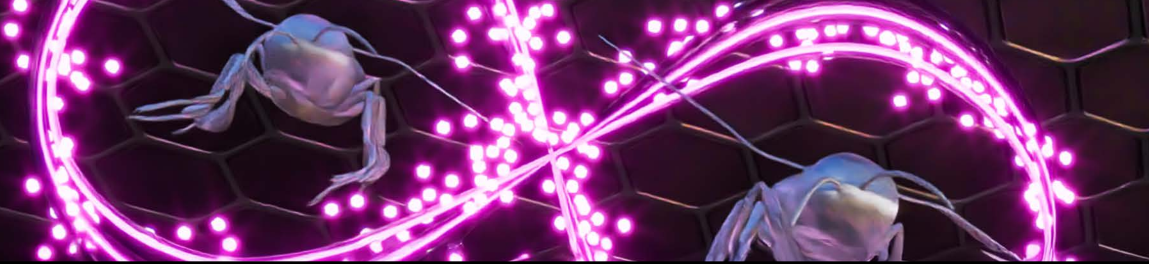
"The Foundry is developing nonlinear photonic materials and architectures that can generate entangled photon sources at much higher rates than has been possible previously," Wilson says. "**John Bowers** [distinguished professor of electrical and computer engineering and materials] and Galan Moody have 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."

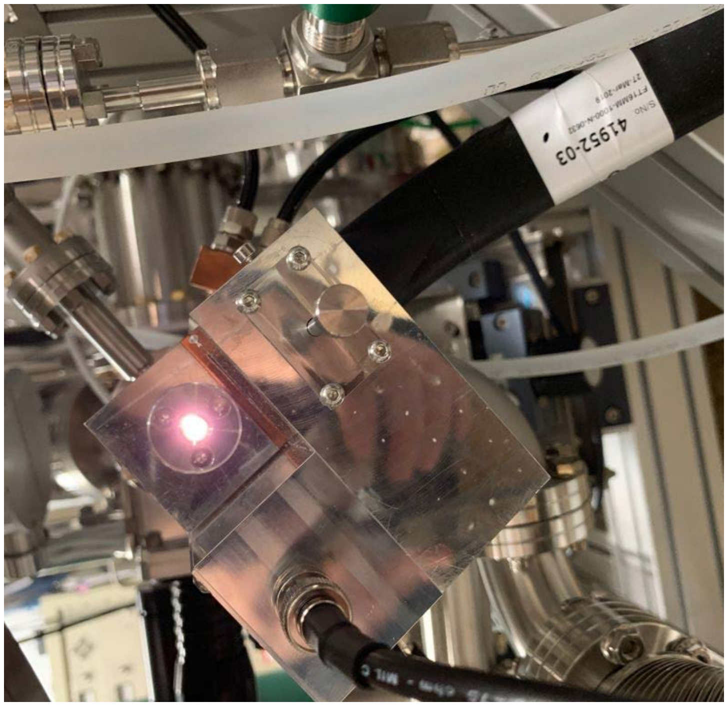
Jayich's research spans the intersection of physics and materials science. "We're now working toward actually utilizing quantum entanglement in the solid state to improve sensors, which has never been done before," she says. "That opens the door to developing materials specifically with these quantum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

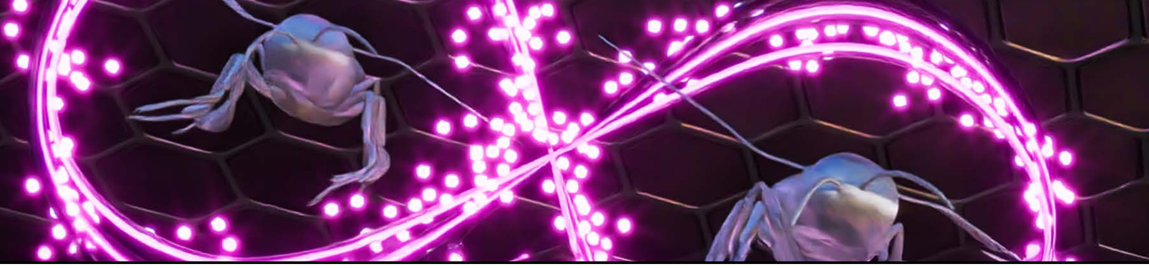
Students, Education, and the Quantum Workforce

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 different ly 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.