IEE at 15

Relentlessly pursuing the goal of using less to do more

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

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

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

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

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

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

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

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

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

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

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

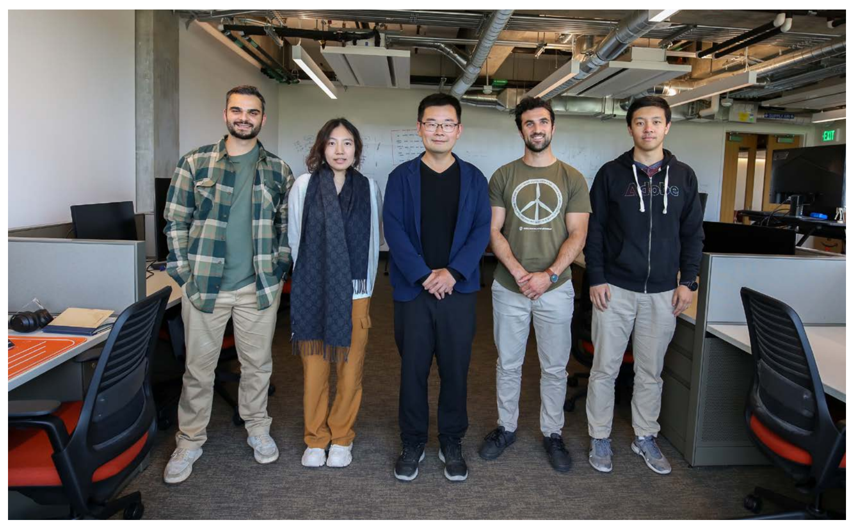
IEE director, John Bowers

AI and Energy

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

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

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



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

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

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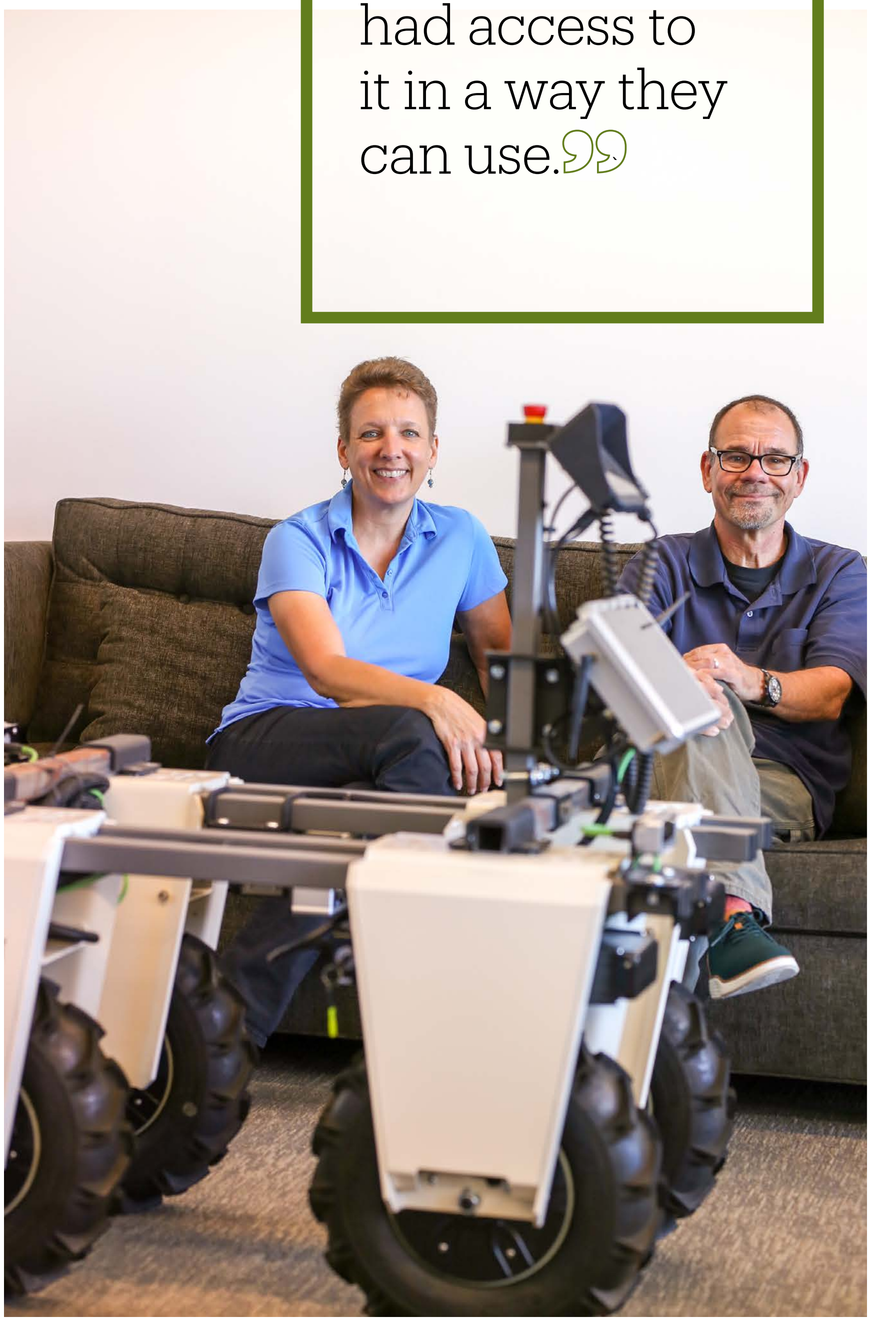


Chandra Krintz and Rich Wolski with their robot, Gort, which they hope will gather data in agricultural fields that can be used to support farmers.

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

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

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

Cloud over Agriculture

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

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

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

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

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

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

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

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

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

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

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

Beyond LEDs

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

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

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

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

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

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

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

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

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

Making Infrastructure "Smart"

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

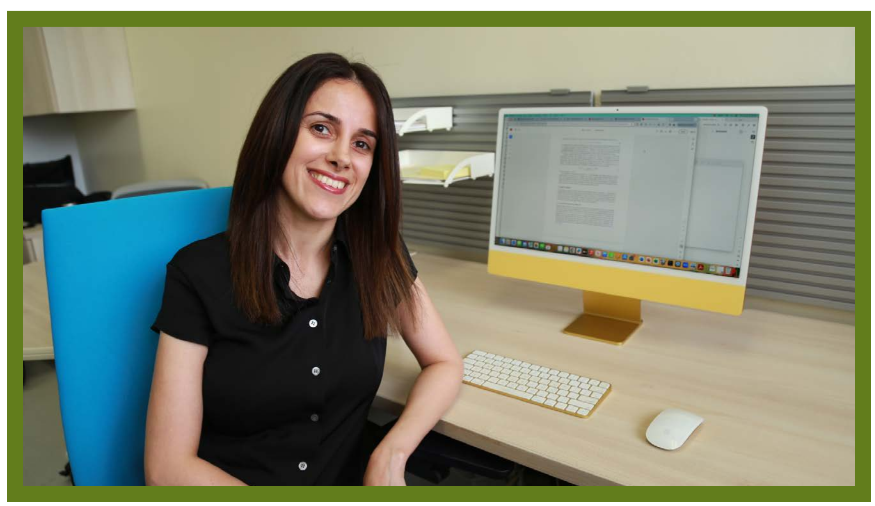
Her work, as well as that of fellow mechanical engineering professor **Igor Mezić** falls within the Smart Societal Infrastructure (SSI) research pillar, but is very much related and complementary to concepts underlying research in the FEWN pillar. SSI research is focused on the operations of the power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

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

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

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

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



Mahnoosh Alizadeh focuses on running the grid more efficiently.

Chasing Quantum

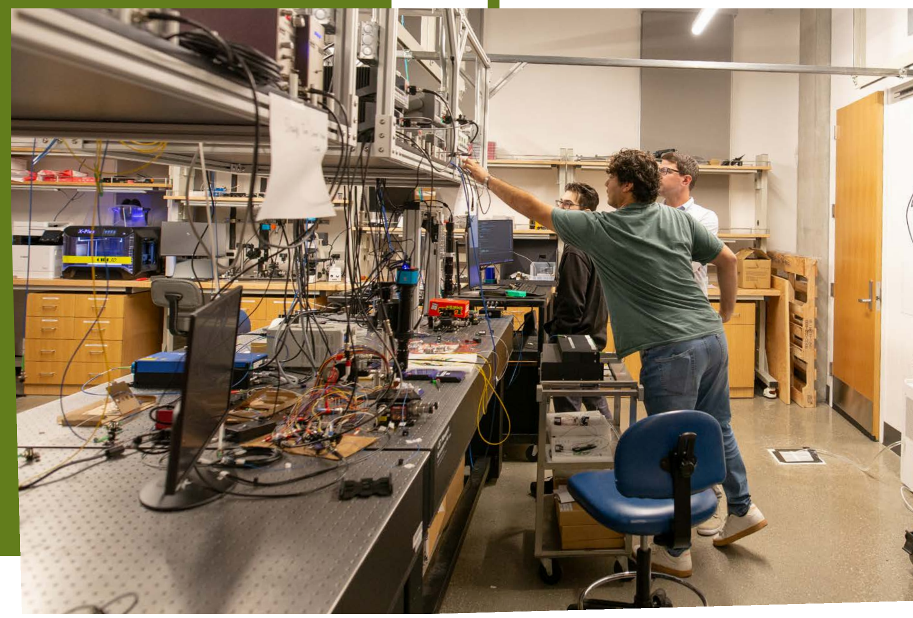
While many technologies are aimed at achieving gains in energy efficiency, some, like those in the quantum realm, must be energy-efficient even to function at all. "Quantum and efficiency go hand in hand," says electrical and computer engineering associate professor **Galan Moody,** who is working to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

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

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

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

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



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

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

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