Quantum Engineering

A New Frontier

The evolving field of quantum science, especially as incubated at Caltech, is a defining example of the Institute's commitment to innovation through deep exploration and understanding across disciplines. When Guruswami Ravichandran, Chair of the Division of Engineering and Applied Science, is asked about the future of science and engineering, he focuses on frontier fields such as quantum engineering, where Caltech is a unique catalyst. "The science of things is getting smaller," he says. "We are also seeing a societal need for things to get smaller—and it doesn't get smaller than the quantum scale, which is an area of historic expertise for Caltech." According to Ravichandran, "the marriage of quantum science and engineering has the potential to result in technologies that can revolutionize all aspects of science."

ENGenious sat down with four EAS faculty members who Ravichandran identifies as part of a select group focused on studying the quantum phenomena "in exquisite detail, with an eye to bringing that detail to usefulness. The group spans the whole spectrum, from the most basic science to information theory and quantum information theory to the reality of devices." These four are Oskar Painter, John G Braun Professor of Applied Physics and Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute (KNI); Keith Schwab, Professor of Applied Physics; Andrei Faraon, Assistant Professor of Applied Physics and Materials Science; and Thomas Vidick, Associate Professor of Computing and Mathematical Sciences.

These researchers are exploring the root concept of quanta on a scale both vast and minute, enabling and limiting. "What we're really thinking about is fully using all the subtlety that is in nature, as described with quantum mechanics, and trying to extract all the functionality and utility out of that model. This full use of nature—it's what we're after," says Keith Schwab. "We ask ourselves: How does the full quantumness of nature help us do things in the world? How does the physics of these things limit what we can do? Nature doesn't always provide capability. The best-known example is probably the sensitivity of LIGO (the Laser Interferometer Gravitational-Wave Observatory). It is limited by the quantum fluctuations of light. We do this dance with nature, working within all of its capabilities and limitations."

Andrei Faraon goes on to explain that the history of quantum engineering is an evolution from ensemble systems to single quantum states. "In the past, quantum mechanics was used to make devices like lasers, which are an ensemble of quantum objects described in a quantum way," he says. "Now we are entering a new era where we are working with quantumness that is fundamental and singular: single atoms, single photons, or single electrons. We are only now trying to develop devices that use these single quantum objects and single quantum states." This trajectory, with the generation of photonics and laser applications giving rise to the more theoretical frontiers of single quantum states, is evident in the range of the respective disciplines of the researchers brought together in this emerging field.

Oskar Painter, like Faraon, comes from the more traditional area historically referred to as quantum electronics or laser physics. He is excited by the potential that such newcomers as Thomas Vidick have brought to the work as the field has expanded into information science. "Thomas works on the boundary of quantum information science," says Painter. "His work broadens the scope of how we can think about the information of quantum physics. His field has huge potential for communications and the

Clockwise from top left: Oskar Painter, Thomas Vidick, Keith Schwab, and Andrei Faraon way we compute and process information." Then there is the important question of measurement, where Painter sees Keith Schwab's contribution as essential: "Keith represents the key in-between and has worked his whole career to develop new types of measurement techniques and sensors that can rely on some of these very subtle properties of quantum physics that are not represented in the more historical work. This idea of precision measurement and the limitations of measurements helps us do things in a better way."

Discussion of applications in the emerging quantum field requires a long view and a respect for the inherent nature of research in general, according to Painter. "Quantumness is by definition at the forefront of science," he says. "It is the fascinating aspect of the physical world that is completely surprising. It is what we are passionate about. The necessity for an application, however, is cultural and gradual. 'What is it good for? What can you DO with it?' are always the first questions we are asked about our work. One good answer I can offer is, 'When the researchers who developed quantum mechanics in the 1920s and 1930s were posed such questions, they didn't know it would lead to a trillion-dollar industry 70 years in the future.' It is a good example of how long it can take the underlying science of a technological revolution to emerge." Schwab agrees that there is a unique set of challenges to working in a field where the "short term" is defined by a period of about 20 years, and this complicates the question of applications. "What makes it hard is that the fundamental science evolves so rapidly that we are always on shifting ground as to where applications might end up, but it is inherent in our nature as researchers to ask, 'How can I use this thing so I can engineer a solution or provide some function?' Applications come, but often not in any direction we can anticipate or any fixed timeline."

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One can already point to such specific applications and aims as advanced cryptography, ever more precise navigation, and atomic clocks, but Ravichandran and Faraon see the future of quantum studies and quantum engineering as being about enhancing productivity across the board. "If you look at the history of humankind, you have to wait until about 1850 for electricity, cities, and cars to define the first really big evolution for human productivity," says Faraon. "Then there were electronics, but since then we haven't had much in the way of advancement in productivity. Quantum engineering could provide that next leap in the productivity of mankind. There is a lot of physical worth we will extract that will lead to better computing, better understanding of chemistry and materials." Getting to this new practical paradigm in a field so deep in theoretical territory is an exercise in layering—of disciplines and processes.

This is where Schwab predicts the real return on the current quantum computing push will be. He explains, "Money flows to cryptography for strong cultural and political reasons, but the real utility of quantum engineering for computation is going to be small-scale quantum computers that do calculations that classical computation can't do, like simulations of Hamiltonians for material science." Faraon points out that at a deeper level, this idea becomes triage for research and can lead to huge efficiency. "Quantum engineers aim to simulate chemical reactions and capture all the subtleties of their interactions on a relatively fast time scale. Having indications of which reactions are most likely to work on the front end of testing could really narrow down the space and provide excellent focus and rapid progress for research."

On the educational side, says Painter, the emergence of the field of quantum engineering has created a need to expose his students to the many overlapping disciplines that guide the research. "There is a recognition I share with my students that if we're going to understand and build new devices that really take advantage of all the aspects of the quantum world, we need to understand information theory in a way I never understood it. We need to understand measurement in a way I never fully appreciated. My own training would be insufficient for their preparation in the field. More and more, I have to teach specialized classes to get the students the depth and interconnection they need across disciplines to be able to perform cutting-edge quantum research."

The future of quantum research and its application at Caltech is strongly linked to its past, in large part through the history and impact of scientific instrumentation. According to the researchers, LIGO's recent detection and observation of gravitational waves not only increases our understanding of the universe but also demonstrates and advances quantum instrumentation, which has a long history at Caltech. That history very much matters to future generations of students and professors, notes Schwab. "Quantum engineering was happening here before the name existed," he says. "Precision measurements, sensitive instruments, and applied new detection make Caltech unique in the field, and this groundwork lives here. Future scientists can use this foundation to go forward to improve and develop the foundation with singular recognized focus."

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Faraon further underscores Caltech's prominence in many areas of quantum science: "Basically every time I go to write or engage in some collaboration with other people, no matter where it starts, I always end up right back here at Caltech by way of a mutual connection," he says. "And I do mean always." The Kavli Nanoscience Institute (KNI) has enabled much of this prominence in quantum research and instrumentation. According to Faraon, "KNI is a place that can be tailored to the individual needs of the research. It's not a generic cleanroom hoping to cater to everyone. It can be shaped to accommodate the very specific needs of the faculty. It is one of the ways that your voice is truly heard as a Caltech faculty member. That combination of facility and autonomous direction is as good as it gets."

Theorists come to Caltech for that kind of access, says Vidick. "I am a computer scientist, and I'm here because this place is very small and very strong," he explains. "I sit in a computer science department alongside quantum information researchers. There are all kinds of strong physicists around for me to learn from. Caltech is unique in this way. I will bump into people a lot, and these valuable conversations would never happen if I were in a larger institution." Painter adds creativity to the list of Caltech's essential attributes, along with scale and size, saying, "Caltech is unique in its nurturing of creativity in that it gives faculty a lot of room to play. As a result, there is a tendency for our research to spin off and suddenly sprout up elsewhere in some new area for the next generation of engineers."

Schwab sees great value in that kind of creativity, as well, pointing to the essential ability of creative scientists to identify the kind of research that is most valuable. "I fully believe that the experiments and theories that are being done at Caltech today are exactly the ones that should be done," he says. "I don't know what will be the most interesting outcome, but the experiments of today in manipulating single quantum elements and working with them is absolutely the right trajectory for the field. If you are the kind of person who wants to strike out into blue sky in quantum science, Caltech is the place for you. It has the financial strength, vision, creativity, and people to meet the challenges unique to frontier science." And Vidick, like Ravichandran, frames that work as vital and necessary because of its potential for societal impact, even if some of that remains theoretical for now, offering a reminder that he and his colleagues "are guided by usefulness all the time. Not in the sense of selling a product, but in the sense that the understanding we build by exploring today's questions positions us to formulate and address tomorrow's challenges. Quantum engineering is a deeply integrated field, and it is in the making at Caltech." ENG

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