Full Committee Hearing to Examine DOE's Efforts in the Field of Quantum Information Science
Senate Energy and Natural Resources
Tuesday, September 25, 2018

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Chairman Murkowski, Ranking Member Cantwell and distinguished members of the Committee, thank you for asking me to testify at this important hearing.

My name is Irfan Siddiqi and I am the Director of Berkeley Quantum, or BQ, a strategic partnership between Lawrence Berkeley National Laboratory, a Department of Energy (DOE) Office of Science multipurpose laboratory, and the University of California, Berkeley. BQ was established to leverage the outstanding resources and capabilities in quantum research, education, and technology innovation in Berkeley and throughout the greater San Francisco Bay Area. Although this exciting partnership is new, it brings together efforts that have been long and well established. The goal of BQ is to partner collaboratively with other quantum researchers and consortiums, research institutions, and industry throughout the nation to no less than ensure U.S. international leadership in quantum information science (QIS).

At the core of BQ will be the recently announced Advanced Quantum Testbed to be located at Berkeley Lab. The AQT will enable industry, academic, and lab researchers to explore superconducting quantum processors and evaluate how these emerging quantum devices can be utilized to advance scientific research. The BQ ecosystem also includes other centers and facilities at Berkeley Lab and UC Berkeley, including the Center for Quantum Coherent Science and the Berkeley Quantum Information & Computation Center, both on campus, and a DOE Energy Frontier Research Center in quantum materials at Berkley Lab. Additionally, Berkeley Lab operates several DOE Office of Science User Facilities that provide state-of-the-art resources for scientists to advance quantum science. These include the National Energy Research Scientific Computing Center (NERSC), the Molecular Foundry, and the Advanced Light Source (ALS).

BQ would not be possible without these investments, and we are indebted to the DOE Office of Science, to the Department of Defense, and to Lawrence Berkeley National Laboratory for these longer-term investments, seed funding, and for the new awards. We are eager to show an optimal return on the federal investment.

In addition to leading BQ, I am a Faculty Scientist at Berkeley Lab and a Professor of Physics at UC Berkeley. Quantum information sciences, in particular quantum electronics and computing, have been the focus of my research and my teaching career for over 21 years. As both an academic and a member of the national lab ecosystem, I am thrilled about extending the quantum frontier.

In particular, grand challenges identified by Department of Energy and specifically its Office of Science are well aligned with some of the most promising areas for quantum information science. For example, scientific computing is dominated by chemical structure inquiries and high energy physics computations. These could be revolutionized by QIS. Additionally, extreme sensing and communication are two sides of the same quantum coin and are well aligned with Office of Science research that surveys terrestrial phenomena and events in the cosmos.

The federal government has the seminal role in building a balanced approach among academia, national laboratories, and industry to advance quantum research and development. The Committee's careful consideration of this challenge is very necessary and very much appreciated. I am grateful to have an opportunity to share my insights and comments with you on such an important topic. My testimony represents my own views and does not necessarily represent the views of the University or the Department of Energy.

The Quantum Backstory

Quantum science is the study of the behavior of the physical world at extremely small scales – at the scales of atoms and electrons, for example. Researchers, as early as the start of the 20th Century, began noticing that at these scales, matter and light behave differently and counterintuitively to behavior at larger scales. Today, more than one hundred years later, scientists and technologists are developing the theory, tools, methods, mathematics, and processes needed to manipulate and control the unique properties of the quantum world for transformational advances in computing, sensors, physics, and communication sciences.

We are only now at the beginning of harnessing the full power of quantum information science for useful applications. The founding fathers of physics, especially Einstein, had serious questions about whether quantum entanglement (the property that allows quantum objects to exist in numerous combinations and thereby store/process large amounts of information) could exist between physically separated objects – now we are of the opinion that the very fabric of the universe needs quantum entanglement to stay together and is, indeed, connected!

The first quantum revolution showed us that the world is granular and that objects can exist in two places at one time. We then went through an observational phase where it was proven that quantum effects can be observed over a variety of physical systems, ranging from atomic to macroscopic. We are now in what we may call the second quantum revolution in which we are able to engineer quantum coherence – that is, **we are now able to put knobs, controls, on quantum phenomena.** The quantum observer is no longer relegated to simply watch exotic quantum effects decay away on fast timescales, but rather is able push the boundaries of knowledge and usefulness by engineering longer-lived quantum systems possibly designed for societal benefit.

One of the grand challenges in quantum technologies is to construct physical systems that exhibit entanglement across many elements and for long periods of time. The way quantum mechanics works is that a system may exist in many different realities simultaneously until an observer makes a measurement – for example a cat may be asleep and awake at the same time until someone looks and classical sensibility has to be restored; the cat can only be observed in one of these two outcomes. The same principles apply to a bit which stores information as ‘0’s or ‘1’s. Classically, a single transistor can only be in either pure zero or pure one at any given time. Quantum mechanically, any weighted combination of ‘0’ and ‘1’ (say 25% ‘0’ and 75% ‘1’) can exist, vastly expanding the amount of information that can be held in each bit. Many such bits entangled together can hold more information than all the particles in the universe, if they were each classical bits.

The design task therefore in quantum information processing is to produce an algorithm that manipulates an array of quantum bits without measuring them to the end of a computation. We now have algorithms that take advantage of the vast combinatorial space afforded by quantum bits by executing special logical operations (similar to ‘and’, ‘or’ operations in classical computing) to factor numbers for cryptography and communication, numerical optimization, chemistry and materials science, information physics in cosmology, etc. The challenge is that current devices are both noisy and short lived, allowing only on the order of 10-100 logical operations to be executed with 95-99 percent accuracy – 99.9 is a good target goal (many thousands would be needed for general purpose computing). The reason for this is that even though the algorithm has been designed not to interrogate the quantum array during the computation, and the quantum computer scientist does not measure the machine, the environment does make an uncontrolled measurement and does not share information obtained during the measurement with the observer. For example, stray light, vibrations in the solid materials, stray electrons, and perhaps even eventually fluctuations in gravity, all interact with qubits (a qubit is the basic unit of quantum information) and extract information and scramble their state.

This phenomenon is known as decoherence and manifests itself in different ways for different physical systems. For example, sources of noise relevant to trapped ion systems (e.g., which are very sensitive to stray electric fields on the surfaces of structures used to trapped them) can be very different from those present in 1000x times larger superconducting circuits (e.g., which are prone to radiate information away at microwave frequencies). **Creating large numbers of long-lived quantum bits is thus a fundamental, albeit very different, problem in all technology platforms requiring large scale, tightly integrated basic science and engineering development at the multimillion-dollar level.**

It is remarkable the amount of rapid progress made in the field of QIS. The first superconducting qubit developed by the NEC group in 1999 had a ~ 1 nanosecond coherence time; we are now approaching 1 millisecond (a million-fold improvement). Not only can we reduce spurious measurements by the environment, such as those listed above, we have improved the tools necessary to unravel the most intricate and subtle details that comprise quantum phenomena. The decoherence process was for a long time thought of as an instantaneous reduction of a quantum superposition (cat asleep *and* awake) to a single outcome (cat asleep or awake). This was the so-called ‘collapse of the wave function’ and quantum mechanics instructor, Sidney Coleman (see interesting bio https://en.wikipedia.org/wiki/Sidney_Coleman) did not believe in many ideas related to this collapse. It was a true honor for me to give a lecture in the same room that I took a class with

Coleman at Harvard, Jefferson 251, nearly 20 years later and tell an audience about how we had reconstructed wave function collapse, one quantum trajectory at a time. We also used these real time measurement tools to fight decoherence by stabilizing a state using continuous measurement.

Quantum Possibilities

We are now in a position to build quantum computers that will perform tasks that classical machines cannot. We need to look at what classical resources are needed to stabilize quantum machines and gauge the net advantage with system size. This has to be done by a scientific body that equally values both positive and negative results. Negative results simply mean that the most important applications may be found elsewhere, and not that quantum technologies are a bust!

A good example of the potential of quantum computing is the development of more energy-efficient catalysts. Catalytic processes are chemical agents and recipes that speed-up reactions – they are often used in industrial processes to make the mass production of chemicals more economic. Better catalysts produce better yield and require less energy. Computer modeling and simulation of catalytic processes have improved dramatically over the past 30 years owing to better algorithms and faster computers, but certain kinds of processes have evaded detailed explanation and are thought to require unattainable conventional computing resources to model effectively. Quantum computers, even noisy, relatively small-scale devices of 10 to 100 qubits, have the possibility to model these systems in a way impossible on a conventional device.

One of the most tantalizing possibilities is to imagine the impact if we could replace the standard energy intensive industrial process to make ammonia, the precursor to most fertilizers. Ammonia production consumes 17% of all the energy within the chemical and petrochemical sector - the world's largest industrial energy consumer. A potential alternative is an analog to a low-energy process used by plants. Currently, though, this process takes place using a biological enzyme, nitrogenase, via a mechanism that is poorly understood using current computer modeling techniques. If this mechanism could be understood using a quantum computer, it might be leveraged for the development of an industrial process that is faster, cheaper, and more environmentally sustainable. It could literally help us feed the world.

Quantum simulation also provides excellent examples of quantum's power to address fundamental questions about our world and the universe as a tool to unravel the basic structure of other extremely complicated and tremendously interconnected systems. Questions of deep importance to the DOE Office of Science and the world's scientific community generally. As an example, consider mysterious black holes. They contain matter so dense that particles entering them have their information scrambled instantaneously. But, because information can never be destroyed, scientists believe it is radiated away in the form of Hawking radiation, a special form of radiation named for the famous British physicist Stephen Hawking. Quantum machines, unlike current classical ones, can help us validate the theories about the structure of black holes and their dynamics, and what happens to particles when they enter them – giving us a window into our quantum universe that is currently unavailable.

A little closer to home, that is to everyday life, quantum simulation offers a window into energy transport processes with the potential to help aid the design of new classes of solar cells and light emitting diodes. As you know, the conversion of light to energy is carried out by biological systems, such as photosynthesis, and forms the basis of plant life. Many light harvesting processes can be enhanced via quantum effects, but a tremendous amount of science and technology development is required. If successful, advancements in energy transport processes could greatly reduce the cost of and simplify the manufacture and distribution of transformative energy technologies such as novel solar cells, LEDs, and even the direct production of liquid fuel from sunlight and water.

As has always been the case with federally supported science, discoveries – new knowledge – in the quantum space will lead to solutions for society. Just as scientific advances in electronics led to the information technology revolution, the development of energy efficient technologies, and other transformative economic drivers, quantum research and development will drive technology development and create economic wealth. The U.S. must lead in this effort.

Finally, for all the science geeks in the room, advanced quantum tools are ultimately required to test the limits of quantum mechanics. We are now testing this theory in a regime that has never been explored and which will probably need fundamentally new theories. **Is quantum mechanics complete or is it part of a grander, broader, yet to be discovered world view?** This is the broadest question in the field!

Our Quantum Future – Where do we go from here?

At this critical time in QIS research, basic notions that have been and will be developed in academic labs need to be evaluated, refined, tested, and matured in order to bring novel quantum applications and products to society. This process requires a partnership, a linkage, among: academia, serving as an engine of ingenuity; national labs, for scaling up applications to address broader problems and for initial deployment to the scientific community; and finally, industry, with a set of tried and tested principles that can help drive solutions and products to the public.

The national labs thus serve a critical role in verifying the soundness and gauging the practicality of ideas developed in academia, especially for scalability and application. The labs play a key role in gleaning from the large number of ideas developed in academia the most promising ones in an impartial and scientifically rigorous fashion. **When this process is carried out solely within industry, it can't benefit from the full space of good ideas that comes with the diversity of disciplines and approaches found in the broader scientific community. If ideas to explore are not identified in an optimal fashion, we run the risk of missing golden chances and putting too much confidence in early stage designs.**

An optimized and impactful National Quantum Initiative (NQI) will avoid this scenario by supporting a balance within the quantum research and technology ecosystem, making sure each member of the academic-national lab-industry team is able to produce maximal results within their spheres of expertise, capabilities, and influence. The NQI should promote research at universities and national laboratories that builds foundational science and creates linkages between industry and other partners – doing what the federal government does best, seeding new ideas and funding risky science, building a foundation of science for industry research, and development focused on short term delivery of products to customers.

The DOE Office of Science, understanding the potential to advance its mission objectives and the importance of maintaining international leadership in the quantum space, has embarked on a series of investments to look at QIS technologies across the board. With support from the Office of Science, researchers at Berkeley Lab are looking at new classes of materials compatible with quantum coherent phenomena, new sensors that operate using quantum states of light and matter, and hardware for quantum control, inspired by decades of precision engineering of accelerator technologies. The Office of Science is making similar strategic investments across its portfolio and among national laboratories and universities. Its leadership will push the frontiers of science and open new doors into the application of quantum capabilities across a broad range of research and technology fields. This will directly contribute to the nation's leadership and the flow of economic opportunity.

Another exciting development is the utilization of a new modality of QIS research that is well established in other disciplines, such as particle physics and astronomy, in which researchers rely on the collective achievements of a community to advance the field. Under the aegis of the DOE testbed program, with a generous award just announced by the Office of Science's Advanced Scientific Computing Research program, we are building a quantum computing facility that aims to establish and sustain the state of the art in superconducting devices. With multiple cores that will be built with partnerships from academia, other federal research labs, and industry, we will harness the collaborative expertise of our field to drive innovation. We will learn what works and what doesn't work. What does not work, to a physicist, simply defines another application – a bug is always a feature in quantum mechanics. Every quantum device is good for something, we simply have to find its appropriate application.

Conclusion

The federal government can help tackle the most critical questions in QIS research and development with an independent, scientific view point: what is it good for, how does one know, and how do we achieve results? Industry, on the other hand, should be looking for novel use cases that can benefit society more immediately. Their research needs to be very applied with tangible benefit. They can also develop specific technologies to aid universities and national labs in their core quantum research and development mission. A healthier balance between industry and the research community can be achieved if high-risk, fundamental work is orchestrated by national labs.

Where there are linkages with national labs and academia, federal investment in industry activity may be warranted and even beneficial. But, policymakers should understand that quantum computing is not like classical computing where a consumer simply can purchase the latest and greatest technology. The state of quantum research is still very much in a developmental phase. Commercially available quantum technologies, while of course allowing one to test the waters in a given area, represent the totality of what can be built today. National labs can push the frontier much further by developing, honing and applying the expertise, resources, team science mentality, and long-term commitment needed for risky undertakings.

Finally, academia, national labs, and industry need a qualified quantum workforce to ensure U.S. leadership and the economic benefits following. Fortunately, QIS has had a tremendous galvanizing effect on young researchers, with talented minds from diverse scientific backgrounds eager to help usher in the era of quantum devices. To grow and sustain a highly skilled workforce, we need to create opportunities for the large pool of graduates who would like to pursue technology-focused careers that still have some of the flexibility and independence of academia. The Department of Energy national labs are a perfect home for such researchers, and sustained federal investment in quantum research and development will provide the means to attract graduates from STEM fields to shape the next generation quantum workforce.

Again, thank you for holding this important hearing and for the opportunity to testify. I am happy to answer any questions that you may have.