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THE DEPARTMENT OF ENERGY'S EFFORTS IN THE FIELD OF QUANTUM INFORMATION SCIENCE

HEARING

BEFORE THE

COMMITTEE ON ENERGY AND NATURAL RESOURCES UNITED STATES SENATE

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THE DEPARTMENT OF ENERGY'S EFFORTS IN THE FIELD OF QUANTUM INFORMATION SCIENCE

TUESDAY, SEPTEMBER 25, 2018

U.S. SENATE,
COMMITTEE ON ENERGY AND NATURAL RESOURCES,
Washington, DC.

The Committee met, pursuant to notice, at 10:08 a.m. in Room SD–366, Dirksen Senate Office Building, Hon. Lisa Murkowski, Chairman of the Committee, presiding.

OPENING STATEMENT OF HON. LISA MURKOWSKI, U.S. SENATOR FROM ALASKA

The CHAIRMAN. Good morning, everyone. Welcome to the Senate Committee on Energy and Natural Resources. We will come to order as we convene for a hearing on quantum information science (QIS).

As I came into the hearing room the hallways were packed with reporters and I thought, yes, we are finally here.

[Laughter.]

We have such excitement and enthusiasm about quantum information science. We do have a full committee room, and I think that is good.

I welcome each of you as experts in this area, an opportunity for us to learn more. We are here because our nation has never shied away from tackling the world's biggest scientific challenges. Whether mapping the human genome or landing on the moon, we have seen how committed research efforts can truly change the world.

Today we face another outsized scientific challenge. As computing power nears the realization of Moore's law, newer, faster, and more efficient means of computing will be required. That is where quantum computing, and the broader field of quantum information science, comes in. Quantum promises to revolutionize the speed and the scale at which we process data which could enable discoveries and advances that border on science fiction.

The potential reward from investments in quantum are tremendous, and we are hardly the only ones to recognize that. A number of other countries and the European Union (EU) are devoting significant sums to develop this technology, none more so than China which recently announced a $10 billion investment.

But I think we know here in this country that we always want to stay ahead of the curve. To that end the Department of Energy (DOE) is exploring ways to leverage resources and form partnerships to solve these challenges and that is a reflection of how we chose our witnesses today, with the Under Secretary for Science joined by representatives from the labs, university and industry.

We are very glad to have all of you here today, although I will note that it was another company, it was Intel, who caught my attention on this based on their decision to name a new superconducting test chip after a chain of lakes in Alaska. This is Tangle Lake, which is also a reference to the extreme cold temperatures and snarled state that quantum bits desire to function.

The technology is complicated, so I am going to leave those details to you and ask you to help educate us, again, as our expert witnesses. But, I think, also recognizing opportunities that exist with quantum are also easy to understand, quantum science could allow for breakthroughs in energy, medicine, communications and almost every other facet of our lives. So great possibilities here.

I am proud to be working with the House Science Committee and the Senate Commerce Committee on quantum legislation. I am glad to see strong interest in this subject, as evidenced by the Administration's summit on quantum which was held yesterday at the White House.

We have a lot of work in front of us and, as that proceeds, I want to make clear that funding for quantum is not a replacement for the investments that we need to make in supercomputing and exascale computing. Instead, we should see quantum as a tool that will augment and improve our nation's computing capability and work in tandem with more traditional computing capabilities.

Again, I look forward to hearing from our distinguished panel. I will turn to Senator Duckworth this morning for her opening comments. Thank you for being here this morning and filling in for Senator Cantwell.

STATEMENT OF HON. TAMMY DUCKWORTH, U.S. SENATOR FROM ILLINOIS

Senator DUCKWORTH. Thank you, Madam Chairwoman, and thank you for scheduling this important hearing to examine the Department of Energy's efforts in the field of quantum information science.

The only thing I know about quantum information is I can spell it.

[Laughter.]

The CHAIRMAN. We are learning.

Senator DUCKWORTH. We are learning, we are learning.

But it certainly is vital to, not just science, but our economic competitiveness on a global scale.

Quantum information science is a wide-ranging area of research that is expected to lay the groundwork for the next generation of computing as well as an array of other innovative technologies. Quantum technologies can result in breakthroughs with applications in sensing, communications, computing and simulation. They also have potential to address some of the world's most challenging problems and the United States is poised to be a leader in this development.

Researchers at private companies, universities and national labs across the country, but especially in my home State of Illinois, are leading in the development of quantum technologies. Although most states do not have any national labs, Illinois is blessed with two. Both Fermi and Argonne are global leaders in the area of quantum information science. For example, in Illinois we have the Chicago Quantum Exchange which is a collaboration between the University of Chicago, Argonne and Fermi for advancing academic, industrial and governmental efforts in the science and engineering of quantum information. These partnerships between the private sector, universities and national labs create efficiencies for research and they must be well funded to continue making progress in this field.

I am pleased that the Department of Energy plans to invest just over $100 million in quantum-related research next year. And just yesterday, I am pleased to announce that DOE announced $218 million in funding in this field. DOE should continue and expand its quantum research program for both fundamental science and providing access to the necessary science infrastructure. Quantum information science research is primarily basic, fundamental scientific research at this stage, and there is a clear federal role in making these science investments. These investments will be pivotal in maintaining U.S. leadership for quantum technologies and ensuring that the United States' competitiveness while other countries like China are also investing billions in research. As we continue to invest more into research and infrastructure of quantum sciences, it is clear that there will be an increasing need for people to perform jobs in this growing industry. This is the future. The Department of Energy should work with other federal agencies and these existing regional collaborations to develop a program to ensure that there will be a qualified and trained workforce for future quantum development.

I would like to end my remarks by extending a warm welcome to all of the witnesses and to give special thanks to Dr. Guha who is testifying today on behalf of Argonne National Laboratory. Dr. Guha is a Senior Science Advisor at Argonne National Laboratory and the Director of the Center for Nanoscale Materials there. He is also a Professor at the Institute for Molecular Engineering at the University of Chicago. Dr. Guha came to Argonne at the University of Chicago in 2015 after spending 20 years at IBM Research where he was Director of Physical Sciences. While there, he pioneered the Materials Research that led to IBM's high dielectric constant metal gate transistor, one of the most significant developments in silicon microelectronics technology. Dr. Guha has specialized in the discovery science of new materials for information processing (IP). I am personally thrilled he is with us today.

So, once again, I thank the Chair for holding this very important hearing, and I look forward to the testimony of our witnesses.

The CHAIRMAN. Thank you, Senator Duckworth.

We will begin with our panel which will be led off this morning by the Honorable Paul Dabbar, who is the Under Secretary for Science for the Department of Energy. Welcome back to the Committee.

He will be followed by Dr. Supratik Guha, who has just been introduced by Senator Duckworth, who is jointly associated with the University of Chicago and Argonne National Lab. Welcome.

Mr. Todd Holmdahl is the Corporate Vice President, Quantum, with Microsoft.

Rounding out the panel we have Dr. Irfan Siddiqi, who is the Director of Berkeley Quantum. This is a strategic partnership between Berkeley Lab and UC Berkeley.

We welcome each of you to the Committee. We ask that you try to keep your comments to about five minutes. We will have an opportunity for questions and your responses following that.

Under Secretary Dabbar, if you would lead us off.

STATEMENT OF HON. PAUL M. DABBAR, UNDER SECRETARY FOR SCIENCE, U.S. DEPARTMENT OF ENERGY

Mr. DABBAR. Thank you, Chairman Murkowski and Acting Ranking Member Duckworth and members of the Committee, I'm pleased for this opportunity to discuss the emerging field of quantum information science to highlight the potential for our nation's continued economic competitiveness and national security.

First, I would like to thank this Committee and the whole Chamber for the support on innovation in sciences. The amount of focus of resources that have been applied are at an all time high, and we very much appreciate the leadership of this Committee and the others on the investment and innovation for this country.

QIS represents a new frontier in information technology. Unlike today's computers, which rely on transistors, quantum applications use elementary particles like photons or electrons to store and use data. Such applications are challenging but they also open new opportunities.

They are needed because Moore's Law, which was predicted by Intel's co-founder, Gordon Moore, that the computing capacity would double on a regular basis is slowing down due to physical limitations. Transistors are now down to the size of three atoms. It's becoming increasingly difficult for us to go even further. That's where the Department comes in since we have a long history as a global leader in computing as well as in particle physics which are the two enabling technologies.

This past June our summit supercomputer at Oak Ridge was named the fastest supercomputer in the world and the most powerful artificial intelligence machine in the world. Today, we're actively pursuing exascale. The promise of quantum computing is complementary to classical information systems while holding the potential to do some computations more successfully and more speedily than classical systems.

There are three main types of QIS applications: Quantum Computing, Quantum Networking and Quantum Sensing. Let me give you one example of each. In Quantum Computing, utilizing the properties of individual photons or electrons to store information can dramatically increase calculations. If we hit a 50-qubit computer, for quantum computers we will have the capabilities equal to the current capacity of our high-end, high-performance computers, and we are on track to potentially produce machines that are more than double that target which would lead to computers with 10 to the 15th more computing power than what we currently have—very large number.

Quantum Networking would allow us to transmit quantum entangled data through the quantum internet, and Quantum Sensing technology will enable detection of physical properties such as magnetic fields at very small scales such as at the individual cellular level of a human's body. We might be able to map every individual cell in a human, leading to jumps in medicine that are vast such as individual cell, cancer cell, targeting.

Yet, developing quantum information systems presents challenges of physics and physical sciences. The national labs are leaders in basic research in these areas. As you may remember, 40 percent of all the world's Nobel prizes in physics were awarded to researchers who did work in our national labs.

To accelerate our efforts, we announced yesterday $218 million in funding for 85 projects at our national labs and in universities at yesterday's White House event. Among those are the creation of two quantum test beds which will operate in similar ways to our national lab user facilities. As a part of that effort we will continue to work with our sister agencies, the DoD, NSF and NIST.

We continue to achieve these goals can be done by creating cross-cutting technology centers and the DOE has done that, as was mentioned by the Chairman, in such past grand challenges as the Manhattan Project and the Human Genome Project.

Similarly we have been reviewing setting up quantum centers and we believe that setting these up allow a diverse set of bidders, including national labs, universities and private industry consortiums, to allow for the best competition of ideas.

The National Quantum Research Information Center set forth in the draft bill holds great promise. We previously pioneered this model of research of centers across our national lab complex. While it is important for us to sustain our research, in addition, at individual and small research efforts like we announced yesterday, establishing three to five national quantum centers would anchor the national program to ensure discoveries would rapidly translate from technological advances.

Moore's Law is bringing us to the limit of conventional computing but the DOE's national labs specialize in breakthrough boundaries and opening possibilities so, with our partners, we intend to open new frontiers in quantum applications and build a stronger nation.

[The prepared statement of Mr. Dabbar follows:]

STATEMENT BY

THE HONORABLE PAUL M. DABBAR

UNDER SECRETARY FOR SCIENCE

U.S. DEPARTMENT OF ENERGY

BEFORE THE

SENATE ENERGY AND NATURAL RESOURCES COMMITTEE

ON

AMERICAN LEADERSHIP IN QUANTUM TECHNOLOGY

SEPTEMBER 25, 2018

Thank you, Chairwoman Murkowski, Ranking Member Cantwell, and Members of the Committee. I am pleased to come before you today to discuss the emerging field of Quantum Information Science (QIS), to highlight its potential in our Nation's continued economic competitiveness, and to describe the Department of Energy's new initiatives in this area.

QIS represents a new frontier in information technology. Using elementary particles like photons and electrons to store and use data, quantum applications vary from classical computing, which relies on larger transistors and silicon chips.

While the potential of quantum computing has long been recognized in theory, the need to bring it to practice arises from the slowing down and predicted end of Moore's Law. Moore's Law is the famous 1965 prediction of Intel co-founder Gordon Moore that computing power would double every year; then every two years. For over half a century, Moore's Law has defined the trajectory of the Information Age. Moore's overall prediction is still holding, but the pace of growth in computing power is slowing down. There is general agreement that Moore's Law will eventually encounter unsurmountable barriers.

"Classical" physics contains physical limits, while quantum effects could potentially provide a way around these limitations.

Accessing the quantum world has been made possible through changes in the development of nanoscience, the increasing sophistication and capabilities of x-ray light sources and other instruments and our emerging ability to synthesize novel materials.

QIS can be viewed theoretically as a marriage of information theory—the mathematical foundation for information processing developed in the late 1940s—and quantum theory—a major revolution in physics from the early part of the 20th century. QIS applications differ from applications of quantum mechanics by exploiting distinct, non-classical behavior:

- Superposition—quantum particles or systems exist across all their possible states at the same time, with corresponding probabilities, until measured.
- Entanglement—a superposition of states of multiple particles in which the properties of each particle are correlated with the others, regardless of distance.
- Squeezing—a method of manipulating noise in systems that obey the Heisenberg uncertainty principle, by permitting large uncertainty in one variable to improve precision in another correlated variable.

Quantum computing depends on superposition. Instead of relying on bits with a definite value of 1 or 0, quantum computers are composed of qubits in an "in-between" state of superposition. QIS applicability extends well beyond computing and information processing. Other fundamental science topics are benefitting from advance in quantum information:

- Probes of biological cells for advanced drug development;
- the search for dark matter;
- the emergence of space-time;
- furthering Einstein's interpretation of gravity;
- testing fundamental symmetries;
- materials design at the atomic level;
- calculations of molecular catalysis;
- nuclei and particle energy calculations;
- advanced sensor and detector fundamental research; and
- sensing and metrology.

Because QIS will open new vistas for both science and technology development, as well as new commercial markets, the U.S. and other countries are increasing investments in related basic research and technology development.

International Landscape

Worldwide interest in QIS has increased substantially in the past five years. Global investments and developed long-term strategies have shifted the distribution of top-tier research groups. Because many foreign governments are providing strong support to QIS and related technologies, academic researchers in the U.S. have expressed concern that their foreign counterparts have better access to novel materials and custom optics. Some foreign QIS activity follows:

- The largest quantum information science and technology programs outside the U.S. are in the European Union (EU) and China. In 2016, the EU announced a €1 billion ($1.1 billion USD), 10-year Flagship initiative . This is only the third EU Flagship project in future and emerging technologies; the prior ones, launched in 2013, are on Graphene and the Human Brain Project. China dominates Asian investment in QIS research and development with a large, rapidly growing program that initially focused on secure communication, including the widely publicized launch of an experimental quantum communications satellite in 2016, and is now expanding to other areas. The Chinese program includes industry partnership and lucrative offers to recruit top talent abroad.

- The U.K. and Canada have made high-profile budget investments in QIS. The U.K. has four hubs, partnering between universities and industry, on sensors, imaging, networking, and computing. The U.K. has also invested more than £200 million/$255 million USD in student and postdoctoral training. Canada's program was spearheaded by private investment aiming to make their Waterloo the quantum equivalent to Silicon Valley. Their Perimeter Institute and University of Waterloo lead QIS, ranging from blue-sky theory to practical devices and algorithms, and awarded $76 million CAD/$56 million USD in 2016 from the Canada First Research Excellence Fund.
- Australia and the Netherlands have made targeted, high-profile investments in quantum computing. Australia's 2016 National Innovation and Science Agenda included a $70 million AUD ($53 million USD) public-private partnership to advance quantum computing for commercial applications that is complementary to a new $33 million AUD ($25 million USD) fundamental research effort to support the scale-up of silicon quantum integrated circuits. The Netherlands is also home to a government-funded quantum software research center.
- A number of countries without a coordinated national QIS agenda or initiative nonetheless have strong, well-funded research groups, including Germany, Austria, Switzerland, Japan, and Singapore. Russia and Brazil also appear to be building national research communities.

To maintain leadership in this "next frontier" of science, the U.S. must build on its investment in QIS to generate new technologies and, ultimately, important new commercial opportunities. Federal agencies have supported research in QIS and related areas since the field emerged over 20 years ago, with basic and applied federally-funded research now supported at more than $200 million annually from agencies such as the Department of Defense, the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), and the Department of Energy (DOE). In FY2018 DOE invested $62.38 million, and DOE is working on the FY2019 plan at this time at a level of approximately $120 million.

Summary of Scientific Challenges and Office of Science-Specific Efforts to Date

Several program offices in the Department of Energy's Office of SC (SC) have important roles in QIS research and development.

Quantum Science—Coherence and Entanglement of Quantum States

Materials and Synthesis

The SC's Office of Basic Energy Sciences (BES) is focusing on research for materials synthesis and processing. Materials synthesis is required for quantum systems to address a basic science gap preventing "synthesis by design." This requires establishing generalized rules of assembly for complex materials in different platforms, to understand and control phases of quantum materials. New functionalities could include superconductivity and robust entangled states approaching room temperature, or dissipationless charge and spin transport relevant to quantum computation, neuromorphic computing, and ultra-low loss digital computation beyond silicon. Conversely, understanding of fundamentals of competitive heat/electron transfer could demonstrate limitations on quantum computation.

Instrumentation for Quantum Control: Sensing and Metrology
Two offices in SC are addressing instrumentation development for measurement and control of quantum phenomena. The Office of High Energy Physics (HEP) is developing specialized cavity sensors for detecting new particles and quanta in previously inaccessible frequencies and with greater sensitivity. Such quantum technologies could inform particle physics experiments. BES is characterizing quantum materials through scattering, spectroscopy, and imaging of quantum materials using neutrons, x-rays, and electrons as probes. This could lead to the discovery of new materials and inform theories that predict and explain their properties.

Theory and Modeling of Quantum Entanglement
QIS research has informed particle physics work on relationships among quantum fields, black hole physics, and information entanglement, invoking quantum error correction codes and quantum gravity. Tensor networks provide new models to understand fields, particles, and their interactions. BES is exploring quantum computing to enable fast algorithms for computation of quantum entanglement. Decoherence in entangled systems could potentially be understood via molecular magnets. SC's Office of Advanced Scientific Computing Research (ASCR) plans to explore partnerships with other SC offices to develop tools and algorithms for modeling and simulations, in order to accelerate the computation and understanding of quantum entanglement in different systems.

Quantum Devices and Systems for Computing, Information, and Other Applications

Qubit Technologies
Qubits are the basic building blocks for quantum computing that embody superposition of states. Implementing these systems involves a variety of issues, including specific material properties, manufacturability, scalability, stability, integration, and other concerns. Some potentially useful materials for qubit systems include high-temperature superconductors, trapped ions, quantum dots, nitrogen-vacancy complexes (NV centers) in localized defect structures, topological insulators and two-dimensional electron gas (2DEG) systems that support the fractional quantum Hall effect, miniaturized skyrmions, and nano-magnets. BES research and facilities already encompass investigations in many of these areas, including the five Nanoscale Science Research Center (NSRC) user facilities to advance the fabrication and testing of these materials.

Quantum Sensors and Detectors
Many devices developed as a qubit system for quantum computing can also be used as a quantum sensor, with potential applications to precision measurements and detection of particles across the entire range of SC topics. Electronic, magnetic, and structural properties and ultrafast dynamics can be investigated with tools including pump-probe experiments at femtosecond resolution, ultra-high field neutron scattering, angle-resolved photoemission, and scanning probe imaging. Ultrasensitive magnetometers can be constructed based on NV centers, and single-photon detectors based on quantum aspects of superconducting materials. The NSRCs supported

by BES can fabricate over the necessary spatial and temporal scales, and utilize extensive characterization capabilities through SC user facilities and National Laboratory capabilities. Detectors and superconducting radio-frequency technology for nuclear physics experiments also may be relevant to instrumentation for quantum control.

Fabrication and Testbeds

Testbeds provide the research community with access to early stage devices, accelerating the development of hardware well-suited to scientific computing as well as applications that make effective use of new hardware. They can potentially serve as standardized environments for preserving coherence, extent of entanglement, and other key criteria. Testbeds can also facilitate comparison of different devices and can develop production-quality software for novel computing architectures.

ASCR issued a program announcement to DOE National Laboratories for research into development of quantum testbeds in April 2018. Multidisciplinary efforts to explore the suitability of implementations of quantum devices for science applications will advance engineering of quantum information systems and perhaps overcome practical limitations. Strong collaboration among government agencies, academia, and industry will enable device fabrication and testbeds. National Laboratory facilities are well-positioned in capabilities and infrastructure to enable the needed collaborative integration of advanced synthesis, fabrication, characterization, theory, modeling, testing, benchmarking, and development-to-scale.

Novel Architectures, Quantum Simulators/Emulators, and Systems-Level Control

Exploring novel architectures from the device level through the system level will allow DOE to invest in the quantum computing technologies best-suited to mission needs. Some applications, such as quantum chemistry, appear to benefit from an approach that pairs classical feedback with inherently quantum processing. Other applications may run best on a larger quantum processor with classical computing only required for control. Qubit simulators will facilitate early exploration of architectures; emulators that parameterize key features of larger quantum devices will allow efficient system-level design that can proceed hand-in-hand with research and development in systems-level control.

Algorithms

DOE generally, and its SC programs in particular, have extensive computational problems to solve; quantum computing can support a robust and versatile set of algorithms. Research into quantum speedups for linear algebra, integration, optimization, and graph theory could ultimately facilitate performing a wide variety of scientific computing tasks. An initial program announcement to DOE National Laboratories regarding the development of quantum algorithm teams was released by ASCR in May 2017.

Software Implementation and Reliability

Realizing quantum computing's potential will require advances in hardware and algorithms, and advances in optimizing languages and compilers to translate these abstract algorithms into concrete sequences. A systematic research agenda to develop a software infrastructure from high-level languages to debuggers and benchmarking metrics, when executed in coordination with hardware and architecture design, will also lead to effective strategies that find balance between systems-level control and error correction.

Quantum Networks and Complexity
Significant research effort is needed to develop, test, and deploy continental scale Quantum Wide Area Networks composed of many nodes, multi-hops, multi-users, and high-speed optical quantum channels. High-performance quantum communication network components are needed to secure distributed quantum systems processing and sharing data sets over continental distances. Critical components include quantum communication network hardware, architectures, and protocols; quantum-enabled software defined networks; and all-optical network extension for quantum key distribution (QKD) and understanding QKD security loopholes.

FY 2018 DOE Office of Science Initiative in QIS

The Department recently announced $218 million for new research awards in QIS sponsored by ASCR, BES, and HEP at both universities and national laboratories.

ASCR's awards (total $81 million) will support the development of both hardware and software for quantum computing, and the creation of two additional Quantum Testbed sites, one at Sandia National Laboratories and the other at Lawrence Berkeley National Laboratory. These sites will provide prototype quantum computers and related instrumentation on an open, competitive basis to a community of outside users, similar to the Office of Science X-ray light sources or the Leadership Computing Facilities at Argonne and Oak Ridge National Laboratories Users will harness quantum computing in the effort to address real-world research problems. ASCR is also providing substantial support for algorithm and software application development for quantum computing.

BES awards (total $106 million) cover both research and facilities. Areas of research include: controlling the quantum dynamics of nonequilibrium chemical and materials systems; unraveling the physics and chemistry of strongly correlated electron systems; embedding quantum hardware in classical frameworks; and bridging the classical–quantum computing divide.

To address the challenge of new materials synthesis, a second category focuses on basic experimental and theoretical research on the discovery and characterization of quantum phenomena to enable the design and discovery of novel quantum materials and information systems. Areas of research include: synthesis of materials for the development of quantum coherent systems that involve *in situ* characterization and real-time machine learning and target quantum information functionality; creation and control of coherent phenomena in quantum systems emphasizing an improved understanding of entanglement and enhanced coherence lifetimes; and transduction of quantum coherent states between disparate physical systems (light, charge, spin) with high fidelity. BES is also providing $33 million for the Department's five NSRCs, focused primarily on synthesis of new quantum materials at the nanoscale.

HEP awards (total $31 million) focus on connections between cosmic phenomena like information scrambling in black holes and quantum error correcting codes, in five areas: collaborative research on quantum gravity, information theory, and entanglement, with simulations on qubit systems aimed at study of the universe; foundational field theory development, along with tests on nascent quantum computers and emulators; quantum computing for innovative data analysis and to model cosmic quantum phenomena; potential adaptation of HEP developed tools and technology such as superconducting radiofrequency cavities and quantum controls for improved qubit performance; and exploration of the potential of highly sensitive quantum-based sensors to detect elusive phenomena such as neutrinos or candidate dark matter particles.

The Path Forward

DOE is committed to a strategic approach to the next steps in QIS. The Department of Energy's Office of Science has unparalleled capacity to support foundational, and therefore path-breaking, original research—leveraging the strengths of the nation's higher-learning institutions, and the unique capabilities of the DOE National Laboratories, with their unsurpassed scientists, intellectual property, and suite of scientific user facilities and other advanced instrumentation. It is critical for American economic competitiveness that U.S. research efforts in QIS systematically capture the valuable intellectual property likely to flow from new discoveries.

Conclusion

The DOE QIS FY 2018 awards are a strong first step, with very enthusiastic response to these QIS solicitations from scientists in the ASCR, BES, and HEP communities. Universities and the DOE National Laboratories are poised to generate new insights and approaches to information processing and other technologies. With strategic investments, America can remain on the leading edge of this next frontier of Information Age science and technology. I look forward to answering questions from the Committee.

The CHAIRMAN. Thank you, Secretary Dabbar.

Dr. Guha, welcome to the Committee.

STATEMENT OF DR. SUPRATIK GUHA, PROFESSOR, INSTITUTE FOR MOLECULAR ENGINEERING, UNIVERSITY OF CHICAGO, AND DIRECTOR OF THE CENTER FOR NANOSCALE MATERIALS AND SENIOR SCIENCE ADVISOR, ARGONNE NATIONAL LABORATORY

Dr. GUHA. Chairwoman Murkowski, Ranking Member Duckworth and members of the Committee, thank you for the opportunity to appear before you today to discuss the status of quantum information sciences and the role and efforts of the U.S. Department of Energy national laboratories in this regard.

I'm Supratik Guha, a professor at the Institute for Molecular Engineering at the University of Chicago and Director of Argonne National Laboratory's Center for Nanoscale Materials Facility supported by the DOE Office of Science.

Quantum information sciences exploits the unique properties of quantum mechanics to rapidly explore information spaces in a connected manner, rather than the sequential manner of conventional information processing. Building machines and devices that exploit this property, we then expect enormous advantages in certain types of computing such as codebreaking, in the design of molecules for areas such as drug discovery and in the secure transmission of data.

Advances also extend to the measurement, with unprecedented accuracy, of physical parameters important in areas such as geopositioning, as well as the basic sciences, a field known as quantum sensing. The potential impacts are remarkably broad, from sensing within living cells to using highly precise atomic clocks to try to answer the fundamental questions, for instance. Are some of the physical constants we assume in science to be constant really constant?

The time to significantly expand our efforts in quantum information is now, because this technology will offer critical differentiating advantages to the leader. And what is needed is an effort that is broad in scope, spanning science as well as engineering.

This is where the DOE national laboratories come in. They have the size, the massive experimental capabilities and the multidisciplinary skills from computing systems to physics and material science under one roof as well as the professional staff and management skills to deliver on large, complicated projects. Working in close collaboration with industry and academia, which is essential, the national labs can be anchors for future research in quantum information sciences. The DOE labs have a proven track record. From the 1940s through the 1960s, Argonne played a major role in developing nuclear reactor technology. More recently, the DOE national labs, working with computer companies and academic partners, anchored the development and scientific utilization of supercomputing.

The science community is a strong supporter of the DOE laboratory system and is well connected historically through the laboratories' various user facilities such as the light sources, the Nano

Science Research Centers and the computing facilities and the neutron sources.

Quantum advances will require a multidisciplinary vision and a new workforce of quantum engineers who are intimately familiar with quantum mechanics. This philosophy is behind the newly-formed Chicago Quantum Exchange, a collaboration between Argonne, Fermi National Accelerator Laboratory and the University of Chicago involving over 60 scientists from these three institutions.

As an example, the Chicago Quantum Exchange recently has begun research, funded by the DOE, on establishing a 30-mile optical fiber link between Argonne and Fermilabs as a testbed for studying quantum entanglement and teleportation for secure information transfer. This is not something a university could have done on its own and highlights the unique benefits to such national laboratory-university partnerships.

Aiming to create a workforce, the Chicago Quantum Exchange has begun a program, funded by the National Science Foundation, to match students and their academic advisors across the country with industrial and national laboratory members, and this is with students graduating from universities all across the United States. The nearly 20 University of Chicago faculty attached to the Quantum Exchange are some of the world's leading experts in quantum science, and they administer one of the first Ph.D. programs in quantum engineering in the world.

It is also almost certain that quantum information sciences will bring many applications that are as yet unknown, but which will significantly affect our lives. It is, therefore, important to have breadth in our activity going forward, in sharing information and data and drawing from the intimate connections between thought leaders in academia, industry and the national laboratories.

Thank you for your time and attention. I will be happy to respond to any questions you might have.

[The prepared statement of Dr. Guha follows:]

Testimony of Dr. Supratik Guha
Professor, Institute for Molecular Engineering, University of Chicago, and Director of the Center for Nanoscale Materials and Senior Science Advisor,
Argonne National Laboratory,
before the
Senate Committee on Energy and Natural Resources
September 25, 2018

Chairwoman Murkowski, Ranking Member Cantwell, and members of the committee, thank you for the opportunity to appear before you today to discuss the status of quantum information sciences field, and the role and efforts of the U.S. Department of Energy (DOE) national laboratories in this regard. I am Supratik Guha, a professor at the Institute for Molecular Engineering at the University of Chicago, and director of Argonne National Laboratory's Center for Nanoscale Materials facility, supported by the DOE Office of Science.

Quantum information sciences exploits the unique properties of quantum mechanics to rapidly explore information spaces in a connected manner, rather than the sequential manner of conventional information processing. Building machines and devices that exploit this property, we then expect enormous advantages: in certain types of computing such as codebreaking; in the design of materials and molecules for areas such as drug discovery; and in the secure transmission of data. Advances also extend to the measurement, with unprecedented accuracy, of physical parameters important in areas such as geopositioning as well as in basic science—a field known as quantum sensing. The potential impacts are remarkably broad, from sensing within living cells to single-molecule magnetic resonance imaging. As another example, by using highly precise atomic clocks based upon the principles of quantum mechanics, we can try to answer the fundamental question: Are some of the physical constants we assume in science, really constant?

Every once in a while, a technology appears that offers the potential to change our world, and we should seriously recognize quantum information sciences as such a candidate. However, this is still early stage, and there is a lot to be done in developing the science and creating the technology to make quantum information sciences usable for the public good. But the time is now, with China as well as European nations ramping up their investments in this area. It is also imperative for the U.S. to maintain its edge in this field because this technology will offer critical differentiating advantages to the leader.

In the past, companies such as Bell Labs and IBM carried out the bulk of the pre-competitive research and early development of some landmark technologies. Silicon microelectronics and telecommunications are examples. Today, the costs and complications of current cutting-edge research make it no longer possible for industrial research and development to do it all. This is where the DOE national laboratories come in. They have the size, the massive experimental capabilities and the multi-disciplinary skills from computing systems to physics and materials science under one roof, as well as the professional staff and project management skills to deliver on large, complicated systems and programs. Working in close collaboration with industry and academia, the national labs are ideal places to offer the intellectual and infrastructural breadth that is required to anchor future research in quantum information sciences.

Indeed, the DOE national laboratories have a proven track record in working with industry and academia to convert science into impactful technology. From the 1940s through the 1960s, Argonne National Laboratory played a major role in developing nuclear reactor technology for civilian nuclear power. More recently, the DOE national laboratories, working with computer companies and academic partners anchored the development and scientific utilization of supercomputing. Almost every major drug company has worked with the DOE national laboratories and benefitted enormously from the information on protein structure determined using their advanced X-ray light sources. The science community strongly supports the DOE laboratory system and is well connected historically through the laboratories' various user facilities including the Nanoscale Science Research Centers, the advanced light and neutron sources and computing facilities. The contributions of DOE-sponsored university research is yet another traditional connection between DOE and academia.

Developing quantum information science into a technology will require a new workforce of quantum engineers who are intimately familiar with quantum mechanics. This workforce does not currently exist. Quantum advancements also will require a multi-disciplinary research vision that is purpose driven, with teams drawn from academia, industry and the national labs. This philosophy is behind the newly formed Chicago Quantum Exchange, a collaboration between Argonne, the University of Chicago and Fermi

National Accelerator Laboratory, involving over 60 scientists from these three institutions. The Chicago Quantum Exchange recently has begun research, funded by the DOE, focused on establishing a 30-mile optical fiber link between Argonne and Fermilab as a testbed for studying quantum entanglement and teleportation for secure information transfer. This quantum triangle represents a unique multi Lab-University collaboration, using the science basis of entanglement coupled to the technical and network expertise of the labs. It highlights the unique benefits that DOE's national laboratory network brings: the possibility to immediately respond to a major emerging scientific challenge, to draw from intimate connections between thought leaders both in academia and industry, and to convene the necessary intellectual depth and technological infrastructure to advance the nation's interests.

Aiming to create a workforce, the Chicago Quantum Exchange has begun a program, funded by the National Science Foundation, to match students and their academic advisors across the country with industrial and national laboratory mentors. So far, 21 such students have been matched in less than one year. The nearly 20 university faculty attached to the Chicago Quantum Exchange are some of the world's premier experts in quantum information science and they administer one of the first Ph.D. programs in quantum engineering in the world.

We should keep in mind that while we have clear ideas of some of the benefits that quantum information sciences will bring, it is almost certain there are many applications that are as yet unknown, but which will significantly affect our lives. It is therefore important to have breadth in our activity going forward, and diversity of thought. This is yet another area where the DOE laboratories excel, with their range of scientific skills.

Thank you for your time and attention. I would be happy to respond to any questions that you might have.

The CHAIRMAN. Thank you, Dr. Guha.

Mr. Holmdahl, welcome.

STATEMENT OF TODD HOLMDAHL, CORPORATE VICE PRESIDENT, QUANTUM, MICROSOFT CORPORATION

Mr. HOLMDAHL. Chairman Murkowski, Ranking Member Duckworth, members of the Committee, thank you for the opportunity to share Microsoft's perspectives on quantum computing.

My name is Todd Holmdahl. I run the Quantum Computing Group at Microsoft. We've been investing in quantum computing for over the last 15 years. We've amassed a team of computer scientists, scientists and engineers in order to produce a scalable, commercial, quantum computer.

Now, quantum information science is a very big topic. We are specifically focused on building a scalable, commercial, quantum computer built on a high quality, high fidelity qubit. The benefits of quantum computing are many. You can see benefits in terms of energy, food production. You can see it also in terms of climate change, different materials optimization.

One area where we believe that quantum computing can solve a big problem is in terms of producing artificial fertilizers. Today, three percent of the natural gas produced in the world is used to produce artificial fertilizers. The process we use is 100 years old. It was started in the 1900s. It's at a very high temperature and a very high pressure. But we know that there are microbes in the world that can do the exact same thing at a much lower temperature and a much lower pressure, and we believe that a quantum computer can figure out the secrets of what those microbes are doing so that we can produce the same fertilizer at a much lower energy and a much lower cost.

Now everything that's hard needs investing in, in order to realize its full potential. We recommend that the Committee look at investing in quantum computing in three different ways.

First, invest in the quantum workforce. We have very few people who are ready to produce quantum computers. You need engineers. You need scientists. You need computer programmers in order to do that. We recommend that industry, academia and universities develop curriculum that can be posted online or be taught at universities. We recommend on-the-job training for engineers that are already in the field. Many of these engineers have the foundation, but they don't have all the skills necessary to join the quantum workforce and on-the-job training would help that. And the third thing we recommend, is looking at a national program for quantum computing. I've done many products at Microsoft. This is by far the most interesting science and technology out there.

The second recommendation we have for the Committee to look at is in basic research around the fundamentals of quantum computing, particularly in looking at a scalable qubit. The qubit is the fundamental computational element of a quantum computer. It's very fragile. Most of these qubits are operated at 20 millikelvin at almost Absolute Zero, and we need to develop the materials and the fabrication and the manufacturing processes in order to make these things stable so that we can have these big, large-scale quantum computers.

The third thing we recommend is the development of quantum software algorithms. The algorithms that you run on a quantum computer are completely different than the algorithms that you run on a classical computer. But even though we don't have quantum computers today, we can learn about these algorithms if we do a couple of things. One, we recommend that we take large, classical computers and simulate a quantum computer on these large, classical computers with simulation, and with a quantum development kit we can start working on these algorithms today so that when we have the quantum computers, the algorithms will be developed and built to be able to process and solve these big problems. The second thing we recommend is partnerships between academia and industry and the government. We, today, are in a partnership with Pacific Northwest National Laboratory and we're working specifically on solving some of their big, tough, chemistry problems. Quantum computers look like they will help solve these big problems and we're making incredible progress so that when we get the actual quantum computer, we can test it out right away.

An amazing space to be working in, the most exciting thing I've done in my career and, like anything else though, you need to invest in it in order to realize its potential.

Thank you.

[The prepared statement of Mr. Holmdahl follows:]

Written Testimony of Todd Holmdahl
Corporate Vice President, Quantum, Microsoft Corporation

Senate Committee on Energy & Natural Resources
Hearing to Examine Department of Energy's Efforts in the Field of Quantum Information Science

September 25, 2018

Chairman Murkowski, Ranking Member Cantwell, and Members of the Committee, thank you for the opportunity to provide Microsoft's perspective on the promise of quantum computing.

The quantum computing revolution is both essential and inevitable. Not only are we reaching the limit of how fast and small we can make conventional microprocessors, we also have an urgent need to solve problems that would tie up classical computers for millennia—but could be solved by quantum computers in a few hours or days.

The implications of quantum mechanics for technology are broad, spanning quantum information and communication, quantum sensing, quantum security, and quantum computing. But we believe the emergence of a quantum economy will primarily depend on the development of scalable quantum computing.

Microsoft has worked for nearly fifteen years to advance quantum computing, including working to develop a scalable, universal, programmable quantum computing system and to create the hardware and software required to support it. Our team of experts in quantum physics, mathematics, computer science, and engineering has collaborated with universities, industry, and government on cross-cutting research that aims to make scalable quantum computing a reality.

The United States has an opportunity to advance the "quantum economy" by supporting investments in research and development in quantum computing technology. Specifically, we encourage the Committee to:

- Invest in the quantum computing workforce, which will require not only quantum programmers, but also material scientists, fabrication and cryogenic engineers, and algorithm designers, among many others. By partnering with industry to develop curriculum and provide on-the-job training and by establishing a national program to build a quantum computer, the Department of Energy ("DOE") can ensure our workforce is ready for quantum computing technology.

- Support research to foster the development of scalable quantum computing technology, including by pairing quantum technologies with existing research. For example, DOE can identify, test, and help to advance quantum computing systems that promise scaling, thereby spurring new developments in reliable and scalable qubit technologies.

- Support the development of new quantum algorithms *today*, without waiting for advances in quantum hardware. For example, DOE can create a testbed to develop quantum algorithms and foster partnerships among academia, industry, and government that focus on programming and algorithm development.

These actions will encourage the development of quantum computing across industries and sectors, which can deliver broad economic and societal returns.

I. The Need for Quantum Computing

For centuries, science and technology have been at the heart of profound revolutions for mankind, from the printing press to electricity, steam engines, and the internet. Today, more than a century after the discovery of quantum mechanics, we sit at the threshold of an age in which quantum properties not only enable our digital devices but can revolutionize computer science and computer architecture.

Despite their sophistication, the classical computers we currently use are fundamentally limited in their problem-solving capabilities. There are some important problems so difficult that even if all the digital computers in the world worked on the problem in tandem they would still take longer than the lifetime of the universe to solve. That is because traditional computing relies on bits that store information as either 0 or 1. In quantum computing, quantum bits—known as qubits—can store information as either 0 or 1 or *both simultaneously*. This allows qubits to perform multiple calculations at once. As a result, quantum computers can solve problems in a fraction of the time it would take even the fastest conventional systems.

We should not expect quantum computers to power future personal computers or phones, because classical computers will remain cheaper, smaller, and more portable than quantum computers for many everyday tasks. Quantum computers show their strength when running specially designed quantum algorithms that solve certain problems faster (in some cases exponentially faster) than any classical computer. A quantum computer can therefore operate as an accelerator to a classical computer, much like a specialized processor, and can receive instructions and cues from a stack of classical processors.

Quantum computers hold the promise to solve some of our planet's biggest challenges—in energy, climate, materials, agriculture, and health. For example, with a quantum computer it becomes feasible to combat global warming by finding a way to efficiently capture carbon or to synthesize a new generation of environmentally aware smart materials. We believe these types of breakthroughs will be unlocked with a scalable, programmable quantum computer. And, like each scientific breakthrough that has come before it, we believe the promise of quantum computing can be achieved through continued discovery, investment, and learning. Increased investment in quantum computing will shorten the timeline for these important developments.

II. Microsoft's Investment in Quantum Computing

At Microsoft, we aspire to create a universal, programmable quantum system and to identify revolutionary, commercially-impactful applications to run on it. We focus on three issues: developing a scalable and reliable qubit, creating a full-stack end-to-end quantum system, and fostering a collaborative approach that brings together academia, government, and industry experts in physics, mathematics, engineering, and computer science to drive innovation.

A. Scalable Qubits

One of the most significant hurdles in quantum computing is the fragile nature of qubits. Even the slightest interference can cause qubits to collapse, destroying the information they contain. As a result, it is extremely difficult to keep a quantum computation on track.

At Microsoft, we believe the *quality* of qubits is the key factor in creating useful scale for quantum computing. Today's mainstream qubit approaches are inherently noisy. But scaling this technology requires reliable qubits with extremely high fidelity. One way of increasing fidelity is called quantum error correction, a process that combines multiple noisy *physical* qubits to create a single *logical* qubit of higher fidelity. But if physical qubits are too noisy, this process becomes more expensive and can require more than 10,000 physical qubits to represent a single logical qubit.

Microsoft is therefore focused on using topological qubits which, by their nature, are extremely reliable. These materials are exotic low-temperature systems in which individual qubits and their attendant quantum computations are naturally protected from noise. A topological qubit, unlike other qubits, is built in a way that inherently protects the information it holds and processes. It can therefore perform longer or more complex computations with greater accuracy than other methods. Because of the higher fidelity of these topological qubits, fewer of them are needed to achieve fault-tolerant computation. That means we can dramatically reduce the number of physical qubits a quantum system needs in order to solve real-world problems.

Topological qubits achieve this additional protection in two ways:

- **Ground state degeneracy.** Topological qubits are engineered to have two ground states—known as ground state degeneracy—making them more resistant to environmental noise than standard qubits. This is not feasible in normal systems, which cannot distinguish between the two ground states. Topological systems can use processes like braiding or measurement to distinguish those states and achieve additional noise protection.

- **Electron fractionalization.** A topological state is one in which an electron can be split (or "fractionalized") so that it appears in different places within a system. Splitting the electron achieves a protection akin to data redundancy, because it means that the quantum information is stored in both halves of the electron. As a result, it is harder to disturb because doing so requires disturbing each place where information in the electron is stored at the same time. This increases reliability because it means that if one half of the electron encounters interference, enough information is stored in the other half that the qubit may continue its calculations. The farther apart these pieces of electrons are stored, the greater protection the topological qubit provides.

B. Full-Stack Quantum System

Microsoft is developing a "full quantum stack" that consists of scalable quantum hardware, software, and a control system to program the quantum computer, as well as the applications and algorithms to run on it.

Building a quantum computer requires not only manufacturing physical quantum computing devices, but also engineering the cold electronics and refrigeration systems needed to store and control qubits at temperatures close to absolute zero to minimize noise and interference. The system also requires software to program the quantum computer, including an advanced cryogenic classical computer to interact with the quantum computer, a runtime software platform, and application development tools. At Microsoft, we have created a quantum-focused programming language and suite of development tools to empower the broadest set of customers to benefit from quantum technology; we also expect to enable users of our Azure service to access quantum processing alongside classical processing and data storage, for a streamlined solution-improving experience.

C. Cross-Disciplinary Approach

Microsoft aims to connect experts in industry, academia, and government to make quantum computing a reality. Our team has brought together mathematicians, condensed matter theorists, engineers, and computer scientists to drive new computation capabilities. Our global team extends to TU Delft, Niels Bohr Institute at the University of Copenhagen, University of Sydney, Purdue University, University of California at Santa Barbara, and partners with over a dozen other academic and scientific institutions around the world. Our quantum team in Redmond is also focused on developing software for emerging quantum hardware systems and the necessary cryogenic control components. Together, our teams combine theoretical insights with experimental breakthroughs to develop the hardware and software to enable quantum computing technology.

III. The Benefits of Quantum Computing

Through theory alone we have seen a handful of problems in mathematics and computer science that would take millennia to solve on a classical computer but require less than a day on a quantum computer.

One concrete example of the benefits of quantum computing is its ability to reduce the amount of resources required to create artificial fertilizer. This affects some of the biggest challenges facing our world, such as global hunger and energy conservation. Our current process for creating fertilizer was invented in the early 1900s, long before computers, and consumes approximately three percent of the world's natural gas. Yet certain microbes found in nature can create fertilizer more efficiently than our industrial approach. The quantum computer, working with a classical supercomputer, enables us to understand how those microbes perform this task in a matter of weeks or days, letting us engineer our own more efficient catalysts. In contrast, a classical supercomputer could not complete that task during the lifetime of our universe.

Quantum computers will advance a range of scientific research areas, and in turn impact a broad span of industrial sectors, including:

- *Computational Chemistry.* Advanced quantum computers are expected to contribute to advancements in drug discovery, development of pigments and dyes, and the development of catalysts for industrial processes such as breaking down pollutants in exhaust streams, extracting atmospheric nitrogen to make fertilizer, and carbon capture.[1] For example, a quantum computer may help us identify a way to extract carbon from our environment more efficiently, to combat global warming.

- *Materials Science.* There are many areas of condensed matter theory, material science and chemistry that we cannot accurately study with existing methods, including high-temperature superconductors. Superconductors can conduct electricity without resistance, i.e., without losses, and thus could have enormous prospective applications in energy technology, including efficient power transmission. Unfortunately, in most materials this effect occurs only at temperatures near absolute zero. Despite having been studied for more than 30 years, this unusual phenomenon is yet to be understood and applied. With quantum computers, though, the many-electron states that occur in materials science can be naturally mapped onto a system of many qubits, enabling us to help identify materials that superconduct at high temperature, which could spur development of lossless power grids.

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[1] T. Simonite, *Chemists are First in Line for Quantum Computing's Benefits*, MIT Technology Review, March 17, 2017, *available at* https://www.technologyreview.com/s/603794/chemists-are-first-in-line-for-quantum-computings-benefits.

- *Nuclear and Particle Physics*. The equations governing nuclear and particle physics are well established but solving them to make accurate predictions is notoriously difficult. Within the DOE alone, the annual expenditure of supercomputer time on this problem extends well into the hundreds of millions of CPU hours every year. In contrast to conventional computers, quantum computers can solve this problem orders of magnitude more efficiently. Such quantum solutions will enable the prediction of nuclear reactions and high energy particle collisions, both manmade in particle accelerators and naturally occurring in cosmic rays.

Quantum computers will also improve the electronic systems and applications we use today, including by:

- *Improving Machine Learning and Artificial Intelligence.* Quantum machine learning has emerged as one of the most exciting applications of quantum technologies.[2] Recent advances in machine learning have already led to self-driving cars, real-time speech translation and advanced artificial intelligences that can best human players at complex games like Go or Jeopardy. Quantum computing will speed up the ability to train machine learning models and provide richer models for the underlying data. That means quantum machine learning will not just make machine learning faster—it will also make it smarter. These benefits result from two attributes of quantum computing: (1) its ability to leverage millions or billions of training examples at once,[3] and (2) quantum neural networks,[4] which can find correlations in data in a method analogous to the human brain, learning patterns that classical computers would be unlikely to detect.[5]

- *Creating Better Scientific Computing and Computer Aided Design*. Many tasks within scientific computing, engineering, and computer-aided design rely, at their core, on fast computational methods for solving large systems of linear equations. Quantum computers will be able to more rapidly solve problems such as the calculation of radar

[2] Jacob Biamonte, Peter Wittek, Nicola Pancotti, Patrick Rebentrost, Nathan Weibe, & Seth Lloyd, *Quantum Machine Learning*, Nature, Sept. 14, 2017, at 195.
[3] Nathan Wiebe, Ashish Kapoor, & Krysta M. Svore, Quantum Algorithms for Nearest-Neighbor Methods for Supervised and Unsupervised Learning, *Quantum Information & Computation*, March 2015, at 316.
[4] Jonathan Romero, Jonathan P. Olson, & Alan Aspuru-Guzik, *Quantum Autoencoders for Efficient Compression of Quantum Data*, Quantum Science and Technology, Aug. 18, 2017, 045001.
[5] Mária Kieferová & Nathan Wiebe, *Tomography and Generative Training with Quantum Boltzmann Machines*, 96 Phys. Rev., 062327 (2017).

signatures, simulation of seismic wave propagation for oil and gas exploration, computer aided design of mechanical parts, and financial option pricing.[6]

- *Improving Optimization*. Optimization problems are ubiquitous. They include traffic routing, flight scheduling, toolpath optimization for manufacturing, financial portfolio optimization, risk management, power grid management, and computer aided design, among many others. A number of sophisticated optimization algorithms have been developed that can solve special classes of optimization problems efficiently. However, many real-world optimization problems remain intractable. Quantum algorithms have the potential to address many of those problems. Moreover, mathematical advances arising from the study of quantum algorithms have spawned a new class of optimization methods called Quantum-Inspired Optimization, which run on today's classical computing hardware and can dramatically outperform previous software.[7] When run on a future scalable quantum computer, the performance of those solutions will be even greater. Microsoft works with several commercial companies on quantum-inspired optimization solutions to run on today's conventional computers and on tomorrow's scalable quantum computers.

- *Making Better Classical Computers.* Quantum computers will also be of great value in improving the quality of classical computing. Today we have no way to verify the absolute "correctness" and security of classical software. But whereas the number of potential states of a classical software program cannot be fully enumerated by using a classical computer, such verification should be feasible with a quantum machine.

IV. Developing the Quantum Economy & Workforce

This wealth of new quantum applications will readily translate into economic growth.

A. The Current Global Landscape

Governments worldwide recognize the need for investments in quantum computing. In the United States, federal agencies have supported research in quantum information science for

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[6] B. Clader, B. Jacobs, & C. Sprouse, *Preconditioned Quantum Linear System Algorithm,* 110 Phys. Rev. Lett., 250504 (2013); A. Montanaro & S. Pallister, *Quantum Algorithms and the Finite Element Method*, 93 Phys. Rev. A, 032324 (2015); P. Costa, S. Jordan, & A. Ostrander, *Quantum Algorithm for Simulating the Wave Equation*, ARVIX (2017).
[7] Z. Shu, C. Fang, and H. Katzgraber, *borealis: A Generalized Global Update Algorithm for Boolean Optimization Problems*, ARXIV (2016), *available at* https://arxiv.org/abs/1605.09399; Todd Holmdahl, Microsoft Quantum Helps Case Western Reserve University Advance MRI Research (May 18, 2018), *available at* https://blogs.microsoft.com/blog/2018/05/18/microsoft-quantum-helps-case-western-reserve-university-advance-mri-research.

more than 20 years.[8] While the overall annual federal budget for quantum R&D is difficult to calculate because of the many agencies that receive funding, analysts have put that figure between $200 and $250 million.[9] That investment level is similar to China, which has designated quantum information science as one of four "megaprojects" in its 15-year science and technology development plan for 2006-2020; its annual funding for quantum R&D is estimated at $244 million.[10] China was also the first country to achieve two quantum communication milestones: operating a long-distance quantum communication landline between Beijing and Shanghai and conducting the first quantum-encrypted video call.[11] Moreover, China may be the top filer of certain quantum-related patent applications, with one study finding Chinese applicants filed 156 quantum key distribution patents between 1991 and 2014, more than applicants from the U.S. (151), Europe (78), or Japan (100).[12]

In Europe, the European Commission in 2016 announced the launch of a € 1 billion flagship initiative on quantum technology, and estimated then that it had already invested € 550 million in quantum technologies over the past 20 years.[13] The United Kingdom in 2013 established a 5-year, £ 270 million National Quantum Technologies Program to expedite development of commercial quantum technologies; in 2016, it announced investments in doctoral training and developing skills, specialist equipment and facilities for quantum research.[14] Russia, Australia, Japan, Singapore, and Canada are also making significant investments in quantum.[15]

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[8] Committee on Science and Committee on Homeland and National Security of the National Science and Technology Council, *Advancing Quantum Information Science: National Challenges and Opportunities*, at 2–3, July 2016, *available at* https://www.whitehouse.gov/sites/whitehouse.gov/files/images/Quantum_Info_Sci_Report_2016_07_22%20final.pdf.
[9] Patricia Figliola, Cong. Research Serv., 7-5700, Federal Quantum Information Science: An Overview, 1–2 (2018).
[10] *Id.*
[11] *Id.*
[12] A.M. Lewis, M. Kramer & M. Travagnin, Eur. Comm'n Joint Research Ctr., Quantum Technologies: Implications for European Policy, at 8–9 (2016), *available at* http://publications.jrc.ec.europa.eu/repository/bitstream/JRC101632/lbna28103enn.pdf.
[13] European Commission Will Launch €1 billion Quantum Technologies Flagship, European Commission (May 17, 2016), *available at* https://ec.europa.eu/digital-single-market/en/blog/entering-preparatory-phase-towards-quantum-technology-flagship.
[14] *See* U.K. Government Office for Science, *The Quantum Age: Technological Opportunities*, at 18 (2016); Engineering and Physical Sciences Research Council, *Minister Announces £ 204 Million Investment in Doctoral Training and Quantum Technologies Science* (March 1 2016).
[15] *See, e.g.*, About Us, Russian Quantum Center, http://www.rqc.ru/about (describing creation of the Russian Quantum Center in 2010 as intended to make "Russia a world leader in the field of quantum technology"); Media Release, *Australia Ministers for the Dep't of Indust., Innovation & Sci., Major Leap Forward for Australian Quantum Computing* (Sept. 20, 2016), *available at*

B. Recommendations for U.S. Investment in Quantum Computing

There could be immense benefits for the United States if we seize the opportunity of quantum computing. In pursuit of that goal, Microsoft makes the following recommendations for U.S. investment in quantum computing: (1) invest in a quantum workforce; (2) support research that will foster the development of scalable quantum technology, including pairing quantum technologies with existing research on exascale computing, and (3) support the development of new quantum algorithms today, using huge simulation systems to advance research without waiting for advances in quantum hardware.

1. First Recommendation: Invest in the Quantum Workforce

Today, fewer than one in 10,000 scientists, and even fewer engineers, have the education and training necessary to leverage quantum tools, even when they are enabled by a quantum machine. Practitioners entering this field need to learn key concepts in math, physics, and computer science, and be able to combine them in new ways. This includes not only quantum software engineers and developers, but also quantum application scientists, quantum materials specialists, fabrication engineers, and cryogenic engineers who can design the systems needed to house qubits.

The DOE has already recognized the importance of developing a quantum computing workforce, including by supporting internships and postdoctoral research at national labs and by funding other quantum-related research. For example, DOE has established the Science Graduate Student Research program, which supports research in priority areas including quantum information science, and sponsored a Quantum Testbed Stakeholder Workshop that allowed academia, industry, national laboratories, and government to provide perspectives on the objectives for a quantum testbed program. DOE's Early Career Research Program also

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https://www.minister.industry.gov.au/ministers/hunt/media-releases/major-leap-forward-australian-quantum-computing (describing a $25 million AUD investment by the Australian government in a Center for Quantum Computation and Communication Technology); Introduction, Nat'l Inst. for Quantum & Radiological Sci. & Tech, *available at* http://www.qst.go.jp/ENG/about/outline.html (listing Japanese government's FY 2018 budget for its National Institutes for Quantum and Radiological Science and Technology at 42.9 billion yen); Center for Quantum Tech., *Singapore's National Research Foundation Awards CQT $36.9 Million Funding* (June 12, 2014), *available at* https://www.quantumlah.org/about/highlight.php?id=158 (announcing Singapore's award of $36.9 million to the Centre for Quantum Technologies, following a $158 million founding grant in 2007); Gov't of Canada, Budget Plan 2017, Chapter 1 - Skills, Innovation and Middle Class Jobs (2017), *available at* https://www.budget.gc.ca/2017/docs/plan/chap-01-en.html#Toc477707303 (listing the Canadian government's investment of $158 million CAD in funding to support organizations including the Institute for Quantum Computing and Premier Institute for Theoretical Physics).

supports the development of individual research programs for outstanding scientists early in their careers to stimulate research in disciplines including quantum computing.

We recommend supplementing those efforts in three ways.

First, DOE can create a partnership among government, industry, and academia on curriculum development, to ensure programs for learning quantum programming and quantum software and algorithm development are available at DOE, online, and at universities. As one example, Microsoft partners with the Pacific Northwest National Laboratory ("PNNL") to develop quantum algorithms and software solutions and also teaches courses at the University of Washington on quantum computing using our quantum-focused coding languages and tools. These collaborative efforts support early adopters, who are critical for innovation.

Similarly, in the United Kingdom, industry and government have together developed "hubs," that span undergraduate and graduate programs in fields relevant to quantum computing.[16] These hubs enable students to obtain degrees in quantum computing and arm them with business and entrepreneurship skills, in addition to the necessary skills in quantum computing, facilitating the growth of quantum-driven startups. This is another model for the DOE to consider in developing the quantum-related curriculum needed to educate our workforce at a wide array of institutions.

Second, DOE can partner with industry to increase opportunities for on-the-job training. For example, Microsoft has a vibrant internship program to support a substantial number of undergraduate and graduate internships for students whose studies intersect with our work. DOE is well-positioned to explore partnerships to fund internships, including in coordination with local universities. Partnering with industry in those efforts would also help DOE understand the demand for the many types of quantum-related jobs, and enable DOE to target its other educational efforts accordingly.

Third, DOE can establish a national program to advance scalable quantum computing in conjunction with commercial efforts to do so, which could ignite a passion to explore this new and exciting frontier. There could scarcely be a more powerful or exciting vehicle for re-energizing STEM education in the United States than quantum computing. Just as America's early space program offered a vision of science and engineering so compelling and immediate that it inspired a generation of young people, so too could establishing a national program to build a quantum computer similarly captivate today's youth.

Together, these investments in training a workforce for quantum computing will complement our other recommendations on supporting research on scalable quantum computing technology and development of new quantum algorithms. Enabling on-the-job training and

[16] *See*, *e.g.*, U.K. Nat'l Quantum Tech. Program, *A Roadmap for Quantum Technologies in the U.K.*, at 22 (2015), *available at* https://epsrc.ukri.org/newsevents/pubs/quantumtechroadmap.

supporting access to and use of quantum machines will also ensure more people learn about quantum computing technology and are able to contribute to its advancement.

2. Second Recommendation: Invest in Scalable Quantum Computing Technologies

A pivotal role for the DOE will be to invest in areas critical to the development of quantum computing capabilities. We encourage the Committee to support two types of investment in quantum hardware. First, the Committee should invest in and prepare for quantum computing as a complement to the exascale computing in which DOE has already invested. Second, the Committee should create new programs to drive research on reliable and scalable qubits.

a) Quantum Computing as a Complement to Exascale Computing

The DOE has recently emphasized the importance of exascale computing, which focuses on high-performance computing systems capable of at least a billion billion calculations per second—50 to 100 times faster than the most powerful supercomputers in use today. But the gap between exascale and commercial cloud offerings is quickly shrinking, as the private sector develops high-speed cloud services to power large-scale machine learning. In fact, in this important area, commercial cloud systems are now roughly five times faster than the fastest conventional supercomputer recently deployed by DOE. These commercial clouds now offer a variety of computing capabilities—and they are working to add a quantum computer as the next option. DOE's exascale computing efforts will similarly benefit from considering how to augment exascale models with quantum computation.

Just as the private sector views quantum computing as an accelerator for cloud-based machine learning/artificial intelligence offerings, it can also accelerate machine learning/artificial intelligence for exascale computing. For either technology, quantum can improve training speeds, speed up inferences, and create smarter models of systems and data.

b) Programs to Increase Scale and Quality of Quantum Hardware

Another critical investment area is the manufacturing process required to build a quantum computer, including the fabrication capabilities, materials, characterization capabilities, and validation and verification of a quantum computer. DOE has already begun exploring this area through the potential of Quantum Testbeds. Microsoft encourages the DOE to create a new testbed to focus on improving the scale and quality of quantum computing hardware systems.

As noted above, one significant challenge in this area is improving the reliability and scalability of qubits. The DOE has an opportunity to play a critical role in helping to identify which types of qubits may scale, how to engineer a scalable system, and validating and verifying the quality of qubits. For example, DOE can identify, test, and advance systems that promise scaling. It can also assist in the quest for demonstration of a path to scaling.

At Microsoft, we have pursued reliable and scalable qubits through our focus on topological qubits. But we encourage DOE to support research and investment not only in this technology, but also in other technologies that achieve the same goal of increasing the reliability and scalability of qubits that power quantum computing. DOE should also support research and investment in other technologies required to enable quantum computing at scale, including control electronics, cryogenics, and the classical computers required to control quantum computers.

3. Third Recommendation: Support Development of Quantum Algorithms Today

Another critical area of investment is in the development of quantum algorithms—which can be architected and coded today, without waiting for advancements in quantum computing hardware. Microsoft encourages the DOE to support the development of quantum algorithms in two ways.

First, DOE can create a testbed focused on the development of quantum algorithms. That testbed can identify and develop source code that will be needed for quantum computers, based on how quantum computers may be used in science and energy. Developing a quantum algorithm only requires a software development kit and a quantum simulator, which involves modeling a small quantum computer on a very large classical computer. DOE is uniquely positioned to support such development, because of its existing investments in large classical machines, which are well-suited to testing quantum algorithms in advance of scalable quantum hardware. This will require methods for easily programming, debugging, and testing quantum algorithms. For example, one key advance will be allowing the study of heuristics on real hardware. Another will be the ability to better test quantum algorithms in classical simulation environments, before running them on quantum hardware. Finally, we need debugging and verification tools to identify errors in quantum programs.

Second, DOE can encourage algorithm development by creating new partnerships in academia, government, and industry that bring together scientific experts and quantum programmers. As noted earlier, Microsoft's partnership with PNNL is one example of a successful industry-government partnership advancing quantum computing. That partnership focuses on the development of novel quantum algorithms and software tools for studying and understanding the most challenging problems in quantum chemistry. Later this year, we expect to release a new chemical simulation library developed in collaboration with PNNL that can be used in conjunction with NWChem, an open source, high-performance computational chemistry tool funded by the DOE's Office of Science. Together, the chemistry library and NWChem will allow researchers and developers a higher level of study and discovery as they tackle today's computationally complex chemistry problems.

Given the strong partnerships between PNNL and the University of Washington, and the deep relationships between the University of Washington and Microsoft, the Pacific Northwest can also be a regional center for quantum computing, with coordination and collaboration between these three entities. We encourage DOE to support such partnerships and the development of regional centers that foster innovation in developing quantum algorithms.

V. Timeline and Challenges

It requires some imagination to foresee the coming quantum economy, and considerable judgment in deciding how to shape, promote and leverage its development. Yet there are immense opportunities for the United States if we are able to seize this opportunity.

Despite the substantial challenges on the path to a quantum computer, we are making continual progress. It is hard to identify the exact date on which we will have a scalable quantum computer. While quantum computers exist today, they contain only tens of qubits with low quality. We need a machine with several orders of magnitude more. To more rapidly advance, we need to bring together industry, academia, and government to tackle the challenges outlined here. Quantum computers will be delivered far sooner, and have more useful applications, if we increase funding and workforce development. Encouraging the next generation to tackle challenges in quantum computing will bring new ideas and creativity to the field, enabling breakthroughs and innovation.

With growing demand for faster, more powerful, and more versatile computing that approaches the limits of conventional microprocessors, we must turn to quantum physics for a new era of intelligent devices. We have an opportunity, through quantum computing research and the creation of a quantum-ready workforce for the United States, to lead the world in the quantum revolution. Strengthened by national investment in these technologies, government, industry, and academics can together pioneer the development of scalable quantum computing.

The CHAIRMAN. Thank you, Mr. Holmdahl.

Dr. Siddiqi.

STATEMENT OF DR. IRFAN SIDDIQI, FACULTY SCIENTIST, LAWRENCE BERKELEY NATIONAL LABORATORY, PROFESSOR, UNIVERSITY OF CALIFORNIA, BERKELEY, AND DIRECTOR, BERKELEY QUANTUM

Dr. SIDDIQI. Chairman Murkowski, Senator Duckworth, all the honorable Senators and members of the Committee that are here, I would like to thank you for giving me the chance to tell you about why I think quantum is so exciting this morning.

I will start off by saying I started working in this domain before there were superconducting qubits. So for more than 20 years I've been thinking about quantum mechanics, and my role is really both as a physics professor at UC Berkeley and also someone that works at Lawrence Berkeley Lab.

I want to start off by asking, why quantum? Why now? You know, I just taught 200 quantum mechanics students over the last three weeks, the mathematics of this theory which is more than 100 years old. Right? So why now? Why are we, sort of, now figuring out what to do with this?

And, moreover, what's rather striking is that quantum theory is the backbone of most modern technology, whether it's lasers or computers or MRI scanners or CT scanners. But what's amazing is we still have not really tapped into quantum yet. And the reason for that is we spent 100 years trying to figure out if a cat can be asleep and awake at the same time. Really, right? And I think the verdict is out. We believe that cats can do this.

[Laughter.]

Right? And that's an amazing philosophical statement because if cats can do this then bits can do this. Right?

And the point is that systems that we observe, in fact, have an inherent complexity which goes well beyond what we observe. To the point that if you have even a modest array of quantum bits, the number of parameters you would need to explain or describe that array is more than the particles in the universe. That's true.

So the idea is if I really have a small chunk of quantum matter, quantum bits, a computer or simulator, then in fact, if I can harness it, it's extremely powerful. Right?

And we can list some of the applications that my honorable colleagues were mentioning, but I would say the best of quantum is still yet to come. Right? Because we have not really even thought about what are the full implications, in fact, of having this technology.

So really the task at hand for all of us is to manage intellectual capital in an efficient way, without knowing actually the full potential of that capital just yet. But with having that little glimmer of hope that says, for sure this will be transformative because now we know how the world really works.

Staying to the subject of today's discussion, the role of the Department of Energy in such an endeavor. We are still in the discovery phase, and the Department of Energy has a rather critical, crucial role to play in discovery-driven science.

In particular, progress in quantum information science hinges upon critical advancements in materials that sustain quantum behavior, engineering advances to control quantum machines and new ideas in computer science to find the most impactful implications. DOE labs have core expertise in exactly these three areas. In fact, they have a long history of shepherding discovery-driven research that is ultimately needed to bring quantum in every home. Alright? That's something we still need to think about and how to implement.

In particular, if we are really serious about training the next generation workforce, and I see them every day, then we need to have projects for them to engage in. Right? Where will all our Ph.D.s go when they finish working on this subject?

In fact, academia and industry, to me, represent two particular areas but there's a big area in the middle where, in fact, DOE labs can shepherd all these nascent scientists. And, in fact, it's a great place to hone your skills and become a professional scientist at a DOE lab.

Of course, as was mentioned by other Committee members, the DOE labs do not exist in a vacuum. Right? They are a critical part of the quantum ecosystem that has partners in both academia and industry. What I would like to say is that each of these entities has a unique role to play in this process, and greatest progress is made when competitive overlaps are turned into synergistic partnerships.

National labs can naturally extend the reach of the university researcher while identifying the most promising technologies for commercialization. The DOE brings continuity and stability to the picture. Progress in quantum technologies extends well beyond the life of one graduate student, and extends beyond the life, in fact, of a very near-term industrial endeavor.

As for the structures of these centers, perhaps the hybrid approach is best, where we have both vertical integration and horizontal integration. Vertical integration on a particular technology brings everyone in the same room so we all speak the same language. There's nothing that's lost in translation between engineers and scientists and physicists and computer scientists. We also identify those gaps where we need to fill and really make progress. Horizontal integration, amongst common topics, has its natural benefits.

Moreover, I feel that these centers could be endowed with the ability to have deeper partnerships with industry which go beyond simply using nascent technologies. We are still trying to identify the technologies that are most important for us. They could have the ability to grant fellowships to students and postdocs to keep them in the field and to sponsor community building activities, both between workers in this field and also to sponsor that we are all engaged with.

At Berkeley we have started Berkeley Quantum, a partnership between the lab and the university, and we are now endeavoring with the help of the Department of Energy to seed, if you like, the analog of a light source or a particle accelerator for quantum information technology, specifically superconducting qubits, so we can look at all the fundamental questions as a community and move forward from there.

I thank you again for giving me the opportunity to share these remarks, and I'm happy to answer any questions that you may have.

[The prepared statement of Dr. Siddiqi follows:]

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

Irfan Siddiqi
Faculty Scientist, Lawrence Berkeley National Laboratory
Professor, University of California, Berkeley
Director, Berkeley Quantum

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.

The CHAIRMAN. Dr. Siddiqi, thank you. I have to admit, I am still thinking about the cat.

[Laughter.]

So this is all about education and we certainly are benefited by your comments this morning, and really, your leadership in an area that is quite exciting. I think you put it into context quite well at the end. This is not something new and yet it is breathtakingly new in terms of its scope and its possibilities.

Let me ask, because I think almost all of you have mentioned the necessity, as we move forward with these extraordinary opportunities, that we have the workforce and how we build that, how we develop the engineers, how we are able to partner, and I appreciated the mentoring program at Chicago Quantum Exchange Mentoring Program. But let me ask the question, in terms of our level of preparedness. I appreciate what was announced yesterday at DOE with $218 million in the research awards. I think that is significant. But when we think about what is happening around the world, I mentioned and it has been mentioned, the incredible investment that China has put forth—$10 billion. The EU has a quantum manifesto to move forward with a $1.1 billion flagship initiative. The UK has invested $440 million in a national quantum technologies program. There is Australia. There are other nations, the Netherlands.

As we compete for these individuals that will help us advance, are we growing our own? Are right-focused individuals being wooed away by other nations that are, perhaps, investing more in this initiative? Help me out in understanding, kind of, where we are in competing for the best and the brightest, and how we can do more to ensure that everything lines up in terms of our opportunities. And I throw that out to the whole panel.

Mr. Holmdahl, if you want to start?

Mr. HOLMDAHL. Yeah, thank you, Senator Murkowski.

Yeah, we've been developing a team, again, for a number of years and we're all over the world right now. We have labs in the Netherlands. We have a lab in Copenhagen. We also have a lab in Sydney, Australia. We happen to have labs in Purdue and Santa Barbara as well and then, of course, in Redmond.

There was no way that we were going to be able to get enough physicists to come to Redmond, so we had to go throughout the world in order to staff our program.

I would say, in my humble opinion, that the rest of the world seems to be a little bit ahead of us in terms of generating the next level of workforce. A lot of kids in physics and a lot of kids in engineering there.

What we're able to do as a multinational company, at Microsoft, we're able to attract these resources and have them work on the programs that we've been working on. I would say we do, and I will try to outline it. We do need to continue to work on this quantum workforce. We don't have enough people coming from our universities yet and there are not a lot of great schools, again, in my opinion, that are pumping out the type of people that we're going to need for this quantum economy. Because it's going to be big, and you're going to need people to build the machines. You're going to need people to fabricate the machines. You're going to need people to engineer the machines, people to program the machines, and it's a whole list of different opportunities out there.

And the more that we can get the universities built up, the more that we can go down into the high schools and develop programs, the more that we can do on-the-job training, the better opportunity we'll have to do it in the United States.

The CHAIRMAN. Dr. Siddiqi?

Dr. SIDDIQI. Let me address the question in two parts. The first one is about our colleagues, right, in other countries and their investment in this particular subject. I think the good news for us is that I still get hundreds of applications for graduate students and postdocs that want to work with us. So we must be doing something right.

In particular, we focus in our academic system on creative ideas and developing that talent. So we are raising the plants properly. The question is, what happens when they want to leave and get a job, right? Is there an opportunity there? And that was what I was alluding to in my remarks.

What I have seen amongst graduate students is that, first of all, they're much smarter than I am and have ever been. They're the real reason we do any successful work in the lab. That means that we must treat them really as equals, and be honest with them and say, what are the right career choices? Where can you go, you know, with that talent? And I must say, before quantum really took off in this particular phase, I would have many different suggestions for them, perhaps in biotech or someplace else, because physics is a way of thinking. There are many things you can do with that degree.

But I think it's very exciting to now have this endeavor take off. I think the critical part will be to not only train these folks, but also give them a way, honestly, that they can actually contribute positively to the ecosystem. And they are very smart people. They know where to go and how to work with their careers. In fact, they are at some level a commodity, but at some level human beings. So it's critical to make sure that there's honesty in the endeavor and there are things that they can be productive in as they go forward.

The CHAIRMAN. I appreciate that.

Dr. Guha and then we will go to Under Secretary Dabbar.

Dr. GUHA. Just a couple of quick comments.

First of all, yes, I think we are noticing over the past some years that there's increased recruitment of bright students who are being given a lot of facilities and resources and being hired in other countries. But I think that is fine. I mean, that is the way, you know, the research world is progressing, as long as we are also able to recruit them from outside and back into here, I think it's fair game.

In terms of the workforce, there is a need for a quantum trained workforce, essentially engineers who know how to do quantum mechanics. And we need to be smart in the way we do this. Today, for instance, most of the people involved in quantum information sciences come with physics backgrounds, chemistry backgrounds, and the material science community is just getting into it, the computer science community is just getting into it. But this now also needs to include the electrical engineers, the mechanical engineers, the packaging research people. So that whole ecosystem needs to be pushed out. That is not happening right now and we need to consciously work toward that.

And finally, I will say that the, you know, the coupling between the educational establishment and the national laboratory system and industry, in my experience, is probably the strongest in the United States still today. And the U.S. is still in a leadership position, particularly in quantum information sciences.

So we need to simply build on these. A lot of the other countries are essentially trying to, you know, grow from a position that's below, in terms of the sophistication. So, I think, if we do this smartly with our investments, I think we can continue to be ahead.

The CHAIRMAN. Thank you.

Under Secretary Dabbar, I am well over my time, but since everyone has brought this up I will certainly allow DOE to weigh in here.

Mr. DABBAR. Thank you, Chairman.

So, I think, just to state a few facts. The United States is the leader in particle physics in the world. As I mentioned, 40 percent of all the Nobel Prizes in the world in physics are from people who were just in our national labs, so not even counting people who have not. People still want to come to this country and people are very excited about this topic. So I'm very—every day when I sit and talk with my labs and talk about where we are in technology versus others, I think we're in a very positive place. I can tell you that there are people around the world who would rather know what's going on at Argonne and at Berkeley than what they're doing themselves. I can say that with a high degree of confidence. So I think we are in an excellent place for the beginning of a long journey.

When it comes to workforce, I can say that having toured a lot of the major universities—MIT, Caltech and Stanford, and Chicago—over the course of this last year, there's a tremendous rush of interest of students.

And so the point is, is how do we build upon some of the points that was just discussed which is, how do we provide support for research, and how do we provide connections with the private sector? I am very positive about that interconnection. Yesterday was a good additional step forward. The dynamic interaction between universities, the national labs and the private sector in this is unparalleled in this country.

So what can we do more? We could do more by, I think, some of the things that are being proposed by the bill, in part, led by the National Science Foundation where they're specifically looking at rolling out some workforce development. So that's part of the bill, and we very much support that.

And then, as our role as part of this is continuing to fund the research. Actually, we go hire PIs and at the end of the day they go higher in number of students to support them. So there is seed money, to use a venture capital term, an effect that we cause for the rest of the sector.

The CHAIRMAN. Thank you.

Senator Duckworth.

Senator DUCKWORTH. Thank you, Madam Chair.

I would like to, sort of, dig a little bit into what Dr. Siddiqi had mentioned. But I am going to address a question at Under Secretary Dabbar.

You know, when we talk about this competition for this talent, and Dr. Siddiqi talked about where does this talent go once they are trained. I understand that the private sector, who will lead the way in commercialization for the discoveries made at our laboratories, face bureaucratic road blocks to entering public-private partnerships with our labs. My question really is, how do we grow those public-private partnerships? How do we help industry and entrepreneurs to get into this and be able to work with our national laboratories? What steps are you taking to simplify and expedite the process of entering into these types of partnerships between the national labs and private sector and what are you doing to really promote industry, whether it is a Microsoft or even a venture, something, two physics students are graduating, how do we grow this? Because as Dr. Siddiqi rightly states, they have to go somewhere, and I would rather they go to U.S. companies that are working directly with our labs in a very symbiotic way.

Mr. DABBAR. Thank you, Senator. So I think there's two parts to answer your question.

First of all, is how do we actually bring additional private sector involvement in with the work at our labs? That's not just this area, I could actually apply it to pretty much any of the research areas but, in particular in this area, a lot of people in this industry have not worked with national labs on a commercial level. We have more interaction with biotech and high-performance computing.

And so, I think yesterday was a good first step of reaching out to the private sector and explaining our capabilities and that the private sector uses our national labs, as you know, labs in your state, a tremendous amount of private interaction. And for them to realize what we're there—and to figure out how we can make the connections of doing work to support them and also to figure out which specific dollars that you budget for us to go spend will make the biggest impact.

So that's the Pasteur's quadrant to a user-inspired research philosophy that we're very much a part of and very much pushing. As a part of that, doing specific events to connect more with people. So we just did one on battery research out at Stanford this last week.

When it comes to specific administrative aspects that you effectively touched on, I completely agree with you. The biggest challenge with the DOE lab complex is that we, as a principal, have all sorts of legal requirements and in order to step through, and reviews, which many times in a large entity is slow and it's hard for private industry to work with. I agree with you. It's something we've been attacking on a broad basis, including in this sector, and we're actually implementing a number of specific areas which make it easier.

I'll comment on one which was asked previously here which was delegating authority for smaller agreements, below about $1 million to the national labs with proper oversight in terms of auditing. But we're going to be making it easier, especially for involvement with anyone in the private sector, in any sector, in order for the labs to take the lead without having all the different bureaucracy that comes from Forrestal. We have analyzed that 50 percent of all the commercialization discussions with the private sector will be covered by this delegation of authority and should accelerate it significantly.

Senator DUCKWORTH. Wonderful. Thank you.

I do see that this workforce development and really exploiting this field is a three-legged stool, right? You have the national labs, you have private industry, and then the third is, of course, our universities.

Dr. Guha, welcome, again and thank you for testifying today. My question to you is going to deal with that last leg of the stool. And as you cite in your testimony, university researchers, like those at University of Chicago and University of Illinois, benefit from the national laboratory's infrastructure. You are also eligible for funding from DOE's Office of Science which allocates grants directly to university researchers in a variety of areas of quantum research for the universities. Can you discuss how university-based quantum research complements the work performed at the national laboratories and how these three legs come together? Because I do think that you need all three in order to continue to grow this workforce, grow the field.

Dr. GUHA. So there are several ways in which there is synergy between the universities and the national labs.

First, as we've talked about the workforce development piece, a lot of these students end up getting trained in the national labs. For instance, just at Argonne there's about 1,000 students and postdoctoral scientists who come by every year. And the number, I would say, is typical for the other DOE national labs as well. I just happen to know the numbers for Argonne.

A lot of the academia and researchers use the user facilities, which is a jewel for the national lab systems, the light sources, the nanoscience research centers, neutron sources, the computing facilities. Just as an example again, the advanced photon source has about 6,000 users annually, most of them from, you know, university researchers across the world.

The nanoscience research centers, there are five across the nation, on average have about 500 users, often 500–600 users, something like that per nanoscience center. So those are—so that type of engagement is a second way of engagement.

And the third is, you know, we—the universities and the national labs together, when they work together along with industry, there's a diversity of thought that's required. As I mentioned, I believe we don't really know a lot of the uses of quantum information right now that will be useful to us in the years going forward, and this diversity of thought, this sharing of information, looking at it from different angles, is very, very important. I think that's a third area where the university, lab and industry interaction can happen.

So it is very important going forward for research, not just in quantum information, but other areas such as artificial intelligence, for instance, needs to be purpose-driven. You set an agenda, then you put the team together, you know, be it universities, industry, academia and have it across different disciplines, multidisciplinary, computer sciences to engineering to science, and that's where this type of interaction really shines.

Thanks.

Senator DUCKWORTH. Thank you. I am over my time, Madam Chair.

The CHAIRMAN. Thank you, Senator Duckworth.

Senator Cassidy.

Senator CASSIDY. Gentlemen, it is with trepidation that I ask a technical question, but nonetheless, I feel as if I must. As I gather from reading about qubits, they are inherently unstable and only at a certain temperature, et cetera, will you be able to have that. What if somebody pulls the plug out of the machine? I gather that in our current system the data is stored and you put the plug back in.

Now, of course, I am speaking metaphorically, I am not speaking literally. But what if there is a disruption in how the data is being processed/stored, and how do you do a quality review to make sure disruption did not occur since the complexity and speed, et cetera, et cetera, et cetera.

Whomever would wish to speak to that, please do.

Dr. SIDDIQI. Thank you, Senator Cassidy, for the question.

So quantum mechanics has some very interesting features, right? To directly answer the question, how do we ensure that the machine has not lost functionality, has not drifted or has some other difficulty along the way?

Senator CASSIDY. Even for a nanosecond.

Dr. SIDDIQI. Even for a nanosecond we can run calibration sequences and they're part and parcel of making sure that the machine is functioning at its optimal performance.

There are very specific tests in quantum mechanics. Some that we know now, others that we are developing within the domain of what's called verification and validation. There's a whole field of quantum verification and validation where you run this particular set of algorithms to make sure that your machine, for example, has not——

Senator CASSIDY. Ensuring you know the results of those algorithms would be beforehand and if the result comes out as you anticipate then——

Dr. SIDDIQI. Correct. And, in fact, they're on very solid footing because they are predicted by quantum mechanics itself.

Senator CASSIDY. So then let me ask you, how do you store the data? Because if there is a problem then everything you have worked on prior to that point is "poof."

Dr. SIDDIQI. Right. I think an important point to also bring up here is how quantum technologies complement classical technologies, right? In particular, this combinatorial space that you can access with quantum is really the power of quantum but things like storing numbers, adding numbers, minimizing things are perfectly well done on classical machines. So, in fact, most of the near-term applications really use a hybrid model where the quantum is used only for the little quantum step and all the other steps are classical. In fact, the new gains to all the benefits of what you're seeing in classical technologies and——

Senator CASSIDY. So then, let me ask, seeing how all this is, kind of, a great unknown as to how we are going to pull this off, will those who develop it have a proprietary—if Microsoft is the one that answers this question, would Microsoft then have the ability to restrict other people's access to the technology without a license fee, et cetera, et cetera, et cetera?

Mr. HOLMDAHL. Well, what Dr. Siddiqi was saying is absolutely true, that in today's world most of the algorithms that we're looking at are a combination of classical and quantum and they would sit in some sort of data center so you could access that information through a data center.

We are actively building a—what we're calling a scalable, stable, quantum computer built on a qubit that's highly stable and highly scalable. We are doing a lot of IP that, it will—we're writing patents around it and it will ultimately belong to Microsoft. These algorithms will ultimately run in our data centers so customers will have access to it through our data centers.

But it is something that we're putting a lot of Microsoft people on to develop something that we can—believe that will solve a lot of problems both, you know, commercial and non-commercial problems.

Senator CASSIDY. Yes, sir.

Mr. DABBAR. Senator, so the way I would separate this is that there's still basic research that will be open access. That's a lot of what the universities and national labs do that will be applicable to anyone who is trying to commercialize a particular product.

And then, obviously, there is a wide array, growing exponentially it seems like, in terms of private industry, around all the different three major applications. They will develop their technologies and each one will have their particular way of attacking, computing and sensing, and so on, that will be dynamic. I think it's a good thing for the country.

I would make a comment around hybrid computing. Besides being in basic research, the Department of Energy is a major consumer of high-performance computers, right? We build Summit, we build exascale, and they have been—we've actually pioneered hybrid systems. The GPU system, which is a hybrid, which is what the current high-end performer systems are which is classical, CMOS chips plus graphics processors to pick out which areas we pioneered and is part of our computers.

We expect that, I think it was just said, that future computers, instead of having graphics processor units plus traditional CMOS might have attached quantum computers with a traditional classical computing system that will transfer data back and forth, memories and saving data and optimizing which should be calculated into which part of the computer.

Senator CASSIDY. Very good.

Dr. Guha.

Dr. GUHA. I'd like to make a quick point that quantum information, you know, this is not the x+1 development of an existing form of computing that we know about very well like classical computing. This is a case where we're not so sure about the hardware, the software, the algorithms or the use cases.

So there needs to be, in my view, a large component of open basic research. There is a time for black box research, and there's a time when a lot needs to be open——

Senator CASSIDY. I totally accept that, but I think Microsoft is more interested in black box——

Dr. GUHA. There needs to be a balance somewhere.

Senator CASSIDY. I didn't mean to throw——

Mr. HOLMDAHL. No, let me answer that.

We do—we have—we work with a lot of universities and we have a tiered program where we do basic research with the universities, and then also—which they own that IP and we have access to it. And then we also do some specific research, which you call black box, that's specifically dedicated for the product or the solution that we think, as Dr. Guha was saying, that we think is going to enable quantum computing. So we're doing actually both of those.

Senator CASSIDY. Yes.

Yes, sir.

I am over, am I allowed?

The CHAIRMAN. Go ahead, Dr. Siddiqi.

Dr. SIDDIQI. Just a very small comment to, sort of, link all of these different ideas together. There will be a time where quantum computers outperform classical ones. So how do you know that the answer from the quantum one is reliable? In precompetitive research, at the moment there's tremendous value in performing the same computation on a quantum machine and a classical machine so we can verify that the quantum one is working the way we think it is. And we're very much, deeply in this phase at the moment.

I think there is quite a period of time where we can, sort of, learn about these machines, vet them, so on and so forth and then, of course, there will be different roads by different consumers of this product whether it's in the civilian or military disciplines and so on and so forth.

Senator CASSIDY. Thank you.

The CHAIRMAN. Senator Manchin.

Senator MANCHIN. Thank you, Madam Chairman, and thank all of you for being here today.

I wanted to speak about rare earth elements, or rare earth minerals, which I am sure are being used and needs to be used as far as in this type of technology for quantum computing.

WVU, West Virginia University, and then also the Department of Energy's National Energy Lab you have in Morgantown, have really been on the forefront of looking at how we can be able to develop our own supply which right now I understand we do no mining at all. We depend on outside sources, mostly China for this, for what assets we need.

I had a bill last year, Senate bill 1563, which put $20 million into research and extending that because we know there is enough for mine drainage, acid mine drainage, that has enough of these rare earth elements that could carry us well into the future.

Do you all agree that we are in jeopardy of not having our own supply and could be held hostage? I think, Mr. Dabbar, the Department of Energy is where this lies right now. Do you all look into this? Are you exploring this? Has it been brought to your attention?

Mr. DABBAR. Senator, yes, I mean, of course, critical materials is an important part of DOE. We obviously have a focus on that at a number of our labs, including the one in your state. And——

Senator MANCHIN. Were you aware of what they have done in, basically, research right now in conjunction with WVU on showing that they can recover these rare earth elements, rare earth minerals?

Mr. DABBAR. Yes, in terms—yes, Senator, in terms of different recovery, yes, absolutely. And to link it back to, I think, the sort of research that might be helpful here in terms of materials research. Clearly a lot of materials are quantum systems. That's a little bit of materials and mechanical engineering. And at the end of the day the sort of research that we could do on the material side, on quantum systems, with these, sort of, with quantum systems could make critical materials. We could identify how to utilize them better and possibly reduce our risks.

Senator MANCHIN. Well, not just this, not just what we are talking about just for quantum computing. Do you believe it is a risk for the United States of America to be held in jeopardy from not having our own supply and we are relying on outside sources in other countries?

Anybody want to comment on that?

Mr. HOLMDAHL. Yeah, I will. I do think it's a risk. You know, right now——

Senator MANCHIN. I don't hear anybody raising it——

Mr. HOLMDAHL. No, it is a risk and, you know, what we're actually doing, and I can't comment on whether it's rare earth materials or indium or antimony or arsenic, but we are actually doing an extensive look at our supply chain right now and looking at what it takes to build a quantum computer from the qubits to the cryogenic layer that controls the qubits until the helium that you need in order to keep everything cold. So that's an exercise that's just started with us, but we realize the importance of the supply chain and we are diligently working through that and trying to figure out where all these things come——

Senator MANCHIN. Let me follow up with my second question here and I will go right to you on this second question. I think it is your sweet spot.

The Federal Government has been conducting quantum information science research and development since the mid–1990s. We have been at it for a while. However, it has not explicitly made advancements in quantum information science a priority. The overall annual federal budget is spread across many departments and it is estimated to be $200–250 million.

Now, the South China Morning Post has reported that China will invest approximately $10 billion, $10 billion, in a national laboratory focused on QIS that is expected to open in 2020, and technology in the facility would be of immediate use to the armed forces. It has also been reported that China has created a new form of quantum radar capable of defeating the electromagnetic stealth technologies employed in the $1 trillion F-35 program. In addition, Chinese technology corporations like Alibaba and Baidu are investing heavily in quantum computing.

Do we run a risk of falling behind the curve with China and also the threat of our nation being at risk?

Dr. SIDDIQI. Thank you, Senator Manchin, for the question.

So the way I approach this particular subject is I would often have to remind my students how we, sort of, started working in this field. Looking at coherence times—this is a metric, for example, that tells how well your quantum computer is working. We have a team of four, right, on this particular topic and, in fact, other entities had teams of hundreds. In fact, we still have some of the most respectable times in the field.

Senator MANCHIN. Are you concerned just strictly about China superseding us and leading in this technology?

Dr. SIDDIQI. Right. So I think my statement is that our ability to, sort of, be agile and maneuver will always keep us ahead of anything and that particular spirit keeps it going. But we must worry, of course.

Senator MANCHIN. Do you believe we are ahead right now?

Dr. SIDDIQI. I think it's difficult to say what is ahead and what's behind. We are all trying to figure out what's——

Senator MANCHIN. We do not seem to be prioritizing it and China put $10 billion to prioritizing for armed forces.

Dr. SIDDIQI. I would very much say that we should prioritize this research for all of the reasons that have been mentioned, and with our capability to be creative we will, no doubt, be leaders in this as in many other fields.

Senator MANCHIN. Dr. Guha, do you have——

Dr. GUHA. Yeah, I think we need to increase our sustained investment in this field. If you look at the way China is investing, China also invests in focused centers across the nation. I know the European Union, sort of, spreads it around, roughly. My own feeling is that our investments need to be focused around centers, and we really need to ramp up our investment in this area. The U.S. has the lead today. I think that's very clear. But in order to maintain it over the next five years or so, we really need to invest.

Senator MANCHIN. Thank you.

Thank you, Madam Chairman.

The CHAIRMAN. Thank you.

Senator Gardner.

Senator GARDNER. Thank you, Madam Chairman, and thanks to the witnesses for being here today.

We have talked about the amount of money that the Federal Government is spending through laboratories and other research agencies on quantum programming, computing. Do we have any idea what the private sector is spending in this area of research as well?

Mr. Dabbar.

Mr. DABBAR. Senator, we have very good connections in terms of our research with the leaders in this sector. We have—it's not completely visible about exact dollars that they're spending against it. I think we have a very good view of which universities and which private sector entities and which specific technologies that they're approaching.

I would agree with the comment that was just said, that the energy and the diversity both, across all three different areas—private, universities and national labs—is a winning bet.

Senator GARDNER. Do we have an idea of roughly what that is? Not the exact amount but, I mean, is it a billion? Is it billions? Is it hundreds of millions?

Mr. DABBAR. I would say that it's definitely in the billions if you add up all those different areas. I'm not certain if it would add up to ten, but it's—if you add up everything, it's quite large.

Senator GARDNER. And we have talked a lot about the work that is being done at DOE, the work that is being done in the labs, the work that is being done through the DOE lab system, NIST, NSF, DoD. How are you coordinating those dollars, those research dollars, and is there an adequate flow of information between everybody who is touching this research?

Mr. DABBAR. Yes, Senator.

I would say that the fact that this chamber and the one next door's efforts have stepped up our efforts in terms of coordination. We regularly get together with NSF, DOD and NIST on this topic now. We follow your lead in terms of your interest and your focus and also with other defense-related agencies. And so, that's accelerating. And I think with the advent of this bill which actually, you know, has this to coordinate, I think that will continue to progress.

Senator GARDNER. Thank you.

In terms of the partnerships with the private sector, you mentioned the work that is being done in the lab systems with the private sector. China's work, they are working with the private sector, so to speak, as well. Correct?

Mr. DABBAR. Yes, Senator.

Senator GARDNER. Are they working with U.S. companies in China on quantum computing, quantum information issues?

Mr. DABBAR. I'm not familiar. It wouldn't surprise me if they weren't, but not that I know of.

Senator GARDNER. Mr. Holmdahl, has China worked with Microsoft on quantum information science?

Mr. HOLMDAHL. Yeah, so we, like—not in my group, in particular. My group is all outside of—it's in, again, it's in Santa Barbara. It's in Purdue. We have a team in Sydney, Redmond and two in Europe.

I do believe that Microsoft has, I know they do, they're a big multinational company and they do have a research center in China. And my understanding is that they have looked at some quantum stuff, as would a big research center in India, but that was all public information.

Senator GARDNER. Dr. Guha, you talked about some of the national security implications of quantum. Can you talk a little bit more of concern about this area if we fall behind protecting the information? What would we do should somebody get ahead of us from a national security perspective?

Dr. GUHA. Yes, so this is an area where I think China has made a lot of progress. As you may know, they have demonstrated a quantum link from a satellite to ground over roughly, I believe, about 1,000 kilometers or so. I don't believe they broke any scientific barriers here, but it was an engineering tour de force. I think we have to give it to them. There are issues with this technology. Data rates are slow, et cetera, et cetera. But the fact that they were able to do this should alert us.

And you know, the entities that are able to do this sort of secure communication, there's two things: one is a quantum link, to be able to send data that if somebody tampers you know about; and the other is decrypting data or decoding data that somebody else is trying to send. These are two ways that you can address the security issues. And if anybody has this superiority, it will be a landmark change in the way we transmit data. So we should take this very, very seriously.

Senator GARDNER. Thank you.

Thank you, Madam Chair.

The CHAIRMAN. Thank you, Senator Gardner.

Senator Hirono.

Senator HIRONO. Thank you, Madam Chair.

Are all of you convinced that we have to support the development of quantum information science to stay competitive with countries like China? That we do not have a choice in this matter, we need to move forward? Are all of you convinced of that?

Mr. DABBAR. Yes.

Dr. SIDDIQI. Yes.

Senator HIRONO. What about Russia's capability in this area because in the defense space China and Russia are our major competitors. Where is Russia in terms of their development of quantum science?

Mr. DABBAR. Senator, thank you for the question.

In general, if you look at the number of the enabling technologies associated with quantum, whether it's in RF, whether it's in cavities, whether it's in cryo, whether it's in algorithms—in general, they are much farther behind as a country in this particular technology.

I can tell you that there are definitely researchers who are experts in physics individually in Russia and many of which end up coming to the United States. But in terms of a national footprint, the Russians have a much smaller footprint than many, many countries in the world.

Senator HIRONO. Okay, thank you, including of course, the countries of the EU.

We care a lot about internet security, and this is for Dr. Guha. How would a quantum computation-based internet enhance the security of information we send on the internet, and when do you expect a nationally-deployed quantum internet could be available to the public?

Dr. GUHA. So if you had a quantum secured internet, there's—you would be guaranteed secure communication in the sense that if you sent some data and somebody was eavesdropping on it, you would know. And so that would make it failsafe.

As to when there will be a quantum internet, it's difficult to say. I would prefer not to look into the crystal ball and give a number.

But I think, I mean there are companies already who are close to having products over, say, a few hundred-kilometer lengths. Those might be expensive. They might be only for very specific purposes. So it's certainly not going to be of broad usage. But that type of technology, we're only a few years away from seeing this across the world, but specific instances of few hundred-kilometer lengths.

Senator HIRONO. It sounds as though quantum computer systems, computer science, can be a huge benefit in terms of security of a lot of our systems as we deal, especially as I sit on the Armed Services Committee and on this Committee, infrastructure—they are all vulnerable. Our space infrastructure, all of these are very vulnerable to cyberattacks. Would you say that quantum science could play a big role in ensuring the safety of these systems? Yes?

Dr. SIDDIQI. Thank you, Senator Hirono.

Yes, very much so, because I think as my colleague, Dr. Guha, was mentioning, that in quantum mechanics if you make a measurement, you know that that's happened. So that fundamental principle is different than classical physics.

That applies in many, many things, right? For example, if someone copies your credit card number you will not know until they use it, right? But that's not the case in quantum mechanics. So having that fundamental change of how information and measurement works together, that applies not only to communication but also to storage and so on and so forth. So there is very much a need there.

And I wanted to maybe make a brief comment about the previous question that you'd asked about Russian involvement and other entities. I have many colleagues from all around the world, be it Russia or China or Japan and so on and so forth, and I think to summarize the last few questions that were coming out, you know, how much have we invested, how far are we ahead? I think all large nations have made some investment of some quantity, right? And they've, sort of, all come up to the same level saying that we realize that quantum can do something. It's very powerful. The question is, who is going to then invest in the next huge lift after that to bring it to market? And some have started to invest in this and they have been named so far. So I think having funds is not necessarily the most needed thing for success, but if you don't have an investment then I can guarantee you will not have it, right?

So I think it's very critical for us to make that investment and move forward and, in fact, not worry so much necessarily about what's happening, just make sure that we can do the best job that we can because we really do have the resources and the workforce to do it. But that does require an investment.

Thank you.

Senator HIRONO. I hope the Chair will allow me to go over a little bit.

So another question for you, Dr. Siddiqi. Your testimony mentioned the potential application of quantum simulations to solar energy technologies and Hawaii is really at the forefront in the use of solar energy. Could you elaborate on how quantum computers could help develop new solar technologies and how far in the future such developments could take?

Also, I was so intrigued by two of you mentioning that we can use quantum computing to make fertilizer and how far in the future would that be because, of course, making fertilizer using less energy would have major impacts on food production across the world.

Dr. SIDDIQI. Absolutely. Let me briefly comment on the science behind both of those.

So, for example, plants take in light and turn out energy at the end of the day in photosynthesis. And solar cells are not so different, right? Light comes in, it excites something whether it's electronic or vibronic, some kind of motion in a particular solar cell that converts into energy. The thought is this conversion of photonic or light energy into electrical energy can then be enhanced by having some sort of quantum coherence. The first step in this is to run a simulation to see how that energy transfer happens, right? And that's, sort of, the current state of simulations in this field. If we are able to figure out the optimal recipe for taking light and turning it into electricity, then one could imagine this type of application. And so, that comes under the title of artificial light harvesting, right? We'd like to harvest light, not exactly as plants do but in, perhaps, some inspired way for doing this.

The issue with fertilizer production, of course, we're referring to the Haber process developed by Fritz Haber, where one brings together nitrogen and hydrogen at 400 degrees Centigrade and 200 atmospheres pressure and this does consume, like the numbers we heard, quite a significant part of the world's energy budget. As a gardener I know the legumes underground do this at ambient temperature, but they do this, in fact, using an iron-molybdenum catalyst, right? And to understand the structure, the chemical structure and dynamics of this catalyst is really beyond anything classical computing technologies can do at the moment. So the picture at hand is if we are able to simulate now these chemical processes, we would be able to understand something about catalysis.

So in our own work we've done hydrogen, others have done a few more atoms. There's a few more atoms to go to get up to iron but, you know, we're working on it.

Senator HIRONO. So how far in the future do you think before we can create fertilizer in the method that you described?

Dr. SIDDIQI. I would say near-term quantum devices have tremendous potential in the next 5 to 10 years, or a few years to 10 years, because one other thing which is very interesting about this is what if the answer from your computation is fuzzy but still useful?

For example, we're not able to figure out the exact structure, but nonetheless we can guide chemists to say, you know, this is the phase space you should look in, this is the combinatorial space you could look in. That's already extremely valuable. We wouldn't be looking for a needle in a haystack. We could, sort of, narrow down, well, the haystack is over here, right? And one could have, you know, a classical effort to find it. That's another level of technology that may come out of this.

Senator HIRONO. Thank you.

Thank you, Madam Chair.

The CHAIRMAN. Senator Daines.

Senator DAINES. Chair Murkowski, thank you. I have not had this kind of conversation since my chemical engineering days.

[Laughter.]

This is great.

Thank you for holding this hearing today, Chair Murkowski. It is probably not customary for this Committee to dive into something as technical as quantum computing or that we have Microsoft testify here in front of us, but for me, this is a fascinating and very important topic.

I spent 28 years with my chemical engineering degree in the private sector before coming to Congress, but 12 of those years were in the cloud computing business. We helped build a company that was a little startup that grew to about 1,100 employees, at cap was about $1.8 billion. We took the company public and it was acquired by Oracle.

So I have had a chance to see a startup from the early stages, before the cloud was even called the cloud then, and grew it to a large company that had, at present, 17 offices of 33 languages, offices around the world.

I have also seen the challenges of what it takes to build a business like that, how hard it is to build a technology company, the issues of innovation, of hiring, of expansion. And I believe that quantum computing faces many of the same hurdles that we faced a decade before regarding investment and a trained workforce.

I do believe we are making good strides. And by the way, Montana—this company I told you about was headquartered in Bozeman, Montana, with offices in London and Tokyo; Sydney, Australia; Chicago; Dallas; Washington, DC. And we have some Montana companies actually leading the way.

My alma mater, Montana State University, proud of—many of the leading quantum and photonic companies are growing right there in Bozeman, Montana, and around our state.

But I do fear—one of the things that keeps me awake at night, is we are falling behind China. I spent six years working in China with Proctor & Gamble. I was in Guangzhou back in the '90s and leading the startup there for P&G. So I keep a close eye on what is going on competitively. This is a race that I don't think we can lose. It would not only have implications on our economy and academia, it could have serious implications for national security.

Mr. Holmdahl, Microsoft is one of the top companies investing and working in quantum computing. As an international company, you also have a unique view of the global quantum race. I have heard from experts in the field, on the ground in China, on the ground in Hong Kong and other places, on the ground in Menlo Park, that we are losing this race to China. Where do you see the U.S. in the quantum race?

Mr. HOLMDAHL. Senator Daines, it's a great question. I think there are a couple of ways to look at it. I think that if you look at the commercial sector, the big U.S. companies are doing good work. Microsoft, Intel, Google, IBM are all doing good work. We have—you're starting to see the startup community get into the quantum race as well. Rigetti is being funded by Andreesen Horowitz.

That said, I do worry, again, and I said in my opening statement that the quantum workforce is going to be—and you hit the nail on the head, we have to build a complete end-to-end system, you know, all the way from the qubits that are down for us at the bottom of the refrigerator to the cryogenics controlling it, to the software to control all that, to the applications and the algorithms. And that is where I really worry that our workforce today is not necessarily, is not skilled in order to be able to jump into this quantum economy. We do need to do more work at the university level, on-the-job training, more partnerships. There are other countries out there that are investing in it. I don't know about China specifically, but I do know that for us to be successful we need to continue to invest in the workforce and continue to invest in research and then continue to look at other partnerships.

Senator DAINES. On this workforce question, look at the graduation numbers of STEM grads coming out of U.S. universities versus STEM grads coming out of Chinese universities. I think the number, it is a seven to eight time factor. The scale that is being built in terms of innovation ecosystem in China is remarkable.

So follow, what do you see as the national security implications, and I think Senator Gardner touched on this a little bit as well earlier, of China taking the lead in the quantum information space?

Mr. HOLMDAHL. Well, you'd be happy to know both my kids graduated with machine learning degrees so I'm trying to contribute to that.

Indeed, yeah, there are obvious security issues with somebody, any country, getting the ability to decrypt, essentially, our encryption algorithms. You know, RSA–2048 has—it's no secret that people with a big enough quantum computer can crack that. I would think it would be in our best interest to make sure that we have the ability to do that before others and that we also, and like Microsoft and others are working on, develop post-quantum crypto algorithms so that when quantum computers are out there we're no longer using the encryption methods that we have today.

Senator DAINES. Thank you. I am out of time.

We touched on there that the commercial side, certainly long-term competitiveness for our nation, but also the national security implications of breaking encryptions and so forth and where this all goes and the importance of this topic. I want to thank you, Chair Murkowski, for bringing this to light in this Committee and for the experts here to help us articulate what the challenges are going forward.

Thanks.

The CHAIRMAN. Thank you, Senator Daines.

Senator Heinrich.

Senator HEINRICH. I want to take a step back and maybe give folks a little bit of a window into why some of these principles exist that we are talking about and what is so unique about quantum with regard to observation and applications like secure communications.

Dr. Siddiqi, could you talk a little bit about just what is quantum entanglement and what does that mean for those applications?

Dr. SIDDIQI. Sure. Thank you, Senator Heinrich, for the question of what is quantum entanglement which, in reality, is the resource that makes quantum systems unique and powerful.

If I'm allowed to use my pencil I will use this as an illustrative tool, right? So there's a property called spin, for example, right? So an electron which has charge can also have spin which we know points up or down. But the debate that Einstein and Bohr had is how does a spin know which way to point until you measure it, right? It's only when you measure along this axis will it be up or down because up or down doesn't have meaning until you define what's up and what's down. The idea then is that the spin, in fact, can be in any state. This is the same principle as the cat. It could be asleep or awake. It can be in any state until you define that axis.

Now let's imagine I have two pencils. We'll assume this is a pencil. If I have two pencils or more, then the number of combinatorial states that they can be in grows exponentially, right? So that's entanglement.

The idea that I can't write this as just one object, individual objects and, in fact, it's one combined object is entanglement. And that's what adds the power to computation or communication, et cetera. But then, of course, the critical part is you have to have the right algorithm to take advantage of this.

Senator HEINRICH. But you can also separate those two particles over vast distances and still what you observe in one applies to the other.

Dr. SIDDIQI. Correct.

Senator HEINRICH. Which is——

Dr. SIDDIQI. Correct. This is what is known as——

Senator HEINRICH. ——what makes this so powerful.

Dr. SIDDIQI. Absolutely. This is the question of Einstein, Podolsky and Rosen, right? The idea that you can separate out these two and quantum mechanics would exist all over the universe and all tests show that it does.

Senator HEINRICH. So that has obvious applications in things like communications.

I am going to resist the urge to ask you about the potential for entanglement of your cats and move on to an engineering question for Dr. Holmdahl.

What should we be doing now in our engineering schools to prepare the workforce that is actually going to take all of this basic research in physics and begin to apply it to the applications that we will really need to make this a utility in the future?

Mr. HOLMDAHL. Yeah, that's a great question, Senator.

I think there are like three main areas, at least three main areas, that we need to work on.

One is just in basic quantum physics and the materials associated with that. I don't think we have the answers to how these qubits are going to look, and we need to make sure that we have that workforce that can not only figure out what the right materials are and the right designs are, but how to manufacture and fabricate those. It's—we used to say in the engineering world, it's kind of easy to build one of something, but trying to build a million is much harder. And so, you have to have a manufacturing and design at the same time.

The second part is that the engineering of these, in most cases, is done at cryogenic levels——

Senator HEINRICH. Right.

Mr. HOLMDAHL. ——you know, 4K and below and we need, like, we're trying to hire many cryogenic engineers and they're just not out there today. And so, more work and that might probably be in the mechanical engineering side of the things. If the universities could up the level of cryogenic engineers they have that would be a big help.

The third bucket is in programming the quantum computer, the paradigm is a completely different paradigm than a classical computer and the algorithms are different. We need to develop that next level of programmers, quantum programmers, in order to be able to solve some of these tough problems.

Senator HEINRICH. Why do you think there has not been more interest in land grant universities in jumping out to start, you know, filling the pipeline for these sorts of educations?

Mr. HOLMDAHL. You know, I don't personally know. I think this is the most amazing topic. I came to it later in my life, like the last two or three years, but it's incredibly inspiring.

I think being in the QIS meetings yesterday, it sounds like universities are starting to really grasp the power and excitement around this. I'm hopeful in the next few years you're going to see more and more of it.

Senator HEINRICH. Great.

Thank you, Madam Chair.

The CHAIRMAN. Senator Cortez Masto.

Senator CORTEZ MASTO. Thank you, Madam Chair, and thank you for this hearing today.

Gentlemen, thank you so much, very enlightening testimony.

Let me start with Under Secretary Dabbar. I am reviewing the National Strategic Overview for Quantum Information Science. Let me ask you this—the NSTC Subcommittee on Quantum Information Science—are you comfortable that that subcommittee members contain all of the federal partners that are necessary to address this issue and work with private sector, academia and the national labs on this issue, on QIS?

Mr. DABBAR. Yeah. Yes, Senator, I am.

It has been a very inclusive process that OSTP ran and it includes all the—from the basic sciences to the applied applications across the federal agencies.

Senator CORTEZ MASTO. Is there anything that you are hearing today from the private sector and the national labs that you think needs to be addressed, or taken back to this subcommittee, in addition to the recommendations that they have made or more information that they should be aware of?

Mr. DABBAR. So the short answer is yes. And between today and the meetings that we had yesterday at the White House and earlier before that this last week, is that we've been soliciting input across the whole spectrum of private and public, and there's a number of key takeaways.

It's around infrastructure that, obviously, this Committee has a lot about building out infrastructure at our national labs. It's about connections, and I think that came up here earlier today, that the Chairman asked about earlier. And it's also about how do we help private sector transition? So all these conversations here in the near-term have also been very helpful input for us.

Senator CORTEZ MASTO. Thank you.

And then, let me just say, I echo all of the questions that have been asked. I mean, this has been a great conversation today.

Let me ask you three gentlemen: What should we be doing at the federal level? What should we be prepared to address for the future that was not talked about so far when it comes to the use of QIS? I will start with Dr. Siddiqi.

Dr. SIDDIQI. Thank you, Senator Cortez Masto, for the question.

What I want to talk about is something very mechanical in terms of how we fund programs, how we evaluate programs. So on the surface, of course, we have many great programs for graduate fellowships, for industry engagement with the SBIR program and all things that normally would look like they are, sort of, building the linkages that we need but, in fact, dedicating some subset of them and removing the bureaucratic difficulties of getting those through and dedicating them for a quantum initiative would be tremendously beneficial, right? Because in my mind, a center that has the ability to give out those fellowships to, sort of, build those linkages with industry rather than saying that we will be one of the 12 topics that compete for very precious dollars would be a tremendous investment and a tremendous step forward. So any mechanical methods which, in fact, streamline this process of bringing together these three entities, both in communication and funding, would be tremendously appreciated.

Senator CORTEZ MASTO. Thank you.

Mr. Holmdahl.

Mr. HOLMDAHL. Yeah, one thing that I would point out. I'm a big believer in doing these grand challenges and grand strategies and there's—certainly, you want to have a lot of individual research going on but I would like to see us do our moonshot, whether it be quantum computing or the quantum network, and try to rally all the resources that the country has in commercial and in universities and academics and put that together because these are multidisciplinary systems that require people from physics, from computer science, from mechanical engineering, from electrical engineering, from business, all to come together, and it's going to take a lot of people to do one of these big things. And when you go through that process you learn an incredible amount, and everybody has this vision and this goal in their mind and they know what they're doing and why they're targeting it.

Senator CORTEZ MASTO. Thank you.

Dr. Guha.

Dr. GUHA. Thank you, Senator.

So, very quickly, I think I would ask that you view this as an area that is a priority for investment, that it is really time we invested in this. And I would also request consideration of focused centers of excellence instead of spreading things around and diluting it.

And then there is the workforce part. There are areas of the workforce that need to get on this field, you know, traditional engineering areas, et cetera. So that investment should also be done astutely.

Senator CORTEZ MASTO. Thank you.

Gentlemen, thank you.

Thank you so much, Madam Chair, for the conversation today.

The CHAIRMAN. Thank you.

Senator King.

Senator KING. Thank you, Madam Chair.

I apologize for being late. The schedule around here needs a quantum system——

[Laughter.]

——in order to figure out how we can be in two places at once. If you could work on that.

This may be an obvious question, but give us the strategic implications of this. How will this change the world? What are we talking about?

Doctor.

Dr. SIDDIQI. It's a great question, Senator King.

And you know, physicists, we look at the 50-year time scale. Where will we be when we think about these technologies?

I think it will radically change, first of all, in the grandest scale, the way we think about the world and what our theories, in fact, tell us about what the physical world is like, at the grandest levels. Because, in fact, it's these machines that may tell us what entanglement is in the universe. What's the fabric of the universe? What are black holes? What are theories of this type of grandeur, and how does one think about that?

So that has deep implications for everything in terms of theoretical aspects of physics that enter in material science and——

Senator KING. It worries me that you are headed for Douglas Adams' most elaborate and scary torture machine ever devised, the total perspective vortex.

Dr. SIDDIQI. That's right.

Senator KING. Which looks like a phone booth and when you step in it shows you your true place in the universe.

[Laughter.]

Dr. SIDDIQI. That's right.

We will like to—I will defer to my colleague from Microsoft for building.

[Laughter.]

But indeed, that's sort of a very grand vision, right?

But in terms of——

Senator KING. Give me specifics. How will it change life?

Dr. SIDDIQI. Yeah.

So for specifics, it will change the way we synthesize materials, right? I am also a chemist-in-hiding, a little bit, I have a chemistry degree. So quite often this is discovery-driven rather than by rational synthesis. So that's a radical change in thinking about how we think about new materials and classes of materials and catalysts, and so on and so forth.

In the computing domain, right, it's very different in terms of optimization from that we simply cannot access at the moment. In particular, for example, how does one think about logistics of very large operations in systems that have many moving parts. So that's a very applicable thing.

Going again in terms of atomic systems, how do we think about technologies at the atomic scale, right, very different views of what sensors are like, right, what communication tools are like.

It's really across-the-board thinking from the smallest scales of the atom, the photon, so on and so forth, all the way to the grandest scales which are what is the model of the universe. I view it really as a transformative technology.

Senator KING. Mr. Dabbar, are we in an arms race in terms of this technology? We are competing. As I understand it, both the Chinese and the Russians are making significant investments as is the EU. What are the implications of not getting there first?

Mr. DABBAR. So I would split it up between economic and security, that particular question.

From an economic point of view, you could characterize it as how important is the computing and the semiconductor industry is to this country and everything that applies to our phones, to our computers, how we communicate, how we make inventions, is vast. And so, this could be a major jump in that.

In sensing—I gave a comment earlier about life sciences. The impact of quantum sensing potential to health in this country to replacements for MRI machines at levels that would—you talk to any doctor about those implications and they hear about it and they look at what impact they could have on various aspects of life sciences, is actually hard to bound.

So there's a lot of basic science, a lot of economic value that we've already seen——

Senator KING. Decrypting is one of the possibilities. Is that not the case?

Mr. DABBAR. Yes, Senator.

So on defense I would hit on two, there's many examples but let me hit on two.

The first one is, obviously, for crypto. Right now, obviously, many things in the world, including on the defense side, are coded and there's been some work done by professors, one in particular, about the ability to use high qubit machines to be able to break current codes at the most highest level, which has broad implications. And so, for us to be able to do that—and by the way, that's not just a defense topic, it's every single credit card payment, everything in the financial system, you know, that's currently encrypted has implications.

And then there's another one that's also very important, which is clocks. And right now, we use atomic clocks to code to do very specific timing for both security and for financial reasons. And there's risks around, we were talking about earlier, around space and satellites and so on, around how that's currently done today, in terms of clocks. And, obviously, if we have the capability of that, it certainly provides for greater security around that topic.

Senator KING. Where do we stand in the international competition?

Mr. DABBAR. Senator, so the way I would characterize it is I will always bet on America and, meaning that I think the diversity that you see here of private industry and universities and the federal complex is more dynamic and comes up with more ideas. We haven't had time to talk about all the different technologies that are being developed across many of the different areas, but it is a very dynamic space.

But I worry that we need to put more resources against that to leverage all this different input that we have. There's one certain country that likes to put a tremendous amount of money into a particular topic. That's a command and control dictatorship way of trying to invest. And many times they bet, whenever you have command and control, it looks like a lot of money. We should be worried for the reasons both economically and defense. We should be focused on it.

But I think, with the focus of this body and the nation across all the different areas, I have a high degree of confidence for this country.

Senator KING. Madam Chairman, I am out of time but could I ask one question that follows up on that?

The CHAIRMAN. You may. You missed my long series of questions.

Senator KING. Okay, thank you.

The CHAIRMAN. Go ahead.

Senator KING. So the question is how do we organize? And this would go to any or all of you. How do we organize our approach to this problem? Is it a Manhattan Project—a focused government-led project with private sector and all those people—or is it a diverse, Caltech does something, MIT does something, Microsoft does something and, hopefully, we get there?

Dr. SIDDIQI. So being at Berkeley with the Manhattan Project idea, I'd like to comment that, I think, we need a balance of both, right? Certainly, we need vertical integration that brings all the elements that we've been talking about, the computer scientists, the physicists, into one room so we can really fill in those technology gaps and build the products that we're looking for.

At the same time, there are very deep and difficult theoretical questions that we could all benefit from. So there may be a tiling of the phase space with some horizontal integration as well.

Senator KING. But I would think that would be something you all could help us with is to suggest how this should be organized, because that is a function that the Federal Government can supply as the organizational principle here.

Yes?

Dr. GUHA. So, if you look, you know, 30, 40 years back, a lot of the technologies that we use today like telecommunications, silicon, microelectronics, a lot of the basic early work was done by companies such as Bell Labs and IBM. Those business models don't exist today anymore. And research is also much more expensive today for industrial R&D to do it alone.

My own feeling is that something like this, with this sort of national importance and wide breadth, needs to be centered around the national labs working very closely with academia and industry. So there has to be learning on both sides over here.

But I do feel that the national labs have the infrastructure and the, you know, just the breadth and the size of equipment and the capabilities and the outreach to academia and industry that this, you know, these are the places where we should be doing the research of the future.

Senator KING. Okay, thank you.

Thank you, Madam Chair.

The CHAIRMAN. Senator Cantwell.

Senator CANTWELL. Thank you, Madam Chair.

And thanks so much to the witnesses for being here and your testimony. We have tried to follow it from afar here as we've been doing other things. I so appreciate, particularly, the focus on workforce which I do want to ask about.

Madam Chair, again, thank you for having this hearing, it is such an important topic. I think DOE is more in the forefront of what we need to do to better skill our competitiveness as a nation, secure us on cybersecurity and do so many things. I think today is another example that, really, this Committee can do a lot in bringing attention to those investments and strategies.

I also want to thank my colleague, Senator Duckworth, for filling in earlier for me and, I guess, you and she both did ask questions about workforce. But I will get back to that in a second.

Mr. Holmdahl, thank you so much for being here and for your leadership. I wondered if you could talk a little bit about the relationship between Microsoft and the Pacific Northwest National Lab and what you are doing in collaboration? Dr. Siddiqi mentioned chemistry, I don't know if that's the main focus, but if you could elaborate on that, it would be so helpful.

Mr. HOLMDAHL. Yeah, sure, Senator Cantwell.

One of the things about quantum computing is the algorithms are very different from the algorithms that you find in classical computing. And so, we already have a team of people that are going out and talking to people in the government space as well as the enterprise space, like, you know, figuring out what their tough problems are and how might quantum algorithms solve those problems. So one of the things that we think that a quantum computer can solve are quantum chemistry problems. It, kind of, fits right into the wheelhouse of the quantum program.

So we've been working with the Pacific Northwest National Laboratory for over probably a year now. They have, you know, some of the best chemists in the world. I think there are 4,500 people that work there.

We have been exploring, like, what are their tough problems that they're trying to solve? How might a quantum computer solve those problems? We've continued to engage in those discussions. They're very fruitful discussions.

I think the thing that really helps, too, is as we design our quantum computer and we know what problems they have, it informs how we design that computer going forward so that when we get this computer complete, it will solve real problems that people have. And I look at this as an example that industry and the government as well as universities can have coming together in trying to solve these with all three bodies working together.

Senator CANTWELL. It reminds me of, you know, in other areas of science where we're applying data and information, like on the human genome project and others.

Dr. Siddiqi, since you represent a lab, did you want to weigh in here about what that relationship between labs can do for us?

Dr. SIDDIQI. Absolutely, thank you, Senator Cantwell, for the question.

Perhaps the easiest way is to give an example of what we're doing in our domain. A small example of how, in my mind, real partnerships are built between national lab elements, academic elements and industry is really through our industrial incubator program, called Cyclotron Road, at Lawrence Berkeley Laboratory.

So, in particular, we have a company that's willing to develop various technologies in the quantum domain, and we have partnered with them. And, in particular, their task at the near-term is to build the packaging, all the boxes and wires that go around the chip and we are very good at producing the chip. So we had a real discussion saying that, what are you comfortable sharing with us and what are we comfortable, you know, sharing with you? And it was a great discussion, right? So we've now handed over to them our chips and said, please go ahead and design what you think is the package, and we have some ground rules, right, about what to talk about, what not to talk about, so that they remain competitive and we also remain happy.

So I think these partnerships can very much be nucleated. They start with, as Dr. Guha was saying, you know, the model of R&D has changed over the years. So I think it'd be very critical for us to identify what's the space of that basic research and we're, sort of, sharing what's the space that becomes competitive research, so on and so forth.

And as an academic I think about the fact that, you know, we should be giving talks and different sessions and conferences, right? There are sessions that are really academic questions. There are sessions that are, sort of, basic science at the larger scale and, really, industrial sessions.

So in my own field I'm actually an engineer that works on RF stuff by training. There's big conferences that have these things split up in three sections, right? There's the fundamental science section. There's the large-scale science and what have you. So I think that would be very healthy in the quantum domain so that we can all sit down and figure out how to tile the phase space in a very synergistic way.

Senator CANTWELL. But, no doubt, you welcome the partnership and you welcome DOE's role?

Dr. SIDDIQI. Absolutely.

Senator CANTWELL. So that brings up—listen, I have been involved with tech transfer a long time and it is always an interesting question about what actually gets done in tech transfer. Obviously we could have a whole hearing, probably a week, on tech transfer from our national laboratories if we wanted to but, for today, this notion of the workforce issue and on-the-job training. What do we need to do here to make sure—I just think about what we have been able to do at the Washington Technology Center as it related to the University of Washington and Boeing. That partnership let them focus on a lot of things and, in the end, they ended up focusing on composite manufacturing and solving some of the big problems that were going to be in the future of composite manufacturing. But when everybody is there working on the job, you know, I have met these young students years later and now they are the leaders within Boeing because they got the on-the-job training as the technology was just cutting-edge.

I see everybody nodding. So what do we need to do to make sure that happens?

Mr. Holmdahl.

Mr. HOLMDAHL. Yeah, I think an interesting parallel might be the machine learning explosion that we've had in the last couple of years. You saw a lot of engineers that hadn't gone to school with machine learning backgrounds but, not only the companies themselves, but universities started doing a whole bunch of work in offering, like, either online classes or all-day classes or 12-week classes in order to get the engineering populations up to speed on what's going on in machine learning and AI.

If you look at today's workforce, the problems you need to solve in quantum are varied. Again, they go from manufacturing all the way to cryogenics to new computing algorithms.

I do think that the fundamental engineers that we have in the force can be taught to do the work necessary for quantum, but it's like taking a mechanical engineer and making sure that they have the right training around cryogenics either from a university or from some training center or from a company that allows them to know more about cryogenics.

Superconductivity is another big one that's important. You need, typically, superconducting circuits to control your quantum qubits. Engineers have the background, but they need that additional training. We put all of our engineers through like 10 weeks of training in order to get them up to the superconductivity speed.

The other one that we're doing a lot around is these quantum algorithms that we talked about. We've put out a kit, a quantum development kit, that teaches you how to program a quantum computer. And we've also developed a bunch of katas which are like short learning exercises for developers. And you know, it's unbelievable how many developers are inspired by being part of the quantum revolution, and now they have an opportunity to learn very quickly with these little, simple katas on how to develop quantum algorithms.

Senator CANTWELL. Yes, Mr. Dabbar.

Mr. DABBAR. Senator, so I would like to highlight something that's in the bill that's before you that I think is very interesting, and we certainly support the structure as proposed in the bill which is around the quantum centers and allowing who can be allowed to bid for the particular centers. The bill specifically says that as a centers as we, assuming it gets passed by this body, that the three to five centers would, the people who could bid could be national labs, universities, private sector or consortiums thereof. And I certainly expect that as we potentially go out and do that, that there will be groups of that, that very much along the lines of your question regarding having some people probably part of a consortium from a private partner, from an industry, from a national lab and from a university and bringing people together and how they actually approach, to your Boeing example, how they approach a particular problem, how do they train people. And I think it's going to be very interesting as we get those groups together.

And the one thing that I could say about this particular point in the bill which we support, is that the ripples, even though it's not passed, I can tell you that the number of national labs talking to private industry, talking to universities today, basically, trying to partner up to figure out that when this bill gets passed, what the centers are going to be, what the focal points of each are going to be which is a longer conversation, and then who is going to partner with who between the private sector, universities and national labs is already happening in this country. It's very exciting to be part of that conversation.

Senator CANTWELL. But you definitely believe that DOE should play a role in helping us get workforce training in this particular area?

Mr. DABBAR. Yes, yes, Senator.

A big part of what we do, so out of the 85—I'll give an example. We announced 85 different grants yesterday for $218 million. Not only does the money go to a PI for a particular topic, they go hire a bunch of, you know, juniors at their particular lab or their university who are still studying. And so, there's an effect as we go through it and it's very much part of our thought process when we go fund particular areas, including this one yesterday.

Senator CANTWELL. Well, I just happened to run into a bunch of Sea Grant fellows, Madam Chair, on the way here. I don't know where we would be in the United States Congress on maritime and fishing policy if we did not have Sea Grant fellows.

I am just a big believer in an information age that we do everything we can, particularly on cutting-edge technology and transformative areas, of also bringing the workforce along with us. I think we definitely need to do that in cyber. I definitely think we need to do it here. DOE can play that role. I hope they will.

I hope we will think about how we, as I said, having witnessed this from the university and tech transfer perspective to now see them, you know, working in the field, particularly a lot of young women, who have gone into composite manufacturing. It has been very heartening to see that we established those environments in which they could learn and earn and get educated on cutting-edge technology at the same time.

So thank you.

Thank you, Madam Chair.

The CHAIRMAN. Senator Cortez Masto, the two of us have had 10 minutes. Would you care to ask anything final?

Senator CORTEZ MASTO. The only one I would have a follow-up with is Under Secretary Dabbar.

I noticed you were going to have a comment to Senator King's question about what the structure should look like. Were you able to answer that with the last question?

Mr. DABBAR. Yes, Senator.

Senator CORTEZ MASTO. Okay.

Mr. DABBAR. I think the comment I just gave about the structure of the centers addressed, I think, similar to his question.

Senator CORTEZ MASTO. Thank you.

The CHAIRMAN. Thank you, Senator.

Gentlemen, thank you for your comments this morning. It has been encouraging. It has been exciting.

As we think about how we grow a workforce, there are things that we can do at the federal level. There are incentives that we can put in place, but I guess my experience is that young people are really smart and they are going to go where they think that there is a level of opportunity, that it is exciting, that it is cutting-edge, that they are making things happen. And so, if we send the right signals that we are leading in this, that we are where you want to be, I do think that just generates that level of enthusiasm and we are able to do more when it comes to developing that good strong workforce and then keeping them here with those opportunities. It is the keeping them here part that, I think, when somebody mentioned "are we in an arms race here" in terms of who is going first. It is important, the investment that is being made. But again, I think as long as young people believe that there is greatest opportunity here to be pushing out in these areas, I think this is how we stay ahead.

I appreciate all that you have contributed to this conversation. I admit that I have learned a great deal more in the two hours that we have been sitting here. It has been great from my personal advantage, and I thank you for that, but thank you for sharing with the Committee.

I think, between what we have been doing here and then the hearing that we had a few weeks back on block chain and crypto currency, we are doing fun, forward-thinking things here. So watch the Energy Committee.

Thanks so much and we stand adjourned.

[Whereupon, at 11:59 a.m. the hearing was adjourned.]

APPENDIX MATERIAL SUBMITTED

U.S. SENATE COMMITTEE ON ENERGY AND NATURAL RESOURCES
The Department of Energy's Efforts in the Field of Quantum Information Science
Questions for the Record Submitted to the Honorable Paul Dabbar

September 25, 2018 Hearing

QUESTIONS FROM CHAIRMAN LISA MURKOWSKI

Q1. The House recently passed quantum legislation to authorize new DOE quantum research centers that could be hosted at National Labs or universities. However, the bill is silent on DOE's ongoing efforts in quantum – such as providing funding for testbeds and Energy Frontier Research Centers, as well as general basic science.

Q1a. In order for the Department to facilitate the types of interdisciplinary work that you envision, is a broad program that includes DOE's ongoing quantum work needed, in addition to new quantum centers?

A1a. Yes, DOE's Quantum Information Science program builds on the wide variety of research modalities that the Office of Science has maintained over the years---from single investigator long-term research in high risk, high reward projects; to collaborations between research teams such as Scientific Discovery through Advanced Computing (SciDAC) application partnerships or Energy Frontier Research Centers; to large partnerships such as the Hubs.

Q1b. DOE's ongoing work provides a broad base on which to build impactful interdisciplinary quantum research, from the fundamental science of quantum phenomena to tool development and prototype fabrication. What are the specific programs or mechanisms currently utilized by DOE that are important for the long-term growth of quantum information science?

A1b. In addition to the research modalities noted above, DOE's Nanoscale Science Research Centers (NSRCs) are an excellent example of the type of specific capabilities that are critical for accelerating progress in quantum information science (QIS). In fact, DOE's QIS strategy relies heavily on the NSRCs, which will play a key role in the fabrication, characterization and testing of quantum structures and devices up to mesoscale through innovative instrumentation and multi-lab synergies, including partnerships with the Advanced Scientific Computing Research's quantum test beds. Other DOE user facilities, such as the x-ray light sources, neutron sources and high performance computing facilities, will also play key roles in advancing quantum science and evolution of new technologies.

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Q2: We have many different versions of public/private partnerships that have demonstrable track records of success. How do you envision the most effective quantum collaborations between industry and researchers at universities and National Labs?

A2: One of the lessons learned from the Department's Exascale Computing Initiative is the power of co-design for effective collaborations between industry and researchers at universities and National Laboratories. The foundation of co-design is a rigorous feedback process between all partners throughout the project. This is facilitated by frequent, ongoing interaction in a team environment. In the case of a quantum collaboration co-design project, information would flow continually from the design and development of new quantum materials through initial testing in quantum testbeds which would provide access to the user community to test algorithms and tools.

Q3. DOE utilizes multiple mechanisms for engaging the private sector in collaboration and for technology transfer, including, but not limited to, the Energy Innovation Hubs, National Network for Manufacturing Innovation institutes, small business vouchers, and the Lab-Embedded Entrepreneurship Programs.

Q3a. Does DOE have sufficient authority to foster appropriate collaboration and technology transfer between any DOE funded quantum research programs and industry?

A3a. As noted, DOE has a number of existing mechanisms to engage the private sector, and a long history of doing so. We believe the existing DOE mechanisms for funding research and development, as well as the mechanisms available for fostering collaborations with industry through partnerships with DOE national laboratories, provide the needed authorities to effectively foster technology transfer and collaboration with industry.

Q3b. Would new programs better facilitate such collaboration and technology transfer that are authorized but not established?

A3b. QIS is evolving very rapidly, in terms of both fundamental science and foreseeable technological horizons. Programs that can adapt quickly to changing competitive environments will be essential. The authority DOE currently has with existing funding mechanisms to define the size, scope, and partnering options within solicitations provides

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the needed flexibility for tailoring solicitations to evolving research and development needs.

Q4. How should DOE quantum information science programs collaborate with quantum research and development programs in other nations?

A4. Collaborations with quantum information science programs in other nations can be desirable, particularly in continuing to build open standardized software so that researchers are able to develop quantum applications that can be executed on a variety of quantum hardware. Where appropriate, open science benefits the U.S., which historically is able to stay at the leading edge and to attract talented scientists to further accelerate our research progress. There may be some sensitive quantum research areas where collaborations with limited sharing of information may be the most appropriate approach.

Responses of Dr. Supratik Guha,
Professor, Institute for Molecular Engineering, University of Chicago, and
Director of the Center for Nanoscale Materials and Senior Science Advisor,
Argonne National Laboratory,
to the Questions for the Record related to the hearing of the
Senate Committee on Energy and Natural Resources
September 25, 2018

Questions from Chairman Lisa Murkowski

Question 1: The House recently passed quantum legislation to authorize new DOE quantum research centers that could be hosted at National Labs or universities. However, the bill is silent on DOE's ongoing efforts in quantum – such as providing funding for testbeds and Energy Frontier Research Centers, as well as general basic science.

- In order for the Department to facilitate the types of interdisciplinary work that you envision, is a broad program that includes DOE's ongoing quantum work needed, in addition to new quantum centers?

Quantum information sciences (QIS) research ongoing within the DOE Labs is valuable and wide in scope. The research includes systems and algorithms work; underlying materials science research for high coherence entangled systems; fundamental physics research; and building new tools needed for QIS research. Multiple DOE program offices support inter-disciplinary research. It is important that such research continue in addition to new quantum centers. We envision the quantum centers focused on particular topics and agendas, against a background of broad, curiosity-driven QIS research also essential at this stage. The Nanoscale Science Research Centers (NSRCs) and the recently awarded Energy Frontier Research Center on Quantum Coherence in Materials (Lawrence Berkeley Labs and Argonne) are a couple of examples that I am familiar with that carry out such broad, curiosity driven research.

The fundamental science supports and complements the larger scale mission of the centers; co-locating these activities provides significant leverage and avoids duplication of laboratory work and even research programs. Coordination is critical; for example, center scientists could immediately deploy and objectively qualify a new protocol for generating and swapping entanglement on a communications testbed, feeding results back to the fundamental studies.

Finally, I would note that, QIS research today requires a significant infusion of new investment and resources above and beyond current activity in order to move to the next level, and in order to retain US leadership.

Question 2: We have many different versions of public/private partnerships that have demonstrable track records of success.

- How do you envision the most effective quantum collaborations between industry and researchers at universities and National Labs?

Collaborations effectively connect industry, academia, and the national laboratory system. An example that I referred to in my testimony is the Chicago Quantum Exchange among Argonne, Fermi National Accelerator Laboratory and the University of Chicago. Such collaborations are most effective when partners share ownership of scientific/technical problems statements, feel like "one team" (with appropriate IP and other agreements in place), and work physically side-by-side. Based on my significant experience working in similar partnerships during my time in industrial research and development (R&D), where companies collaborate closely to share the risk of exploratory R&D programs, I believe there is merit in people working together in physical proximity for the most efficient progress.

A successful model is the Interuniversitair Micro-Electronic Centrum (IMEC) in Belgium, where university students, assigned industry researchers, and IMEC staff work side-by-side on microelectronics R&D. Notably, effective collaborations are ultimately driven by shared graduate students, jointly mentored, in highly collaborative environments where they are exposed to complementary workstyles.

- What are the specific quantum programs or mechanisms, currently utilized by DOE, are important for the long-term growth of quantum information science?

Specific quantum programs
The DOE Office of Science has recently announced multiple QIS programs (in offices including High Energy Physics, Advanced Scientific Computing Research and Basic Energy Sciences) that are essential for long-term growth in the field.

Mechanisms
DOE Energy Innovation Hubs such as the Joint Center for Energy Storage Research (JCESR) and the Joint Center for Artificial Photosynthesis (JCAP) have brought together national laboratories, universities, and industry. Under the Hub model, DOE provides funding to national laboratories and universities, which connect to industry to ensure a focus on application and the possibility of emergent outcomes—where discoveries in one create opportunities in others.

DOE user facilities, such as the x-ray light sources, neutron scattering facilities and nanoscale science research centers, house state-of-the art research equipment that is a mainstay of the U.S. physical sciences research community. Such facilities, used extensively by the growing QIS research community, also will be very important for long-term QIS growth.

Question 3: DOE utilizes multiple mechanisms for engaging the private sector, including, but not limited to, the Energy Innovation Hubs, National Network for Manufacturing Innovation institutes, small business vouchers, and the Lab-Embedded Entrepreneurship Programs.

- Does DOE have sufficient authority to foster appropriate collaboration and technology transfer between any DOE funded quantum research programs and industry?

The DOE has a number of successful mechanisms to foster collaborations. Examples include standard technology transfer agreements included in Strategic Partnership Projects and Cooperative Research and Development Agreements, and separately, consortia-based approaches. The DOE Hub Model, such as JCESR, is an example of the latter.

Battery technology is an excellent example of successful technology transfer to the private sector. In the mid-1990s, the DOE provided sustained support for investigations aimed at a more stable and greater capacity electric vehicle battery. In 2000, the original lithium-rich Nickel-Manganese-Cobalt (NMC) blended cathode structure for which Argonne is now known was patented; 2007 saw the beginning of worldwide licensing agreements with various companies who now mass produce and market Argonne's patented materials for advanced batteries. In 2011, Argonne's technology made its market debut in the Chevy Volt; the technology is now also part of the Chevy Bolt. The technology is also being increasingly used in grid storage applications globally.

The QIS field is in a stage of rapid development and there needs to be flexibility in directions as well as approaches for partnerships and engagements. Authorizations to DOE should maintain this spirit of flexibility.

- Would new programs better facilitate such collaboration and technology transfer that are authorized but not established?

The national laboratories continue to work with the DOE on a broad range of mechanisms to engage industry. Most recently they developed the Agreement for Commercializing Technology (ACT) to give DOE laboratories and facilities more flexibility in engaging with industry on research and technology transfer projects. The ACT provides terms and conditions that are more consistent with industry practice than those permitted under DOE's traditional research agreements.

Question 4: How should DOE quantum information science programs collaborate with quantum research and development programs in other nations?

Pre-competitive basic research collaboration should occur on an as-needed basis. U.S. scientists can tap into considerable international expertise in a "compete-and-collaborate" spirit. Such collaboration is also important if, in sum, we wish to out-innovate our international colleagues. Additionally, such collaborations typically create a beneficial pipeline for hiring and bringing in world-class talent into the U.S.

Question 5: You hold a joint appointment as a researcher at a university and at a national lab. We had a great meeting called Alaska National Lab Day earlier this year, where we explored opportunities for the University of Alaska to work with National Labs on common challenges and opportunities. The university is exploring such joint appointments.

- How do these joint appointments work?

- What are the benefits to you, to your students, and to the evolution of research in your field?

Joint Appointment Models

There are a few ways that I am familiar with:

- A university-employed scientist spends a fraction of her/his time, paid or unpaid, working at the national lab.
- A scientist has separate employment agreements with a national lab and a university.
- A national lab-employed scientist has a university affiliation, often as an "adjunct professor."

  Depending upon the specifics, that scientist can then supervise graduate students (and be a student's doctoral thesis advisor) or have principal investigator (PI) status—that is, able to submit research proposals under university affiliation.

In all cases, arrangements are covered via a formal joint research agreement between the national lab and the university. The agreements generally allow for some type of IP sharing, the ability for students and researchers to work seamlessly at labs in both locations and some mechanism to transfer funds between the organizations per the needs of the joint study.

Such arrangements are significantly advantageous for high quality science. Graduate students are able to work in the national labs with excellent research equipment and experience a much wider practice of science. In turn, students infuse the national labs with their curiosity, enthusiasm, and fearlessness. I have experienced similar industry-academia interactions during my time at IBM and earlier at 3M.

The agreements also ensure optimal utilization of national lab resources. Additionally, students are a great catalyst for bringing national lab scientists and university professors together. We have seen the benefits in action at Argonne and the University of Chicago. Many university doctoral students and post-doctoral scientists, including some from my own research group, do a significant part of their research at laboratories within Argonne.

It is also worth noting that students have the opportunity to engage in larger-scale scientific/engineering challenges than they normally would in an academic setting. Lastly, they also have opportunities to experience team-based research across broad disciplines, preparing themselves for future careers in national labs, academia and industry where interdisciplinary research is becoming increasingly important.

Question 6: You have mentioned many of the ongoing efforts of your respective quantum programs. Many of the points you make revolve around the importance of collaborations to furthering quantum information science.

- If DOE hosted centers with a focus on quantum, what should they look like and what should they do?

Centralized hub model

One possibility is to use a more centralized innovation hub model. The centralized hub model would be partnerships among national labs, academia, and industry with the teams co-located at a few locations, enabling researchers to work side-by-side in physical proximity. University professors, for example, could have their students do a significant portion of their research on the national labs campus, taking advantage of her extensive scientific resources. Industry partners could similarly embed their employees within lab research teams.

This model would enable students' joint advisors to serve as a direct link between industry and academia, with the center as primary laboratory and research home. Such a hub model would also facilitate information sharing and a certain level of open scientific research essential at this point. In addition, the centers could serve as a central database for materials modeling, and device characterization, in order to set objective and meaningful standards for a rapidly emerging field.

- Should they focus on technologies, research disciplines, or themes?

It is important that DOE and key scientific stakeholders discuss this question. In my view, focusing on themes or "sub-areas" within QIS can be an efficient, bundled approach to the underlying science and technology with clear scientific goals. QIS is at too early a stage to begin resolving centers by "technologies."

For instance, some themes or "sub-areas" could be around

- Discovery science of new materials and architectures for solid-state qubits and their entanglement;
- Algorithms, systems research, and theory.
- Quantum sensing;
- Developing practical quantum networks and links;
- Developing a quantum computing infrastructure;

Stakeholders then need to horizontally connect such theme-based centers, in order to utilize the considerable synergies that will exist within them

Themes enable the community to constantly monitor developments, match discoveries to technology needs that would likely be invisible to academia alone, and harvest short-term benefits of research that may have longer-term goals. Themes could involve the basis for technology, such as quantum sensing where medical applications can co-exist with novel detectors.

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Questions from Chairman Lisa Murkowski

Question 1: The House recently passed quantum legislation to authorize new DOE quantum research centers that could be hosted at National Labs or universities. However, the bill is silent on DOE's ongoing efforts in quantum – such as providing funding for testbeds and Energy Frontier Research Centers, as well as general basic science.

- In order for the Department to facilitate the types of interdisciplinary work that you envision, is a broad program that includes DOE's ongoing quantum work needed, in addition to new quantum centers?

Yes. The United States has an opportunity to advance the "quantum economy" by supporting investments in research and development in quantum computing technology. Specifically, we encourage the Committee to:

- Invest in the quantum computing workforce, which will require not only quantum programmers, but also material scientists, fabrication and cryogenic engineers, and algorithm designers, among many others.

- Support research to foster the development of scalable quantum computing technology, including by pairing quantum technologies with existing research.

- Support the development of new quantum algorithms today, without waiting for advances in quantum hardware.

These actions will encourage the development of quantum computing—and complement the creation of new quantum research centers—across industries and sectors, which can deliver broad economic and societal returns.

- What are the specific programs or mechanisms currently utilized by DOE that are important for the long-term growth of quantum information science?

Expanding on the three recommendations outlined above, the DOE can make investments in the following areas.

1. First Recommendation: Invest in the Quantum Workforce

Today, fewer than one in 10,000 scientists, and even fewer engineers, have the education and training necessary to leverage quantum tools, even when they are enabled by a quantum machine. Practitioners entering this field need to learn key concepts in math, physics, and computer science, and be able to combine them in new ways. This includes not only quantum software engineers and developers, but also quantum application scientists, quantum materials

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specialists, fabrication engineers, and cryogenic engineers who can design the systems needed to house qubits.

The DOE has already recognized the importance of developing a quantum computing workforce, including by supporting internships and postdoctoral research at national labs and by funding other quantum-related research. For example, DOE has established the Science Graduate Student Research program, which supports research in priority areas including quantum information science, and sponsored a Quantum Testbed Stakeholder Workshop that allowed academia, industry, national laboratories, and government to provide perspectives on the objectives for a quantum testbed program. DOE's Early Career Research Program also supports the development of individual research programs for outstanding scientists early in their careers to stimulate research in disciplines including quantum computing.

We recommend supplementing those efforts in three ways.

First, DOE can create a partnership among government, industry, and academia on curriculum development, to ensure programs for learning quantum programming and quantum software and algorithm development are available at DOE, online, and at universities. As one example, Microsoft partners with the Pacific Northwest National Laboratory ("PNNL") to develop quantum algorithms and software solutions and also teaches courses at the University of Washington on quantum computing using our quantum-focused coding languages and tools. These collaborative efforts support early adopters, who are critical for innovation.

Similarly, in the United Kingdom, industry and government have together developed "hubs," that span undergraduate and graduate programs in fields relevant to quantum computing.16 These hubs enable students to obtain degrees in quantum computing and arm them with business and entrepreneurship skills, in addition to the necessary skills in quantum computing, facilitating the growth of quantum-driven startups. This is another model for the DOE to consider in developing the quantum-related curriculum needed to educate our workforce at a wide array of institutions.

Second, DOE can partner with industry to increase opportunities for on-the-job training. For example, Microsoft has a vibrant internship program to support a substantial number of undergraduate and graduate internships for students whose studies intersect with our work. DOE is well-positioned to explore partnerships to fund internships, including in coordination with local universities. Partnering with industry in those efforts would also help DOE understand the demand for the many types of quantum-related jobs, and enable DOE to target its other educational efforts accordingly.

Third, DOE can establish a national program to advance scalable quantum computing in conjunction with commercial efforts to do so, which could ignite a passion to explore this new and exciting frontier. There could scarcely be a more powerful or exciting vehicle for reenergizing STEM education in the United States than quantum computing. Just as America's

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early space program offered a vision of science and engineering so compelling and immediate that it inspired a generation of young people, so too could establishing a national program to build a quantum computer similarly captivate today's youth.

Together, these investments in training a workforce for quantum computing will complement our other recommendations on supporting research on scalable quantum computing technology and development of new quantum algorithms. Enabling on-the-job training and supporting access to and use of quantum machines will also ensure more people learn about quantum computing technology and are able to contribute to its advancement.

2. Second Recommendation: Invest in Scalable Quantum Computing Technologies

A pivotal role for the DOE will be to invest in areas critical to the development of quantum computing capabilities. We encourage the Committee to support two types of investment in quantum hardware. First, the Committee should invest in and prepare for quantum computing as a complement to the exascale computing in which DOE has already invested. Second, the Committee should create new programs to drive research on reliable and scalable qubits.

a) Quantum Computing as a Complement to Exascale Computing

The DOE has recently emphasized the importance of exascale computing, which focuses on high-performance computing systems capable of at least a billion billion calculations per second—50 to 100 times faster than the most powerful supercomputers in use today. But the gap between exascale and commercial cloud offerings is quickly shrinking, as the private sector develops high-speed cloud services to power large-scale machine learning. In fact, in this important area, commercial cloud systems are now roughly five times faster than the fastest conventional supercomputer recently deployed by DOE. These commercial clouds now offer a variety of computing capabilities—and they are working to add a quantum computer as the next option. DOE's exascale computing efforts will similarly benefit from considering how to augment exascale models with quantum computation.

Just as the private sector views quantum computing as an accelerator for cloud-based machine learning/artificial intelligence offerings, it can also accelerate machine learning/artificial intelligence for exascale computing. For either technology, quantum can improve training speeds, speed up inferences, and create smarter models of systems and data.

b) Programs to Increase Scale and Quality of Quantum Hardware

Another critical investment area is the manufacturing process required to build a quantum computer, including the fabrication capabilities, materials, characterization capabilities, and validation and verification of a quantum computer. DOE has already begun exploring this area through the potential of Quantum Testbeds. Microsoft encourages the DOE to create a new testbed to focus on improving the scale and quality of quantum computing hardware systems.

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As noted above, one significant challenge in this area is improving the reliability and scalability of qubits. The DOE has an opportunity to play a critical role in helping to identify which types of qubits may scale, how to engineer a scalable system, and validating and verifying the quality of qubits. For example, DOE can identify, test, and advance systems that promise scaling. It can also assist in the quest for demonstration of a path to scaling.

At Microsoft, we have pursued reliable and scalable qubits through our focus on topological qubits. But we encourage DOE to support research and investment not only in this technology, but also in other technologies that achieve the same goal of increasing the reliability and scalability of qubits that power quantum computing. DOE should also support research and investment in other technologies required to enable quantum computing at scale, including control electronics, cryogenics, and the classical computers required to control quantum computers.

3. Third Recommendation: Support Development of Quantum Algorithms Today

Another critical area of investment is in the development of quantum algorithms—which can be architected and coded today, without waiting for advancements in quantum computing hardware. Microsoft encourages the DOE to support the development of quantum algorithms in two ways.

First, DOE can create a testbed focused on the development of quantum algorithms. That testbed can identify and develop source code that will be needed for quantum computers, based on how quantum computers may be used in science and energy. Developing a quantum algorithm only requires a software development kit and a quantum simulator, which involves modeling a small quantum computer on a very large classical computer. DOE is uniquely positioned to support such development, because of its existing investments in large classical machines, which are well-suited to testing quantum algorithms in advance of scalable quantum hardware. This will require methods for easily programming, debugging, and testing quantum algorithms. For example, one key advance will be allowing the study of heuristics on real hardware. Another will be the ability to better test quantum algorithms in classical simulation environments, before running them on quantum hardware. Finally, we need debugging and verification tools to identify errors in quantum programs.

Second, DOE can encourage algorithm development by creating new partnerships in academia, government, and industry that bring together scientific experts and quantum programmers. As noted earlier, Microsoft's partnership with PNNL is one example of a successful industry-government partnership advancing quantum computing. That partnership focuses on the development of novel quantum algorithms and software tools for studying and understanding the most challenging problems in quantum chemistry. Later this year, we expect to release a new chemical simulation library developed in collaboration with PNNL that can be used in conjunction with NWChem, an open source, high-performance computational chemistry tool funded by the DOE's Office of Science. Together, the chemistry library and NWChem will allow researchers and developers a higher level of study and discovery as they tackle today's computationally complex chemistry problems.

Given the strong partnerships between PNNL and the University of Washington, and the deep relationships between the University of Washington and Microsoft, the Pacific Northwest can also be a regional center for quantum computing, with coordination and collaboration between these three entities. We encourage DOE to support such partnerships and the development of regional centers that foster innovation in developing quantum algorithms.

Question 2: We have many different versions of public/private partnerships that have track records of success. How do you envision the most effective quantum collaborations between industry and researchers at universities and National Labs?

As outlined above, Microsoft's partnership with the Pacific Northwest National Lab ("PNNL") is one example of a successful industry-government partnership advancing quantum computing. That partnership focuses on the development of novel quantum algorithms and software tools for studying and understanding the most challenging problems in quantum chemistry. Later this year, we expect to release a new chemical simulation library developed in collaboration with PNNL that can be used in conjunction with NWChem, an open source, high-performance computational chemistry tool funded by the DOE's Office of Science. Together, the chemistry library and NWChem will allow researchers and developers a higher level of study and discovery as they tackle today's computationally complex chemistry problems.

Given the strong partnerships between PNNL and the University of Washington, and the deep relationships between the University of Washington and Microsoft, the Pacific Northwest can also be a regional center for quantum computing, with coordination and collaboration between these three entities. We encourage DOE to support such partnerships and the development of regional centers that foster innovation in developing quantum algorithms.

In addition, the research in this area is also strengthened by global partnerships. Our global team extends to TU Delft, Niels Bohr Institute at the University of Copenhagen, University of Sydney, Purdue University, University of California at Santa Barbara, and partners with over a dozen other academic and scientific institutions around the world. These partnerships help not only to develop the requisite technology components, including materials, hardware, and software, but also to inspire a next generation of quantum thinkers. Our quantum team in Redmond is also focused on developing software for emerging quantum hardware systems and the necessary cryogenic control components. Together, our teams combine theoretical insights with experimental breakthroughs to develop the hardware and software to enable quantum computing technology.

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- In order for the Department to facilitate the types of interdisciplinary work that you envision, is a broad program that includes DOE's ongoing quantum work needed, in addition to new quantum centers?

  Absolutely. DOE's capabilities and resources in quantum research rely very heavily on previous work in materials development, computational research, engineering and other basic sciences funded through a variety of Office of Science programs. New quantum centers should not replace this important research, but rather consistently leverage it to ensure the greatest return on the federal investment. Likewise, advances made and capabilities built at the centers can be leveraged across the Office of Science's research portfolio.

- What are the specific quantum programs or mechanisms, currently utilized by DOE, are important for the long-term growth of quantum information science?

  Larger, specifically quantum research investments are relatively new within the DOE Office of Science portfolio. However, long standing basic research programs and research capabilities developed across multiple fields at the national labs and among the university research community have built a strong foundation on which to build a world leading and productive quantum research and technology development ecosystem. Examples of this type of foundational research include investments made by the DOD in quantum hardware, quantum control protocols, and quantum systems engineering and NSF funding in basic quantum algorithms and the theory of quantum computation. Additionally, underpinned by strategic LDRD investments at some of the national labs, the Office of Science has recently made strategic investments in quantum research that have quickly galvanized researchers and incentivized them to explore research opportunities, develop world leading scientific proposals, and form collaborations and partnerships to advance the science. Examples of these new DOE investments, include ASCR's test bed program to look at near term applications of quantum computing, the QAT program for algorithm development, HEP funded research to identify the overlaps between physics and quantum, and BES funded research to look at new materials for quantum machines. A particularly good example of how earlier DOE investments in basic science, laboratory LDRD spending, and new DOE awards have led to new and exciting quantum research is the Advanced Quantum Testbed recently awarded to Berkeley Lab. The award would not have been possible without: DOE funding for foundational research in science at the nano and atomic scale, from imaging to

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manipulation and fabrication; a Berkeley Lab LDRD investment in a prototype quantum computing testbed; an initial Office of Science investment; and the Office of Science's commitment to increase funding for quantum specific activities.

Finally, utilizing DOE's well-established national user facilities' model, leveraging existing and developing new facilities, is an excellent mechanism to ensure the dissemination of quantum science and technology across the federal research enterprise and among industry stakeholders.

Question 2: We have many different versions of public/private partnerships that have demonstrable track records of success. How do you envision the most effective quantum collaborations between industry and researchers at universities and National Labs?

As stated in my testimony, the best approach would be a balanced approach. Industry, universities and national labs each bring to the quantum research table an array of capabilities, resources, incentives, specializations, imperatives and organizational structures. Each have an important and vital role to play in driving quantum science, technology development and applications. As examples, although not exhaustively so, universities are and always will be hotbeds of the riskiest ideas, of scientists and their students working hard to make spectacular breakthroughs on a specific challenge. Rarely are the P.I.s linked to a broader, end-to-end approach to how their work fits into the larger technology develop pipeline. On the other end of the spectrum, industry is governed by the need for a quick return on their investment. Their research dollars need to translate to revenue quickly and therefore they do not have the ability to invest in research and development for risker, yet potentially higher payoff, science. The national laboratories exist in the middle of this spectrum with a unique ability to build large multidisciplinary teams focused on whole systems – they are engines of integration.

At each level, each spot along the spectrum, there are opportunities for public/private partnerships. These opportunities need to be encouraged through legislation and through DOE policies and procedures. For instance, at the latter stage of the technology development cycle, there should be an ability, through federal funding, for quantum centers and other vehicles, such as testbeds, to engage with incubators and similar startup organizations, such as Cyclotron Road, to help with the maturation of technologies. Likewise, at the earlier stages of research, within EFRCs, testbeds and centers, there should be mechanisms to integrate industry participation, input and jointly funded pre-competitive research to identify and tackle the most fundamental questions to guide future research.

Question 3: DOE utilizes multiple mechanisms for engaging the private sector, including, but not limited to, the Energy Innovation Hubs, National Network for Manufacturing Innovation institutes, small business vouchers, and the Lab-Embedded Entrepreneurship Programs.

- Does DOE have sufficient authority to foster appropriate collaboration and technology transfer between any DOE funded quantum research programs and industry?

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See second paragraph above for ideas regarding industry engagement. I am not an expert in DOE's authorities, but am aware of many excellent examples of DOE/industry collaboration, work for others and research partnerships. From the Joint BioEenrgy Institute to the semiconductor industry funded work at the Advanced Light Source and the CalCharge CRADA with California battery companies, there are many examples of how this is done. However, I do believe that DOE should be given the authority and resources to more directly invest in technology maturation activities as stated above.

- Would new programs better facilitate such collaboration and technology transfer that are authorized but not established?

  Possibly. It would depend on the Department and its willingness to engage in new activities. Although I'm not certain, I believe that the DOE has enough flexibility under current authorizations to develop creative technology transfer regimes, but that history and bureaucratic inertia are hindrances. Again, back to the example of Cyclotron Road, the applied energy programs at DOE have seen the value of providing funding to startup companies to utilize and benefit from the investment made at the national labs to advance hard energy technologies. Whether this is an appropriate responsibility of the Office of Science related to quantum research is a question for discussion. However, whether funded through the applied portfolio or the Office of Science, some sort of funding stream could be seminal in the germination of quantum industries in the United States.

Question 4: How should DOE quantum information science programs collaborate with quantum research and development programs in other nations?

The United States has the resources, expertise and capabilities needed to develop a world leading quantum information sciences ecosystem. Additionally, unlike the Large Hadron Collider for particle physics or LBNF-DUNE for neutrino science, tools at large scale are not needed; However, science is an international endeavor and it is critical to keep apprised of the latest development in the field.

Question 5: You hold a joint appointment as a researcher at a university and at a national lab. We had a great meeting called Alaska National Lab Day earlier this year, where we explored opportunities for the University of Alaska to work with National Labs on common challenges and opportunities. The university is exploring such joint appointments.

- How do these joint appointments work?

  DOE National Laboratories offer a range of mechanisms to strengthen ties with university faculty. LBNL is no different, employing several levels of engagement, with joint appointments representing a mutual institutional commitment.

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While terms vary somewhat among participating campuses, faulty appointments at LBNL can be those that are split 50/50 between the Lab and the participating university campus or can be what are called "shared" appointments, where the split between the Lab and the campus are not an even split. Both institutions are responsible for the recruitment, compensation, performance, conduct and promotion of the faculty appointee in accordance with the relevant regulations and practices of each institution. In recognition of their joint or shared status, these appointments carry part-time teaching loads, but otherwise are full members of their campus departments and LBNL divisions to ensure that promotions are held to the same standards for evaluation of teaching, research and service.

Since LBNL employees and campus faculty are University of California (UC) employees, the UC policies and processes supports the administration of this activity between the two institutions. Joint appointments outside of the UC system are being explored, but may look slightly different than the UC appointments.

- What are the benefits to you, to your students, and to the evolution of research in your field?

  Joint appointments are used to build capacity and capabilities in areas of mutual and strategic interest to both parties. They strengthen connections through participation in large-scale research efforts, access to unique and specialized facilities, the involvement of students in research and the ability of faculty members to lead initiatives at LBNL. In all respects, joint appointments can be a rich resource for a national quantum initiative.

Question 6: You have mentioned many of the ongoing efforts of your respective quantum programs. Many of the points you make revolve around the importance of collaborations to furthering quantum information science.

- If DOE hosted centers with a focus on quantum, what should they look like and what should they do?

  My first recommendation is that centers reflect what the Department of Energy does best. As stated previously, the DOE, and in particular the national labs, are the best at building teams of scientists across many different fields, different types of engineers, theorists, analysts, etc. integrated vertically and focused on a seriously difficult and focused objective – e.g. build a quantum computer with useful scientific applications. My second recommendation is that the Department not take a cookie cutter approach to standing up centers. They should focus on different aspects of the quantum opportunity/challenge and not necessarily all be funded at the same level. Additionally, some centers should be housed primarily under one roof, like the Joint BioEnergy Institute, or two primary roofs such as the Joint Center for Artificial Photosynthesis.

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This is a key element to quickly advancing the science and leveraging, taking full advantage of the multidisciplinary advantages a center can offer. In some case, however, a more distributed approach may work well. The mission and objectives will drive the organization of the center.

- Should they focus on technologies, research disciplines, or themes?

  The proposed centers should not be equivalent to NSF or DOE grants made to PIs and teams of postdocs and graduate students focused on discreet scientific and technological issues – they should be stood up for much broader purposes and impact. Therefore, focusing on themes, that are broader than individual science fields, or scientific and technological challenges, may be the best way to think about how to organize and establish centers. Themes that DOE should consider include:

  Software controls needed to operate quantum machines, from the high-level user input all the way down to the hardware.

  The classical hardware needed to efficiently communicate quantum signals – a cross cutting theme needed throughout QIS.

  Quantum algorithms for addressing near-term and long-term computational problems/challenges throughout different scientific domains. What can you do with quantum machines?

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September 24, 2018

The Honorable Lisa Murkowski, Chair
The Honorable Maria Cantwell, Ranking Member
Committee on Energy and Natural Resources
United States Senate
304 Dirksen Senate Office Building
Washington, DC 20510

Dear Chair Murkowski and Ranking Member Cantwell,

I am writing in connection with the Committee's work on authorizing legislation for the Department of Energy's (DOE) investment in quantum information science (QIS), a bedrock discipline that will enable the next frontiers of computation, communication, big data analysis, and artificial intelligence. It is tremendously gratifying to see the Committee considering this issue, but it is critical to ensure that the Department pursues the best path to achieving the Committee's goals.

As both Dean of the School of Engineering and Applied Science at Princeton University and as a faculty member at Princeton University and UCLA for more than 30 years, I have had extensive experience with diverse federal agencies that fund scientific research. I have received continuous funding over this entire 30-year period to perform cutting-edge research. The funding came at various times from a spectrum of agencies including the National Science Foundation (NSF), the DOE Office of Science and Office of Energy Efficiency and Renewable Energy, the Department of Defense (DOD) Army Research Office, Office of Naval Research, and Air Force Office of Scientific Research (AFOSR), among others. During my career, I have worked with diverse funding models, from individual investigator awards to large, multi-investigator center grants. With this as context, I offer brief thoughts on how the taxpayer and society will obtain the best value for their investment, and propose a model that I urge the Committee to adopt for the investments in QIS.

For grand challenge problems like QIS, the optimal solution is never obvious and it often is not just one solution. It is therefore critical to "let a thousand flowers bloom" and not rely on only one or a few ideas. This points to the importance of funding individual investigator grants along with relatively lean centers; there may also be a need for a couple of larger centers. The individual investigator funding will enable many ideas to be tried, which is critical in high risk/high payoff, cutting-edge research. We do not know, ahead of time, which solutions will actually work and so we must invest in many visions of the future. At the same time, funding only individual investigator grants would be limiting because most of the grand challenge problems left for science and engineering to solve are so complex that they require expertise that no one investigator has, e.g., they require experts from multiple disciplines. Centers are, therefore, also important to advancing the field.

I urge the Committee to give careful consideration to the optimal approach to authorizing centers. Based on my participation in many models—from NSF MRSECs to DOE EFRCs to DOD MURIs, and others—I strongly believe that the DOD-MURI (multidisciplinary university research initiative) is the best structure for achieving the best result for the taxpayer. Its structure is lean and mean, typically a half-dozen principal investigators with complementary expertise, who work together to produce fundamental scientific discoveries that none of them would have been able to do on their own. The funding covers research and meetings of the MURI team but no ancillary activities. I am concerned that the larger structures currently envisioned in drafts of the legislation providing funding for five very large centers (akin to DOE Innovation Hubs) restricts the possible visions of the QIS future, and undoubtedly requires larger infrastructure investments and less funding for researchers. While there may be reasons to fund a couple of national facilities to provide development of expensive instrumentation that many researchers could use, the main focus should be on authorizing a large number of MURI-type teams and large number of individual investigators.

Thank you for considering these comments. I would be pleased to meet with the Committee or answer any questions.

Sincerely,

Emily A. Carter