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

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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

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[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

[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

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[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.