Testimony of

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American Leadership in Quantum Technology

Good afternoon, Chairwoman Comstock, Chairman Weber, Ranking Member Lipinski, Ranking Member Veasey, and members of the Subcommittees. My name is Jim Kurose and I am the Assistant Director of the National Science Foundation (NSF) for Computer and Information Science and Engineering (CISE).

As you know, NSF is dedicated to advancing progress in all fields of science and engineering. NSF funds fundamental research across all science and engineering disciplines; supports education of the next generation of innovative thinkers, discoverers, and leaders; and contributes to national security and US economic competitiveness. I welcome this opportunity to highlight NSF's investments in quantum information science (QIS) specifically, including our efforts to work collaboratively with other Federal agencies and industry stakeholders.

Investments in fundamental, long-term, transformative research such as QIS are crucial to an effective national strategy for achieving and sustaining U.S. technological leadership. NSF co-chaired a recent National Science and Technology Council (NSTC) report titled *Advancing Quantum Information Science: National Challenges and Opportunities*[1]. This report, which was developed jointly by the NSTC Committees on Science as well as Homeland and National Security, provides a brief description of the field of QIS, summarizes developments and potential impacts in various areas of fundamental research and technology, surveys existing Federal investments, and articulates a path forward for overcoming barriers to QIS progress, including transitioning promising research to practice and supporting education

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[1] *Advancing Quantum Information Science: National Challenges and Opportunities*, https://www.whitehouse.gov/sites/whitehouse.gov/files/images/Quantum_Info_Sci_Report_2016_07_22%20final.pdf.

and training. In particular, the report recommends that QIS be considered a priority for Federal coordination and investment in order to ensure sustained US leadership in QIS and associated emerging technologies for decades to come. NSF's investments in QIS are aligned with this report. Additionally, a series of workshops have continued to inform NSF's investment strategy in QIS, and enabled strong coordination and collaboration with Federal agency partners and industry stakeholders.

Over the last several decades, NSF has sought to fund the frontiers of QIS research, capitalize on the intellectual capacity of both young and experienced investigators in our Nation's academic and research institutions, and promote connections between academia and industry. Collectively, these activities are essential for innovation in QIS, and in turn contribute to national security and economic growth in both the near and long terms.

Indeed, we are already witnessing how many powerful QIS innovations being led by industry today are predicated on fundamental research outcomes generated with NSF funding. Let me share with you a few examples of the important contributions made recently by the QIS research community with NSF as well as other Federal support, and how they are being leveraged in industry today:

- As early as 1999, NSF served as a "convener," stimulating workshops and so-called "Ideas Labs" that brought together multidisciplinary perspectives from academia, industry, and government to identify opportunities to accelerate the emerging field of QIS.
- Dr. Krysta Svore, an NSF-funded graduate student at Columbia University in the 2000s, made advances in the theory of computational complexity in the context of quantum computing. More than a decade later, today she is a leader at Microsoft in developing real-world quantum algorithms, understanding their implications, and designing comprehensive software architecture for programming such as algorithms on a quantum computer[2].
- Dr. John Martinis, a physics professor at the University of California, Santa Barbara (UCSB), was hired, along with his entire team, by Google in September 2014 to develop new quantum computing hardware[3]. With funding from NSF, Dr. Martinis and his team at UCSB contributed significantly to breaking barriers in the construction of a quantum computing device beginning as early as 2005. Much of his work has focused on the stability of quantum bits, or "qubits" (the quantum analog of the digital bits in today's computers) – one of the foremost challenges in QIS.
- Recognizing the inherent multidisciplinary aspects of QIS, which spans physics, engineering, computer science, and materials science, among other domains, NSF has long funded cross-disciplinary research centers integrated with early-career development activities. These investments are often in collaboration with universities, private foundations such as the Gordan and Betty Moore Foundation, and other Federal agencies including those represented at this hearing this morning. These larger, more comprehensive research activities have served to create the next generation of quantum scientists for U.S. companies such as Google, Microsoft, and IBM. Examples include the Institute for Quantum Information and Matter at the California Institute of Technology, the Center for Integrated Quantum Materials at Harvard University, and the Center for Quantum Information Control at the University of New Mexico, one of only four Research/Doctoral-Extensive institutions in the country to also be designated as Hispanic-serving.

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[2] Krysta M. Svore, Principal Research Manager, Microsoft Research, https://www.microsoft.com/en-us/research/people/ksvore/.

[3] "The Man Who Will Build Google's Elusive Quantum Computer," *Wired*, Sept. 5, 2014, https://www.wired.com/2014/09/martinis/.

Moreover, as I will describe later in my testimony, NSF is pioneering multidisciplinary, collaborative research programs in QIS across its directorates. Looking forward, NSF will continue to bring the problem-solving capabilities of the Nation's best and brightest minds to bear on the persisting QIS challenges of today and tomorrow.

QIS research and education are now at an "inflection point," with rapid advances and growing domestic and international investments in QIS, particularly in industry. Now is the time to build on past Federal investments in QIS research and education to enable frontier advances in QIS that will transform:

- Fundamental science and engineering, both in discovering unanticipated phenomena and using them to study nature;
- Technology that leads to novel computing architectures and methods, combined with radically new quantum-based sensing and imaging technologies, modeling and simulation approaches, and secure communication tools;
- The workforce, which will be trained to "think quantum" across many disparate fields;
- The economy, where new industries will arise that will be crucial for maintaining U.S. leadership; and
- National security, by harnessing QIS capabilities and nurturing the next-generation workforce to provide national security practitioners with the best tools to protect systems.

Defining QIS: The Potential for Transformative Societal Impact

Quantum information science (QIS) harnesses quantum phenomena to create measurement systems with greater precision, sensors and detectors that are more accurate, and computers that will outperform the most powerful digital supercomputers available today. But QIS is far more than this set of technological applications; it is an area of deep scientific inquiry in and of itself.

Today's conventional computing and communication devices use binary digits (or "bits") as the basic unit of information. A bit can have only one of two values at any given moment, most commonly either "0" or "1." By contrast, quantum computing relies upon quantum bits (or "qubits"), which can be in a "superposition" of both states at the same time, i.e., a qubit can be "0," "1," or both simultaneously. Let me draw an analogy: if a bit is similar to a stationary coin, where the head is *0* and the tail is *1*, a qubit can be thought of as the coin while it is tossed in the air; the coin is spinning with no determined value (head, *0*, or tail, *1*) at any given point in time, until it is caught. This superposition – a quantum mechanics property – coupled with other quantum mechanics properties (e.g., "entanglement," or the ability for a quantum particle to change its state instantaneously upon an operation on or measurement of a completely different but entangled particle), allows qubits to provide massive memory, sensing, and computational capabilities. QIS systems thus offer the potential to solve many challenges that are intractable with today's traditional digital technologies, from modeling deadly diseases to enhancing cybersecurity.

For example, QIS offers the promise of transcending today's cybersecurity challenge by providing absolutely secure communication. At the same time, quantum computers have the potential to render today's cryptographic approaches insecure, including those used for nearly all electronic commerce transactions. Quantum computing at scale would thus require a complete revision of cryptographic standards and protocols.

Quantum computers may also help with the design of new materials and compounds, including potential therapeutics, by allowing more efficient, higher-resolution computational simulations of material properties and protein folding patterns. Quantum computing has the potential to significantly reduce cost and create opportunities in the design process, enabling new types of materials and compounds not known today.

In these examples, the promise of quantum computing results from it being able to compute answers far faster than a traditional digital computer. Indeed, for some computing challenges, a quantum computer could be so much faster that it could be capable of solving problems that simply cannot be solved by traditional digital computers.

Similarly, quantum sensors such as magnetometers can offer higher sensitivity, with reduced energy, cooling, and shielding requirements than conventional magnetometers. As a result, they promise to make new forms of cancer imaging possible, with fewer deleterious effects. For example, quantum sensors could radically improve the sensitivity and resolution of microwave tomography, offering significant potential in imaging breast cancer.

A History of Sustained NSF Investment in QIS: The Foundations for Future Advances

In keeping with its mission "to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…," NSF has long supported fundamental research related to QIS. For example, in 1999, NSF funded a landmark workshop, titled *Quantum Information Science: An Emerging Field of Interdisciplinary Research and Education in Science and Engineering.* This workshop outlined key research areas for the community to pursue with increased investment[4].

NSF's investments in QIS have continued to grow since that seminal workshop. From FY 2000 to FY 2004, QIS was a component of the NSF's Information Technology Research (ITR) program, with relevant research supported by multiple NSF directorates. Also during this period, in FY 2001 and FY 2002, NSF ran the Quantum and Biologically Inspired Computing (QuBIC) program, supporting interdisciplinary research that led to new insights and understanding in QIS as well as biologically-inspired computing; a key goal of QuBIC was to unite information science across computer science, physics, biology, and engineering. In FY 2005, the Quantum Information Science and Revolutionary Computing program was established by NSF's Directorate for Mathematical and Physical Sciences (MPS), with funding and engagement from the CISE directorate as well as the Directorate for Engineering (ENG); this program continues today as the Quantum Information Science program. In FY 2012, the CISE-MPS Interdisciplinary Faculty Program in Quantum Information Science was launched.

In FY 2016, NSF's ENG directorate invested $12 million in quantum technologies for secure communication through the Advancing Communication Quantum Information Research in Engineering (ACQUIRE) research area within its Emerging Frontiers in Research and Innovation (EFRI) program – a longstanding program that seeks to expand the limits of knowledge in the service of grand challenges and national needs. This EFRI/ACQUIRE project currently supports six interdisciplinary teams consisting

[4] *Quantum Information Science: An Emerging Field of Interdisciplinary Research and Education in Science and Engineering*, https://www.nsf.gov/pubs/2000/nsf00101/nsf00101.htm.

of 26 researchers at 15 institutions to perform transformative, fundamental research to develop systems that use photons in pre-determined quantum states as a way to encrypt data.

In addition to these focused programs supporting QIS research and capacity building, NSF also supports research and education activities in QIS through a number of core research programs within its CISE, ENG, and MPS directorates. For example, NSF's Secure and Trustworthy Cyberspace (SaTC) program, which is led by the CISE directorate in partnership with the Directorates for Education and Human Resources (EHR), ENG, MPS, and Social, Behavioral, and Economic Sciences (SBE), supports post-quantum cryptography, i.e., the development of cryptographic systems that are secure against both quantum and classical computers, and that can interoperate with existing communication protocols and networks.

Lastly, NSF has frequently supported QIS workshops to build capacity within the research community. Bringing together academics from across the many disciplines that are core to QIS, along with stakeholders in other Federal agencies and industry, has proved to be tremendously fruitful in developing a forward-looking research agenda.

Promising QIS Research Areas

Building on these past investments, NSF continues to support science and engineering research at colleges and universities across the Nation to advance our understanding of underlying QIS phenomena and to develop radically new technologies at the quantum frontier. In particular, NSF investments span four key areas:

1. **Quantum Fundamentals:** Advance fundamental understanding of uniquely quantum phenomena and their interface with classical systems across a broad range of conditions;
2. **Quantum Elements:** Transform our ability to measure, model, control, and exploit quantum particles in single and multi-particle quantum systems;
3. **Quantum Systems:** Design and develop hardware, software, and underlying algorithms needed for controllable and scalable quantum information processing; and
4. **Quantum Workforce:** Train a new generation of scientists, engineers, and educators for a transdisciplinary, globally competitive workforce in QIS.

NSF is well positioned to support this multidisciplinary research through its research directorates, and continues to work in collaboration with Federal agency partners and industry leaders to realize innovations with societal impact.

Next I will elaborate on the four areas defined above.

The first, *Quantum Fundamentals*, offers the ability to understand and control quantum de-coherence, and generate, measure, and manipulate quantum entangled states; characterize, verify, and exploit the full range of capabilities of quantum algorithms and simulations for exponential speedup, along with their application to a growing range of problems, including expanding quantum complexity theory; and discover, analyze, and understand the fundamental properties of novel quantum many-body states of matter with tailored properties that can be exploited for quantum technologies, including controlling multiple degrees of freedom using light-matter interactions at fine resolutions.

The second area, *Quantum Elements*, aims to transform our ability to measure, model, control, and exploit quantum phenomena in single and multi-particle systems into technologies that can be harnessed to build components that together will constitute a usable quantum system. Research challenges here include utilizing quantum superposition of states, entanglement, and quantum squeezing in metrology; characterizing and minimizing noise, and developing, testing, and implementing quantum error corrections; and developing efficient, high-resolution methods to generate, control, manipulate, read, and write qubits.

The third, *Quantum Systems*, includes the co-design of a quantum platform – system control software, application-specific hardware, and application-specific quantum algorithms – that is ultimately where quantum sensing, metrology, simulation or computation happens. Research challenges include identifying advantages and limitations of quantum and classical devices; developing quantum circuits and system designs that provide stable, controllable, scalable, and relatively error-free quantum capabilities for a wide of range of states; pursuing programming paradigms for quantum sensing, computing, and communication; employing interdisciplinary teams to enable technological advances by providing viable platforms for quantum computing and testbeds for rapid prototyping, characterization, and optimization; generating on-demand, scalable systems of quantum objects in superposition states, while enabling information exchange across the quantum-classical boundary; studying properties of quantum information and quantum algorithms including issues of quantum computational complexity and computability; ensuring socially-responsible design and innovation of quantum platforms for use in complex socio-technical systems; and exploring novel and emergent applications of quantum technology.

Finally, *Quantum Workforce* underpins the activities by enabling the necessary supply of intellectual capital. Investments in the *Quantum Workforce* support training for a new generation of scientists, engineers, and educators in a transdisciplinary, globally competitive QIS workforce. I will describe this area in more detail next.

QIS Education and Workforce Development

NSF's investments in QIS research are accompanied by investments in education and workforce development. Research undertaken in academia not only engages some of our Nation's best and brightest researchers, but because these researchers are also teachers, new generations of students are exposed to the latest thinking from the people who understand it best. As these students graduate and transition into the workplace, they bring this knowledge and understanding with them.

Dr. Scott Aaronson of the University of Texas at Austin exemplifies how NSF-funded researchers and educators are leading the way in QIS discovery and innovation. Dr. Aaronson is a theoretical computational scientist whose research focuses on the limitations of quantum computers and computational complexity theory more generally. His research addresses a variety of topics, including the information content of quantum states, the physical resources needed for quantum computers to surpass classical computers, and the barriers to solving computer science's vexing "P versus NP" question (i.e., whether every problem whose solution can be quickly verified by a computer can also be quickly solved by a computer). At the same time, Dr. Aaronson is a founder of the *Complexity Zoo* wiki, which catalogs over 500 computational complexity classes. Dr. Aaronson was awarded NSF's highest honor, the Alan T. Waterman Award, which every year recognizes an outstanding young researcher in any field of science or engineering supported by NSF who has made significant progress in his or her field, early in his or her career. In 2012, the award was given to Dr. Aaronson for his advances in a diverse range of QIS priority areas.

As part of its education and workforce investments, NSF has supported several Research Experiences for Undergraduates (REU) Sites in the area of QIS. REU Sites are based on independent proposals that seek to initiate and conduct projects engaging a number of undergraduate students in research. Each REU

Site must have a well-defined common focus, based in a single discipline or spanning interdisciplinary or multidisciplinary research opportunities with a coherent intellectual theme, which enables a cohort experience for participating students. Each REU Site typically supports 8 to 12 undergraduate students each summer, including housing and stipend support, with each student involved in a specific project guided by a faculty mentor. REU Sites are an important means for extending high-quality research environments and mentoring to diverse groups of students. Examples of NSF-funded REU Sites that align with QIS include:

- Nano-, Bio-, and Quantum Photonics, University of Rochester, led by Drs. Andrew Berger and Anthony Vamivakas[5]. This REU Site offers students summer research opportunities exploring photonic spectroscopy for bone quality monitoring and novel device fabrication for generating quantum states of light. The REU Site supports a diverse cohort of students from underrepresented groups and institutions with limited research opportunities.
- Rice Quantum Institute, Rice University, led by Dr. Naomi Halas[6]. This REU Site provides students from universities beyond Rice with interdisciplinary summer research projects in QIS. This has been a longstanding REU Site and reflects a partnership with the US Department of Defense, which co-funded the REU Site with NSF.
- Materials Physics, University of Florida, led by Drs. Selman Hershfield and Kevin Ingersent[7]. This REU Site offers research experiences for students to explore the experimental, theoretical, and computational aspects of the design, measurement, and understanding of novel materials and quantum phenomena. This REU Site recruits students nationwide with an emphasis on increasing participation by women and other members of groups underrepresented in QIS.

NSF also emphasizes support for research at primarily undergraduate institutions (PUIs)—those that do not typically award graduate degrees. A series of investments have been made to enhance QIS research and opportunities for students at PUIs. One example project is:

- Unconventional Anisotropic Order in Strongly Correlated Fermi Systems, Prairie View A&M University[8]. Through this project, Dr. Orion Ciftja and his students are investigating quantum mechanical states of electrons that are curiously analogous to the states of long molecules in liquid crystals that form the basis of modern display technology. This research contributes to the intellectual foundations for potentially new electronic and optical device technologies. Prarie View A&M University is a Historically Black College or University (HBCU), and the project involves minority undergraduate students in research, training them in skills that will be valuable in the modern technical workforce.

NSF has also funded early-career investigators through the Faculty Early-Career Development (CAREER) program, which offers NSF's most prestigious research award in support of early-career faculty who exemplify the role of teacher-scholars through outstanding research, excellent education, and the

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[5] REU Site: Nano-, Bio-, and Quantum Photonics at University of Rochester, https://www.nsf.gov/awardsearch/showAward?AWD_ID=1659539&HistoricalAwards=false.

[6] REU Site: Research Experiences for Undergraduates at the Rice Quantum Institute, https://www.nsf.gov/awardsearch/showAward?AWD_ID=0755008&HistoricalAwards=false.

[7] REU Site: Materials Physics at the University of Florida, https://www.nsf.gov/awardsearch/showAward?AWD_ID=1156737&HistoricalAwards=false.

[8] RUI-Unconventional Anisotropic Order in Strongly Correlated Fermi Systems, https://www.nsf.gov/awardsearch/showAward?AWD_ID=1410350&HistoricalAwards=false.

integration of education and research within the context of the mission of their organizations. Two CAREER award examples include the following:

- Quantifying Noisy Quantum Resources, led by Dr. Graeme Smith at University of Colorado Boulder[9]. This award supports research to identify, quantify, and ultimately understand the fundamental resources in quantum information theory, including quantum communication links and noisy quantum states.
- Interactions with Untrusted Quantum Devices, led by Dr. Thomas Vidick at California Institute of Technology[10]. This research project tackles the broad challenge of how classical devices may establish and maintain a trusted interaction with unknown and untrusted quantum devices. This research is critical and broadly applicable, from developing new and secure communication protocols, such as for online bank transactions, to new computing paradigms.

Beyond these investments, NSF contributes to enhancing QIS education and workforce development by:

1. Mobilizing existing institutions to educate and engage communities in QIS and promote interaction among, and an exchange of scientists from different disciplines, across academia, industry, and national labs, as well as with international partners in the national interest;
2. Serving the public by promoting engaging media, public education, and innovation; and
3. Conducting systematic studies of the social and economic benefits and risks for society in the development of quantum sensors, quantum computers, and other quantum platforms; such studies would include the impacts of their migration between the academia and industry, and of their large-scale production and use.

As one example, in FY 2017, NSF made an award to the University of Chicago, under the leadership of Dr. David Awschalom, to support students working in a focused academic-industry collaboration to pursue research and gain valuable industry experience[11]. This project specifically supports the development of a cohort of "triplets," or multiple teams comprising a university investigator, an industry partner, and a graduate student, working together over a period of three years. All triplets will form a Quantum Information Science and Engineering Network (QISE-NET). This novel approach to integrating research, education, and technology transfer is highly convergent and crosscutting in nature, with representative triplets anticipated from the materials sciences, chemistry, device engineering, computer science, and physics. It aims to increase the number of students in the US with the knowledge, understanding, and expertise in multiple convergent fields serving the next quantum frontier. It also aims to increase the academia-industry interactions to advance technological goals by leveraging facilities and expertise, and sharing scientific and technical challenges.

Another illustrative example is an FY 2016 award to the University of Nebraska at Omaha, under the leadership of Dr. Abhishek Parakh[12]. His team is developing a pedagogical game-based simulator that

[9] CAREER: Quantifying Noisy Quantum Resources, https://www.nsf.gov/awardsearch/showAward?AWD_ID=1652560&HistoricalAwards=false.
[10] CAREER: Interactions with Untrusted Quantum Devices, https://www.nsf.gov/awardsearch/showAward?AWD_ID=1553477&HistoricalAwards=false.
[11] Convergence QL: Workshop Series: Cross-Sector Connections in Quantum Leap, https://nsf.gov/awardsearch/showAward?AWD_ID=1747426&HistoricalAwards=false.
[12] EDU: QuaSim: A Virtual Interactive Quantum Cryptography Educator-A Project-based Gamified Educational Paradigm, https://nsf.gov/awardsearch/showAward?AWD_ID=1623380&HistoricalAwards=false.

provides students with an interactive experience to improve learning by transforming subject-based lectures in quantum cryptography into project-based virtual simulations.

The Quantum Leap Big Idea and the Role of Convergent Research and Co-Design in QIS

In FY 2016, NSF announced a set of bold questions that will drive the agency's long-term research agenda—questions that will ensure future generations continue to reap the benefits of fundamental research. These 10 "Big Ideas" aim to capitalize on what NSF does best: catalyze interest and investment in fundamental research, which is the basis for discovery, invention, and innovation. The Big Ideas define a set of cutting-edge research agendas and processes that are suited for NSF's broad portfolio of investments, and will require collaborations with industry, private foundations, other agencies, science academies and societies, and universities. These ideas will push forward the frontiers of US research and provide innovative approaches to solve some of the most pressing problems the world faces, as well as lead to discoveries not yet known. They will provide platforms to bring together every field of study, from science and education, to engineering and astrophysics, to radically alter the conduct of science and engineering across the scientific enterprise in a manner that is not possible by simply continuing discipline-specific efforts at current levels.

One of the 10 Big Ideas is focused on QIS. Called "The Quantum Leap: Leading the Next Quantum Revolution," this Big Idea aims to build upon and extend our existing knowledge of the quantum world, fostering breakthroughs in our fundamental understanding of quantum phenomena and enabling the exploitation of these phenomena to disrupt our science and engineering landscape. These advances will unleash the potential of the Nation's quantum-based scientific enterprise, economy, and security.

Another of the 10 Big Ideas, a process Big Idea called "Growing Convergence Research at NSF," seeks the deep integration of knowledge, techniques, and expertise from multiple fields to form new and expanded frameworks for addressing scientific and societal challenges and opportunities.[13] Convergence is a necessary paradigm in the Quantum Leap and QIS, as transformational developments in QIS will come from *ab initio* collaborations across disciplines and from a new workforce conversant in these technologies. Within this framework there needs to be convergence of materials scientists, engineers to turn the materials into devices, physicists and chemists to develop methods of modelling, operating, controlling, and entangling the quasiparticle states, and computer scientists to develop efficient algorithms for programming and utilization of the final device. As an example, convergence research on decoherence will lead to our ability to design, build, and test a novel, stable qubit, construct a quantum computer based on such a qubit, and develop the skilled workforce needed to operate it. NSF is well positioned to enable this convergence research and co-design in QIS.

To this end, NSF has established a Quantum Leap Working Group that is overseeing various activities and encouraging convergence and a deeper collaboration across disciplines. The work by the Quantum Leap Working Group has already resulted in several calls for proposals. For example, in FY 2017, NSF issued a call for summer schools, cross-sector awards, and community workshops[14], and funded two workshops and jointly funded with the US Department of Energy a quantum science summer school[15].

[13] Convergence Research at NSF, https://www.nsf.gov/od/oia/convergence/index.jsp.
[14] Dear Colleague Letter: Growing Convergence Research at NSF, https://www.nsf.gov/pubs/2017/nsf17065/nsf17065.jsp.
[15] NSF issues first Convergence awards, addressing societal challenges through scientific collaboration, https://www.nsf.gov/news/news_summ.jsp?cntn_id=242889.

NSF also launched a new program in FY 2017, Ideas Lab: Practical Fully-Connected Quantum Computer Challenge (PFCQC), that challenged the research community with building a practical quantum computer through advances in hardware, software, and quantum algorithms[16]. The program recently supported a week-long Ideas Lab that brought together physics, engineering, and computer science; full proposals are due later this fall. These types of cross-disciplinary activities will help bridge the gap between various research fields, and fertilize future research directions.

Coordination and Collaboration Across the Federal Government

NSF's close coordination and collaboration with other Federal agencies pursuing QIS research and development is critically important in shaping its long-term investments. NSF coordinates closely with other stakeholder agencies as co-chair of the Interagency Working Group on Quantum Information Science (QIS IWG). An initial NSTC report, *A Federal Vision for Quantum Information Science*, was drafted with significant input from NSF representatives. In April 2009, NSTC sponsored the Workshop on Quantum Information Science, and a report of the workshop was produced in July 2009[17]. In October 2014, the QIS IWG was chartered under the NSTC Committee on Science, and is currently chaired by DOE, the National Institute of Standards and Technology, and NSF.

In FY 2016, the QIS IWG led the development of the aforementioned NSTC report titled *Advancing Quantum Information Science: National Challenges and Opportunities*[1]. This report explores three key themes, and outlines the role of US government investment and associated path forward. The themes include:

1. *QIS and Technology*, specifically technology developments in sensing and metrology, communication, simulation, and computing enabled by QIS;
2. *QIS and Fundamental Research*, detailing the benefits of and need for continued fundamental research to grow the capacity of QIS in the future; and
3. *Addressing Impediments to Progress*, which includes the need for convergence research crossing institutional boundaries, education and workforce training opportunities, increased emphasis on technology and knowledge transfer from the lab to the market, and stable funding sources to grow innovations in QIS and ensure sustained US leadership.

The report notes NSF's role as the key agency in supporting QIS fundamental research that spans multiple disciplines, education and workforce preparation, and technology transfer for research innovations.

Beyond the specific efforts of the QIS IWG, NSF has collaborated with Federal agencies through various "mission-bridging" activities, including participating in various workshops and jointly funding research. For example, representatives from NSF actively participated in a February 2017 workshop on quantum testbeds convened by DOE[18]. That workshop sought to identify the individual capabilities and interests of various stakeholder groups in quantum computing hardware and its use for science applications; share best practices for management of collaborative research facilities, including topics such as

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[16] Ideas Lab: Practical Fully-Connected Quantum Computer Challenge (PFCQC), https://www.nsf.gov/pubs/2017/nsf17548/nsf17548.htm.

[17] *Report of the Workshop on Quantum Information Science*, http://calyptus.caltech.edu/qis2009/QIS-Workshop-Report-1-July-2009.pdf.

[18] Quantum Testbeds Stakeholder Workshop, https://www.orau.gov/qtsws/default.htm.

workforce training and building strong relationships with the research community; and identify technology that will be important for the success of a testbed facility with the goal of advancing quantum computing for scientific applications in the next five years. Similarly, NSF attended a NIST-led workshop in October 2017 that discussed opportunities for research and development; means and methods of inducing interaction and collaboration; support for emerging market areas; identifying barriers to near- and far-term applications; and understanding workforce needs[19].

Engaging with Industry: Transitioning to Practice

NSF-funded QIS research has led to the formation of numerous start-up companies, enabling transition of research results to deployment and implementation. NSF has supported these start-ups through its Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, which stimulate technological innovation in the private sector by strengthening the role of small business concerns in meeting Federal research and development needs, increasing the commercial application of Federally-supported research results, and fostering and encouraging participation by socially- and economically-disadvantaged, Historically Underutilized Business Zones (HUBZones), service disabled veteran-owned small businesses, and women-owned small businesses. Outcomes of several NSF-funded QIS research projects have led to NSF SBIR and STTR grants. For example, in FY 2017, NSF issued an SBIR Phase 1 award to Axion Technologies[20]. Building on innovations from previous NSF-funded research, this Florida startup is developing a prototype of a quantum-based random number generator, which will aid in quantum cryptography. Similarly, the NSF Innovation Corps™ (I-Corps™) is a public-private partnership that teaches grantees to identify valuable product opportunities that emerge from academic research, and offers entrepreneurship training to student participants. Since the inception of the NSF I-Corps program in 2011, several I-Corps™ Teams in the QIS domain have participated in the I-Corps™ curriculum.

NSF also supports mutually-synergistic interactions with industry, including the participation of industry researchers at NSF-funded workshops and in invited talks at NSF. A number of NSF-funded researchers, particularly those working in larger, inter- or multidisciplinary teams, collaborate closely with industry to deepen and extend the outcomes of their research activities.

Conclusions

My testimony today has emphasized the potential presented by QIS in a wide range of areas, from secure communication that has game-changing potential for cybersecurity to novel therapeutics for treating some of our most vexing diseases to never-before-seen computing power for myriad other scientific, industrial, and societal challenges. NSF has made significant investments, across multiple directorates, in foundational and multidisciplinary QIS research over the last several decades. These investments have resulted in important advances that are giving rise to fundamentally new research directions and opportunities for the future. I have also described how NSF's interdisciplinary education research portfolios are contributing to a next-generation workforce capable of pursuing QIS research and taking on new jobs that will soon be created across multiple sectors of the economy. Across our

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[19] Building the Foundations for Quantum Industry, https://www.nist.gov/news-events/events/2017/10/building-foundations-quantum-industry.

[20] SBIR Phase I: Quantum Random Walking for Ultra-High Speed, Parallel and Truly-random Number Generation, https://nsf.gov/awardsearch/showAward?AWD_ID=1646995&HistoricalAwards=false.

research and education investments, NSF partnerships with other Federal agencies and industry are also helping to advance QIS and transition innovations into the marketplace.

Our Nation needs to continue to invest in long-term, fundamental, and game-changing research – and education – if we are to maintain US leadership in an emerging quantum world. With sustained support for QIS research and development in both the executive and legislative branches, there is a unique opportunity for further breakthroughs in our fundamental understanding of the underlying physical phenomena and the development of radically new technologies that will form the basis of a new quantum world. As Microsoft's senior advisor to the chief executive officer and former chief research and strategy officer, Craig Mundie, recently stated about quantum computing, "For the first time in 70 years we're looking at a way to build a computing system that is just completely different. It's not an incremental tune-up or improvement. It's a qualitatively different thing."

This concludes my remarks. I appreciate the opportunity to have this dialogue with members of these Subcommittees on this very important and timely topic, and I would be happy to answer any questions at this time.

Biographical Sketch
JAMES F. KUROSE

James F. Kurose is Assistant Director of the National Science Foundation for Computer and Information Science and Engineering (CISE). Prior to joining NSF, he was a Distinguished Professor in the School of Computer Science at the University of Massachusetts Amherst, where he led research projects on computer network protocols and architecture, network measurement, sensor networks, multimedia communication, and modeling and performance evaluation. Dr. Kurose also currently serves as co-chair of the Networking and Information Technology Research and Development (NITRD) Subcommittee of the National Science and Technology Council (NSTC) Committee on Technology, providing overall coordination for the IT R&D activities of 18 federal government agencies and offices.

At NSF, Dr. Kurose guides the CISE directorate in its mission to advance the Nation's leadership in computer and information science and engineering through its support for fundamental and transformative research, as well as the development and use of cyberinfrastructure across the science and engineering enterprise. These activities are critical to ensuring economic competitiveness and achieving national priorities. With a budget of over $900 million in FY 2017, CISE supports ambitious long-term research and innovation, advanced cyberinfrastructure to enable and accelerate discovery and innovation across all disciplines, broad interdisciplinary collaborations, and education and training of the next generation of computer scientists and information technology professionals with skills essential to success in the increasingly competitive, global market.

Over the last three decades at the University of Massachusetts Amherst, Dr. Kurose served in a number of administrative roles including chair of the Department of Computer Science, interim dean and executive associate dean of the College of Natural Sciences, and senior faculty advisor to the Vice Chancellor for Research and Engagement. He has been a visiting scientist at IBM Research, INRIA, Institut EURECOM, the University of Paris, the Laboratory for Information, Network and Communication Sciences, and Technicolor Research Labs. He helped found and lead the Commonwealth Information Technology Initiative and the Massachusetts Green High Performance Computing Center.

He has served as editor-in-chief of the Institute of Electrical and Electronics Engineers (IEEE) *Transactions on Communications* and was the founding editor-in-chief of the IEEE/Association for Computing Machinery (ACM) *Transactions on Networking.* With Keith Ross, he coauthored the textbook, *Computer Networking: A Top-Down Approach,* which is in its seventh edition.

Dr. Kurose has received recognition for his research, including the IEEE International Conference on Computer Communications (INFOCOM) Achievement Award and the ACM Special Interest Group on Data Communications (SIGCOMM) Lifetime Achievement and Test of Time awards. He has also been recognized for his educational activities, receiving the IEEE/CS Taylor Booth Education medal and the Massachusetts Telecommunication Council Workforce Development Leader of the Year award.

Dr. Kurose has served on a variety of advisory boards, including on the NSF/CISE Advisory Committee and the Board of Directors for the Computing Research Association.

Dr. Kurose holds a Bachelor of Arts degree in physics from Wesleyan University, and a Master of Science and a Ph.D. in computer science from Columbia University. He is a fellow of the IEEE and ACM.