AMERICAN LEADERSHIP IN QUANTUM TECHNOLOGY

JOINT HEARING

BEFORE THE

SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY
&
SUBCOMMITTEE ON ENERGY

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

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Panel II

AMERICAN LEADERSHIP IN QUANTUM TECHNOLOGY

Tuesday, October 24, 2017

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON RESEARCH & TECHNOLOGY AND
SUBCOMMITTEE ON ENERGY
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittees met, pursuant to call, at 10:06 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Barbara Comstock [Chairwoman of the Subcommittee on Research and Technology] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
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American Leadership in Quantum Technology

Tuesday, October 24, 2017
10:00 a.m.
2318 Rayburn House Office Building

Witnesses

Panel I:

Dr. Carl J. Williams, Acting Director, Physical Measurement Laboratory, National Institute of Standards and Technology

Dr. Jim Kurose, Assistant Director, Computer and Information Science and Engineering Directorate, National Science Foundation

Dr. John Stephen Binkley, Acting Director of Science, U.S. Department of Energy

Panel II:

Dr. Scott Crowder, Vice President and Chief Technology Officer for Quantum Computing, IBM

Dr. Christopher Monroe, Distinguished University Professor & Bice Zorn Professor, Department of Physics, University of Maryland; Founder and Chief Scientist, IonQ, Inc.

Dr. Supratik Guha, Director, Nanoscience and Technology Division, Argonne National Laboratory; Professor, Institute for Molecular Engineering, University of Chicago

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HEARING CHARTER

October 17, 2017

TO: Members, Subcommittee on Research and Technology & Subcommittee on Energy

FROM: Majority Staff, Committee on Science, Space, and Technology

SUBJECT: Joint Subcommittee Hearing: "American Leadership in Quantum Technology"

The Subcommittee on Research and Technology and the Subcommittee on Energy of the Committee on Science, Space, and Technology will hold a joint hearing titled *American Leadership in Quantum Technology* on Tuesday, October 24, 2017, at 10:00 a.m. in Room 2318 of the Rayburn House Office Building.

Hearing Purpose:

The hearing will identify where the U.S. currently stands in the international race to the development of commercially available quantum-based technologies, particularly quantum computing. In addition, this hearing will focus on the research and development currently supported by both the government and private sector, provide feedback on what more can be done to improve efforts in quantum information science and engineering, how to effectively train a workforce to prepare for this next generation of technology, and how to successfully compete with other countries.

Witness List

Panel 1:

- **Dr. Carl J. Williams**, Acting Director, Physical Measurement Laboratory, National Institute of Standards and Technology
- **Dr. Jim Kurose**, Assistant Director, Computer and Information Science and Engineering Directorate, National Science Foundation
- **Dr. John Stephen Binkley**, Acting Director of Science, U.S. Department of Energy

Panel 2:

- **Dr. Scott Crowder**, Vice President and Chief Technology Officer for Quantum Computing, IBM Systems Group
- **Dr. Christopher Monroe**, Distinguished University Professor & Bice Zorn Professor, Department of Physics, University of Maryland; Founder and Chief Scientist, IonQ, Inc.
- **Dr. Supratik Guha**, Director, Nanoscience and Technology Division, Argonne National Laboratory; Professor, Institute for Molecular Engineering, University of Chicago

Staff Contact

For questions related to the hearing, please contact Sarah Jorgenson of the Majority Staff at 202-225-6371.

Chairwoman COMSTOCK. The Committee on Science, Space and Technology will come to order.

Without objection, the Chair is authorized to declare recesses of the Committee at any time.

Good morning, and welcome to today's joint hearing titled "American Leadership in Quantum Technology." Due to a scheduling conflict, I would like to first recognize the Chairman of the full Committee for a statement, Mr. Smith.

Chairman SMITH. Thank you, Madam Chairwoman, and let me explain, I have a Judiciary markup. Otherwise I would be happy to wait my turn, but I appreciate your deferring to me.

The technology that we will review today is complex but it has the potential to revolutionize computing and to strengthen or undermine our future economic and national security.

Quantum technology can completely transform many areas of science and a wide array of technologies including sensors, lasers, material science, GPS, and much more.

Quantum computers have the potential to solve complex problems that are beyond the scope of today's most powerful supercomputers. Quantum-enabled data analytics can revolutionize the development of new medicines and materials and assure security for sensitive information, but even Bill Gates finds quantum technology to be challenging. He reportedly said, "I know a lot about physics and a lot of math. But the one place where they put up slides and it is hieroglyphics, it's quantum."

We are fortunate this morning to be able to learn from expert witnesses who thoroughly understand and can explain in plain English all of quantum's complexities. How is that for a setup?

Although the United States retains global leadership in the theoretical physics that underpins quantum computing and related technologies, we may be slipping behind others in developing the quantum applications, programming know-how, development of national security and commercial applications.

Just last year, Chinese scientists successfully sent the first-ever quantum transmission from Earth to an orbiting satellite. A team of Japanese scientists recently invented an approach that apparently boosts calculating speed and efficiency in quantum computing. And European research teams are focusing on training quantum computer programmers and developing essential software.

What if the Bill Gates and Steve Jobs of quantum computing are from Germany?

According to a 2015 McKinsey report, 7,000 scientists worldwide, with a combined budget of about $1.5 billion, worked on non-classified quantum technology. Of these totals, the United States' estimated annual spending on non-classified quantum-technology research was the largest. But China, Germany and Canada were close behind. We need to continue to invest in basic research.

We must also take steps to ensure that we have the workforce that the future will demand. The Bureau of Labor Statistics projects that employment in computer occupations will increase by 12.5 percent, or nearly a half-million new jobs, by 2024. That is more than any other STEM field. But future jobs in engineering, health sciences and all of the natural sciences will require computing and electronic information skills.

The United States must also cultivate a new generation of visionary entrepreneurs and additional millions of scientists, engineers, designers, programmers and technicians who can compete in quantum-enabled technologies and other emerging fields.

I thank our witnesses today for testifying on this important topic. I look forward to their testimony on the current state of quantum research and their recommendations about how to improve efforts in this area.

Thank you, Madam Chairwoman, and I yield back.

[The prepared statement of Chairman Smith follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
October 24, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Chairman Lamar Smith (R-Texas)

American Leadership in Quantum Technology

Chairman Smith: Good morning. The technology that we will review today is complex, but it has the potential to revolutionize computing and to strengthen or undermine our future economic and national security.

Quantum technology can completely transform many areas of science and a wide array of technologies, including sensors, lasers, materials science, GPS, and much more.

Quantum computers have the potential to solve complex problems that are beyond the scope of today's most powerful supercomputers.

Quantum-enabled data analytics can revolutionize the development of new medicines and materials and assure security for sensitive information.

But even Bill Gates finds quantum technology to be challenging. He reportedly said, "I know a lot of physics and a lot of math. But the one place where they put up slides and it is hieroglyphics, it's quantum."

We are fortunate this morning to be able to learn from expert witnesses who thoroughly understand and can explain in plain English all of quantum's complexities.

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I thank our witnesses today for testifying on this important topic. I look forward to their testimony on the current state of quantum research and their recommendations about how to improve efforts in this area.

###

Chairwoman COMSTOCK. Thank you, Mr. Chairman.

And I now recognize myself for a five minute opening statement.

Good morning, and I think if Bill Gates is intimidated by this topic, the rest of us mere mortals are very indebted to our expert witnesses today, so thank you for joining us.

The topic of this morning's hearing, "American Leadership in Quantum Technology," is important to our national security, global competitiveness and technological innovation. This hearing will provide us with a view of U.S. and other nations' research and development efforts to develop quantum computing and related technology. It will also identify what, if more, can be done to boost efforts.

R&D in information technology provides a greater understanding of how to protect essential systems and networks that support fundamental sectors of our economy, from emergency communications and power grids to air-traffic control networks and national defense systems. This kind of R&D works to prevent or minimize disruptions to critical information infrastructure, to protect public and private services, to detect and respond to threats while mitigating the severity of and assisting in the recovery from those threats, in an effort to support a more stable and secure nation. As technology rapidly advances, the need for research and development continues to evolve.

At the same time, I am hoping that we are preventing any duplicative and overlapping R&D efforts, thereby enabling more efficient use of government resources and taxpayer dollars.

Considering the significant increase in global interconnectedness enabled by the internet, and with it, increased cybersecurity attacks, the potential security and offensive advantage that quantum computing and quantum encryption may provide is more essential than ever.

Research in advanced materials and computer science continues to push the envelope of classical computing power and speed. Developments in quantum information science have raised the prospects of a new computing architecture: quantum computing. I am looking forward to our witnesses explaining more about this architecture, including superposition and interconnectivity.

As difficult as the underlying science is for many of us to understand, it is easier to understand how quantum computing can change the world by revolutionizing the encoding of electronic information and supporting data analytics powerful enough to solve currently complicated or inexplicable problems. In today's hearing, I hope we are able to learn more about how quantum technology will revolutionize computing and how to promote continued technological leadership in the United States.

I am also looking forward to learning how industry and others are engaged. As noted in a 2015 PCAST report, "Today's advances rest on a strong base of research and development created over many years of government and private investment. Because of these investments, the United States has a vibrant academia-industry-government ecosystem to support research and innovation in IT and to bring the results into practical use."

It is clear that focusing our investments on information technology research and development is important to our nation for a variety of reasons, including economic prosperity, national security, U.S. competitiveness, and quality of life.

I look forward to the hearing.

[The prepared statement of Chairwoman Comstock follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
October 24, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Chairwoman Barbara Comstock (R-Va.)

American Leadership in Quantum Technology

Chairwoman Comstock: Good morning. I want to welcome everyone here today. The topic of this morning's hearing, American Leadership in Quantum Technology, is important to our national security, global competitiveness and technological innovation.

This hearing will provide us with a view of U.S. and other nations' research and development efforts to develop quantum computing and related technology. It will also identify what, if more, can be done to boost efforts within the United States.

R&D in information technology provides a greater understanding of how to protect essential systems and networks that support fundamental sectors of our economy, from emergency communications and power grids to air-traffic control networks and national defense systems.

This kind of R&D works to prevent or minimize disruptions to critical information infrastructure, to protect public and private services, to detect and respond to threats while mitigating the severity of and assisting in the recovery from those threats, in an effort to support a more stable and secure nation.

As technology rapidly advances, the need for research and development continues to evolve. At the same time, I am hoping that we are preventing any duplicative and overlapping R&D efforts, thereby enabling more efficient use of government resources and taxpayer dollars.

Considering the significant increase in global interconnectedness enabled by the Internet, and with it, increased cybersecurity attacks, the potential security and offensive advantage that quantum computing and quantum encryption may provide is more essential than ever.

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As difficult as the underlying science is for many people to understand, it is easier to understand how quantum computing can change the world by revolutionizing the encoding of electronic information and supporting data analytics powerful enough to solve currently complicated or inexplicable problems.

I am excited for today's hearing, and I hope we are able to learn more about how quantum technology will revolutionize computing and how to promote continued technological leadership in the United States. I am also looking forward to learning how industry and others are engaged. As noted in a 2015 PCAST report, "Today's advances rest on a strong base of research and development created over many years of government and private investment. Because of these investments, the United States has a vibrant academia-industry-government ecosystem to support research and innovation in IT and to bring the results into practical use."

It is clear that focusing our investments on information technology research and development is important to our nation for a variety of reasons, including economic prosperity, national security, U.S. competitiveness, and quality of life. I look forward to hearing from each of our witnesses on this important topic. Thank you for being here.

###

Chairwoman COMSTOCK. And I now will yield to the Ranking Member, Mr. Lipinski, for his opening statement.

Mr. LIPINSKI. Thank you, Chairwoman Comstock and Chairman Weber, for calling this hearing.

The last time this Committee focused on quantum technology was in 2000 when a hearing was held on quantum and molecular computing. The state of the science and technology has come a long way since then, and so has the international competition.

The underlying theory of quantum mechanics began to take shape in the 1920s. The first accurate atomic clock was built in the 1950s. It wasn't labeled as a quantum technology, but it took advantage of the quantum phenomenon known as superposition. Physicist Richard Feynman first mused about the possibility of quantum computers in 1981. In 1994, mathematician Peter Shor developed the first efficient algorithm for a quantum computer, demonstrating that quantum computing, when it arrived, would topple our current system of public-key encryption. Until then, quantum information science was still largely the purview of physics departments.

In the years following Shor's breakthrough, quantum information science became increasingly interdisciplinary, attracting scientists and engineers from diverse fields.

As we will hear from the witnesses today, quantum information science is at another significant turning point. Publications and patent applications are on the rise. Small companies are being formed. Major companies such as IBM, Google, and Microsoft are accelerating their investments in quantum-enabled technology.

I want to highlight in particular the research partnership of the University of Chicago, Argonne National Lab, and Fermi National Accelerator Lab, which has been dubbed the Chicago Quantum Exchange. As we will hear from Dr. Guha, the Exchange was created to develop and grow interdisciplinary collaborations for the exploration and development of new quantum-enabled technologies, and to help educate a new generation of quantum information scientists and engineers. Partnership with the private sector is also an important element of the Exchange. The Chicago Quantum Exchange may be a model for the future of R&D in quantum information science.

With respect to practical applications, the market for quantum sensing and metrology is very close to taking off. Technology developers envision a future in which quantum sensors eliminate the need to use GPS satellites for navigation, can be embedded in buildings to measure stress, can be woven into clothing to monitor vital signs, and can even be injected into our blood to help diagnose disease.

Another practical application is quantum communications. This is an ultra secure method that uses quantum principles to encode and distribute critical information, like encryption keys, and will reveal if they were intercepted by a third party in transit. Multiple countries are investing heavily in this technology, which may be next in line for the commercial market. The world especially took note of China's launch of a quantum-enabled prototype communications satellite last year.

Quantum computing may be further from becoming a reality, but the potential applications for both science and the commercial market are mind-boggling. These are exciting technologies. They also open the door to important policy discussions.

As other countries are increasing their investments in quantum technology, in some cases guided by long-term strategies, now is the time for the U.S. to start developing a more coherent strategy of our own. We must consider the scale, scope and nature of federal investments, how best to facilitate and strengthen partnerships with the private sector, and the education and workforce training that will be required to power a quantum revolution. I have no doubt other important policy issues will emerge in this hearing, including, importantly, the impact on cybersecurity.

I hope this hearing is followed by additional hearings in this Congress and the coming years that more deeply explore specific technologies and policy implications. In the meantime, I look forward to today's introduction to quantum information science and technology.

I thank all of the witnesses for being here this morning to share your expertise, and I yield back the balance of my time.

[The prepared statement of Mr. Lipinski follows:]

OPENING STATEMENT
Ranking Member Daniel Lipinski (D-IL)
of the Subcommittee on Research and Technology

House Committee on Science, Space, and Technology
Subcommittee on Research and Technology
Subcommittee on Energy
"American Leadership in Quantum Technology"
October 24, 2017

Thank you Chairwoman Comstock and Chairman Weber for calling this hearing. The last time this Committee focused on quantum technology was in 2000 when a hearing was held on quantum and molecular computing. The state of the science and technology has come a long way since then. So has the international competition.

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I thank all of the witnesses for being here this morning to share your expertise, and I yield back.

Chairwoman COMSTOCK. Thank you, and I now recognize the Chairman of the Energy Subcommittee, Mr. Weber, for his opening statement.

Mr. WEBER. Thank you, ma'am.

Good morning and welcome to today's joint Research and Technology and Energy Subcommittee hearing. Today, we will hear from a panel of experts on the status of America's research in quantum technology, a field positioned to fundamentally change the way we move and process data. Hearings like today's help remind us of the Science Committee's core focus: the basic research that provides the foundation for technology breakthroughs. Before America ever sees the commercial deployment of a quantum computer, a lot of discovery science must be accomplished.

Quantum technology has the potential to completely reshape our scientific landscape. I'm not going to attempt to explain quantum computing to you all; I'll leave that to the experts here today. But theoretically, quantum computing could allow for the solution of exponentially large problems, things that cannot be accomplished by even the fastest supercomputers today. It could allow us to visualize the structures of complex chemicals and materials, to model highly detailed flows of potential mass evacuations with precise accuracy, and to quantify subatomic interactions on the cutting edge of nuclear research.

Quantum computing may also have profound implications for cybersecurity technology. With China and Russia focusing their efforts on quantum encryption, which could allow for 100 percent secure communications, it is absolutely imperative that the United States maintain its leadership in this field.

In order to achieve this kind of revolutionary improvement in technology, we are going to need foundational knowledge in the advanced computing and materials science required to construct quantum systems. For example, quantum hardware must be equipped to completely isolate quantum processors from outside forces.

Further, because quantum computing differs from today's methods at the most basic level, quantum algorithms must be built from the ground up. Support for basic research in computer science and for computational partnerships between industry, academia, and the national labs is necessary to develop algorithms needed for future commercial quantum systems.

The Department of Energy (DOE) Office of Science is the leading federal sponsor of basic research in the physical sciences, and funds robust quantum technology research. At Lawrence Berkeley National Lab, the National Energy Research Scientific Computing Center allows scientists to run simulations of quantum architectures. At Argonne National Lab's Center for Nanoscale Materials, researchers study atomic-scale materials in order to engineer the characteristics of quantum information systems. And at Fermi National Accelerator Laboratory, scientists are applying their experience in high-energy physics to the study of quantum materials. DOE must prioritize this kind of ground breaking basic research over grants for technology that is ready for commercial deployment. When the government steps in to push today's technology into the market, it actually competes against private investors and uses limited resources to do so. But when the government supports basic research, everyone has the opportunity to access the fundamental knowledge that can lead to the development of future technologies.

I want to thank our accomplished panel of witnesses for testifying today, and I look forward to a productive discussion about the future of American quantum technology research. I think I speak for my fellow members when I say that this is a complex topic, and Congress will need to rely on experts like you all to chart the course for quantum technologies.

I thank the Chair, and I yield back.

[The prepared statement of Mr. Weber follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
October 24, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Chairman Randy Weber (R-Texas)

American Leadership in Quantum Technology

Chairman Weber: Good morning and welcome to today's Joint Research and Technology and Energy Subcommittee hearing. Today, we will hear from a panel of experts on the status of America's research in quantum technology, a field positioned to fundamentally change the way we move and process data.

Hearings like today's help remind us of the Science Committee's core focus – the basic research that provides the foundation for technology breakthroughs. Before America ever sees the commercial deployment of a quantum computer, a lot of discovery science must be accomplished.

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And at Fermi National Accelerator Laboratory scientists are applying their experience in high energy physics to the study of quantum materials.

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###

Chairwoman COMSTOCK. Thank you. And I now recognize the Ranking Member of the Energy Subcommittee, Mr. Veasey, for his opening statement.

Mr. VEASEY. Thank you, Chairwoman Comstock and Chairman Weber, for holding this hearing, and thank you to the witnesses. I really appreciate you being here today. As was mentioned, this is a very complex topic, and you being here, providing your expertise, I think is going to come in very handy today.

Quantum technologies have the potential to solve problems that were previously out of reach and push scientific discovery to new levels. A major breakthrough in this area could result in a significant transformation in our communications systems, computational methods, and even how we understand the world we live in.

In addition to the distinguished group of researchers on our second panel, I am also delighted that we will hear from many of the most important federal agencies that lead our nation's research in this very important field. I hope this becomes a practice that we can expect for every relevant hearing this committee holds. The activities within the federal government that support the development of quantum technologies cut across many agencies, as we will see by those testifying on the first panel.

I should note that in addition to NIST, NSF, and DOE, there are also a number of quantum-related activities taking place within the Department of Defense in DARPA and the military branches, as well as within the intelligence community.

In 2016, the Obama Administration published an interagency working group report that highlighted the need for continued investment across all these federal agencies. It also called for stronger coordination and focused activities to address the impediments to progress in this field. Congress has provided consistent funding for these activities, though I would note that in order to compete with countries like China, Japan, Canada, and Italy, we will need to grow the investments that we are already making.

Sadly, as we have come to expect with every hearing this Committee holds highlighting an important area of research, you can trust that the Trump Administration has proposed making cuts. Vital research in quantum materials is happening within the Department of Energy's Basic Energy Sciences program, and yet this year the Trump Administration has proposed to cut this critical program by $295 million, or 16 percent. While the Advanced Scientific Computing Research Program saw a slight increase in funding, most of that increase was to the exascale computing project. The research portfolio within this program that would actually support advancements in quantum computing saw a 15 percent cut in the budget proposal released earlier this year. This is not, this is not a path towards any sort of technological breakthroughs or quantum leaps.

I would be remiss not to mention the Energy Frontier Research Centers also. The centers have generally enjoyed bipartisan support since the Obama Administration launched these innovative research collaborations across our national labs, universities, and industries. A few of these centers do important work that has the potential to advance our understanding of quantum technologies. They may provide us the breakthroughs we need to launch this field to new heights. While the Trump Administration also proposed cuts to these centers, I hope and expect my colleagues in Congress will continue to voice our strong support for researchers and their vital work. Strong and sustained investment across our research and innovation ecosystem is the only way we can expect to see results from our world-class researchers at our national labs, universities, and private companies. Quantum technologies are certainly no different in that regard.

I look forward to hearing from both panels today on where this field can take us and what exciting new possibilities are on the horizon.

Thank you again, Madame Chair, and I'd like to yield back the balance of my time.

[The prepared statement of Mr. Veasey follows:]

<u>OPENING STATEMENT</u>
Ranking Member Marc Veasey (D-TX)
of the Subcommittee on Energy

House Committee on Science, Space, and Technology
Subcommittee on Research and Technology
Subcommittee on Energy
"American Leadership in Quantum Technology"
October 24, 2017

Thank you Chairwoman Comstock and Chairman Weber for holding this hearing, and thank you to the witnesses for being here today. Quantum technologies have the potential to solve problems that were previously out of reach and push scientific discovery to new levels. A major breakthrough in this area could result in a significant transformation in our communications systems, computational methods, and even how we understand our world. In addition to the distinguished group of researchers on our second panel, I am also delighted that we will hear from many of the most important federal agencies that lead our nation's research in this field. I hope this becomes a practice that we can expect for every relevant hearing this committee holds.

The activities within the federal government that support the development of quantum technologies cut across many agencies, as we will see by those testifying on our first panel. I should note that in addition to NIST, NSF, and DOE, there are also a number of quantum-related activities taking place within the Department of Defense in DARPA and the military branches, as well as within the intelligence community. In 2016, the Obama Administration published an interagency working group report that highlighted the need for continued investment across these federal agencies. It also called for stronger coordination and focused activities to address the impediments to progress in this field.

Our work here in Congress has provided consistent funding for these activities, though I would note that in order to compete with countries like China, Japan, Canada, and Italy, we will need to grow the investments that we are already making. Sadly, as we have come to expect with every hearing this Committee holds highlighting an important area of research, you can trust that the Trump Administration has proposed to cut it. Vital research in quantum materials is happening within the Department of Energy's Basic Energy Sciences program, and yet this year the Trump Administration has proposed to cut this critical program by $295 million or 16%. While the Advanced Scientific Computing Research Program saw a slight increase in funding, most of that increase was to the exascale computing project. The research portfolio within this program that would actually support advancements in quantum computing saw a 15% cut in the budget proposal released earlier this year. This is not the path towards a technological breakthrough or quantum leaps.

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I am looking forward to hearing from both panels today on where this field can take us and what exciting new possibilities are on the horizon. Thank you again, Madame Chair, and I yield back the balance of my time.

Chairwoman COMSTOCK. Thank you, and I now recognize the Ranking Member of the full Committee for a statement, Mrs. Johnson.

Ms. JOHNSON. Thank you very much, and good morning. I really appreciate you for holding this important hearing, and I want to thank the witnesses for being here today.

Quantum technology is an emerging field that will likely have a large impact on our nation's competitiveness in the industries of tomorrow. Its current and potential applications are frankly too numerous to mention, as they range from enabling vast improvements in our ability to discover and develop new pharmaceuticals to ensuring the security of our most critical infrastructure. So, as the Committee of the future, this is exactly the kind of area that we should be focusing our attention on, and I would encourage our Majority to hold many more hearings that follow this example.

I also believe that we should strongly consider developing a National Quantum Initiative, and I look forward to engaging with my colleagues on the other side of the aisle in the hope that we can put together bipartisan legislation to make this happen.

I would note that it will be much more difficult to ensure U.S. leadership in this crucial field if we don't at least provide sufficient resources to maintain our current rate of progress. Yet the Administration is proposing significant cuts to the agencies and programs that are at the vanguard of this effort. This would include an 11 percent cut to the National Science Foundation, a 6.6 percent cut to the quantum science research at the National Institutes of Standards and Technology, and a 16 percent cut to the Department of Energy's Basic Energy Sciences program. I look forward to hearing more about the impacts of these proposed cuts from both of our witness panels. Based on their written testimony alone, I expect that we will hear more than enough justification for substantially increasing our support for these quantum R&D efforts over the next several years.

I thank you and yield back.

[The prepared statement of Ms. Johnson follows:]

<u>OPENING STATEMENT</u>
Ranking Member Eddie Bernice Johnson (D-TX)

House Committee on Science, Space, and Technology
Subcommittee on Research and Technology
Subcommittee on Energy
"American Leadership in Quantum Technology"
October 24, 2017

Thank you Chairwoman Comstock and Chairman Weber for holding this important hearing, and thank you to the witnesses for being here today. Quantum technology is an emerging field that will likely have a large impact on our nation's competitiveness in the industries of tomorrow. Its current and potential applications are frankly too numerous to list, as they range from enabling vast improvements in our ability to discover and develop new pharmaceuticals to ensuring the security of our most critical infrastructure.

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I look forward to hearing more about the impacts of these proposed cuts from both of our witness panels. Based on their written testimony alone, I expect that we will hear more than enough justification for substantially increasing our support for these quantum R&D efforts over the next several years.

Thank you again and I yield back.

Chairwoman COMSTOCK. Thank you.

I will now introduce our first panel of witnesses. Our first witness today is Dr. Carl Williams, Acting Director of the Physical Measurement Laboratory at the National Institute of Standards and Technology. Dr. Williams is a Fellow of the Joint Quantum Institute and the Joint Center for Quantum Information in Computer Science, and he is an Adjunct Professor of Physics at the University of Maryland. He also directs the Quantum Information Program and helps lead the National Strategic Computing Initiative at NIST.

Additionally, he's a member and chairs interagency efforts in support of these activities under the Committee of Science of the National Science and Technology Council. He received a Bachelor of Arts in physics from Rice University and a Ph.D. from the University of Chicago.

Dr. Jim Kurose is our second witness. He's the Assistant Director of Computer and Information Science and Engineering Directorate at the National Science Foundation. Prior to NSF, he was a Distinguished Professor in the School of Computer Science at the University of Massachusetts-Amherst.

He also currently serves as Co-Chair of the Networking and Information Technology Research and Development Subcommittee of the National Science and Technology Council Committee on Technology, which provides overall coordination for the IT research and development activities of 18 federal government agencies and offices. He holds a Bachelor of Arts in physics from Wesleyan University as well as a Masters of science and a Ph.D. in computer science from Columbia University.

Dr. Stephen Binkley is our third witness today, and he is Acting Director of Science at the U.S. Department of Energy. In this role, he provides scientific and management oversight for the six science programs of the Office of Science including advanced scientific computing research. Previously, he has held senior positions at Sandia National Laboratories, the Department of Homeland Security, and the Department of Energy. He has conducted research in theoretical chemistry, material science, computer science, applied mathematics, and microelectronics. He received a Bachelor of Science in chemistry from Elizabethtown College as well as a Ph.D. in chemistry from Carnegie Mellon University.

I now recognize Dr. Williams for five minutes to present his testimony.

TESTIMONY OF DR. CARL J. WILLIAMS, ACTING DIRECTOR, PHYSICAL MEASUREMENT LABORATORY, NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Dr. WILLIAMS. Thank you. Ranking Member Johnson, Chairwoman Comstock, Chairman Weber, Ranking Member Lipinski, Ranking Member Veasey, and members of the Subcommittees, I am Dr. Carl Williams, the Acting Director of the Physical Measurement Laboratory at the Department of Commerce, National Institute of Standards and Technology, known as NIST. Thank you for the opportunity to appear before you today to discuss NIST's role in quantum science and quantum computing.

As this nation's national metrology institute, NIST conducts basic and applied research in quantum science to advance the field of fundamental metrology as part of it's core mission by developing more precise measurement tools and technologies to address industry's increasingly challenging requirements. This work has positioned NIST both as a global leader among national metrology institutes, and as one of the world's leading centers of research and engineering.

While NIST's work in quantum science is revolutionizing the world of metrology, it also has direct application to quantum communications and quantum computation. Today I'll describe in detail more of NIST's quantum research efforts and how they are being leveraged to positively advance the field.

Many nations view leadership in quantum computing as critical to making significant breakthroughs in medicine, manufacturing, artificial intelligence, and defense and reaping the rewards from those investments and breakthroughs. The United States has long been viewed as a leader in quantum science, information, and computing. Significant historic investments by the U.S. government have supported a robust base of fundamental research and this has led to several transformational breakthroughs in the field.

Today, U.S. leadership in quantum science and technology is increasingly dependent on significant investments from U.S. technology giants and major defense companies with a natural interest in many commercial applications of quantum technology beyond computing. These applications include quantum communications, quantum algorithms and software, data security, imaging, and quantum sensors, and could be applied to anything from national security to the Internet of Things to advance sensors for gas and oil exploration.

While NIST has made significant breakthroughs, the rest of the world has not been standing still, and U.S. companies are taking notice. Worldwide interest in investment quantum computing-related technologies have spiked in recent years, following important increasingly complex technological demonstrations by overseas research efforts.

At NIST, our researchers study and harness quantum mechanical properties of light and matter in some of the most well-controlled measurement environments to create the world's most sensitive and precise sensors and atomic clocks. NIST has been a leader in the field of quantum information from the beginning and its multiple Nobel prize-winning contributions have helped move quantum computing and quantum information scientific fields of study to technological ones.

These breakthroughs in precision timekeeping have critical real-world applications to navigation and timing. Today, commercial atomic clocks contained in GPS satellites provide the timekeeping precision that we take for granted when we use our GPS devices to pinpoint our location to within a meter of almost anywhere on Earth. Atomic clocks are just one example of NIST research focus on measurement science and has applications to quantum computing.

Superconductors are also used by researchers at NIST to make ultrasensitive single photon detectors using precision photonic measurements. These specially designed sensors have become essential components in experiments at NIST to test the foundations of quantum mechanics and realize quantum teleportation. Progress in quantum teleportation is expected to be essential for eventual commercial quantum computing and for other forms of quantum information transfer.

NIST's programs on quantum algorithms and postquantum cryptology further build on our core effort in quantum information theory with a focus on addressing security challenges anticipated when practical quantum computers are realized. NIST, working with industry has played a leading role since the 1970s in developing cryptographic standards. NIST researchers are using their understanding of quantum algorithms to create new classical encryption algorithms, commonly referred to as post-quantum cryptography, that will be resistant to quantum computing attacks.

NIST recognizes that it has an essential role to play in U.S. leadership in quantum computing and information. However, that role is not to build a quantum computer. NIST's role, consistent with its mission, is to develop the foundational knowledge and measurement science support for U.S. leadership in quantum computing and to ensure that our cybersecurity infrastructure remains resilient in the quantum era.

NIST is extremely proud of the world-class quantum science, quantum information, mathematics and computer science programs, and we appreciate the support of this Committee for NIST's research efforts. Sustained advancements by NIST in these fields continue to underpin success in many parts in its measurement science mission and to contribute to U.S. leadership in quantum computing.

Thank you for the opportunity to testify today. I would be happy to answer any questions you may have.

[The prepared statement of Dr. Williams follows:]

Testimony of

Carl J. Williams, Ph.D.

Acting Director
Physical Measurement Laboratory
National Institute of Standards and Technology
United States Department of Commerce

Before the
United States House of Representatives
Committee on Science, Space, and Technology
Subcommittee on Research and Technology
and
Subcommittee on Energy

"American Leadership in Quantum Technology"

October 24, 2017

Introduction

Chairwoman Comstock, Ranking Member Lipinski, Chairman Weber, Raking Member Veasey, and members of the Subcommittees, I am Dr. Carl Williams, the Acting Director of the Physical Measurement Laboratory (PML) at the Department of Commerce's National Institute of Standards and Technology (NIST). Thank you for the opportunity to appear before you today to discuss NIST's roles in quantum science and quantum computing.

As this nation's national metrology institute, NIST's overall mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. NIST does this through programs focused on national priorities from cybersecurity, advanced manufacturing and the digital economy to precision metrology, biosciences, and more.

NIST conducts basic and applied research in quantum science to advance the field of fundamental metrology as part of its core mission, by developing more precise measurement tools and technologies to address industry's increasingly challenging requirements. This work has positioned NIST both as a global leader among national metrology institutes, and as one of the world's leading centers of quantum research and engineering. While NIST's work in quantum science is revolutionizing the world of metrology, it also has direct application to quantum communications and quantum computation. Today, I'll describe in more detail some of NIST's quantum research efforts and how they are being leveraged to positively advance the field.

Quantum Computing and Quantum Information Science

Quantum mechanics revolutionized science in the 20th century, leading to technological breakthroughs including the invention of the laser and the transistor. Today's most advanced communication and computation technologies are based on those mid-20th century inventions.

Science and society is poised for a second quantum revolution in the 21st century, one in which we will employ our new-found ability to exploit quantum mechanical phenomena to push beyond the limits of classical computing and communications. Phenomena such as superposition (the ability of a particle to be in several different states at the same time) and entanglement (the ability of two particles to share information even at a distance) lie at the heart of what makes a quantum computer so much more powerful than even today's most advanced classical supercomputers.

So, what are quantum computing and quantum information? Unlike classical computers, which process high and low voltages as 1's and 0's to form bits of information that get shuttled around, quantum computers manipulate quantum bits of information, or qubits. A qubit's information is in the form of a discrete state, such as the magnetic spin of an electron. Due to quantum mechanical phenomena such as superposition, these qubits can be both a 1 and a 0 at the same time.

To understand this, we can imagine a normal classical bit as able to represent only two points on the surface of a sphere—such as the north and south poles of the earth. In contrast, a qubit could represent any point on the surface of that sphere. This superposition, together with the shared fate resulting from entanglement between multiple qubits together, is what gives a quantum computer the superior computational power that will make it uniquely capable of solving complex problems, including perhaps most notably the breaking of current encryption schemes.

NIST's expertise in quantum science is mainly focused on the use of quantized states of light and matter and their manipulation and interaction as quantum bits of information to make ultra-precise sensors and measurement tools. This application falls under a broader field of study that we refer to as "quantum information science," which lies at the intersection of computer science, mathematics, and quantum science. The breakthroughs that NIST is making in this field will have direct relevance and application to quantum computing.

Recent Investments and Advancements Abroad

Many nations view leadership in quantum computing as critical to making significant breakthroughs in medicine, manufacturing, artificial intelligence, and defense, and to reaping the rewards from those investments and breakthroughs. The U.S. has long been viewed as a leader in quantum science, information, and computing. Significant historic investment by the U.S. government has supported a robust base of fundamental research, and this has led to several transformational breakthroughs in the field.

Today, U.S. leadership in quantum science and technology is increasingly dependent on significant investments from U.S. technology giants and major defense companies with a natural interest in the many commercial applications of quantum technology beyond computing. These applications include quantum communications, quantum algorithms and software, data security, imaging, and quantum sensors, and could be applied to anything from national security to the Internet of Things, to advanced sensors for gas and oil exploration. Applications for quantum sensors include novel approaches to precision navigation and timing, as well as technologies that could provide a backup or holdover function for global positioning systems or GPS.

While the U.S. has made significant breakthroughs, the rest of the world has not been standing still—and U.S. companies are taking notice. Worldwide interest and investment in quantum computing and related technologies has spiked in recent years, following important and increasingly complex technological demonstrations by overseas research efforts.

The European Union has launched an effort to invest 2 billion euros over the next 10 years in a recently launched EU Flagship Quantum Program. The United Kingdom has created a set of quantum hubs aimed at exploiting the various application spaces within quantum information science.

Perhaps even more noteworthy is China's rapid investment in quantum technology and the dramatic advances by China in the area of quantum communication. Earlier this year, China sent entangled photons from a satellite to the ground 1200 kilometers away, smashing several quantum communication distance records. More recently, China has demonstrated the world's first atomic clock in space using cold atoms, which can far outperform the atomic clocks in U.S. GPS, and can further support future advanced quantum networks.

NIST's History and Role in Quantum Computing and Information

At NIST, our researchers study and harness the quantum mechanical properties of light and matter in some of the most well-controlled and defined measurement environments to create the world's most sensitive and precise sensors and atomic clocks. NIST has been a leader in the field of quantum information from the beginning, and its multiple Nobel Prize-winning contributions have helped move quantum computing and quantum information from purely scientific fields of study to technological ones.

NIST scientists began researching quantum information in the early 1990s in their quest to make better atomic clocks. Qubits and atomic clocks may seem worlds apart, but experimentally they are very much the same thing. By 2000, NIST had established a formal quantum information program.

Atomic Clocks: The Power of One Qubit
Atomic clocks define the second and tell time with amazing precision. For example, the most accurate U.S. atomic clock currently used for defining the second is the NIST-F2. It keeps time to an accuracy of less than a millionth of a billionth of a second. Stated in another way, the NIST-F2 clock will not lose a second in at least 300 million years. And just this month, NIST published a description of a radically new atomic clock design—the three-dimensional (3-D) quantum gas atomic clock. With a precision of just 3.5 parts error in 10 quintillion (1 followed by 19 zeros) in about 2 hours, it is the first atomic clock to ever reach the 10 quintillion threshold, and promises to usher in an era of dramatically improved measurements and technologies across many areas based on controlled quantum systems.

These breakthroughs in precision timekeeping have critical real-world applications to navigation and timing. Today, commercial atomic clocks contained in GPS satellites provide the timekeeping precision that we take for granted when we use our GPS devices to pinpoint our location to within a meter almost anywhere on earth.

NIST's most advanced atomic clocks, so precise that they will not lose a second over the life of the universe, also are being applied to make the world's most sensitive measurements of quantities other than time. For example, NIST is actively pursuing the use of atomic clocks as quantum sensors, another application of quantum information, for a range of entirely new technologies. NIST is now able to detect the barely perceptible slowing of time in a large gravitational potential. This is the second form of time dilation predicted by Einstein in his general theory of relativity and may help scientists detect gravitational waves or prospectors find hidden oil reserves and mineral deposits. The technology might even have the potential to allow scientists to predict earthquakes days or even weeks before a cataclysmic event.

Quantum Logic
NIST's breakthroughs in the measurement of time also have laid the technological foundations for how to manipulate quantum information. NIST's pioneering work in the cooling and trapping of ions and atoms to improve timekeeping provided NIST researchers with the experimental platform to demonstrate the first two-qubit quantum logic gate in 1995, by controlling and entangling the energy levels of two ions. Logic gates in classical computers are used to process information. By analogy, quantum logic gates form the basic building block for

quantum computing. Scaling up to experiments involving multiple logic gates provides a platform to test more complex quantum computing theory.

Other Quantum Computing Technologies
Atomic clocks are just one example of NIST's research focused on measurement science that has applications to quantum computing. NIST also is the world's leader in specially designed devices, made from superconductors, known as Josephson Junctions. Josephson Junction technology is used by NIST to realize and disseminate NIST's quantum voltage standard. The quantum voltage standard is also integral to the proposed 2019 effort to redefine the international system of units (colloquially, the metric system) to be based on fundamental constants of nature, as defined through world-leading experiments at NIST such as the "electronic kilogram". This same technology is being explored as a key competitor to trapped ions and atoms as another way to manipulate and store quantum information.

Additionally, Superconductors are used by researchers at NIST to make ultra-sensitive single photon detectors used in precision photonic measurements at NIST and by external stakeholders. These specially designed sensors have become essential components in experiments at NIST to test the foundations of quantum mechanics and realize quantum teleportation. In quantum teleportation, quantum information gets transmitted instantaneously from one qubit to another. Discrete photons, like ions and atoms, can also be carefully controlled and entangled to form qubits. Prior to China's recent 1200 kilometer demonstration, NIST had held the distance record for quantum teleportation, transmitting information between photons separated by 100 kilometers. Progress in quantum teleportation is expected to be essential for eventual commercial quantum computing, and for other forms of quantum information transfer.

In the end, building a quantum computer will involve many disparate quantum technologies. Those technologies will need to be integrated to provide long-term storage and memory, transmission or teleportation, transduction, and detection of qubits while not corrupting the qubit's extremely delicate state.

Quantum Information Theory and Validation and Verification
In 2002, NIST hired its first quantum information theorist. This began a quantum information program which has led to new and improved approaches for quantum error correction, techniques for reliably characterizing quantum states produced in the laboratory, and concepts for randomized benchmarking of quantum gates. These concepts have provided crucial insights, which NIST has used to further improve our experimental efforts and those of other research groups. For example, randomized benchmarking has become the standard by which research groups around the world characterize and compare the quality of their computational paradigms.

Quantum Algorithms and Post-Quantum Cryptography
NIST programs on quantum algorithms and post-quantum cryptography further build on our core efforts in quantum information theory with a focus on addressing security challenges anticipated when practical quantum computers are realized. NIST, working with industry, has played a leading role since the 1970s in developing cryptography standards. Today's classical computers and computer networks employing Public Key Cryptography are using cryptography standardized by NIST. Unfortunately, these standards will not be resistant to attack by quantum computers. NIST researchers are using their understanding of quantum algorithms to create new

classical encryption algorithms, commonly referred to as post-quantum cryptography, that will be resistant to quantum computing attacks.

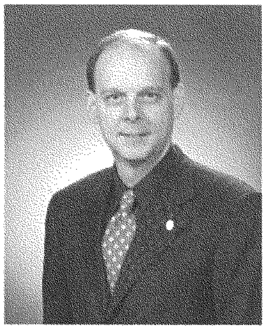
NIST's Joint Institutes with Universities
NIST also supports joint centers with the University of Colorado Boulder (UC) and the University of Maryland (UMD). JILA at UC was founded in 1962 and has been doing research in quantum science and in atomic clocks and is evolving into quantum information science. Two joint centers in quantum information science at UMD were established more recently. The Joint Quantum Institute (JQI) was established in 2006 through a cooperative effort between NIST, UMD, and the Laboratory for Physical Sciences. The Joint Center for Quantum Information and Computer Science (QuICS) was established in 2014 to complement JQI's experimental and theoretical work by focusing the use of quantum systems to process, transmit and store quantum information. Taken together, NIST's joint institutes interact strongly to push the frontiers of quantum science, information, and computing and provide a training ground for industry's future quantum workforce.

Conclusion

NIST recognizes that it has an essential role to play in U.S. leadership in quantum computing and information. However, that role is not to build a quantum computer. NIST's role, consistent with its mission, is to develop the foundational knowledge and measurement science support for U.S. leadership in quantum computing, to create the basis for characterizing quantum logic gates, to explore approaches to quantum control and error correction, to develop rudimentary quantum processors that are capable of creating the exotic quantum states that will allow improvement of our measurements beyond the standard quantum limit, and to ensure that our cybersecurity infrastructure remains resilient in the quantum era. Part of this foundational knowledge will come from using NIST's measurement platforms to experimentally conduct quantum simulations and validate quantum computing theory. NIST also anticipates that the early adoption of the quantum technologies that emerge as NIST continues to develop the world's most precise atomic clocks (quantum logic clocks) and quantum based sensors will ultimately provide substantial support to the effort to build a quantum computer.

NIST is extremely proud of its world-class quantum science, quantum information, mathematics, and computer science programs, and we appreciate the support of this Committee for NIST's research efforts. Sustained advancements by NIST in these fields continue to underpin success in many parts of NIST's measurement science mission and contribute to U.S. leadership in quantum computing. Thank you for the opportunity to testify today. I would be happy to answer any questions you may have.

Carl J. Williams



Carl J. Williams is Acting Director of the Physical Measurement Laboratory (PML), National Institute of Standards and Technology (NIST). He is a Fellow of the Joint Quantum Institute and the Joint Center for quantum Information in Computer Science and Adjunct Professor of Physics at the University of Maryland (UMD). He directs the quantum Information Program and helps lead the National Strategic Computing Initiative at NIST. He is a member and chairs interagency efforts in support of these activities under the Committee of Science of the National Science and Technology Council. He is a member of the Executive Leadership Team within the PML and represents the PML to other federal agencies.

As Acting Director of PML, Dr. Williams is responsible for the maintenance, development, and dissemination of the U.S. national measurement standards. He also manages the full suite of NIST calibration services in dimensional, electromagnetic, ionizing radiation, mechanical, optical, thermodynamic, and time and frequency metrology.

Education:

Ph.D. from the University of Chicago in 1987

B.A. in Physics from Rice University in 1981

Chairwoman COMSTOCK. Thank you, and I now recognize Dr. Kurose for five minutes to present his testimony.

TESTIMONY OF DR. JIM KUROSE, ASSISTANT DIRECTOR, COMPUTER AND INFORMATION SCIENCE AND ENGINEERING DIRECTORATE, NATIONAL SCIENCE FOUNDATION

Dr. KUROSE. Thank you very much. Good morning, Ranking Member Johnson, Chairwoman Comstock, Chairman Weber, Ranking Member Lipinski, and Ranking Member Veasey. My name is Jim Kurose. I'm the Assistant Director at the National Science Foundation for Computer and Information Science and Engineering. As you know, the National Science Foundation supports fundamental research in all areas of science and engineering disciplines; supports for education and training for the next generation of discoverers and innovators, and contributes to national security and U.S. economic competitiveness. I welcome this opportunity to highlight the promise of quantum information science, which I'll call QIS—so that's a little bit of an acronym alert here—and NSF's investment in QIS and their impact on our nation's security and economy.

QIS harnesses quantum phenomena with the promise of creating more precise measurement systems, more accurate sensors, more secure communication, and more advanced computers that will outperform today's most powerful digital supercomputers on a range of problems in materials science, molecular simulation, design and optimization, and cryptography. There will be benefits in nearly all areas and all sectors of the economy as well as new challenges, particularly in the area of cybersecurity.

NSF's investments in fundamental long-term research have been crucial to a national strategy for sustaining leadership in QIS. For several decades, NSF has funded research that has defined the frontiers of QIS. NSF's investments in QIS research span multiple disciplines including mathematical and physical sciences, engineering, and computer science, and in four areas: in the fundamentals that advance our understanding of uniquely quantum phenomena and their interaction with classical systems; in elements that model, control, and exploit quantum particles and measure them; in software systems and in algorithms that enable quantum information processing; and in the workforce including training a new generation of scientists, engineers, and educators for a globally competitive workforce.

NSF annually has invested approximately $30 million in QIS research and education activities plus another $40 million in facility-related investments. Looking forward, QIS will continue to be an important part of NSF's research portfolio.

The National Science Foundation recently announced 10 Big Ideas that form a cutting-edge research agenda. One of these Big Ideas, the Quantum Leap: Leading the Next Quantum Revolution, is aimed squarely at advancing QIS. Another Big Idea, Growing Convergence Research at NSF, seeks the deep integration of knowledge, techniques and expertise from multiple fields that are needed to address scientific challenges in areas including QIS.

NSF's investments in QIS research have been accompanied by investments in education and workforce development as well. Academic QIS researchers are also teachers. They take their latest developments from the lab to the classroom and they mentor research students and postdocs. For example, Dr. Krysta Svore was an NSF-funded graduate student at Columbia University focusing on computational complexity in quantum computing. Today she's a leader at Microsoft Research developing real-world quantum algorithms and designing quantum software architectures. Dr. Svore is emblematic of the unique flow of ideas and people and artifacts between academia and industry in our nation. In information technology areas, this flow has been characterized by the so-called "tire tracks diagram," which documents in multiple reports from the National Academies the flow of ideas, people and artifacts back and forth. Indeed, NSF frequently partners with industry to accelerate programs in mutual areas of interest, and QIS is one of these areas.

NSF's close coordination and collaboration with other federal agencies has been critical in shaping its QIS investments. Together with DOE and NIST, NSF co-chairs the Interagency Working Group on Quantum Information Science, which was established in 2009 under the National Science and Technology Council's Committee on Science. Last year, the QIS working group released a report, Advancing Quantum Information Science: National Challenges and Opportunities, which notes the promise in this area and NSF's key role as an agency in supporting QIS fundamental research, workforce development, and technology transfer.

My testimony today has really emphasized the potential of QIS in a wide range of areas from harnessing unrivaled computing power to securing communications to developing novel therapeutics for some of our most vexing diseases. NSF has made significant long-term investments in fundamental and multidisciplinary QIS research. These investments have laid the foundations for QIS as we know it today, and in turn are enabling U.S. researchers and industry to lead abroad. I've described how NSF's education portfolio is working to develop a next-generation QIS-capable workforce.

This concludes my remarks, and I'm very happy to answer questions.

[The prepared statement of Dr. Kurose follows:]

Testimony of

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National Science Foundation for
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Before the
Subcommittee on Research and Technology
and the Subcommittee on Energy

For the
Committee on Science, Space, and Technology
U.S. House of Representatives

October 24, 2017

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 activies. 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 digitial 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

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[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 controling 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, controlable, 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 explornig novel and emergent applications of quantum technology.

Finally, *Quantum Workforce* underpins the aforementioned 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

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[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].

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[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 afirementioned 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 fundemantal 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

[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

[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.

Chairwoman COMSTOCK. Thank you, and I now recognize Dr. Binkley for five minutes.

TESTIMONY OF DR. JOHN STEPHEN BINKLEY, ACTING DIRECTOR OF SCIENCE, U.S. DEPARTMENT OF ENERGY

Dr. BINKLEY. Thank you, Chairwoman Comstock, Chairmen Weber, Ranking Member Lipinski, Ranking Member Veasey, and Members of the Subcommittee. I'm pleased to come before you today to discuss quantum information science and technology, the Department of Energy's research efforts and interagency collaboration in this area, and where the United States stands relative to international competition.

I am presently the Acting Director of the Office of Science at the U.S. Department of Energy. Quantum information science, or QIS, for short, which includes quantum computing, is a rapidly evolving area of science with great scientific and technology import, and because it will open new vistas for both science and technology development and hence new commercial markets, the U.S. and other countries are increasing investments in related basic research and technology development. DOE and other government agencies believe that QIS will continue to grow in importance in the coming decade and are planning our investments accordingly.

Current and future QIS applications differ from earlier and ongoing applications of quantum mechanics such as those that led to the laser by exploiting distinct quantum behavior that does not have classical analogs and does not arise in non-quantum systems such as superposition and entanglement.

Quantum information concepts are providing increasingly important—or providing increasingly important in advancing understanding across a surprisingly large range of fundamental topics in the physical sciences including the search for dark matter, the emergence of space time, testing of fundamental symmetries, the black hole information paradox, probing the interiors of cells in plants and animals, and possibly even photosynthesis.

Furthermore, a wide range of applications of QIS are being explored including in sensing and metrology, communication, simulation, and computing. With these motivations, recent QIS advances have been rapid and international, and industry attention and investments have been growing. QIS clearly represents an emerging field with crosscutting importance across DOE Office of Science program offices. DOE is uniquely positioned to cover a wide range of QIS activities with expertise and capabilities in frontier computing, quantum materials, quantum information, control systems, production and use of isotopes, cryogenics and so on spanning the National Laboratory system and multiple program offices within the Office of Science.

At the federal level, quantum information science has been a topic of interest to federal agencies for some time including NIST, the National Science Foundation, and DOE, which are working closely together and has garnered greater attention in the past few years due to a confluence of events, namely theoretical and technological progress in the field, the slowing of an apparently rapidly approaching end to Moore's Law, advancement in semiconductor technology and aggressive investments by other nations.

DOE's National Laboratories have unique attributes that are complementary to those of other agencies and could address gaps identified in the national ecosystem for quantum information science and technology. The Department of Energy labs are well equipped to address challenging problems in fundamental research that requires sustained efforts or are too large in scope for university research groups. DOE labs additionally stand out in their ability to fabricate and characterize novel materials and devices, their expertise in using high-performance computing resources, and their diverse range of high-caliber scientists and engineers that can form the basis of interdisciplinary teams, which are the type that are needed to solve QIS problems.

Worldwide interest in QIS and related technology has increased substantially in the past five years. While the United States remains the leader in the field, other nations have made significant new investments and have developed long-term strategies that already have shifted geographical distribution of some top-tier research groups. The largest quantum information science and technology programs outside the United States are in China, the European Union, and the United Kingdom, and those countries are planning ambitious investments.

I would like to thank you for the opportunity to come before you today to discuss the importance of QIS and the Department of Energy's efforts in this area. I look forward to discussing this topic with you and answering your questions.

[The prepared statement of Dr. Binkley follows:]

STATEMENT BY

J. STEPHEN BINKLEY

ACTING DIRECTOR, OFFICE OF SCIENCE,

U.S. DEPARTMENT OF ENERGY

BEFORE THE

HOUSE SCIENCE, SPACE AND TECHNOLOGY COMMITTEE,

SUBCOMMITTEE ON ENERGY AND SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY

ON

AMERICAN LEADERSHIP IN QUANTUM TECHNOLOGY

OCTOBER 24, 2017

Thank you Chairwoman Comstock, Chairman Weber, Ranking Member Lipinski, Ranking Member Veasy, and Members of the Subcommittees. I am pleased to come before you today to discuss quantum information science and technology, the Department of Energy's research efforts and interagency collaboration in this area, and where the U.S. stands relative to its international competition.

Introduction

Quantum Information Science (QIS), which includes quantum computing, is a rapidly evolving area of science with great scientific and technology import. It combines the important features of quantum theory, which was developed in the early Twentieth Century, with Information Theory, which was developed in the late 1940s. Because it will open new vistas for both science and technology development, and hence new commercial markets, the U.S. and other countries are increasing investments in related basic research and technology development. DOE and other U.S. Government (USG) agencies believe that QIS will continue to grow in importance in the coming decade and are planning appropriate investments accordingly.

QIS—including quantum science and instrumentation for next-generation computing, information, and other fields—arises from the synthesis of quantum theory and information theory. It springs from the recognition that uniquely quantum phenomena can be harnessed to advance information collection, processing, and fundamental understanding in ways that classical approaches can only do less efficiently, or not at all. Current and future QIS applications differ from earlier (and ongoing) applications of quantum mechanics, such as the laser, by exploiting distinct quantum behavior that does not have classical counterparts and does not arise in non-quantum systems, including:

- *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 information concepts are proving increasingly important in advancing understanding across a surprisingly large range of fundamental science topics, including the search for dark matter, emergence of spacetime, testing of fundamental symmetries, the black hole information paradox, probing the interiors of biological cells, and possibly even photosynthesis and the navigation systems of migratory birds. Quantum approaches based on the characteristics listed above also show promise in providing new capabilities and tools to pursue fundamental research, such as advanced sensors and detectors. Furthermore, a wide range of applications of QIS are being explored including in sensing and metrology, communication, simulation, and computing. With these motivations, recent QIS advances have been rapid, and international and industry attention and investments have been growing.

Program offices within the Department of Energy's (DOE's) Office of Science (SC) have identified areas in which they have important or unique roles, and bring unusual capabilities to bear. Brief descriptions of these equities and contributions follow:

- *Advanced Scientific Computing Research (ASCR)*—Strong foci in research, partnerships, and provision of leadership-class computing and networking resources to the research community. Key elements include providing early access to new technology, exploring the DOE-relevant application space in partnership with other SC programs, and ensuring that application needs inform next-generation device design and basic research programs in applied mathematics, networking, and computer science.
- *Biological and Environmental Research (BER)*—QIS imaging and sensing approaches will expand experimental observation capabilities across varying environmental parameters or collocation of heterogeneous biological and physical materials. Understanding of biological, earth, and environmental systems via complex multi-scale models will be improved by development of faster and more powerful quantum computing devices, control systems, machine learning, and algorithms.
- *Basic Energy Sciences (BES)*—Contributions center on advancing the control of quantum coherence and entanglement to enable applications encompassing information processing, secure communication, sensors, energy generation, and control of chemical reactions. Collectively, research and user facilities offer the tools and infrastructure to enable collaborative integration of advanced synthesis, fabrication, characterization, theory, modeling, testing, benchmarking, and development-to-scale to advance QIS.

- *High Energy Physics (HEP)*—Primary emphases are on exploiting entanglement and QIS-driven technologies to address the HEP community's science drivers; developing new computational and foundational techniques; and broadly advancing the national QIS enterprise and ecosystem. With particular attention to partnerships, HEP plans a three-prong research approach including thrusts in Foundational QIS and Quantum Computing, Quantum Sensor Technology, and Experimental QIS.
- *Nuclear Physics (NP)*—Applications of quantum computing may include many-nucleon problems of relevance to nuclei, nuclear structure and reactions, and bulk nuclear matter. QIS may also impact solution of fundamental field theories that underlie nuclear physics, such as quantum chromodynamics. Experimental programs include manipulation and control of quantum systems such as trapped ions, and the DOE Isotope Program could produce enriched stable isotopes for novel quantum devices.

Quantum information science clearly represents an emerging field with cross-cutting importance in most of the program offices of DOE-SC. Both its fundamental and more applied aspects bear directly on the Office of Science mission: *the delivery of scientific discoveries and major scientific tools to transform our understanding of nature and to advance the energy, economic, and national security of the United States.* Furthermore, DOE is uniquely positioned to cover a wide range of QIS activities, with expertise and capabilities in frontier computing, quantum materials, quantum information, control systems, isotopes, and cryogenics spanning the National Laboratory system and multiple program offices. These considerations provide impetus now for community-building and initiatives across SC offices and with external counterparts. This document summarizes the interests, activities, and overall approach of the Office of Science in QIS.*

Background and Context for Federal Activity

Quantum information science has been a topic of interest to Federal agencies for some time, but has garnered greater attention in the past few years due to a confluence of events: theoretical and technological progress in the field, including the demonstration of multiple-qubit systems by numerous groups including companies; the advent of and controversies surrounding adiabatic quantum computers, or quantum annealers, on the open market; the slowing and apparently rapidly-approaching end of Moore's-law advancement in semiconductor technology; and aggressive investment by other nations. The rapid progress of the field is also signaled by the growth in QIS-related publications, as shown here for 2000-2015 (figure from *Advancing Quantum Information Science: National Challenges and Opportunities,* NSTC report of July 2016).

* For convenience, in this document the term "quantum information science" or "QIS" will be used as shorthand, but is intended to encompass the full range of activity associated with quantum information, including basic science, tools, engineering, technology, and applications.

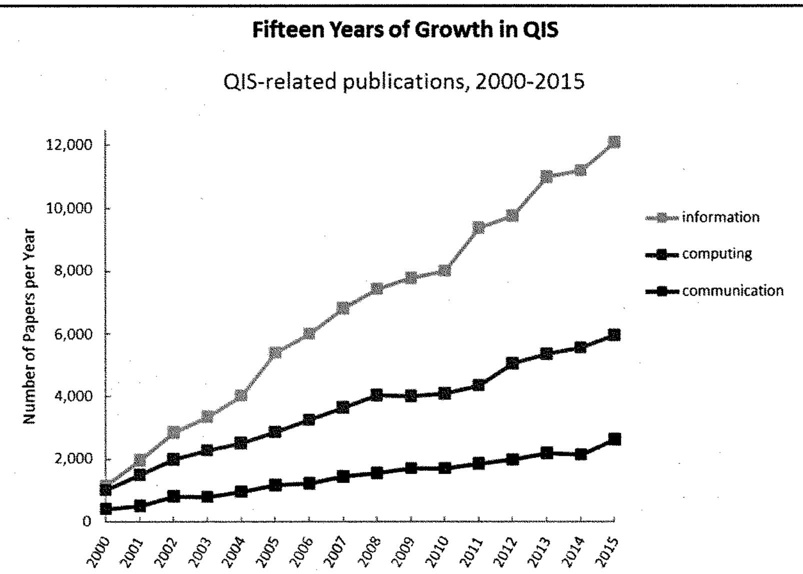

Figure 1. A Google Scholar search for publications (excluding patents and citations) containing the terms "quantum information," "quantum computing," and "quantum communication" illustrates how the field has grown in recent years.

The primary mechanism for high-level coordination of science and technology activities across Federal agencies is the National Science and Technology Council (NSTC), an internal-to-government body that is nominally chaired by the President and includes Cabinet-level (or, for independent agencies, Director-level) representation. The work of the NSTC is carried out through its many subgroups. In January 2009, an NSTC Subcommittee released a document entitled *A Federal Vision for Quantum Information Science.* While this addressed the challenges and opportunities at the time, further action in the next few years was limited. With subsequent rapid developments in the field, however, a new Interagency Working Group on Quantum Information Science was chartered under the NSTC in October of 2014. That body, which is co-chaired by DOE, the National Science Foundation (NSF), and the National Institute of Standards and Technology (NIST), issued a report titled *Advancing Quantum Information Science: National Challenges and Opportunities* in July 2016[†]. The report identified the major challenges to progress in QIS as: institutional boundaries; education/workforce needs; technology and

[†] https://www.whitehouse.gov/sites/whitehouse.gov/files/images/Quantum_Info_Sci_Report_2016_07_22%20final.pdf

knowledge transfer; materials and fabrication; and level and stability of funding. It highlighted a path forward founded on stable, sustained core programs; strategic targeted investments; and controlled growth, close monitoring, and adaptability, and emphasized that "QIS should be considered a priority for Federal coordination and investment." Building on release of that report, the Office of Science and Technology Policy in the Executive Office of the President, with assistance from the QIS Working Group of the NSTC, hosted a Forum on QIS at the White House complex in October 2016.

The NSTC Interagency Working Group on QIS continues to meet to exchange information, monitor developments, coordinate agency activities, and plan next steps. In addition, individual agencies—including DOE—have hosted or supported a large number of QIS workshops or symposia and issued other studies in recent years (see References for a partial listing). Other agencies have also taken further action, such as the creation of a multi-directorate QIS "metaprogram" by NSF in 2016 and inclusion of "The Quantum Leap" that includes this topical area among NSF's 10 "Big Ideas" driving the long-term research agenda for the agency.

Efforts in QIS also relate to, and are referenced in, other major Federal initiatives. Qubit development and quantum computing are viewed as one path for post-Moore's-Law computing in the National Strategic Computing Initiative. Other connections include overlaps or synergies with the National Nanotechnology Initiative, the Materials Genome Initiative, and coordinated Federal efforts in optics and photonics.

DOE Role in the Federal Interagency Context

The DOE National Laboratory system is unique in the Nation with a history and proven track record of creating multidisciplinary scientific capabilities that are beyond the scope of academic and industrial institutions and to which the government requires assured access. Several of DOE's National Laboratories have been fostering research in various areas of QIS as well as related topics in computer science and applied mathematics. HEP groups at several laboratories, including Fermi National Accelerator Laboratory, SLAC National Accelerator Laboratory, Lawrence Berkeley National Laboratory (LBNL), and Argonne National Laboratory (ANL) are engaged in QIS technology research and development, quantum sensors, and in developing related techniques for data analysis. User and other facilities provide opportunities for possible interactions with other agencies and the researchers they support; for example, the BES-managed Nanoscale Science Research Center (NSRC) user facilities offer opportunities for synergies across the lab complex. NP groups at ANL, Brookhaven National Laboratory, Thomas Jefferson National Accelerator Facility, Los Alamos National Laboratory (LANL), LBNL and Oak Ridge National Laboratory (ORNL) are engaged in the development and implementation of sensors, research and development on superconducting radio frequency (SRF) devices, cryogenic polarized nuclear spin targets, polarimetry, and atom trapping techniques, which may be useful in advancing QIS technology. Sandia National Laboratory is regarded as a world leader in the fabrication and operation of ion traps for qubit experimentation, and has ongoing activities in other QIS areas including validation and verification of quantum devices. LANL hosts a D-Wave quantum annealer that is available as a resource across the lab complex. ORNL fosters collaborations with external partners via its Quantum Computing Institute, and is the location of enriched stable isotope production capabilities developed for the DOE Isotope Program.

DOE's National Laboratories thus have unique attributes that are complementary to those of other agencies and can address gaps identified in the national ecosystem for quantum information science and technology. The DOE labs are well-equipped to address challenging problems in fundamental research that require sustained focus or are too large in scope for a university research group. DOE's labs additionally stand out in their ability to fabricate and characterize novel materials and devices, their expertise in using high-performance computing resources, and their diverse range of high-caliber scientists and engineers that can form the basis of interdisciplinary teams.

As noted earlier, DOE has been an active participant in ongoing interagency coordination on QIS, including co-chairing the NSTC Interagency Working Group in this area. Program offices in SC have invited representatives of other agencies to participate in QIS-related workshops and roundtables, and vice versa. In addition, various opportunities exist for informal or formal collaborations going forward, in which DOE's National Laboratory or other programmatic assets can accelerate progress in areas where other agencies have related mission-driven interests. For example, ASCR's interests overlap with several other agencies. ASCR shares with the Department of Defense (DoD) and the Intelligence Advanced Research Projects Activity an interest in advancing quantum computing technology, but with an application focus on science. In contrast with—but complementary to—NSF's blue-sky research approach, ASCR focuses on DOE-specific computing applications, research, and development to make the best use of DOE's high performance computing (HPC) resources. HEP has noted synergistic intellectual and technological interests and expertise with NIST and DoD in the areas of foundational quantum information, entanglement, and quantum sensors, and is exploring potential collaborations or other coordination in these areas.

International Landscape

Worldwide interest in quantum information science and technology has increased substantially in the past five years. While the U.S. remains a leader in the field, other nations have made new investments and developed long-term strategies that have already shifted the geographic distribution of top-tier research groups. Both academic researchers and industry have noted the U.S. Government's comparative silence relative to foreign governments' strong statements of support for quantum information science and technology. Academic researchers in the U.S. have expressed concern that their foreign counterparts have better access to supporting technologies such as novel materials and custom optics. A summary of foreign QIS activity to date 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), 10-year Flagship initiative that is still in the planning stage. 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 investments in a broad range of efforts that are smaller than those in the EU and China but large relative to each nation's overall science and technology effort. The U.K.'s program centers around four hubs, each of which is a partnership between universities and industry focused on a specific set of technologies (sensors, imaging, networking, and computing). The U.K. has also invested heavily (more than £200 million/$255 million USD) in student and postdoctoral training. Canada's program, in contrast to all the others, was spearheaded by private investment aiming to make Waterloo the quantum analogue to Silicon Valley. This has established the Perimeter Institute and University of Waterloo as leaders in QIS ranging from blue-sky theory to practical devices and algorithms, and led to a large award ($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' 2015 investment of €135 million ($144 million) in a center focused on superconducting and silicon-based computing technologies in Delft has attracted additional investment from U.S. industry, including $50 million from Intel. 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. These include Germany, Austria, Switzerland, Japan, and Singapore. Other countries that have not traditionally been leaders in QIS, such as Russia and Brazil, appear to be building national research communities.

Summary of Scientific Challenges and Office of Science-Specific Efforts

Quantum Science—Coherence and Entanglement of Quantum States

Materials and Synthesis

Real quantum materials require synthesis. There remains a fundamental science gap that is an obstacle to the long-term goal of "synthesis by design." This goal requires establishing generalized rules of assembly for complex materials in a variety of platforms, in order to determine, understand, and control reaction/synthesis/deposition/assembly pathways for metastable, kinetically stabilized, and thermodynamic phases of quantum materials. Resulting 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. Research on materials synthesis and processing falls largely within the purview of BES. In addition, the DOE Isotope Program, managed by NP, is developing the capability to produce kilogram quantities of enriched stable isotopes in a cost-effective manner. This may be useful in the synthesis of new materials for research and development studies of solid-state qubit systems.

Instrumentation for Quantum Control: Sensing and Metrology
Existing capabilities and instrumentation development for measurement and control of quantum phenomena are widespread across SC program offices. In BER, there is particular interest in development of sensors that combine quantum metrology and quantum imaging for more accurate measurements using optical sensor systems, such as Lidar (Light Detection and Ranging) instruments at the Atmospheric Radiation Measurement facility. Another BER focus is development of highly precise sensors to allow single molecule nuclear magnetic resonance of biomolecules. For HEP, the possibility exists of development of specialized cavity sensors for detecting new particles and quanta in previously inaccessible frequencies and with greater sensitivity than currently available. Some of the technologies being developed for quantum computing are also candidates for sophisticated sensors for particle physics experiments. HEP also has a strong interest in the use of atomic interferometry and entanglement for discoveries of the unknown and Beyond Standard Model physics. Similarly, NP anticipates that development of detectors and SRF technology for nuclear physics experiments may be relevant to instrumentation for quantum control. Examples include use of highly efficient quantum dot sensors for light collection in experiments to search for lepton number violation in nuclear decays, and exploitation of quantum effects for precision measurements of the electric dipole moment of nuclei to search for violations of fundamental symmetries of nature. BES efforts employ a variety of characterization techniques that have relevance for QIS. Scattering, spectroscopy, and imaging of quantum materials using neutrons, x-rays, and electrons as probes over a broad range of length and time scales can characterize their phenomenological behavior, lead to the discovery of new materials, and inform theories that predict and explain their properties. These tools can also contribute to development of quantum sensors and detectors.

Theory and Modeling of Quantum Entanglement
Research within the scope of HEP at the intersection of particle physics and QIS has formulated relationships between 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. New quantum algorithms and simulations that can incorporate scattering dynamics in hitherto static lattice quantum chromodynamics (QCD) analyses are planned. BES further notes that quantum computing could enable fast algorithms for computation of quantum entanglement. Theory efforts could analyze entanglement entropy in systems with known solutions. Decoherence in entangled systems could potentially be understood via molecular magnets, through their evolution into systems with

weakly interacting spins. ASCR plans to explore partnerships with other SC offices (BES, HEP, BER, and NP) 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

Many candidate systems have been explored or proposed for qubits, the basic building blocks for quantum computing that embody superposition of states. Implementing these systems involves a variety of issues, including not just the specific material properties but also manufacturability, scalability, stability, integration, and other concerns. Some potentially useful materials for qubit systems include Josephson junction arrays (high-temperature superconductors), trapped ions, quantum dots, nitrogen-vacancy complexes (NV centers) in diamond or other localized defect structures, topological insulators and two-dimensional electron gas (2DEG) systems that support the fractional quantum Hall effect, fractionally charged particles or Majorana fermions that lead to non-Abelian statistics, skyrmions miniaturized to the atomic level, and nano-magnets with non-Abelian anyons as excitations. DOE BES research and facilities already encompass investigations in many of these areas, and in particular the NSRC user facilities are well-suited to advance the fabrication and testing of these materials. In addition, the DOE Isotope Program, managed by NP, produces highly pure stable isotopes that could be used in the manufacture of solid-state qubits.

Quantum Sensors and Detectors

Almost any device developed as a qubit system for quantum computing can also be regarded as a quantum sensor, with potential applications to precision measurements and detection of particles across the entire range of topics of interest to SC. As such systems are explored, opportunities arise to exploit the extreme sensitivity of quantum materials for sensing and detection by understanding their electronic phase transitions. 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 under BES are capable of fabrication over the necessary spatial and temporal scales, and extensive characterization capabilities are available through other SC user facilities and National Laboratory capabilities. Development of detectors and superconducting radio-frequency technology for nuclear physics experiments may be relevant to instrumentation for quantum control. Note also that HEP has specifically identified development and use of quantum sensor technology across the HEP science drivers as a key part of the HEP plan for increased activity in QIS.

Fabrication and Testbeds

Testbeds provide the research community with access to early stage devices, accelerating through co-design 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 examining the preservation of coherence, extent of entanglement, and other key criteria. In addition to testing and benchmarking of individual devices, testbeds can facilitate intercomparison of different devices and are a helpful tool for developing production-quality software for novel computing architectures. For these reasons, ASCR issued a program announcement to DOE National Laboratories for research into development of quantum testbeds in May 2017. Multidisciplinary efforts to explore the suitability of various implementations of quantum devices for science applications will advance engineering of quantum information systems and help to define and perhaps overcome practical limitations. Furthermore, device fabrication and testbeds will greatly benefit from strong collaboration between government agencies, academia, and industry. 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

Exploration of novel architectures ranging from the device level (qubit connectivity; hybrid systems of different types of qubits) through the system level (quantum/classical co-processors; quantum devices as HPC accelerators) 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

Solving the wide variety of computational problems addressed by DOE and SC will require quantum computing to support a robust and versatile set of algorithms. Research into quantum speedups for basic primitives of applied mathematics such as linear algebra, integration, optimization, and graph theory will lay the groundwork to develop and optimize quantum simulation and machine learning algorithms for 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

Practical realization of quantum computing's potential will depend not only on advances in hardware and algorithms but also on advances in optimizing languages and compilers to translate these abstract algorithms into concrete sequences of realizable quantum gates, and simulators to test and verify these 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 (Q-WANs) composed of many nodes, multi-hops, multi-users, and high-speed optical quantum channels. Fundamental to this endeavor is the development of high-performance quantum communication network components needed to secure distributed quantum systems processing and sharing data sets over continental distances. Among them are a number of critical components such as quantum communication network hardware, architectures, and protocols; quantum-enabled software defined networks (Q-SDN); and all-optical network (AON) extension for quantum key distribution (QKD) and understanding QKD security loopholes.

Applications of Quantum Computing and Quantum Information

Early Science Applications
Initial scientific impacts and approaches that can be pursued prior to, or on the path towards, longer-term developments have been identified by SC program offices within their respective portfolios, as follows:

Advanced Scientific Computing Research (ASCR)
In partnership with HEP, ASCR sponsored a pilot project that seeks to develop fast quantum and classical algorithms for simulating quantum field theories. Such pilot projects will provide valuable feedback in the planning of larger partnership programs that target multiple science application areas. In addition, quantum testbeds will assist with meaningful evaluation and comparison of different materials, devices, algorithms, and approaches.

High Energy Physics (HEP)
HEP quantum computing interests include use of quantum machine learning and quantum devices for data analysis. Some of these tasks may be amenable to quantum annealing approaches that are available now, rather than requiring a general-purpose quantum computer far beyond what is currently achievable. To that end, HEP has sponsored a pilot project on using a D-Wave system for Higgs event classifier tests. In addition, the lattice QCD algorithms mentioned above are expected to be designed for quantum computers or simulators. HEP also supports several other QIS pilot efforts, including one jointly with BES on dynamics of highly-entangled quantum states that has already yielded several publications. Small-scale experiments to test foundational entanglement and quantum gravity predictions are planned.

Basic Energy Sciences (BES)
Early activity includes exploration of quantum many-body problems in magnetism, molecular magnetism, superconductivity, quantum chemistry, and topological states of matter. Near-term efforts could also include investigation of fractional quantum Hall effect, Heisenberg and multi-orbital Hubbard models as testbeds. Overlapping/complementary efforts with lattice QCD are under consideration as well.

Biological and Environmental Research (BER)
Identified areas of early science include: (1) Creation of novel quantum sensors / use of nanostructured quantum materials to perform noninvasive sensing, monitoring, and imaging of subcellular biological processes in microbes, microbial communities, and plants. This would enable understanding of biomolecular structure-function relationships and provide insights into the spatio-temporal nature of metabolism within/among cells. (2) Creation of novel quantum devices for environmental sensing and observations, able to be deployed at field sites relevant to bioenergy crop production, sensitive earth system geographies (e.g., Arctic permafrost), or radioactive contamination. These quantum devices would be optimized so multimodal data sets with spatial and temporal dimensions can be combined.

Nuclear Physics (NP)
A research group has been formed at the Institute of Nuclear Theory at the University of Washington in Seattle that will investigate possible applications of quantum computing to important problems in nuclear physics. Initial NP applications will likely be analogous to the existing applications in quantum chemistry, which are concerned with many-body quantum mechanical systems. In nuclear physics, the systems of greatest interest in this category are nuclei and bulk nuclear matter, which can be treated as many-fermion (neutron and proton) quantum mechanical systems interacting through pairwise and three-body nuclear forces. The standard quantum mechanical problems for these systems are the determination of ground-state energies and their many-body wavefunctions, the corresponding excited-state energies and wavefunctions (nuclear structure); quantum scattering problems (nuclear reactions); and more complicated time-dependent phenomena such as collective excitations and nuclear fission. Presumably the ultimate goal of QC research in NP will be to simulate the equations of QCD, the fundamental quantum field theory of quarks and gluons that underlies nuclear physics. Possible approaches to simulating simpler versions of quantum field theories, such as scalar field theories in two dimensions, would be early applications of great interest; practical algorithms for this type of problem have not yet been developed.

DOE-SC Collaborations and Longer-Term Directions

The 2015 DOE ASCR Workshop on Quantum Computing for Science made a compelling case for the potential of quantum computing's impact for a number and variety of problems of strategic importance to DOE and SC that are presently limited by the capabilities of conventional high-performance computing. ASCR is leveraging its 15-year experience with the Scientific Discovery through Advanced Computing (SciDAC) program to form partnerships with the other SC program offices via a similar but not necessarily identical model. The general approach will be to tap into the appropriate range of expertise in DOE national laboratories, universities, and other research organizations including industry, but also to ensure that the resulting tools, methods, and resources will be available to the wider QIS community.

Recent DOE reports on quantum sensors (HEP and ASCR) and quantum materials (BES) set out research directions and needs in greater detail. The sensors roundtable report identifies challenges where the science drivers identified earlier by the High Energy Physics Advisory Panel (HEPAP) Particle Physics Project Prioritization Panel (P5) could be pursued via small experiments using quantum entangled sensors and precision measurements beyond our conventional frontiers of study, and also addresses improved performance of qubit ensembles, optimization of quantum networks, materials development, hybrid technologies for multimodal functionality, and new theoretical approaches. The quantum materials workshop report details priority research directions in control and exploitation of electronic interactions and quantum fluctuations, harnessing of topological states, control of coherence and entanglement in nanostructures, and revolutionary tools to accelerate discovery and deployment of quantum materials. It also summarizes status, challenges, and opportunities in superconductivity and charge order, magnetism, transport and dynamics, topological behavior, and heterogeneity and nanostructure in quantum materials. For NP, it is envisioned that SciDAC and exascale computing collaborations, especially those involved in lattice QCD and many-body NP problems, will closely monitor progress in quantum computing and may adjust their research programs to take advantage of any useful developments. BER expects to engage in development of quantum computing/storage/information processing testbeds for multi-scale earth system modeling, and of biology testbeds that combine simulation methods with experimental data collection facilities so that real time feedback can be provided from computation to help guide the experiment. This would require extensive improvements in the scale of codes on supercomputers, real time analysis, better uncertainty quantification, improved load balancing, and methods for analysis of very large eigenvalue problems. Additional areas of considerable scientific interest across one or more program offices include quantum chemistry and applications to machine learning.

Conclusion

In conclusion, quantum information science and technology is rapidly evolving, will continue to grow in the coming decade. QIS holds great potential for broad range of near-term and long-term applications from sensing and metrology, communications, simulation, and quantum computing and is rapidly gaining international and industry attention. The DOE has been integrally engaged in the interagency and community planning to advance QIS research in the U.S. and the DOE laboratories are well positioned to bring their unique attributes and capabilities to bear on many of the scientific challenges and knowledge gaps we face. Federal coordination and investment is critical to continued U.S. scientific leadership in this area, with implications for not only advancing scientific discovery in a number of fields, but continued U.S. economic competitiveness and national security.

Thank you for the opportunity to come before you today to discuss the Department of Energy's efforts in quantum information science. I look forward to discussion this topic with you and answering your questions.

References

Some selected documents from DOE SC, DOE National Laboratories, other Federal agencies, and major foreign entities are listed below. Many other workshops and symposia in QIS and related topics, organized by Federal agencies, professional societies, universities, and others, have been held in the past few years but are not included here.

- HEP-ASCR Study Group Report, Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing, 2015, https://science.energy.gov/~/media/hep/pdf/files/Banner%20PDFs/QIS_Study_Group_Report.pdf
- HEP-BES roundtable report, "Common Problems in Condensed Matter and High Energy Physics", 2015, https://science.energy.gov/~/media/hep/pdf/Reports/HEP-BES_Roundtable_Report.pdf
- LANL workshop report, "Materials Frontiers to Empower Quantum Computing", 2015, http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-15-24386
- ASCR Report on Quantum Computing for Science, 2015, https://science.energy.gov/~/media/ascr/pdf/programdocuments/docs/ASCRQuantumReport-final.pdf
- Quantum Manifesto: A New Era of Technology, 2016, http://qurope.eu/system/files/u7/93056_Quantum%20Manifesto_WEB.pdf
- European Commission webpage on Quantum Technologies, including the Future and Emerging Technologies Flagship initiative in this area: https://ec.europa.eu/digital-single-market/en/policies/quantum-technologies
- HEP-ASCR QIS roundtable report, "Quantum Sensors at the Intersections of Fundamental Science, QIS and Computing", 2016, http://science.energy.gov/~/media/hep/pdf/Reports/DOE_Quantum_Sensors_Report.pdf
- NTSC report, "Advancing Quantum Information Science: National Challenges and Opportunities", 2016, https://www.whitehouse.gov/sites/whitehouse.gov/files/images/Quantum_Info_Sci_Report_2016_07_22%20final.pdf
- National Strategic Computing Initiative Strategic Plan, 2016, https://www.whitehouse.gov/sites/whitehouse.gov/files/images/NSCI%20Strategic%20Plan.pdf
- National Nanotechnology Initiative white paper, "A Federal Vision for Future Computing: A Nanotechnology-Inspired Grand Challenge", 2016, https://www.nano.gov/sites/default/files/pub_resource/federal-vision-for-nanotech-inspired-future-computing-grand-challenge.pdf
- BES Basic Research Needs Workshop on Quantum Materials for Energy Relevant Technology, 2016, https://science.energy.gov/~/media/bes/pdf/reports/2016/BRNQM_rpt_Final_12-09-2016.pdf

- NSF Dear Colleague Letter: Funding Opportunity - A "Quantum Leap" Demonstration of Topological Quantum Computing, 2017, https://www.nsf.gov/pubs/2017/nsf17053/nsf17053.jsp
- ASCR Quantum Testbeds Stakeholder Workshop, 2017, https://www.orau.gov/qtsws/default.htm

Bio for J. Stephen Binkley

Acting Director, Office of Science
Deputy Director for Science Programs
Department of Energy

J. Stephen (Steve) Binkley is the Deputy Director for Science Programs in the Office of Science (SC) at the U.S. Department of Energy (DOE). In this capacity, Dr. Binkley is the senior career science official in the Office of Science, which is third largest Federal sponsor of basic research in the United States, the primary supporter of the physical sciences in the U.S., and one of the premier science organizations in the world.

As Deputy Director for Science Programs, Dr. Binkley provides scientific and management oversight for the six science programs of the Office of Science (basic energy sciences, biological and environmental research, fusion energy sciences, advanced scientific computing research, high energy physics, and nuclear physics), for workforce development for teachers and scientists, and for construction project assessment. The Office of Science supports research at 300 colleges and universities nationwide, at DOE laboratories, and at other private institutions.

Dr. Binkley has held senior positions at Sandia National Laboratories, the Department of Homeland Security (DHS), and the Department of Energy. He has conducted research in theoretical chemistry, materials science, computer science, applied mathematics, and microelectronics. At Sandia, Dr. Binkley managed computer science, fundamental chemistry, combustion science, and chemically reacting flow organizations. He also has served as the manager for the Office of Science's Combustion Research Facility, at Sandia's Livermore, California location. Dr. Binkley managed Sandia's Office of Science Program, comprising activities in materials science, chemistry, geoscience, magnetic fusion energy, atmospheric measurement technology, and scientific computing at Sandia's New Mexico and California locations. He also managed Sandia's program in distributed information systems technology.

At DOE, Dr. Binkley served as a technical advisor to the Assistant Secretary of Defense Programs (subsequently the Deputy Administrator for Defense Programs after the establishment of the National Nuclear Security Administration). At DHS, Dr. Binkley served as the deputy director for technology within the DHS Operations Directorate, where he led and managed the development of systems for monitoring and disseminating situational awareness to federal, state, and local law-enforcement organizations and for coordinating emergency response activities. Returning to DOE in 2006, Dr. Binkley served as a senior technical advisor to the Under Secretary for Science and the Director of the Office of Science.

As head of SC's Office of Advanced Scientific Computing Research, Dr. Binkley served as one of the Associate Directors for the Office of Science, and was responsible for the overall management of the ASCR program including: strategic planning; budget formulation and execution; project management; program integration with other Office of Science activities and with the DOE technology offices; and interagency integration.

Dr. Binkley's present research interests include high-accuracy determination of properties of atoms and molecules, high-fidelity simulation of complex systems such as combustion devices, and the underlying computer science of massively parallel computers and large-data systems.

Chairwoman COMSTOCK. Thank you, and I now recognize myself for five minutes of questions, and this is definitely an intimidating topic. Thank you for your testimony.

Now, Dr. Kurose, conversations around STEM education are often closely tied to demand for certain jobs, and without knowing the exact workforce needs surrounding quantum just yet, how do we prepare for such a workforce, and how can young people be directed? If they're interested in this, what should they be doing now?

Dr. KUROSE. Thank you very much for the question, and it's really great. And maybe let me highlight education and educational opportunities at different levels, and I'll start at the graduate level because I mentioned that in my testimony. Remember that the generation of researchers who are going to push us forward in QIS, they're in labs now and they're graduate students and they're postdocs working in those labs now. Those researchers will then be taking their education out and spreading it and using it in industry, for example. At the undergraduate level, we're seeing courses now in quantum. We're seeing seminar courses there. So I think at the undergraduate level, we're beginning to see the educational opportunities appear.

When we think about the workforce more broadly, I think we really need to think about the STEM pipeline and address issues in K–12. I would say there are focus areas in particular, the notion of computational thinking that the National Science Foundation and other agencies have led in terms of computer science for all and computer science principles. Access to a rigorous and engaging computer science education at the high school level will really help prepare the students in middle schools and in high schools for engaging in computer science and in STEM more broadly, I think, at the college level.

Maybe one other area that I might like to highlight is that when you look at the people that you've invited here to testify that you'll see you have engineers, you have computer scientists, you have physicists, and it's really going to take participation from across all of the STEM disciplines to make QIS really happen. And so it's important broadly across STEM that we train the next generation of researchers.

Yes, my area is computer science so I think it's incredibly important but this is an area that all of STEM—engineering, mathematics, physical sciences, chemistry, computer science—are going to have to be involved.

Chairwoman COMSTOCK. And then how would a national quantum initiative meet the challenge to attract and retain U.S. talent in this field given the significant challenges for all of you. Any of you who'd like to answer on that?

Dr. WILLIAMS. So should Congress and the Executive Branch decide to have a quantum initiative in this area, we'd be happy to work with you to help address some of the impediments that were listed in the 2016 document, and to foster that broader ecosystem that's going to be necessary to translate this from academia and the National Labs into our industrial base because it is that translation into the industrial base that is key.

Dr. KUROSE. I might add that I think our collective sense is that we're at an inflection point with QIS. For many years—and the investments by our agencies go back many, many years that everybody knew quantum was going to be something very, very important, and we were doing the foundational work. I think especially if you look at industry, you look at what's happening in the laboratories in academia across the United States, there's a sense that things have manifestly changed in the last couple of years and now we're seeing programmable computers. Chris Monroe from the University of Maryland will be one of the witnesses in the next panel. You have IBM. Both of them have made general purpose or programming capabilities available on real quantum hardware at this point. I think that was the dream five years ago. We're realizing that reality now. It's going to be a while until we get enough qubits and we can do meaningful computations at scale but we're seeing this now in the real world. We're seeing on hands-on abilities to actually experiment with these systems.

Chairwoman COMSTOCK. Thank you. I appreciated that.

And I will now yield to the Ranking Member, Mr. Lipinski, for his questions.

Mr. LIPINSKI. Thank you. I want to continue on a bit with the Chairwoman's questions but I'll just start out by talking about something that's already been brought up about China launching the quantum-enabled satellite transmittal to secure data, the 1,200-mile quantum communications link between Shanghai and Beijing. China has also recently announced a $10 billion quantum computing center. Europe is also heavily investing in quantum information science as are other nations.

So the question is, where do we go and what do we need to do from here? Unfortunately, the Trump Administration budget proposed an 11 percent cut to NIST, a 6.6 percent cut to quantum information science—actually an 11 percent cut to NSF, 6.6 percent cut to quantum information science at NIST, and 16 percent cut to DOE's Basic Energy Sciences program where Dr. Binkley just testified that much of quantum research is supported. So obviously these cuts would presumably be harmful. What do we need to do? What would you recommend that we do? Obviously the federal government is not going to, you know, spend—go to any length, spend any amount of money, but we certainly need to do something. The idea of having a quantum initiative I think is a great idea. I'm very hopeful that we'll be working on that. We have a National Nanotechnology Initiative. I think a quantum initiative would be great to have, as I think the Chairwoman was talking about, but what do you think that we need to do from the federal government level? Obviously it's not just the federal government involved. There's also the private sector. But what would you like to see happen? How much of an investment do we have to make so that the United States does not really fall behind and miss this? So let's start with Dr. Williams. Any ideas that you would have, what you would suggest?

Dr. WILLIAMS. So I think in winning this game that it is not just what the role of the U.S. government, it's also the commitments by American industry. We need to all work together, and moreover, we need to transition the knowledge base that is currently largely in academia and universities and a few small research environments in industry to where more industry is aware. Because, again, if you look at the broader making up of something like an iPhone or anything else so we can talk about the qPhone in the future, there are many manufacturers that have to come in, and so arranging for all those OEM companies to be engaged, make them aware, to bring them to the table, and so a lot of the impediments that are talked about in the 2016 documents, which is multidisciplinary in nature, must be addressed but we also must address pulling the technology out until there is a real pull from industry because at the moment it's a push because they don't see how to make a profit in this area.

Mr. LIPINSKI. Dr. Kurose?

Dr. KUROSE. Well, actually I'd like to second Dr. Williams' comments. If you look at industry and you see, you know, over the last year where Google and Microsoft and IBM and Intel have been doing, it's clear there's really—when we talked about an inflection point earlier, there's very much increased interest in academia. And you'd mentioned the word partnership so I think partnerships with industry are going to be very important. I mentioned the tire tracks diagram in the information technology area. We have a long history of establishing partnerships between academic institutions with industry and government in a triangle, if you will. At the National Science Foundation, for example, we've done partnerships with Intel, with Semiconductor Research Corporation, with VMware on joint solicitations. This is basic fundamental research, because that's still what's needed now, basic fundamental research, but industry can bring a lot to the table. Other aspects of partnership, again to echo what Dr. Williams was saying, is partnerships among disciplines, you know, bringing together the physicists, the engineers, the computer scientists, we would say up the technology stack, if you will, from the qubits all the way at the very bottom all the way up to the programming at the top. And then again, partnerships among agencies, which I believe all three of us have already talked about.

Mr. LIPINSKI. Dr. Binkley?

Dr. BINKLEY. Just very briefly, the one point that I would add to what my counterparts have suggested is if you look historically, one of the greatest strengths of U.S. science programs has been the emphasis on basic science, and by contrast, if one looks at the efforts that are being put forward both in the European Union and the United Kingdom, they have a very strong technology focus, and I think that we should not lose sight of the fact that much of the innovation that is necessary for making rapid progress in this area does actually come out of the basic science, and so continued investments in the basic science is, I think, at this point very important to sustain.

Mr. LIPINSKI. Thank you. I yield back.

Chairwoman COMSTOCK. I now recognize Mr. Weber for five minutes.

Mr. WEBER. Thank you, Madam Chair.

Doctor—well, first of all, let me do it this way. Dr. Williams, how long have you been involved in the quantum field?

Dr. WILLIAMS. So formally, NIST has had a program since the year 2000, and I've been engaged in there. I was at the first workshop that I think was solely focused on QIS back in 1994 that was held at NIST shortly after Peter Shore came up with his algorithm.

Mr. WEBER. Okay. Dr. Kurose?

Dr. KUROSE. Well, I have an undergraduate degree in physics and learned quantum mechanics as an undergraduate but my involvement with QIS research began when I came to the National Science Foundation three years ago.

Mr. WEBER. So that's 2014.

Dr. Binkley?

Dr. BINKLEY. I did my Ph.D. work in quantum chemistry and got my Ph.D. in 1976, and I've been involved in quantum theory and quantum-related work ever since.

Mr. WEBER. Good gracious. Okay. You should be a quantum leap ahead of everybody else.

Dr. BINKLEY. Sir, I'm afraid it's a terribly difficult subject.

Mr. WEBER. I understand.

Dr. Kurose, your written testimony touches on the differences between classical computing like the exascale computing systems we've heard so much about in this Committee, and quantum computing. Explain the difference for us as briefly as you can.

Dr. KUROSE. Okay. Well, in traditional supercomputers, for example, information is stored in bits, ones and zeros, and we operate on those bits, so we perform operations and all kinds of transformations. That's the way computing technology has been done since its invention 70 years ago. Cubits, as my colleagues with Ph.D.'s in physics can tell you better than I can, are a very different piece. They don't exist in the one-zero state; they exist in a superposition of states, and from a computing standpoint, that allows one to rather than compute deterministically over ones and zeros to deal with probability distributions of how the states of the qubits are in the entanglement, the interrelationship between these qubits. It's a fundamentally different way of thinking about computation and moving from ones and zeros to these qubits.

Mr. WEBER. Okay, to an identifiable state, either one or zero, and now to a single particle that has the ability to do both?

Dr. KUROSE. Right, and I would say in the end, you need an answer that has ones and zeros and so there is going to be a very important coupling between the digital systems that control and program these quantum computers and the quantum technology that's lying at the base underneath.

Mr. WEBER. So very quickly then, what you're saying then is that these two systems will interact. Because you just said in the end, you need the ones and the zeros, the binary code.

Dr. KUROSE. That's right. So traditional computing will play a very important role in terms of the programming and the control of the quantum computing. I'd mentioned earlier the fact that you can now program quantum computers using the digital programming to sort of wrap around the quantum.

Mr. WEBER. So we're going to hear about that in the next panel.

Dr. KUROSE. I think you'll hear about that in the next panel.

Mr. WEBER. Dr. Binkley, for you, we spent a lot of time on this Committee discussing high-performance computing, particularly

DOE's goal to create an exascale computing system by 2021. How does the push to study quantum information systems fit in with that goal?

Dr. BINKLEY. At the Department of Energy, we see quantum computing as something that follows the efforts that we're doing in exascale computing. There are classes of physical problems that are characterized by the Schrodinger equation, which is the basis of all quantum mechanics. For example, most of the materials in chemical sciences fall into that category. Today we do calculations of an approximate nature on digital computers for the purpose of furthering our knowledge in those areas. Quantum computers will enable us to do much, much better calculations, exact calculations, as it were, when they finally become available. However, there will still remain applications in high-performance computing that are not quantum in nature.

Mr. WEBER. Back to the ones and zeros you talked about.

Dr. BINKLEY. Exactly, the ones and zeros, and those calculations, for example, structural calculations of materials looking at doing engineering types of calculations, looking at nuclear fission reactors, looking at heat flow and things like that, will still remain inherently digital. And so there will be a continuing need for simulations of that class.

Mr. WEBER. So you foresee a parallel path, quite frankly?

Dr. BINKLEY. Yes, sir. We see the two different technologies as being very complementary in the future.

Mr. WEBER. Madam Chair, can I indulge for about another two or three hours? This stuff is fascinating.

I yield back.

Chairwoman COMSTOCK. And I now recognize Mr. Veasey for five minutes.

Mr. VEASEY. Thank you, Madam Chair.

I wanted to just kind of piggyback a little bit on Mr. Lipinski's questions earlier revolving around international competition. We know that obviously whatever country is able to capitalize on this, the gains are going to be huge, and I wanted you to expand a little bit more about the cuts. As it was mentioned earlier I believe in my comments that the Trump Administration's budget proposal cuts include 11 percent to NSF, about a 6.6 percent cut to quantum information science at NIST, and a 16 percent cut at DOE, and I wanted to know if all of you could expand more on the impact of the cuts, because I think that that is important, particularly again as it relates to competition.

Dr. WILLIAMS. So at NIST, we always maximize resources that are provided to us by the Committee, and when we go in to optimize our portfolio, we always work to ensure that whatever decisions that are made by Congress and the Executive Branch that we implement them in a manner that provides the best return to the nation.

Dr. KUROSE. So I'd like to simply say that among the agencies that you see here, and other agencies that we have been investing in QIS. We've provided the scientific foundation that we see today. I think again, because we're seeing an inflection point, now is the time, a very opportune time, to accelerate those investments and to accelerate our progress forwards. And you know, I will mention that funding, academic funding in computer science and physics and engineering, is very competitive and we go through a merit review process. If you look at the outcomes of the merit review process we leave lots of good ideas, really great ideas, on the cutting-room floor because we have a budget, we work within those budget constraints, and we maximize the investments that we can make, but there are lots of good ideas that we're not able to fund and that go through the merit review process with very high scores.

And so again, I think especially in an area like QIS where we're at a change point that additional investments simply allow accelerating progress in a very important area.

Dr. BINKLEY. At the Department of Energy in our fiscal year 2018 budget, we obviously had some very difficult decisions to make, and even in light of the significant reductions that were, you know, put forward by the Administration, we did manage to increase funding for QIS. Our budget request contained essentially a $40 million increase in QIS-related funding, and that came about through a long process of planning and thoughtful attention looking at the opportunities in the area, and also what we perceive to be the strategic importance of the area.

Now, obviously, you know, that impacted other activities in the Office of Science portfolio but nevertheless, the judgment of our senior leadership team was that this is an area that, as Dr. Kurose has mentioned, has reached an inflection point and it's timely to really increase investments in this area.

Mr. VEASEY. Dr. Kurose, you talked a little bit about the importance of accelerating the funding. As it relates to competition with other countries, how important is accelerating the funds, accelerating the resources that we need in order to keep that competitive edge here in the United States?

Dr. KUROSE. Well, I think it's important to be accelerating both in the basic science, which I think Dr. Binkley mentioned, and also in the technology. Several members have mentioned China's advances in the quantum satellite communication. In a sense, that was something that folks foresaw as happening. Scott Aaronson, who's a physicist at the University of Texas in Austin, and worksin quantum said this was not unexpected but the real significance of this news, he says, is not that it was unexpected or that it overturns anything previously believed but that simply it's the satisfying culmination of years of hard work. So we need to push forward on the basic science frontiers but there's also now pushing forward on the technology and the implementation sides as well.

Mr. VEASEY. Thank you very much, Madam Chair. I yield back the balance of my time.

Chairwoman COMSTOCK. Thank you.

And I now recognize Mr. Webster for five minutes.

Mr. WEBSTER. Thank you, Madam Chair.

Dr. Williams, there's a lot of talk about how much money we're going to have and what we need it for and so forth. Would you say that even if we were able to maintain or even accelerate the funding, if there was something else that came in and siphoned away some of that money, would that be detrimental to the study of quantum and our success in that? Would you see that being detrimental, anything that would siphon away money?

Dr. WILLIAMS. I think as one moves—again, there's a lot of basic research but as one moves to transitioning this technology into our broader base, whether for national security or for economic security, that if we do not exploit the seed corn that we have created, that other nations will exploit it for us and they will end up reaping the economic benefit of it. So I think that the United States somehow has to figure out how we end up owning this technology the same way that we own the technology for the transistor and all the benefits that came from that.

I and Dr. Binkley were at the EU kickoff, and one of the small European companies basically pointed out the transitor was also found there in Europe and they thought it was a toy. We exploited it, and we reaped the benefits of that. So I think we're going to have to reap the benefits of the corn that we have sowed.

Mr. WEBSTER. And it would be more than economic. You mentioned economic benefits. I mean, there are more benefits than just that, isn't there?

Dr. WILLIAMS. Yes, absolutely. The national security implications because again, sensors are used in our military. They're not only used in the military but they're used for mining and other things. So I mean, there are broad economic and national security implications to QIS technology.

Mr. WEBSTER. Dr. Kurose, do you have anything to add to that?

Dr. KUROSE. Well, I was just standing—sitting here shaking my head yes, yes, yes. So I agree with what Dr. Williams said.

With respect to national security, Chairwoman Comstock mentioned in her opening remarks the importance of quantum—in terms of quantum encryption and postquantum encryption and the powerful nature of quantum computing. It's one area where quantum computing, is not a panacea for all kinds of computing but one area where it's going to be very, very important is in cryptography. It's one of the things that can be done really well there, and that has tremendous ramifications for national security and also for economic competitiveness.

Mr. WEBSTER. Dr. Binkley?

Dr. BINKLEY. Following up on the theme introduced by Dr. Williams, if you look around, digital electronics pervades everything that we do today, and the quantum technologies that are coming about through research in QIS are likely to have a similar effect as we move into the future, and you know, we are in fact at an inflection point and the time really to invest is now.

Mr. WEBSTER. Madam Chair, I would say that in this Committee we've had people come and testify about taking away some of the money and adding it in to another program, but I would say that the testimony here would be a direct assault on that in that having money diverted into some other program by us would be detrimental to our advancement. I mean, there is an imperative. We're not in sort of just a walk. We're in a run, a race. We're trying to be number one. And so I know a lot of people have bought into the fact that STEAM should replace STEM, and all I can tell you is that to me says some of the money gets diverted, and I think that would be a bad thing. There's nothing wrong with the arts and other things, I think those are great, but we're in a race, and if we're going to win this particular race, this race that we're in now, we're going to have to take all of our resources for that particular race and put them there. So long live STEAM, I'm glad for it, but on the other hand, if we want to win this race, we're going to have to focus on STEM. I yield back.

Chairwoman COMSTOCK. Thank you, and I now recognize Ms. Bonamici for five minutes.

Ms. BONAMICI. Thank you, Madam Chair.

Before I begin, I want to recognize a member of the audience, Physics Professor Michael Raymer, a University of Oregon professor, Dr. Raymer received tenure on the faculty at the Institute of Optics at the University of Rochester and he moved to the University of Oregon, my alma mater, in 1988 and served as the Founding Director of the Oregon Center for Optics, now the Center for Optical Molecular and Quantum Science. Dr. Raymer, thank you for joining us today.

I want to start by joining the comments that many have made about the concerns about budget cuts. I also wanted to thank Chair Comstock for mentioning the importance of leadership, and we're all talking about the 2016 report that was done of course with the leadership of Dr. Holdren and others in the White House Office of Science and Technology. OSTP has now been vacant at the top position for the longest time since it was established in 1976 with a fraction of its staff that was there at the time of the 2016 report. So I want to point that out, that that's critical to have that leadership and that position.

I also want to respond to my colleague's comments about STEAM. As the founder and co-chair of the bipartisan Congressional STEAM Caucus, I don't want to use too much of my time but just to emphasize that STEAM does not divert funding. It enhances STEM education by making sure that there's creativity and innovation in the educational process, and just as a point, the Nobel laureates in sciences are much more likely to be engaged in arts and crafts in their spare time. STEAM enhances STEM learning. It does not take away from the funding. What's taking away from the funding is the budget cuts that are proposed by the Administration.

I also wanted to follow up on the point that Chair Comstock made about education and workforce and the gaps in that, and I know the panel has addressed that, but it was an important topic in the 2016 report. One of the things that as a member of the Education Committee, I want to emphasize is the importance of college affordability and accessibility because a lot of the workforce that we could rely on to solve some of these problems and to be leaders in this area are finding challenges with not only college affordability but many of them may be DC. recipients, so immigration reform and college affordability are also important to solving these issues because we know that there are gaps.

So I'm going to ask all the panelists how should quantum computing change the way we think about and plan for cybersecurity? It's something that we talk about a lot here in this Committee and in Congress. Will we have—right now we have quantum encryption in place for existing communications and financial networks before quantum computers upend our current system of public key encryption? In other words, do you expect that quantum computers will create hack-proof replacements? Can you address that? And I'll ask each of the panelists, and then I do have another question as well.

Dr. WILLIAMS. So at NIST, we've already embarked on the path of trying to find algorithms that we can replace our current public key infrastructure with that will be quantum resistant. This is being taken seriously because we know that it is essential to have it, so we believe that it will happen.

With regard to the broader cyber theme, there are other ways that this technology helps. Again, very good clock and good timing can actually increase the robustness of our networks, like with almost all kind of technologies that are both quantum takes and it gives, and it's about learning to understand how we can use the technology to make our systems more robust as well as providing quantum-resistant algorithms to replace current public key infrastructure.

Ms. BONAMICI. Thank you.

Dr. Kurose or Dr. Binkley, do you want to add to that on the cybersecurity issue?

Dr. KUROSE. I would just say that the challenge of postquantum encryption is a very active research area now, and there are a lot of space methods that some of the community are coalescing around, but I think you ask, is there a guarantee right now that they're going to be resistant? I don't think the answer to that is actually known yet, and that's a very active research area.

Ms. BONAMICI. Dr. Binkley?

Dr. BINKLEY. At the Department of Energy, we're not involved in any cryptologic or cryptanalysis type of research so it's not really our lane. But we are very interested in what's going to happen with quantum networking. There are definite possibilities in the future where quantum networking will have impacts on science-type activities. We do operate the largest high-capacity network for science in the nation today, and we are very interested in how that will evolve in the future in light of quantum technologies.

Ms. BONAMICI. Thank you. And briefly, many of you mentioned the importance of the private investment in research, and Dr. Williams, you even said we're increasingly dependent on significant investments from U.S. technology giants and major defense companies, but do you all agree that robust federal investment in fundamental and basic research is critical to the development in the private sector as well??

Dr. WILLIAMS. Yes.

Ms. BONAMICI. Dr. Kurose?

Dr. KUROSE. I think yes, and I think also if you were to go to those technology giants and say is that important, they would also all say yes.

Ms. BONAMICI. Do you agree, Dr. Binkley?

Dr. BINKLEY. Yes, and I think also active partnerships between government research organizations like NSF, NIST and DOE with their counterpart—counterparts in the commercial sector are really important. That's actually proven very successful in the exascale program over the last seven years.

Ms. BONAMICI. Thank you, Madam Chair. I yield back.

Chairwoman COMSTOCK. Thank you, and I now recognize Mr. Hultgren for five minutes.

Mr. HULTGREN. Thank you, Chairwoman. Thank you all for being here. I appreciate your work, and appreciate you spending time with us today.

Dr. Binkley, I wonder if I could address my first question to you. I wonder if you could talk briefly about the work across the Department that's being done in quantum space, not just in ASCR. I know Fermilab, which is in my area, is involved in things like the Chicago Quantum Exchange as well as IMQ Net with AT&T, Cal Tech and the exchange to establish the first nodes of a quantum internet. Can you talk about the impact this work will have throughout our scientific ecosystem and how are the different programs like HEP and the Office of Science working to make sure that this happens?

Dr. BINKLEY. So we're viewing quantum in the broad sense within the Office of Science. We do think of it as quantum information science, which does contain some aspects—which does contain quantum computing. So I'm not going to spend a lot of time dwelling on the ACSR aspects of it, but we do see very, very strong programs already in existence and that need to evolve into stronger programs in the basic energy sciences area that are aimed at quantum materials that could be used in fabricating new types of qubits, for example. We also see the potential for quantum-based technologies for sensors and detectors that could be used in high-energy-physics experiments. It's possible to use concepts like quantum squeezing to improve the sensitivity of certain types of detectors. All of these are very active areas of research right now within the entire breadth of Office of Science programs.

Quantum networking, which I mentioned a moment ago, is something also that I think deserves attention. In summary, within the Office of Science we see opportunities across at least five of our six programs for quantum science and quantum technologies to make impacts on the physical sciences. Again, our emphasis is really on the physical sciences here.

Mr. HULTGREN. Thanks.

Dr. Kurose, I wonder if I could address to you, I understand that for QIS, the system of algorithms and standards would need to be rebuilt from scratch. I wonder if you could give us an idea of how large an undertaking this is. Is it fair to say this area of research cannot be helped along by classical computing methods or do investments in exascale computing support quantum computing in any way?

Dr. KUROSE. Well, first let me address the question specifically with respect to cybersecurity because there the real challenge is that quantum computers will be able to do the kind of factoring of large numbers into prime numbers which are sort of at the key of the RSA encryption algorithms that Member Lipinski was talking about in his remarks. So from a security standpoint, it's the capabilities of a quantum computer to do something that a digital computer cannot do in any reasonable amount of time, which is the real challenge there, and that's why new cryptographic algorithms, the postquantum algorithms that are resistant to having quantum computing, that's why there's so much focus on that right now.

With respect to exascale, one thing maybe I'd like to emphasize is that quantum again won't be a panacea, won't solve all problems in computation, and as Dr. Binkley has pointed out, there are problems that are not well suited to quantum solutions and there we're going to need supercomputers, we're going to need exascale for the kinds of national competitiveness and to push forward science and engineering research. So it's not an either/or, but an and; and both absolutely need to progress.

Mr. HULTGREN. Great. Thank you. I wonder in my last minute here, Dr. Binkley and Dr. Kurose, what will DOE and NSF need to do to prepare the next generation of researchers and programmers to be able to work with quantum machines? Our coding now, as I understand it, is still based on the original linear models from which we started out with punch cards. How long will it take to maximize the effectiveness of these machines and make sure that people are ready to maximize?

Dr. BINKLEY. So I think the way to start that process is to begin to develop and deploy testbed computers, which is one of the things that we and NSF have talked about doing. It's become clear in our advisory panels and other advice bodies that we use that getting to where researchers have hands-on access to actual workable systems, even if they're very small, is what's necessary to allow people to begin to formulate ideas that then can lead to algorithms and computational methods.

If you look back at the history of computing, when digital computers first came out in the late 1940s, early 1950s, they were very, very limited in capability, especially compared to today's computers, and yet having them in the hands of the research community is one of the key factors in accelerating the adaptation of that technology and the development of algorithms and methods.

Mr. HULTGREN. My time's expired. We may follow up, if that's all right, in writing, if that's okay? I yield back.

Chairwoman COMSTOCK. I now recognize Mr. McNerney for five minutes.

Mr. MCNERNEY. Well, I thank the Chair and I thank the witnesses this morning.

It sounds to me like QIS is a fairly broad subject, and quantum computing is one small part of that. Now, one of the things about some of these physics challenges is that there's areas that seem like they're going to be solved in 15 years and it's always going to be 15 years. Is quantum computing one of those areas that we're going to be struggling with 15 years from now with the same sort of vast misunderstanding or not understanding that we do today? Dr. Kurose?

Dr. KUROSE. Well, if you'd asked me that question five years or ago or maybe even three years ago, I might have said yeah, that could be the case, but I think now that you see smaller-scale quantum computing being available, In the next panel you'll have Chris Monroe. Who has a computer—a quantum computing device at the University of Maryland. You'll have IBM, who's put their quantum computing device online. It's becoming real. It's not becoming real yet at the scale of the number of qubits and the size of the computation that could pose a threat to cracking RSA, for example, but we've made a real quantum leap, if you will, from five years ago, to today, to actually having these devices and making these devices available to folks.

Mr. MCNERNEY. So we're going to be seeing application of QIS all over the place, it sounds like. What are some of the inherent scientific and technical challenges that we're going to be seeing or that we're going to have to overcome. Dr. Williams?

Dr. WILLIAMS. So I think there are a number of challenges. I mean, again, it's speaking back toward NIST mission. Small processors can allow us to build several kinds of devices that would—including extremely low-noise amplifiers and other things that could provide signal in places where you can get no signal because we know how we can play around in the amplification world in the quantum level to do things you cannot do classically. So I think this technology is going to really remake a lot of our modern electronics type thing so when you think about computers, I mean, computers are not just sitting on your laptop. They're in every game, in every toy and almost everything that's in your house. The technological challenges of isolating them are hard and yet we know with Nitrogen-vacancy centers in diamonds, for example, that we can maintain coherence in a quantum system at room temperature. We are learning tremendous amounts of new things about where this technology is going, and I think this is one of those areas where the future, probably the most important discoveries, the most important things that will come out of this QIS revolution are yet unknown.

Mr. MCNERNEY. Well, one of the things that we should be worried about is the implications on national security and national economy. So are we making the kind of investments that are necessary to keep control of those two issues as opposed to all of a sudden finding ourselves behind the eight ball?

Dr. WILLIAMS. I believe that we are at that inflection point where it is essential that we figure out how we convert this basic science into the technology because it's the technology that basically produces the broad economy that we tax and pays for science. So we need to ensure that we own the space, and in a "flat world," this is a far more difficult game than it was at the end of World War II where we won the advantages of the transistor and so now we must compete globally with other nations to exploit the science and turn it into technology.

Mr. MCNERNEY. Is it going to be more of a cooperative international effort or a competitive international effort, Dr. Binkley?

Dr. BINKLEY. I think it's actually going to be a combination of both. I mean, there are certain areas where the relationship between our researchers and their counterparts in foreign countries is very collegial and very collaborative but there are also areas where it's very competitive, and in the areas related to quantum science and technology, I think we're going to see a more competitive nature when it comes to international dealings because of the economic forces that will come to bear through the technologies that are ultimately developed.

That said, I think there still be impacts in areas like high-energy physics and nuclear physics where quantum detector technologies will accelerate the pace of science and there it'll be more collegial and collaborative.

Mr. MCNERNEY. Thank you. I yield back.

Chairwoman COMSTOCK. I now recognize Mr. Rohrabacher for five minutes.

Mr. ROHRABACHER. Madam Chairman, thank you very much for your leadership in calling this hearing today and organizing it. We appreciate that.

Let me just note that when I got here years ago, 30 years ago now, there was a big debate as to whether or not we should put $600 million into the development of picture tubes, and we were falling behind. Come to find out, of course, of that $600 million, a significant portion of that would be used in developing analog picture tubes at a time when digital technology was sweeping into that industry. So not all the times when you spend money and you're saying it's for a specific end are you achieving the goal that you want to achieve. In fact, sometimes cuts force people to make priority decisions, for example, not putting money into analog old technology rather than into digital technology. And if you never terminate the least effective research that you're doing, you will drag down the most productive research that you're doing. So the fact that there have been responsible cuts to various programs is something that will actually, I think, make our scientific community more effective rather than less effective.

And when it comes down to this issue, let me just note this has been a terrific hearing. I want to thank the witnesses. I have a better understanding now of the challenge that we face. It sounds like to me, and let me get the pronunciation of Jim Kurose?

Dr. KUROSE. Kurose.

Mr. ROHRABACHER. Kurose. You noted that we were actually ahead in the basic science and we are ahead in that but what it sounds like to me, Madam Chairman, is that we are not really making the transition from the basic science into applied science in a way that America will remain a leader in this effort. Is there something that we can do? Now, applied science is just another word, I guess, for applied for defense, et cetera, but also commercialization is part of what we talk about in terms of applied science. When we didn't have the money for NASA to spend all the money we needed for various space transportation systems, we turned to the private sector and now we have—with the commercial legislation that we passed, we have a very vibrant and important investment in space transportation coming out of our private sector.

Now, is there something that we can do? I mean, okay, I'm the author of the Commercial Space Act so I'm bragging about that, but is there something we can do to make the applied go from the basic to the applied and incentivize the private sector to invest money in the applied scientific approach to this issue, Dr. Kurose?

Dr. KUROSE. Well, thank you for the question, and in my earlier remarks I actually talked about partnerships between industry and the National Science Foundation and the research community, and so really what you're talking about is use-inspired research, and I think one of the advantages of having that collaboration between industry, academia and the federal government is that we are able to bring in use-inspired research challenges into the research.

That's not a replacement for fundamental research but it is important.

Mr. ROHRABACHER. Well, it's utilizing fundamental research.

Dr. KUROSE. It's utilizing fundamental research. Actually, new research problems can be suggested by the use and by the development.

Mr. ROHRABACHER. Well, I would hope that we can come up with some specific ideas how to encourage these private sector companies, which will utilize the information to actually invest in that transition between basic and utilization.

Do any other witnesses have any thoughts on that?

Dr. WILLIAMS. So I agree with Dr. Kurose. Partnerships are important. Other things that can help are things like other transaction authority that would allow us to better interact between academia, industry and the private sector and the government because there are a lot of restrictions around the IP that creates problems, and OTA will give us some flexibility there.

Mr. ROHRABACHER. How about the DOE? Does it have some ideas on that?

Dr. BINKLEY. Well, I come back to the general concept that Dr. Kurose mentioned and also Dr. Williams in that effective partnerships between government research organizations and private companies are a very good way to go.

Mr. ROHRABACHER. Well, we've got to make it profitable for people to do that.

Dr. BINKLEY. Correct. But that has succeeded in several areas in Office of Science programs, and it serves to bring together researchers from essentially the commercial environment and the government-funded side, and often it's beneficial enough to the company that they put their own resources into that as well. So I think that's one of the most effective ways of accelerating the transition of basic science into commercial applications.

Mr. ROHRABACHER. Thank you very much, and thank you, Madam Chairman.

Chairwoman COMSTOCK. I now recognize Mr. Tonko for five minutes.

Mr. TONKO. Thank you, Madam Chair. Thank you to all our witnesses.

Quantum technology is an exciting frontier, and I'm proud of the advances happening in my home State of New York and at universities in my region throughout the capital district. I continue to hear from universities that want to partner with other universities and industry and federal endeavors in quantum technology. I hope that we continue to look toward the future and foster opportunities for universities and industry to grow this critical field. It obviously begins with basic research and so I am concerned that the 2018 budget proposed by President Trump includes an 11 percent cut, as we heard earlier, to NSF, a 6.6 percent cut to quantum information science at NIST, and a 16 percent cut to DOE's Basic Energy Sciences program where Dr. Binkley just testified much of their quantum research is supported. So it's got to set a tone. I believe government sets a tone and provides for basic research and then hopefully move forward, and in light of the international scale and what is happening, it's very problematic to see these proposals coming from our President.

The National Science and Technology Council Interagency Working Group on Quantum Information Science has done crucial initial work to scope and prioritize the research in various efforts. Can any of you provide an update on the Interagency Working Group?

Dr. WILLIAMS. The Interagency Working Group's charter has been extended and continues to meet. In fact, I believe we have a meeting on Thursday this week. That group is trying to come up with a playbook of possible paths forward given different scenarios. I think we see ourselves as very collaborative across the whole of government. We've been working close together for years. We all see that this is vital to our mission space. This includes not only the agencies sitting at the table but many of the agencies that are part of the DOD and the intelligence community as well.

Mr. TONKO. Thank you. All three of your agencies fund research into quantum materials as a fundamental underpinning for a quantum technology revolution. Can you describe in lay terms what quantum materials are and the different aspects of quantum materials research that each of your agencies is supporting? Dr. Williams?

Dr. WILLIAMS. So quantum materials are materials that have specific properties. In some cases, because they are 1 or 2D materials and the various special kinds of films, and in some cases it's because they have specific properties. So some of these are superconducting materials. Some of them are ultrapure silicon so that we can get rid of the nuclear spins that come, isotopically pure silicon so silicon has three isotopes, and those nuclear spins cause problems in quantum computing. So we basically invest in a broad range of different materials that are necessary to support this technology, to create sensors and single proton detectors that have both the properties that they can sense a single photon, reset themselves, and have very high quantum efficiency, which means again putting different types of materials stacked on top of them. So there's a lot of different types of processing going on to do these things so it's a very broad field.

Mr. TONKO. Thank you.

Dr. Kurose?

Dr. KUROSE. I would just add that at the National Science Foundation, we don't fund any intramural research; we fund academic research across the United States in many different areas, so 94 percent of the funding that comes to the National Science Foundation goes out to researchers in academia. How funding is allocated to make the hard decisions that Member Rohrabacher mentioned, that's done through merit review, so the scientists come in and provide advice to the National Science Foundation about what the most promising research activities are among the——

Mr. TONKO. So it seems like a very critical area of federal investment.

And Dr. Binkley, please?

Dr. BINKLEY. So following Dr. Kurose's remarks, the Department of Energy research activities are funded in both universities and in DOE National Laboratories and again through a very rigorous peer review process. In our materials area, we're really focused on what we call functional materials, materials that are essentially designed to achieve certain functions using quantum mechanical principles to begin with. We also focus our research heavily in the characterization of materials. We have tools and diagnostic methods for accurately characterizing materials. Dr. Williams mentioned pure isotopes of certain materials. The DOE research is also focused on methods for production of certain isotopes. In all cases, we coordinate our research activities in quantum materials across our respective organizations to avoid any duplication of effort.

Mr. TONKO. Thank you. I thank all three of our witnesses, and with that, Madam Chair, I yield back.

Chairwoman COMSTOCK. Okay. I now recognize Mr. Foster for five minutes.

Mr. FOSTER. Thank you, Madam Chair, and thank you to our witnesses.

You know, I have to say I'm not surprised at the incredible computing power that's available in the physical universe. I remember, you know, back learning quantum field theory at Harvard more than 30 years old. They told us well, at every point in space time there was infinite—an operator, an infinite dimension matrix, and these were propagated through time with a set of equations that are called the standard model. And just when you think about the incredible computing power that happens in the universe, you know, it's not surprising that there's power out there.

What I am blown away with is the fact that over the last 30 years, we have found ways to tap into that computing power, and that these—you know, it's just really impressive.

I was also very interested in the claim that you can actually preserve quantum coherence at room temperature, which is something I want to follow up with because that means that there may be a possibility of actually having quantum computers in your cell phone whereas previously, you know, the scenario that people were looking at were giant supercomputer front ends to small boxes with cryogenics in it to provide cloud-based access so we may actually—if that is actually true, that could change, you know, the way we actually deploy this.

Now, one of the bright spots of bipartisan agreement in this—on this Committee and in Congress is about robust funding for exascale computing, and so Dr. Binkley, could you discuss how the next generation of exascale computing systems such as the one at Argonne National Laboratory is working to bring online in 2021 could synergize and elevate a robust quantum computing technology ecosystem?

Dr. BINKLEY. Yeah, I can cite a couple of examples of where that occurs. One is that obviously there's a tremendous search on for quantum materials that can be used in cubit technologies and so a lot of the simulation capabilities that exist in our material science and chemical sciences communities can be brought to bear on that problem.

Another area that is under active exploration is that you can simulate quantum computers on classical computers, and in fact, with the largest computers we have today, we can simulate quantum computers that contain up to about 40 or so aubits, and that actually gives us a way to begin to simulate algorithms and do algorithm development, and that will be accelerated when we go to the exascale-class computing.

Also, the exascale computing is giving us the ability to look deeper into particle physics and nuclear physics phenomena, and that'll give us insights on quantum algorithms that can be developed in those areas as well.

Mr. FOSTER. Thank you. And I guess on the next panel of witnesses we're going to see some discussion of what the key skills that you need to get the workforce that can actually do this, and I guess the list that appeared in the written testimony were cryogenics, FPGA programming, superconducting materials development, and microwave engineering. You know, that sounds pretty much like a description of what I did during my 25 years at Fermi National Accelerator Lab. I think somewhere on my laptop back home are hundreds of pages of FPGA code, cryogenic systems calculations, you know, designs of high-power phase shifters for microwave applications and so on.

And so it strikes me that the national labs are really well positioned to play a key role here, and so I guess the question for Dr. Binkley, how exactly is the Department of Energy using the capabilities of Argonne Lab and Fermilab to advance quantum science to hopefully stay ahead of the competition here?

Dr. BINKLEY. So that's a very good question, and so presently, we're really at the very beginning of that process, and as I mentioned a little bit earlier, the first step is to develop and deploy a few testbed computer systems at various of our national laboratories so that researchers can begin to do systematic development of algorithms and computational approaches to problems. And then, you know, later on, depending on where the field of quantum computing goes, there may be opportunities where DOE technologies can be applied in that path as well. But right now our focus is really on the very, very early stage development of quantum computing algorithms using testbeds and also looking at quantum simulation as a technique for looking at molecular problems.

Mr. FOSTER. Thank you. And I guess my last question is for Dr. Kurose and Dr. Williams. There's been two big areas, it seems to me, one of which is the whole encryption, you know, and communication. The other one is just using this as a compute engine for things like, protean folding and all these really intractable problems that we're facing, so how do you see—-in one of these areas, it's probably okay to have open communications with the entire world. The other one just for national defense reasons has to be very closely held. And so how do you handle the communications between, you know, the dark side that has to remain dark and you know, the purely scientific side that maybe shouldn't?

Dr. KUROSE. It's a great question, and I'd say that the National Science Foundation funds open basic fundamental scientific research, and so, if you were to look at prequantum encryption algorithms, there's NSF funding involved in that. Other agencies are involved when you talk about the classified space and there are other opportunities there, but at the National Science Foundation, the work funded is open.

Mr. FOSTER. Do you feel there's adequate communication or is that just a problem you run into all the time?

Dr. KUROSE. Communication among——

Mr. FOSTER. Between, you know, for example, your scientists that work, you know, in the unclassified scientific area and have good visibility into the technologies that are being developed with the nontrivial amounts of money we're putting into the classified sector, or is that a problem where you end up inventing, you know, the same device in two different spaces with a lot of inefficiency there.

Dr. KUROSE. Golly. Given I don't have a clearance, it's a little bit hard for me to comment on both sides at the same time. Maybe I could just—if I could take 20 seconds just to tell you a story that during World War II, some of the fundamentals being RSA encryption were done in the dark at the same time in England, and it was really shocking to imagine that 2,000 years of how we were doing encryption was turned on its head by RSA and the algorithms there, and yet unbeknownst to the team here in the United States, there was another team in England doing the same thing, and so sometimes there are ideas that are in the area, really, really smart people put together these ideas and can come up with not exactly the same but some really similar super, super creative ideas.

Mr. FOSTER. I guess I've exceeded my time.

Chairwoman COMSTOCK. Thank you, and I now recognize Mr. Beyer for five minutes.

Mr. BEYER. Thank you, Madam Chair, very much. Thank you all for being here today. It's not every day you get the opportunity to make a Schrodinger's cat joke, although it is at the same time, right?

Anyway, I want to begin by pushing back a little back on my good friend Mr. Rohrabacher about agreeing that yes, it does make sense to abandon unproductive research efforts but then I deeply believe the money should be redirected to other more productive research efforts. At the end of the day, less research is still less research, and that's not good for any of us.

Dr. Binkley, you're Department of Energy. I've been impressed today how in all the talk about QIS, there's been so little discussion about its impact on energy, and I bring that up because it seems to be half of what we talk about on Capitol Hill, you know, fossil fuels, climate change, a lot of nuclear physics here. You did mention photosynthesis and the impact there, and sort of a passing reference to being able to explore gas and oil better with quantum technology, but can you look at—can you talk a little bit about the larger energy picture and what quantum physics may bring us?

Dr. BINKLEY. Yes. Let's see. To begin with, there are many, many processes for producing energy from various types of fuels. A lot of those processes depend on chemical reactions, and in the case of chemical reactions, quantum computing will enable much speedier, much more accurate calculations and simulations to be done, which will have impacts on those systems. If you consider also the effective utilization of biofuels, a lot of the problems that we face in understanding biofuels and bioproducts or biomanufacturing, for that matter, ultimately become problems in chemical reactions trying to determine activation energies and things like that. Being able to do more accurate, more thorough calculations using quantum computing-based techniques will also accelerate those processes as well. Essentially, any problem that is either materials or chemical sciences is going to become much more tractable with quantum computing at it becomes available in whatever time frame. I would expect that to have direct impacts on the energy——

Mr. BEYER. It sounds like we need to take the all-of-the-above philosophy and add quantum physics to that.

Dr. Williams, you talked about quantum teleportation and entanglement, the whole idea of action at distance which you know Einstein hated, and you talked about the Chinese have now done it over 1,200 kilometers. We also—our Committee is Science, Space, and Technology. Do you see this —so we're now violating the sort of absolute speed of light is the limit with entanglement. Are there ways for us to explore deep space to break the barriers using quantum teleportation?

Dr. WILLIAMS. So break barriers in some ways but not in ones that violate any of the laws of physics. Again, on the quantum teleportation, in order to actually extract the information, you have to also have a classical channel so you are causally limited in order to exploit it. However, again in deep space exploration, the use of entanglement and everything else can give us a couple of things—super dense coding—that is ways of packing more information into a small number of bits. Again, these amplifiers I've talked about, they can come back in because again, that spacecraft is now so far away that its signal takes a long time but its signal also goes out in a very large area so only a small piece of the signal comes back to Earth. Can I build an amplifier that allows me to pick up that extraordinarily weak signal, and this technology allows that. So there's numerous reasons that to agencies like NASA and deep space exploration that this technology will be crucial to helping us further explore and understand the basic principles of the universe.

Mr. BEYER. Thank you very much.

Dr. Binkley, very quickly, can you tell us what quantum gravity is?

Dr. BINKLEY. Well, there's ultimately the question of merging quantum theory with the general theory of relativity, and it's thought that quantum gravity can be explained ultimately in those terms. How that'll affect—I mean, that's not really a quantum computing problem per se but it's a QIS, a quantum information science problem. It's a challenge in the area of quantum information science. It's an unsolved problem at this point.

Mr. BEYER. Okay. So it's—great. Thank you very much.

Mr. Chair—Madam Chair, I yield back.

Chairwoman COMSTOCK. I thank the witnesses for their testimony and the members for their questions. You obviously have a lot of interested Members here today. We will now invite our second panel up to the table, and once we get everyone there, we can welcome and introduce our second panel of witnesses.

Okay. Great. We'll move forward here on our second panel. Thank you for your patience. Now, our fourth witness today is Dr. Scott Crowder, Chief Technical Officer and Vice President, Quantum Computing, Technical Strategy and Transformation for IBM Systems. In this role, his responsibilities include leading the commercialization effort for quantum computers and driving the strategic direction across the hardware- and software-defined systems portfolio, among other things.

He holds both a Bachelor of Arts degree and a Bachelor of Ccience degree in international relations and electrical engineering from Brown University as well as a Master of Arts in economics from Stanford. He also holds a master of science and Ph.D. in electrical engineering from Stanford.

Our fifth witness today is Dr. Chris Monroe, Distinguished University Professor and Bice Zorn Professor in the Department of Physics at the University of Maryland. He's also founder and chief scientist at IonQ, Incorporated, and a Fellow of the Joint Quantum Institute between the University of Maryland, NIST, and the National Security Agency. Additionally, he's a Fellow of the Center for Quantum Information and Computer Science at the University of Maryland, NIST, and NSA.

He received his undergraduate degree from MIT and earned his Ph.D. in physics from the University of Colorado at Boulder, studying with Carl Wieman and Eric Cornell. His work paved the way toward the achievement of Bose-Einstein condensation in 1995 and the Nobel Prize in Physics for Wieman and Cornell in 2001.

He then was a staff physicist at NIST in the group of David Wineland, leading the team that demonstrated the first quantum logic gate in any physical system. Based on this work, Wineland was awarded the Nobel Prize in Physics in 2012. In 2000, Dr. Monroe became Professor of Physics and Electrical Engineering at the University of Michigan, where he pioneered the use of single photons as a quantum conduit between isolated atoms and demonstrated the first atom trip integrated on a semiconductor chip. From 2006 to 2007, he was the Director of the National Science Foundation's Ultrafast Optics Center at the University of Michigan.

And now I will recognize Mr. Lipinski to introduce our third witness.

Mr. LIPINSKI. Thank you. Our third witness is Dr. Supratik Guha who is the Director of the Nanosciences and Technology Division in Center for Nanoscale Materials at Argonne National Laboratory and a professor at the Institute for Molecular Engineering at the University of Chicago.

Dr. Guha came to Argonne in 2015 after spending 20 years at IBM Research where he served as the Director of Physical Sciences. At IBM, Dr. Guha pioneered the research that led to IBM's high dielectric constant metal gate transistor, one of the most significant developments in silicon microelectronics technology. He was also responsible for significantly expanding the size and strategic initiative of IBM's quantum computing group. Dr. Guha is a member of the National Academy of Engineering and a Fellow of the Materials Research Society in the American Physical Society. He's one of only a few scientists who has been a tenured professor, an executive at a major multi-national company, and the division at a major national laboratory. He received his Ph.D. in material science in 1991 from the University of Southern California and B. Tech in 1985 from the Indian Institute of Technology. So welcome, Dr. Guha.

Chairwoman COMSTOCK. Okay. And I now recognize Dr. Crowder for five minutes to present his testimony.

TESTIMONY OF DR. SCOTT CROWDER, VICE PRESIDENT AND CHIEF TECHNOLOGY OFFICER FOR QUANTUM COMPUTING, IBM SYSTEMS GROUP

Dr. CROWDER. Chairwoman Comstock, Chairman Weber, distinguished Members of the Subcommittees, thank you for this opportunity to testify before you today. I am here representing IBM where I lead the company's IBM Q program whose goal is to provide quantum computing access to industry and research institutions for business and science.

We tend to think classical computers can solve any problem if they are just big or fast enough, but that is not the case. There are a whole class of exponential problems that classical computers are not good at and never really will be. One example is simulating the behavior of atoms and molecules. Unfortunately, for anything beyond very small molecules, this task lies far beyond the capacity of conventional computers. Accurately simulating relatively simple molecule like caffeine would require a classical computer 1/10th the size of planet Earth. With better simulation, we could do amazing things. We could develop new life-saving drugs or manufacture incredibly light and durable new materials for airplanes.

When I talk to leading U.S. companies about their unsolved problems, the problems, that if solved, could bring them huge economic benefit and competitive advantage, these exponential problems turn up everywhere. They are problems such as developing new materials at a chemical company, understanding aging of batteries at an automotive company, optimizing the supply chain at a logistics company, and hedging risk and commodity prices at a consumer goods company. What they have in common is they are exponential problems that have real business value if solved.

Quantum computing holds the promise to solve these types of real problems and bring real commercial value to U.S. industry. It is a radically different computing paradigm that could launch a new age of human discovery. IBM has built and made available via cloud access real quantum computers of 5 and 16 qubits for education and exploration. These IBM Q experience systems were the only freely available quantum computing resource until this month when a Chinese institution made a smaller, 4 qubit system available.

IBM has also announced IBM Q, an initiative to build the first universal quantum computing systems commercially available to industry and research partners. Access to 17 qubit systems is planned for later this year with growth to 50 qubit systems in the not-too-distant future. These systems are located in New York and securely accessed by IBM Q partners via the cloud.

When one examines the depth of the commitment other countries are making in quantum computing, our belief is the U.S. Government investment in driving this critical technology is not sufficient to stay competitive.

The European Commission announced last year that it would create a 1 billion Euro research effort called the quantum technology flagship. According to estimates by McKenzie, the European Union has twice the number of quantum researchers as the United States and dedicates 1–1/2 times the funding. China has also increased the national prioritization of quantum technology. That same McKenzie study showed China has more quantum researchers than the U.S. In China, government and industry are working cooperatively. The Chinese Academy of Sciences and Alibaba jointly established the Alibaba Quantum Computing Lab with clearly defined goals to build 50-qubit and larger systems.

Given the growing competition, what can the U.S. do to maintain its quantum leadership? We believe success will require partnerships between industry, academia, and government to drive the basic research, create talent and skills required, and help U.S. industry explore how this new technology can be used for economic advantage. We support and commend the actions of the U.S. Department of Energy's Office of Science to create quantum computing test beds. These efforts should be significantly expanded to ensure we are putting the most advanced quantum computers in the hands of U.S. research scientists and early industry adopters. This should include early stage commercial quantum computers from not just IBM but from other industry participants to ensure exploration of multiple underlying quantum technologies.

In order to ensure continued American leadership in fundamental quantum technology, the U.S. Government should partner with academic institutions to increase funding for basic research in alternative quantum technologies and quantum algorithms.

Finally, we must do more together to drive talent development in quantum computing in this country. Students in the U.S. from over 500 academic institutions are using the IBM Q experience and the related quantum software development kit for education and skill development. But the efforts of industry are not enough to develop the necessary skills in quantum information science. Government at the federal and state levels must work with industry and academia to create both regional centers of excellence for quantum computing and topical centers of excellence for quantum-based solutions in areas such as computational chemistry and optimization.

You're right to focus on U.S. quantum leadership given its critical importance to our national competitiveness and security. Working together, we can ensure that the U.S. continues to lead the way in quantum computing.

Thank you for the opportunity to provide testimony on this very important topic.

[The prepared statement of Dr. Crowder follows:]

Testimony of Scott Crowder
Vice President and Chief Technology Officer for Quantum Computing, IBM
Before the House Committee on Science, Space, and Technology
Subcommittee on Research and Technology and Subcommittee on Energy
Rayburn House Office Building – Room 2318
Tuesday, October 24, 2017

Introduction

Chairwoman Comstock, Chairman Weber, members of the subcommittees. Thank you for inviting me here to testify this morning. My name is Scott Crowder and I am IBM's Vice President and Chief Technology Officer for Quantum Computing.

Quantum computing is not just another emerging technology. It is a radically different computing paradigm that could launch a new age of human discovery. The technology will one day help us to solve problems that are unsolvable today with classical computer systems. You are right to focus on U.S. quantum leadership given its critical importance to our national competitiveness and security.

For the purposes of this hearing, I will focus on the commercial significance of quantum computing. IBM's position is that the commercial world should begin to experience significant benefits from approximate forms of quantum computing within a few years. In contrast, the much larger, fully fault-tolerant universal quantum computers which will be required for practical decryption are several decades in the future.

In my testimony today, I will provide a brief overview of what differentiates quantum computers, the current state of the technology, our longer-term roadmap and how government can help advance quantum research. I'll also touch on the status of quantum research in other countries, and the critical need to develop human skills training in quantum computing here in the U.S.

Why quantum computing is different

Quantum theory changed the world in the early 20th century by explaining the bizarre behavior of subatomic particles. After decades of research, much of it led by IBM, we can now exploit the laws of quantum mechanics in a way that gives us a potential "quantum advantage" in conducting certain calculations that conventional computers cannot manage alone.

This development couldn't come at a more important time. For more than 50 years computing has been guided by Moore's Law: the observation that the number of transistors per square inch on integrated circuits will double every year. This fundamental insight made the technology revolution and everything that defined it possible, from home computers to supercomputers to smartphones. But as we approach the physical limits of silicon-based technology, we must look to new methods to expand computational power. Quantum computing is one of our best hopes.

Quantum computers follow a different set of rules from classical computers. Rather than bits, they use qubits, or quantum bits. These subatomic particles can exist in many different states at the same time. They enable probabilistic processing that exponentially exceeds the capabilities of a traditional computer. This opens the door to tackle problems that have long been considered out of bounds because of memory, processing, or time requirements.

Take the challenge of chemistry. If we could truly simulate the behavior of atoms and molecules, their energies and interactions, we could do amazing things, like develop new, life-saving drugs in a fraction of the time it takes today.

Unfortunately, this task lies far beyond the capacity of conventional computers. There's no realistic way we'll get there with a system based on current technology. In fact, simulating a relatively simple molecule like caffeine would require a classical computer roughly 1/10th the size of planet Earth.

Using quantum chemistry, we could model and research new chemical compounds that lead to stronger, lighter, more efficient materials. These materials could be less expensive to manufacture for use in everything from clothing to airplanes. Airplane manufacturers could use these breakthroughs to design more durable, lighter airplanes that are even safer, while reducing fuel use and the costs to passengers.

Another activity quantum computers will excel at is optimization: finding the best answer when there is a huge, exponential number of possibilities. For example, no classical computer today can optimize the routes, costs, and delivery schedules of 5,000 trucks while accounting for payload, gas mileage, time, weather, and traffic, all of which are changing in real time. With each new variable, the number of possible outcomes increases exponentially. However, quantum computers could potentially solve this problem in no time.

Quantum-enhanced weather simulations could help us better predict and plan for extreme weather events, saving lives and offering a roadmap to better protect vital infrastructure.

Food supply is another problem ripe for quantum solutions. Current synthetic fertilizers are less effective than natural fertilizers because we cannot yet model the complex combinations of their components. With enhanced fertilizers developed with quantum computing models, farmers could grow more food in less space to feed the world's growing population. In this way, we could better address food shortages and lower environmental impacts.

The state of quantum technology today

Quantum computers share another defining characteristic. They are extremely complex and challenging to build. Quantum mechanical states are exquisitely fragile and delicate. Anything can interfere with the successful functioning of the chip such as heat, noise or electromagnetic waves. For that reason, we keep our chips inside a refrigerator that is colder than outer space. It requires intricate engineering to maintain the quantum state of 'coherence' – the lifetime of quantum information – and perform calculations, while sending signals in and out of the system to know what the calculations are.

Existing quantum machines are still too small to fully solve problems more complex than supercomputers can handle. Nevertheless, we've made tremendous progress. The day when quantum computers exceed the capacity of classical machines is now in sight. Let me illustrate this with a few highlights of key developments at IBM.

We've developed algorithms that will run faster on a quantum machine. We now have techniques that prolong coherence in superconducting quantum bits by a factor of over 100 compared to 10 years ago.

We achieved breakthroughs in methods to detect and measure the two types of errors that will occur in any real quantum computer, known as bit-flip and phase-flip. This was a necessary step toward quantum error correction, a critical requirement for building a practical and reliable large-scale quantum computer.

IBM Research has already built and deployed functioning 5-qubit and 16-qubit universal quantum computers and made them available to the public over the cloud. This distinction of "universal" is important. It is the only class of quantum computer that has been proven theoretically to vastly accelerate the solution to certain problems. Thousands of academics and enthusiasts on all seven continents have used access to the IBM quantum cloud service more than a million and a half times to do research, publish papers, educate students, and perform new computations.

Earlier this year, IBM launched the industry's first commercial program to provide access to universal quantum computers, called IBM Q. As part of that program, we will enable IBM clients to use a more powerful 17-qubit processor through the cloud. They can take advantage of it to explore what they will eventually do with this technology. Within a few years, we expect to scale the system to 50 qubits. At that point, we believe quantum computers will begin to solve problems that no traditional computer could solve on its own.

It's important to note that quantum computers will augment, not replace, classical computers. They will be used chiefly to handle specific types of problems, while classical computers will continue to advance for the tasks that they are good for. The most powerful systems of the next decade will be hybrids of quantum computers using classical computers to control logic and operations with large amounts of data. For example, quantum computing will improve artificial intelligence and machine learning by finding the best answers within a huge, exponential number of possibilities.

I hope I've conveyed that quantum computing is real, and its impact on our world is imminent. We at IBM are building universal quantum computers today and people are using them. Now is the time for the federal government to help expedite advancements in the technology to maximize its benefits for the country. Similar efforts are taking place elsewhere and it is imperative for the U.S. to keep up.

The importance of skills development

Training a new generation of people skilled in quantum computing is critical. That's why we launched the IBM Q experience interactive website in May 2016.

To give you some idea of its impact, there are approximately 2,000 experts in quantum information science in the world. But more than 50,000 people have accessed the IBM Q experience, explored our tutorials, and run experiments on our real 5-qubit and 16-qubit processors. Students in the U.S. from more than 500 academic institutions are using the IBM Q experience and the quantum software-development kit for education and skill development. This is but one example of how we can begin to grow the quantum ecosystem and the number of those who are familiar with this technology.

As we have built our quantum computing effort, we have identified three areas where there are skill shortages that must be addressed. Those countries that create the most effective partnerships between industry, academia and government to develop these skills will have a significant competitive advantage.

The first area is the development of quantum system hardware. The most critical skill areas we see in hardware development are cryogenics, FPGA programming, supercomputing materials development and microwave engineering. There is some opportunity for mid-career re-training of engineers and research scientists to meet the skill demands. However, targeted research in these fields at graduate degree programs and curriculum within technical undergraduate programs will be required to satisfy future demand.

The second skill area is deep quantum information science expertise. This is necessary to drive both quantum computer and algorithm development. It requires a strong focus at the undergraduate and graduate levels as well as targeted post-doctoral research. Creation of quantum information science disciplines and funded research in that field is paramount to strengthening this critical skill.

The third skill area is quantum application and solution developers. The IBM Q experience and our open source QISKit software-development kit help by providing useful educational tools. They also reduce the barrier to entry for new programmers, but they are not sufficient. Those countries that undertake targeted research that benefits quantum computation in academic and government research institutions will enjoy a significant advantage. Furthermore, government and industry and must partner together to ensure that these institutions and early industry adopters have access to commercial quantum computers.

Global competition

The U.S. still leads the world in areas such as patents in quantum computing, but competition from other countries is rising sharply. Federal grant-making to universities and other partners for core quantum research and development remains significant, but is also rapidly being eclipsed by other governments. As a result, our belief is that the U.S. government's investment in quantum technology is not sufficient to stay competitive. The race is on, and the field is rapidly expanding. Countries large and small are using novel forms of public-private partnerships to promote quantum commercialization. Let me touch on a few.

Canada has launched a national initiative to grow that country's vibrant quantum ecosystem. Known as Quantum Canada, it seeks to preserve Canada's advantage in quantum technologies and expand them for long-term economic prosperity. In September of last year, Canada committed $76 million to the Transformative Quantum Technologies program at the University of Waterloo.[1] The goal is to tackle three challenges in quantum research: development of a universal quantum processor, quantum sensors and long-distance quantum communications

Australia also announced an AUD $25 million investment for a total of 5 years to help develop a silicon quantum integrated circuit, a critical step in building a functional quantum computer. The funding has been allotted to the University of Sydney and the University of New South Wales.[2]

The European Commission announced last year that it would create a €1-billion research effort called the Quantum Technology Flagship. The focus will be on four quantum technologies: communication, computing, sensing and simulation.[3] A McKinsey consulting report estimated that the European Union had more than twice the

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[1] Government of Canada. 2016. "Government of Canada invests $900 million to transform university research." Canada First Research Excellence Fund. September 6. http://www.cfref-apogee.gc.ca/news_room-salle_de_presse/press_releases-communiques/2016/University_of_Waterloo-eng.aspx

[2] Government of Australia. 2016. "Advancing quantum computing technology," Australian Government National Innovation and Science Agenda. http://www.innovation.gov.au/page/advancing-quantum-computing-technology

[3] Gibney, Elizabeth. 2016. "Europe plans giant billion-euro quantum technologies project." *Nature*, April 26. http://www.nature.com/news/europe-plans-giant-billion-euro-quantum-technologies-project-1.19796

number of quantum researchers and one-and-a-half times the funding for quantum compared to the United States.[4]

The government of China's deep and growing support for quantum research is well known. Quantum technologies are viewed as vital to national security and to strategic competition. Quantum computing holds a prominent place in China's Five-year National Science and Technology plans.[5] Construction is underway for a $10 billion research supercenter for quantum applications, called the National Laboratory for Quantum Information Science.[6] Chinese scientists estimate being able to create a 50 qubit quantum computer that could exceed the world's fastest supercomputer by 2020. The same McKinsey study estimates the country has more quantum researchers than the United States.

The Chinese government is working closely with industry partners to drive their national quantum agenda. Alibaba, along with the Chinese Academy of Sciences, has established the Alibaba Quantum Computing Lab with clearly defined, ambitious goals. These include launching a quantum cloud computing platform by 2017 and scaling up to 100 qubits by 2030.[7]

Recommendations for U.S. government

What can and must the U.S. do to keep pace with these efforts? Let me offer a few recommendations from an industry perspective.

Federal funding for basic quantum research enabled the U.S. to dominate the field of Quantum Information Science for decades. It made many subsequent breakthroughs in quantum computing possible. Now, in the face of intensive global competition, we believe the federal government must do more. It must play a key role in creating an environment within the United States that is better than any other country's at fostering the commercialization and growth of quantum computation.

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[4] Hofman, Sander. 2016. "Start your engines! The race to quantum computing is on." *Medium,* July. https://medium.com/@ASMLcompany/start-your-engines-the-race-to-quantum-computing-is-on-14c3076a5c47

[5] Costello, John. 2017. "Chinese Efforts in Quantum Information Science: Drivers, Milestones, and Strategic Implications." Testimony for the U.S.-China Economic and Security Review Commission. March 16. https://www.uscc.gov/sites/default/files/John%20Costello_Written%20Testimony_Final2.pdf

[6] Lin, Jeffery and P.W. Singer. 2017. "China is opening a new quantum research supercenter." Popular Science. October 10. https://www.popsci.com/chinas-launches-new-quantum-research-supercenter

[7] Costello. Chinese Efforts.

As one relevant example of this, in the mid-1990s, the federal government funded a competition for the development of the world's highest performing supercomputers, called the Advanced Simulation and Computing Program, or ASCI. The goal was to find a way to test and maintain the nation's critical nuclear stockpile. The U.S. Department of Energy (DOE) defined a series of challenge problems to help American industry design the world's leading supercomputers. These powerful machines were built by a consortium of vendors including IBM. Not only was it successful in meeting its objectives, ASCI also went on to define U.S. leadership in the field of supercomputing for years to come. The federal government should consider a similar program for quantum computing.

We support and commend the DOE's Office of Science program to create quantum computing testbeds. This effort should be significantly expanded to ensure that we're putting the most advanced quantum computers in the hands of U.S. research scientists and early industry adopters. This should include early stage commercial quantum computers from a variety of industry partners, not just IBM. In this way, we can ensure the exploration of various underlying quantum technologies.

We also need to do a lot more to build a generation of quantum information scientists to carry this technology forward. As one possibility, the federal government should look to fund the establishment of quantum centers at universities where students are introduced to quantum computing, see state-of-the-art technology, and work with industry. It could do the same within national laboratories to aid the commercialization of the technology. Government at the federal and state levels should work with industry and academia to create regional centers of excellence for quantum computing, along with topical centers of excellence for quantum-based solutions in areas such as computational chemistry and optimization.

Conclusion

We live in an age of astonishing progress in digital technologies. So it's surprising to many to hear that our intuition about what we can compute is often wrong. We tend to think classical computers can solve any problem if they are just big or fast enough. But that is not the case. There is a whole class of exponential problems that classical computers are not good at, and never will be. Quantum computing will enable us to overcome many of these intractable challenges and unleash untold economic benefits for society, if we seize this opportunity now.

I'm confident that we can and we will. America's track record in promoting historic scientific discovery is unmatched. It enabled us to establish the field of quantum information science and has led us to the doorstep of a new era of computing. With quantum technology about to assume a huge strategic importance, now is not the time to slow down. There is too much at stake to allow this country to fall behind. Our nation stands to benefit from quantum computers in ways we can't even imagine right now.

The federal government should do everything in its power to ensure that we continue to lead the way towards a quantum future.

Scott Crowder is currently Chief Technical Officer and Vice President, Quantum Computing, Technical Strategy and Transformation for IBM Systems. His responsibilities include leading the commercialization effort for quantum computers, driving the strategic direction across the hardware and software-defined systems portfolio, leading the agile and Design Thinking transformation, and accelerating innovation within development through special projects. Previously, Scott was Vice President, Technical Strategy within IBM Corporate Strategy. In this role, he helped define the cross-IBM technical strategy for cloud infrastructure, workload optimized systems, Big Data and Analytics, composable services, software-defined infrastructure and cognitive solutions. Scott joined IBM in 1995 and was the lead engineer on the industry's first logic-based embedded DRAM technology before serving in a variety of executive management roles within the semiconductor research and development organization. Scott received A.B./Sc.B. degrees in Electrical Engineering and International Relations from Brown University and a M.A. in Economics and M.Sc./Ph.D. in Electrical Engineering from Stanford University.

Chairwoman COMSTOCK. I now recognize Dr. Monroe for five minutes.

TESTIMONY OF DR. CHRISTOPHER MONROE, DISTINGUISHED UNIVERSITY PROFESSOR & BICE ZORN PROFESSOR, DEPARTMENT OF PHYSICS, UNIVERSITY OF MARYLAND; FOUNDER AND CHIEF SCIENTIST, IONQ, INC.

Dr. MONROE. Thank you, Madam Chairwoman, and the rest of the Committee for the opportunity to be here today to testify.

As a quantum physicist and professor at the University of Maryland and a co-founder and chief scientist at a small company, I have over two decades of experience in the field of quantum technology from both the academic and industrial viewpoints.

I'm testifying here today on behalf of the National Photonics Initiative which is a collaborative alliance among industry, academic, and government institutes established in 2013 to raise awareness of photonics, that is, the study and application of light at its quantum level, also to coordinate U.S. industry, government, and academia to advance photonics-driven fields critical to maintaining U.S. economic competitiveness and national security.

We have outlined a proposed National Quantum Initiative as part of the National Photonics Initiative which will provide infrastructure for the next generation sensors, networks, and quantum computers all based on this quantum technology we've heard about today.

From previous witnesses this morning, we learn that quantum devices follow radical rules. These are new rules with which to compute and process information. For instance, with merely 100 atoms, which is a very tiny amount of material, we can store more information than is on all of the memory in the world and in all the hard drives in all the computers. I bring this up because with these radical rules come radical types of hardware to do this, and the real trick in developing quantum hardware is to isolate it from the environment, and prevent it from being measured until we want to measure it at the end of the game. And photons, since I'm representing the National Photonics Initiative, are the medium that will be used for communication of quantum information because light can travel large distances without interacting with its environment. It's not hard to do that through fiber networks and so forth. A lot of the infrastructure, that exists now can be used for quantum communication.

But there's equally radical hardware for quantum memory; for instance individual atoms, not just atoms as part of a big system but individual atoms, one at a time, that are levitated in free space in a vacuum chamber. They may be cold. They may be at room temperature. There's all kinds of other hardware. I bring this up because with this exotic hardware, there's a particular problem in the field now both at academic institutes and in industry and that is at universities, we don't build things. We don't do engineering. You don't see an airline being built at a university. On the other hand, industry doesn't have the industrial engineering background.

They're vastly growing as we heard from my colleague, Dr. Crowder from IBM, and other industry players are making a big play in this field. But the big challenge is I can hark back to the days when classical computers in the '50s and '60s transitioned from vacuum tubes to silicon. The early silicon transistor was a big beast, and miniaturizing it took the task of a new generation of engineers. They weren't the vacuum tube engineers that did this. And so we're in a sense missing that critical link between research and development.

We propose the National Quantum Initiative to establish several innovation laboratories that will indeed build devices. These would be public-private institutes that take advantage of the best of both worlds, having embedded industrial researchers with young students, maybe in computer science, who don't know so much physics and they want to get in this game. The National Quantum Initiative will be essential for the U.S. to maintain leadership in this field, now and into the future. We've heard lots of testimony of our competition abroad. I sit on advisory boards in Europe, Canada, also in China, and indeed, their coordination is alarming. We've heard multi-billion dollar estimates in China, both at the conglomerate Alibaba and also the government to build quantum centers.

A National Quantum Initiative we feel is critical to move quantum technology from its current research status to real-world applications. Such investment would create the infrastructure, both physical and human capital needed to propel the U.S. into a leadership position in quantum technology. This would create vast opportunities for workforce creation in this field, economic growth in energy, medicine, and security.

I again thank the committee and its leadership for the opportunity to testify today. On behalf of myself and the National Photonics Initiative. I look forward to answering your questions and working with you and the committee to establish a National Quantum Initiative. Thank you.

[The prepared statement of Dr. Monroe follows:]

STATEMENT TO THE
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY
SUBCOMMITTEE ON ENERGY
COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY OF THE
UNITED STATES HOUSE OF REPRESENTATIVES
Hearing on
American Leadership in Quantum Technology
October 24, 2017
Christopher Monroe, PhD
on behalf of the National Photonics Initiative

Thank you for the opportunity to testify, Mr. Chairman. I am honored to be here before you and the Committee to offer testimony on *American Leadership in Quantum Technology.* For your background, I am a quantum physicist and Professor at the University of Maryland, a fellow of the Joint Quantum Institute between the University of Maryland and the National Institute of Standards and Technology (NIST), and the chief scientist and co-founder of IonQ, Inc., with over two decades specializing in the field of quantum information science.

I am testifying today on behalf of the National Photonics Initiative, a collaborative alliance among industry, academia and government formed in 2013, by top scientific societies including the Optical Society, SPIE – the international society for optics and photonics – the IEEE Photonics Society, the Laser Institute of America and the American Physical Society. The mission of the National Photonics Initiative is to raise awareness of photonics – the science and application of light – and the impact of photonics on our everyday lives; increase cooperation and coordination among US industry, government and academia to advance photonics-driven fields such as quantum computing; and, drive US investment in areas of photonics critical to maintaining US economic competitiveness and national security.

Photonic devices, involving light or microwave fields, play essential roles in nearly all aspects of quantum information science. It is within that context and a desire to drive US competitiveness and national security that I am offering testimony on quantum computing and the need for our nation to create and support a National Quantum Initiative (NQI).

About Quantum Information Science

Exponential growth in the power of information technology – Moore's Law – has catalyzed US productivity and economic growth over the last 50 years. But, like much of our nation's aging infrastructure, this growth is now ending as scientific breakthroughs from the 1950s and 1960s reach their technological limits. This jeopardizes the safety and security of the American people and threatens what has been the backbone of US economic growth over the past several decades.

The demise of Moore's Law has mobilized the science and industry communities to search for fundamentally new approaches to information processing. Quantum technologies, based on fundamental particles of nature such as individual atoms and photons, are natural targets for innovation, as they hold great promise to become the computers, networks and sensors of tomorrow. Quantum information science is based on exploiting subtle aspects of quantum physics, such as "quantum superposition" and "entanglement" for valuable, real-world technologies. These technologies can handle computationally complex problems, provide communication security and enhance navigation, imaging and other sensing technologies in ways that are impossible using conventional hardware.

Quantum information science leverages the radical ability of quantum systems to store and process multiple pieces of information simultaneously in individual computing elements. For example, in a quantum computer, merely 300 atoms under full quantum control could store in a state of "superposition" more numbers than there are atoms in the universe. Quantum teleportation allows quantum information to flow securely between distant parties without occupying the space in-between. New applications and algorithms that exploit quantum capabilities are continually emerging, from code breaking, quantum cryptography and database searches to machine-learning algorithms and quantum simulations of biochemical processes and material properties. As quantum information science is developed in the future, the list of applications will continue to grow.

Nearly all implementations of quantum computers will use photonics in a key role for their operations. A quantum Internet will communicate data between quantum computers using pulses of light traveling on optical fibers. Quantum photonics is already used to operate the most accurate clocks on

Earth and the most sensitive probes for biomedical use and geo-exploration.

Efforts to Advance Quantum Information Science Domestically and Globally

Because of the great promise quantum information science holds for next-generation computing and processing, there are several independent federal and industry efforts underway to advance the research and technology. For example, widespread national interest in quantum information science also coincides with a new perspective on quantum sensors and quantum computing from the Department of Energy (DOE) and recent initiatives launched by the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST).

At the same time, publicly funded efforts in quantum information science are now complemented by growing industrial interest in quantum information technology, including efforts at Google, Honeywell, Hughes Research, IBM, Intel, Microsoft and Northrop-Grumman. Several startup companies, funded by venture capital and other equity sources, have risen near universities and laboratories throughout the country.

Perhaps most importantly, the United States is not alone in pursuing quantum research and technology development. In contrast to the decentralized funding structure of quantum information science in the United States, European entities have recently established large, focused, academic/industrial thrusts including the UK Quantum Hub Network ($400 million/five years), the Netherlands QuTech Initiative ($150 million/10 years) and the European Union (EU) Flagship Quantum Program ($1.3 billion/10 years). Outside of Europe, China is aggressive in its commitment to quantum; the country recently launched a satellite devoted to quantum communication protocols, and there is report of a $10 billion investment into a quantum laboratory in Hefei, China. Major initiatives are also underway in Australia and Canada.

This explosion of activity worldwide should be a call for action in the United States. To ensure competitiveness and national security in the field of quantum information science, the United States should dedicate resources to coordinating existing federal and private programs, and filling in critical gaps. Especially important are those gaps that exist between academic and government laboratories that lack systems engineering and product development expertise, and within the private industry, which lacks a trained quantum engineering workforce.

A National Quantum Initiative

A National Quantum Initiative (NQI) will address one of the Grand Challenges of the 21st century – harnessing quantum as a fundamentally new technology to serve national needs in information infrastructure, chemical and biomedical research and development (R&D), cybersecurity and defense capabilities. As quantum information sciences have the potential to touch nearly all areas of science and technology, its development and implementation through the NQI will naturally engage all STEM fields.

Quantum research has conventionally been led by academic institutes and government laboratories. Examples of successful demonstrations of quantum hardware include sensors for gravity and for electromagnetic fields with quantum-limited sensitivity; small quantum networks for the point-to-point sharing of information with guaranteed security; and small quantum processors comprised of 10 to 20 quantum bits. However, the transition from quantum research to usable quantum technology in the marketplace is impeded by several challenges:

- The mismatch between the quantum research community, which does not engineer or manufacture products, and the industrial engineering community, which does not have a sizable workforce with training in the quantum sciences.

- The disparity between small-company innovators and their yet-to-be developed marketplaces.

- An ecosystem of conventional technologies to support quantum devices that has not been developed because quantum technologies are not yet used in high-volume applications.

- Conventional device manufacturers typically do not have the expertise to develop products targeted at quantum systems.

A catalyst is urgently needed to bootstrap the quantum economy, much like early investments by government sparked the development and growth of the Internet. The overarching goal of the NQI is to remedy these gaps in capabilities and marketplaces in order to hasten the development and deployment of quantum information technology, while propelling the United States into a continued leadership role in this vital field.

It is envisioned that the NQI will concentrate on three pillars of quantum technology:

1. *Quantum-enhanced sensors.* Advanced electronic and photonic sensors will be developed and deployed that reach fundamental quantum noise levels of sensitivity and, in some cases, use tailored quantum states of light and matter to reach below these noise floors or enable distributed sensors across space. Examples include the detection of gravitational forces for remote sensing and imaging of subsurface material composition (caves, minerals, underground infrastructure), the sensing of proximal magnetic fields in biomedical imaging, absolute navigation in GPS-deprived environments and networks of portable atomic clocks for navigation and communication.

2. *Optical photonic quantum communication networks.* Similar to its use in the fiber-optics-based Internet that spans the world, light is ideal for the communication of quantum information over distance. Photonic quantum channels between spatially separated systems can exploit the laws of quantum physics to ensure information security or distribute information in new ways for communication protocols that are impossible using non-quantum approaches. Examples include the establishment of a fiber-optic network of quantum entangled nodes for communication including remote, secure access to centralized quantum computers, remote imaging, and multiparty quantum communication to optimize decision-making protocols.

3. *Quantum computers.* In a quantum computer, information is stored as quantum bits, which can represent and process information in an exponentially large space of possible states. This ability holds great promise for solving problems intractable for conventional computers. Apart from widely known quantum algorithms such as factoring large numbers into primes for use in message decryption, quantum algorithms promise to speed the search of unstructured databases or optimize complex functions for applications from logistics to machine learning and pattern recognition for autonomous navigation. Quantum

computers can also be applied to simulate the complex functionality of novel materials, biomolecular processes or complex economic models. One example is minimizing economic cost functions that depend on a complex maze of interacting forces, such as a marketplace that may involve a nearly uncountable number of factors.

About Quantum Innovation Labs

Under the NQI, several Quantum Innovation Labs will need to be established, each created to address aspects of a particular technology and its potential applications. Quantum Innovation Labs will attack the hardest challenges in quantum technology, to help bring the new capabilities to the marketplace. Crucially, they will also train a new generation of quantum engineers armed with the foundation of quantum mechanics combined with computer science, while embedding industrial engineers in government and academic laboratory settings.

The physical basis of quantum information science assumes several forms involving fundamental entities such as photons, atoms, atomic-scale impurities in solids or superconducting circuits. Each of these platforms has certain advantages that are suitable for particular applications and, as a result, a successful national portfolio will involve several concurrent approaches. Each platform will require the advanced engineering of very specific fabrication and operation procedures, such as the fabrication of optical waveguide circuits on a chip, superconducting circuit integration, ultra-high vacuum environments and ultra-low temperature devices.

As envisioned, the Quantum Innovation Labs will serve as a collaborative space shared by academic, government and industrial researchers to create complete systems – quantum "testbeds" – consisting of hardware and software aimed at practical applications. The Labs will be encouraged to integrate sensor, communication and computing technologies, where appropriate. Each Quantum Innovation Lab will include an educational component, closely integrated with the development and innovation activities, to train the next generation of quantum engineers. This may include the establishment of Quantum Engineering degrees granted from partner universities.

For the NQI to succeed, Quantum Innovation Labs will need be located proximal to, but not necessarily embedded in, existing government laboratories, universities and other appropriate facilities. Labs will support efforts at specific sites or may be distributed across collaborating teams at different locations. The number of Quantum Innovation Labs should ideally be four, as deployable quantum technology is now sufficiently defined so that the Labs can specialize in certain physical platforms and goals. Distinct labs may specialize in superconducting circuit quantum computing; trapped-ion quantum computing; silicon-based quantum computing; and, integration between platforms using optical interfaces and interconnects, among other capabilities.

Government and Industry Collaboration

It is envisioned that the NQI will be administered by an inter-agency quantum working group, with funding directly flowing through the federal science agencies such as DOE and NSF, as well as NIST. The Labs should be semi-autonomous (within federal oversight constraints) to enable a flexible and innovative mode of operation. High interest in quantum technologies has also been shown by Department of Defense (DOD) agencies and laboratories including Defense Advanced Research Projects Agency (DARPA) and the US intelligence community, including the Intelligence Advanced Research Projects Activity (IARPA), National Security Agency (NSA) and the National Reconnaissance Office (NRO). These should also act as partners and advisors of the NQI.

Industrial participation in the Quantum Innovation Labs is a critical component of the NQI, and this requires special consideration in three key areas:

1. *Embedded industry engineers.* Industry engineers will be embedded in the Labs and funded by their home companies or through the NQI. This will provide industry players in quantum information technology the opportunity to work alongside experts in a variety of quantum platforms, while exposing the Labs to systems engineering approaches to product development. Additionally, industry participants will be exposed to a trained potential workforce of academic and government NQI researchers and students. It is expected that industry staff would rotate in the Labs for various terms and return to their industry settings armed with new expertise that can be transferred to others.

These scientists and engineers may also spend time at participating universities for studies toward new degrees in Quantum Engineering.

2. *Direct funding of industry quantum efforts.* Industry groups developing quantum hardware that relates to Quantum Innovation Lab efforts could be funded directly from agencies in close coordination with the Labs themselves, perhaps through targeted Small Business Innovation Research (SBIR) or Small Business Technology Transfer (STTR) grants. Such an arrangement may be preferable for certain technologies that require extensive existing infrastructure or involve proprietary processes. Such funding will also assist in bootstrapping companies as they develop marketplaces for new products. Labs will provide bridge funding for accelerated commercialization of the most mature quantum technologies as well as interface with conventional IT, biomedical, military markets and private equity communities.

3. *Intellectual property (IP).* The Quantum Innovation Labs are expected to be fruitful incubators of US intellectual property in quantum technology. IP-sharing and nondisclosure agreements will be negotiated so that industrial players need not expose existing internal IP portfolios. IP created at the Labs themselves will be shared between all entities (including multiple industrial players) while respecting the inventors. In cases where IP generated at the Quantum Innovation Labs involves fundamental quantum device characteristics or functionality, IP-sharing arrangements would be crafted to benefit all industrial players. For higher-level IP that deals with applications for particular markets or pertains directly to products, care will be taken to ensure that each industrial player is able to leverage its activity in the Labs in order to pursue its own IP outside the NQI.

Recommended Funding and Timeline

The proposed federal budget for the NQI over its first five-year period (Phase I) is $500 million, which will fund each of the four Quantum Innovation Labs at $25 to $35 million per year plus support for companies and academic institutions that will collaborate directly with Lab efforts. Proposals for developing a Quantum Innovation Lab will be evaluated by the interagency quantum working group, using an external review process organized jointly through the relevant federal science agencies. In the early stages, these funds will establish the Quantum Innovation Lab administrative structures, facilities infrastructure (e.g. advanced laboratories, materials fabrication facilities, low-noise controlled environments) and equipment (e.g. electronic instrumentation and high-performance computers). In the later stages, the NQI funds will be primarily devoted to Laboratory staff, embedded industry and other personnel, and possible private funding from outside groups collaborating on the use and testing of the developed technology.

After Phase I, the NQI will have shown significant progress in the performance of quantum sensors, quantum communication systems and quantum computers as described above, with clear demonstrations of deployable systems that can be used by others or, in some cases, evolve into commercial products. Embedded personnel at Quantum Innovation Labs are expected to return expertise to their academic, government or industrial homes, with long-standing ties between these entities.

In Phase II (years six and beyond), the NQI will be devoted to new scientific and technological applications of hardware and software developed in the Labs, while also pressing on new technological platforms that may arise. In these ways, the NQI will play a crucial role in the engineering and deployment of quantum devices, as well as the training of a new quantum STEM workforce that will propel quantum technology through the 21st century and assure that the US leads the world in the future of quantum information technology.

Conclusion

Now is a critical time for federal investment to initiate moving quantum technology from its current research status to real-world applications. Such investment will create the infrastructure – both physical and workforce – needed to move the United States into a leadership position in quantum information technology, a technology that will create vast opportunities for workforce creation, economic growth and betterment of society across areas as diverse as health outcomes and information security.

The National Photonics Initiative, and its consortium of leaders from industry and academia with knowledge in information technology and quantum science and technology, strongly recommends the United States establish a quantum information technology base that will lead to new opportunities in communication, sensing and computing; develop a marketplace for companies – small and large – to sell new products based on quantum information science; and, build the much-needed quantum workforce to grow this new industry.

I thank you, Mr. Chairman and members of the Committee, for the opportunity to speak on quantum computing and the need for a nationally focused effort to advance quantum information science in the United States. With extensive reach into the science R&D community, I and the National Photonics Initiative stand ready to work with the government as it considers the recommendations put forth in this testimony.

Summary of Testimony: *American Leadership in Quantum Technology*

U.S. House of Representatives Committee on Science, Space, and Tech., Subcommittee on Research and Tech. and Subcommittee on Energy

Christopher Monroe, PhD (Professor at the Univ. of Maryland, Fellow of the Joint Quantum Institute, Chief Scientist at IonQ, Inc.), on behalf of the National Photonics Initiative

The astounding progression of computing power over the last 50 years and its critical impact on the economy will not continue in its current mode. The exponential growth and power of information technology (commonly referred as "Moore's Law") will soon end as devices approach their technological limits. **Quantum computing** offers a promising new mode of computing that processes superpositions of inputs, effectively performing massively parallel computing for tasks that are impossible on any conventional computer. Quantum computers can break codes, teleport information between distant parties, search and optimize over large data sets for fast pattern-recognition and efficient logistics, and simulate bio-chemical and other substances for designing useful materials for drug delivery or energy conversion. As quantum computers are developed in the future, the list of applications will continue to grow, especially in the cybersecurity area, and quantum technology will have a significant impact on the US economy.

The radical principles of a quantum computer require equally radical technology that has been developed at US university and government laboratories over the last two decades. Good quantum memory is best stored in material systems that have quantum properties, such as individual atoms, simple superconducting circuit loops, or atomic-like defect sites in solid materials. Quantum memory must also be coupled in order to form more complex superpositions and be scaled to solve interesting problems. Such quantum communication between qubit memory will likely involve individual photons.

Many industry groups (including Google, IBM, Intel, and Microsoft) have begun investing in quantum teams and approaches to building quantum computers. However, there is a significant workforce gap between research and fabrication: university laboratories conduct much of the research in this area, but are not equipped to build usable devices, while industrial players do not typically have the expertise in quantum systems to apply engineering skills.

We propose a **National Quantum Initiative (NQI)** that will support four Quantum Innovation Laboratories to help translate university personnel and quantum device know-how to industrial settings where quantum computers will be tested and manufactured. The new Quantum Innovation Labs will embed industrial engineers with academic and government researchers in order to lower the barrier to the production of useful quantum technology. The NQI will train a new generation of scientific and technology leaders in this vital field, while educating the workforce in related STEM fields.

Other countries have begun aggressive programs to accelerate quantum technology development, particularly the European Union. China, for example, recently launched a satellite for secure quantum communication and invested $10 billion in a public-private quantum laboratory. The NQI is critical for the US to stay at the forefront of quantum technology, not only to lead the future of computing, but also to develop new security protocols and contribute to a growing economy.

Christopher Monroe: Biosketch

Christopher Monroe was born and raised outside of Detroit, MI, and graduated from MIT in 1987. He received his PhD in Physics at the University of Colorado, Boulder, studying with Carl Wieman and Eric Cornell. His work paved the way toward the achievement of Bose-Einstein condensation in 1995 and the Nobel Prize in Physics for Wieman and Cornell in 2001. From 1992-2000 he was a postdoc then staff physicist at the National Institute of Standards and Technology (NIST) in the group of David Wineland, leading the team that demonstrated the first quantum logic gate in any physical system. Based on this work, Wineland was awarded the Nobel Prize in Physics in 2012. In 2000, Monroe became Professor of Physics and Electrical Engineering at the University of Michigan, where he pioneered the use of single photons as a quantum conduit between isolated atoms and demonstrated the first atom trap integrated on a semiconductor chip. From 2006-2007 was the Director of the National Science Foundation Ultrafast Optics Center at the University of Michigan.

In 2007 he became the Bice Zorn Professor of Physics at the University of Maryland (UMD) and a Fellow of the Joint Quantum Institute between UMD, NIST, and NSA. He is also a Fellow of the Center for Quantum Information and Computer Science at UMD, NIST, and NSA. His Maryland team was the first to teleport quantum information between matter separated by a large distance; they pioneered the use of ultrafast optical techniques for controlling atomic qubits and for quantum simulations of magnetism; and most recently demonstrated the first programmable and reconfigurable quantum computer.

In 2015, Monroe and Jungsang Kim co-founded IonQ, Inc., a startup company that is fabricating atom-based quantum computer modules with a full software stack and user interface to be accessed via the internet cloud. The company is funded at a level of $22 million primarily through Venture Capital investor groups NEA and GV.

In the last 20 years, Monroe has given over 350 seminars or public lectures and has trained over 100 research scientists, postdoctoral researchers, graduate and undergraduates. He has 160 refereed papers to his name with over 30,000 citations, 5 patents, and his work has been covered repeatedly by media outlets from NPR to the Wall Street Journal. Since 1995, his research has been funded at a level of over $40 million from US Federal Agencies such as DoD, DARPA, IARPA, and NSF. He regularly consults for the US Government, foreign science agencies, and private industry on the topic of quantum science and technology. He sits on the advisory boards of the Institute for Quantum Computing (Canada), the Networked Quantum Information Technologies Hub (United Kingdom), and the Center for Quantum Information (Beijing, China).

Monroe received the Presidential Early Career Award for Scientists and Engineers (1997), the International Award for Quantum Communications (2000), the I.I. Rabi Prize (2001), and the Arthur Schawlow Prize (2015). In 2015, Monroe was named Distinguished Professor at the University of Maryland, and in 2016 he was elected to the National Academy of Sciences.

Chairwoman COMSTOCK. Thank you. I now recognize Dr. Guha.

TESTIMONY OF DR. SUPRATIK GUHA, DIRECTOR, NANOSCIENCE AND TECHNOLOGY DIVISION, ARGONNE NATIONAL LABORATORY; PROFESSOR, INSTITUTE FOR MOLECULAR ENGINEERING, UNIVERSITY OF CHICAGO

Dr. GUHA. Thank you. Chairman Weber, Chairwoman Comstock, Ranking Member Veasey and Ranking Member Lipinski, and Members of the Subcommittees, thank you for the opportunity to appear before you today to discuss the status and future of quantum technologies, as seen from the perspective of the U.S. Department of Energy National Laboratories. I am Supratik Guha, Director of the Center for Nanoscale Materials facility supported by Basic Energy Sciences at the Argonne National Laboratory.

The cost of computing has decreased by about ten orders of magnitude in the past 60 years, due to Moore's Law scaling. Yet, the basic architecture of the computer has remained essentially the same. Recent developments in quantum science promise a new computing architecture dramatically different from anything that we have used before. Quantum computing today is in its early stages. This technology will not replace conventional computing machines, but it will offer unprecedented speed and efficiency advantages over conventional computing in three very important areas. These are in cryptography, complex data analytics, and computational quantum chemistry. Advances in the latter would change the way we invent new materials. If the history of computers is any indication, there will likely be many more applications in future.

Subtle effects in quantum mechanics enable a quantum computer to probe information space simultaneously rather than sequentially, resulting in its vast superiority over classical computing. U.S. companies have recently built small quantum processors containing a few tenths of quantum bits, the unit devices within a quantum computer, but today's state of the art is a long way from where we wish to go. Quantum bits are prone to errors. At today's level of perfection, we need quantum processors containing tens of thousands to a million quantum bits. Advances are required in devices in architectures, and this will only be as good as the materials upon which these are based.

The history of electronics has shown us that there comes a time when massive scale fundamental materials research is needed to propel forward initial demonstrations. This was the case, for instance, with silicon microelectronics, which gave us computing and the Internet. The time for that materials ramp-up has arrived for quantum technology. There is not enough basic materials research going on today to support the growth that is required.

The needs are numerous. For instance, we need new materials for high-quality quantum bits that can operate at room temperature for quantum memory and for quantum channels that can connect quantum chips.

Think of a fully integrated quantum processor as a number of artificial atoms coupled together that compute and store information.

New materials hold the key to the ultimate development of these components.

With the increasingly complex nature of today's materials research, corporate entities are unable to carry out this basic science work like they used to. The task, however, plays into the strengths of the Office of Basic Energy Sciences within the U.S. Department of Energy and the Department of Energy National Laboratories. The Office of Basic Energy Sciences has prioritized investments in quantum materials. The National Laboratories offer unmatched capabilities, large-scale material synthesis, characterization, nanofabrication, and computational materials discovery all integrated under one roof. Their large user facilities, the Nanoscience Research Centers, light sources and the leadership computing facilities, tether university-based ecosystems around them. The National Labs and their user facilities are well-positioned to be major players in the future of quantum research.

We need to develop an educated workforce that is able to engage in quantum mechanics as engineers. Universities nationwide have begun responding to this. As an example, the University of Chicago has launched one of the first Ph.D. programs in quantum engineering. It has also created the Chicago Quantum Exchange, a research and educational collaboratory with Argonne and Fermi National Laboratories.

Quantum computing is a long game but one that we cannot afford to ignore. Thank you for your time and attention. I would be happy to respond to any questions that you might have.

[The prepared statement of Dr. Guha follows:]

Testimony of Dr. Supratik Guha
Director of the Nanoscience and Technology Division
and the Center for Nanoscale Materials, Argonne National Laboratory
before the
Subcommittee on Energy and the Subcommittee on Research and Technology
of the
U.S. House Committee on Science, Space, & Technology
October 24, 2017

Chairman Weber, Chairwoman Comstock, Ranking Member Veasey and Ranking Member Lipinski, and members of the subcommittees, thank you for the opportunity to appear before you today to discuss the status and future of quantum technologies, as seen from the perspective of the U.S. Department of Energy National Laboratories. I am Supratik Guha, Director of the Center for Nanoscale Materials facility supported by Basic Energy Sciences at the Argonne National Laboratory located in Lemont, Illinois. I am also a professor at the Institute for Molecular Engineering at the University of Chicago. Prior to joining Argonne and the University of Chicago in 2015, I spent twenty years at IBM: initially as a research staff member and then, between 2010 and 2015, as Director of Physical Sciences at IBM Research. During this time, IBM's quantum computing group reported to me and I played a key managerial and strategic role in its rapid growth. I am a materials scientist by training, and throughout my career I have specialized in taking demonstrations in exploratory science and converting them into technologies.

The cost of computing has decreased by about 10 orders of magnitude in the past 60 years, driven primarily by the Moore's Law scaling of microelectronics chips. Yet, the basic architecture of the computer—called the von Neumann architecture—has remained essentially the same. Recent developments in quantum information science raise the prospects of a new, rapidly emerging computing architecture. Quantum computing today is in its early stages. This technology will not replace conventional computing machines, but it offers unprecedented speed and efficiency advantages over conventional computing in three very important areas. The first of these is in cryptography—a quantum computer with its orders of magnitude advantage in speed would easily decrypt today's security codes. The second area is that of computational quantum chemistry and physics. For instance, a powerful quantum computer would be able to exactly solve the electronic structure of large molecules: this is unsolvable today using classical computers. We would be able to predict and invent new materials much quicker and cheaply instead of relying upon trial and error experimentation, as we do today. The consequences for basic science and industry in areas such as drug discovery, as just one example, are enormous. The third area is in complex data analytics, say, in large-scale traffic congestion routing problems. A quantum computer will possess a significant speed advantage in solving such challenges. These are three areas of application that we know of today; if the history of computers is any indication, then there will likely be many more in future.

Quantum computing is related to two other important and emerging fields—quantum communications, which enables secure information transfer over long distances; and quantum sensing, the ability to make physical measurements that are more accurate than those achievable by classical techniques. Quantum computing, quantum communications, and quantum sensing—referred together as "quantum information science" —depend upon "quantum entanglement", a subtle effect in quantum mechanics that can have profound end consequences. When two quantum devices are entangled, knowledge about the state of one increases our knowledge of the state of the other, no matter the physical distance between them. It is this property of entanglement that enables a quantum computer to probe information space rapidly, and simultaneously rather than sequentially, resulting in vast superiority over classical computing for some classes of problems. Quantum computing and quantum information can be enabling technologies with a crosscutting impact across a wide swath of our lives from national security, to drug design, to data analytics.

Quantum devices (called quantum bits) are the unit devices of a quantum information system and are the equivalent of a switch in a classical computer. Dramatic improvements in the quality of quantum bits over the past 10 years—brought about by improvement in materials and better physics-based designs—have enabled the building of small quantum processors containing few tens of quantum bits. These quantum bits are prone to errors and require error correction algorithms to be applied. At today's level of quantum bit perfection, it is believed that a quantum processor containing tens of thousands to a million quantum bits would be able to perform tasks of significance that could have clear advantages over classical machines. An example would be the accurate computation of the electronic structure of a large molecule containing hundreds of electrons involved in chemical bonding. As quantum bits improve and better error correction schemes are discovered, the processor will require fewer numbers of quantum bits in its circuitry. Building quantum processors with tens of quantum bits is a landmark demonstration that establishes feasibility. But today's state-of-the-art is a long way from where we wish to go. The challenge now lies in scaling this technology and doing the fundamental science and engineering necessary for this. Advances will require a combined effort in quantum devices and quantum architectures, and this will, in turn, be only as good as the materials on which these are based.

If we look at the history of electronics, there comes a time in the trajectory of technology development when massive scale materials research is needed to propel forward feasibility demonstrations driven by physicists and electrical engineers. This was true with silicon microelectronics, which has given us computing and the Internet. This was also true for compound semiconductor technology, which has given us solid-state lighting and telecommunications. The time for that materials ramp up has arrived for quantum technology. This will be materials science research of a fundamental nature that will inform the effort in devices and architectures that is also needed.

The fundamental materials research needs are numerous. To build their quantum processors a few major US technology companies have used quantum bits that operate at temperatures close to absolute zero —a showstopper for ubiquitous deployment. Opportunities exist for new types of quantum bits, particularly semiconductor quantum bits, which could operate at room temperatures and be scalable using the tools of conventional chip processing. There is a need for quantum channels that can connect different quantum chips together, and needs for new materials for quantum memory so that information can be processed entirely within the quantum space, thereby eliminating bottlenecks. One can think of a fully integrated quantum processor as a number of artificial atoms coupled together that compute and store information. It is important to re-emphasize that this is new territory for materials science and will require a deep scientific understanding of quantum effects and the creation and manipulation of individual quanta of information within materials. New materials hold the key to the ultimate development of mature quantum technologies, just as they have for other information technologies. Quantum computing is a long game, but one that we cannot afford to ignore. It will open up new horizons in information processing.

Fifty years ago, the large industrial research and development laboratories conducted a significant portion of the discovery science and underlying fundamental materials research that led to many of the technologies that we enjoy today, such as the Internet and the mobile phone. With changing business models and the increasingly complex nature of today's materials research, corporate entities are unable to perform this role today. The task does however play into the strengths of the Office of Basic Energy Sciences within the U.S. Department of Energy (DOE) and the DOE National Laboratories. These laboratories, offering unmatched capabilities in large-scale synthesis, nanofabrication, massive parallel characterization, and computational materials discovery under one roof, enable an integrated, focused effort. Further, their large user facilities—the Nanoscience Research Centers (NSRCs), light sources and the leadership computing facilities—anchor university-based ecosystems around them. The five highly successful NSRCs distributed across the nation, authorized and appropriated for funding by Congress a decade ago as part of the National Nanotechnology initiative, are well positioned to act as a springboard for a new National Quantum Materials initiative, partnered with academia and informed by the needs of the industry. One can argue that the emergence of quantum information sciences is a direct consequence of the National Nanotechnology Initiative and a Quantum Materials Initiative could be a sequel to this.

The United States continues to maintain leadership in quantum technologies, but rapid research growth in China and Europe may threaten this position. China has announced multi-billion dollar investments in quantum information research targeted towards specific centers of excellence. European investment is more spread out and totals between one to two billion dollars. China recently has made impressive strides in the demonstration of satellite based secure quantum links over twelve hundred kilometers—a tour de force engineering demonstration.

Future quantum technologies will demand a new type of educated workforce with the multidisciplinary ability to engage in quantum mechanics as engineers. Universities nationwide have begun responding to this. The University of Chicago has launched one of the first Ph.D. programs in quantum engineering in the nation. The Center for Quantum Exchange, announced by the University of Chicago in partnership with the Argonne National Laboratory and the Fermi National Accelerator Laboratory in Batavia, Illinois, will develop a new generation of graduate students who will learn their skills in close collaboration with national laboratory scientists and academics.

DOE and its laboratories are strengthening their presence in quantum materials and information research. The laboratories possess the necessary skills across the entire ecosystem: from algorithm and system architecture to the materials science and physics. The Office of Basic Energy Sciences has prioritized investments in quantum materials and the national laboratories recognize quantum information science research as a strategic focus area. Unique equipment developed at Argonne for research in nanomaterials, such as synchrotron based x-ray microscopy, is being used to "see" exquisitely small distortions in crystals used for building quantum bits. The "Quantum Factory," a comprehensive experimental facility for the synthesis of quantum materials with atomic layer precision has been set up at Argonne in joint collaboration with The University of Chicago.

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

Testimony of Dr. Supratik Guha
Director of the Nanoscience and Technology Division
and the Center for Nanoscale Materials, Argonne National Laboratory
before the
Subcommittee on Energy and the Subcommittee on Research and Technology
of the
U.S. House Committee on Science, Space, & Technology
October 24, 2017

SUMMARY

- Developments in quantum information science raise the prospects of a new, rapidly emerging computing architecture.
- A quantum computer probes information space rapidly and simultaneously, rather than sequentially, with vast superiority over classical computing for some classes of problems and potential impact on national security, drug design, data analytics, and more.
- New materials hold the key to the ultimate development of mature quantum technologies.
- The increasingly complex nature of materials research plays to the strengths of the U.S. Department of Energy (DOE) and national laboratories, with:
  - Capabilities in large scale synthesis, nanofabrication, massive parallel characterization, and computational materials discovery all under one roof
  - Five Nanoscience Research Centers distributed across the nation, positioned to act as a springboard for a new National Quantum Materials initiative, partnered with academia and informed by the needs of the industry
- The United States continues to maintain leadership in quantum technologies but rapid research growth in China and Europe may threaten this position.
- Future quantum technologies will demand a new type of educated workforce with the multidisciplinary ability to engage in quantum mechanics as engineers.
- DOE laboratories are strengthening their presence in quantum materials.
  - For example, unique equipment Argonne has developed for research in nanomaterials, such as synchrotron based X-ray imaging, is being used to "see" exquisitely small distortions in crystals used for building quantum bits.
  - The Center for Quantum Exchange, announced by the University of Chicago in partnership with Argonne and Fermi National Accelerator Laboratory, will develop a new generation of students who will learn their skills in close collaboration with national laboratory scientists and academics.

Argonne NATIONAL LABORATORY

Supratik Guha, PhD
Director, Nanoscience and Technology Division and the Center for Nanoscale Materials
Argonne National Laboratory

Supratik Guha is the Director of the Nanoscience and Technology Division and the Center for Nanoscale Materials at Argonne National Laboratory, and a Professor at the Institute for Molecular Engineering at the University of Chicago.

Dr. Guha came to Argonne in 2015 after spending twenty years at IBM Research where he served as the Director of Physical Sciences (2010-2015), responsible for IBM's worldwide strategy for research in the physical sciences. At IBM, Dr. Guha 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 that enabled the continuation of Moore's Law. Between 2010 and 2015, he was also responsible for significantly expanding the size and strategic initiatives of IBM's quantum computing group, which reported to him.

Dr. Guha is a member of the National Academy of Engineering and a Fellow of the Materials Research Society, American Physical Society and the recipient of the 2015 Prize for Industrial Applications of Physics. He is one of only a few scientists who has been a tenured professor, an executive at a major multinational company, and an executive at a major national laboratory. He received his Ph.D. in materials science in 1991 from the University of Southern California, and a B.Tech in 1985 from the Indian Institute of Technology. At the University of Chicago and Argonne, his interests are focused on discovery science in the area of materials and systems for future information processing.

Chairwoman COMSTOCK. I now recognize myself for five minutes for questions. And let's see. From the testimony given today in both of our panels, we know more about what the United States is doing to pursue quantum research and development, and we also know that other nations are heavily investing in this, in particular the United Kingdom, Netherlands, European Union, Australia, Canada, and, of course, China.

What are the risks to our economy and national security if we aren't the leaders in this research, and in particular, in quantum information science? For any of you.

Dr. MONROE. I might begin. Thank you for the question, Madam Chairwoman. I think one of the risks I see at the university level is students, foreign students. They come here, they want to stay here. They want to be where the best is, and we have the best. The U.S. is well-acknowledged as having the best higher education system in the world. We don't want those people leaving, frankly. I think that is a security issue in the long run. It's an economic issue. These are highly trained and very smart people. We want them here creating economic growth here in the U.S.

Chairwoman COMSTOCK. So stapling the green card to the degree might be helpful. Okay. Others?

Dr. CROWDER. Yeah. I think there's two levels of this. One is building quantum systems in the U.S. So there's just a nascent industry there, both as Chris and I are involved in building a system. But there's also having U.S. companies be early adopters in leveraging it. So they as U.S. companies get the economic benefit and competitive advantage of leveraging these technologies earlier. And both of those things rely on skill development in this country, fundamentally. If we don't develop the skills, we will not be able to execute on them.

Chairwoman COMSTOCK. Okay. Dr. Guha?

Dr. GUHA. I think the point I would like to make to add to my colleagues here is that, you know, we need to double up this set of skills because there are, most likely, as yet unknown new industries that can be jumpstarted from the science that would come out of this, in addition to, you know, to the benefits we would have in leading areas of cryptography or materials design.

So it would be extremely important to be able to have strong educational, fundamental scientific base in the quantum information sciences in the U.S.

Chairwoman COMSTOCK. Okay. Thank you. And I did want to take this opportunity now, since we have a staffer here, Sarah Jorgenson. This is her last hearing because she's moving to another committee and leaving us. So, I did want to thank her for all of her great work, and you got a really exciting, interesting hearing for your last hearing. Thank you for your leadership on the committee, and we look forward to many great things from you.

I'll now yield to Mr. Lipinski.

Mr. LIPINSKI. Thank you. I thank all the witnesses for their testimony. In Dr. Monroe's testimony, he presents the idea of establishing a new quantum engineering degree programs at universities as a component of the National Quantum Initiative. And Dr. Guha, I know that the University of Chicago has already established one of the first quantum engineering degree programs.

So Dr. Guha, could you describe the program at UC? Is there any advice you'd give to other universities interested in launching their own programs such as this?

Dr. GUHA. Thank you. So, the Chicago Quantum Exchange was formed very recently out of an organic need to connect industry, university, and the National Laboratories together. We believe that the future of education, particularly in the quantum information sciences, lies in establishing multidisciplinarity and the ability to connect academia and industry together in order to make progress in an important area such as this.

So the Chicago Quantum Exchange has been formed by the University of Chicago, as I mentioned, along with Argonne National Labs and Fermi Labs. Students will work with staff scientists in the government labs as well as with academia. We have recently received some funding from the National Science Foundation, along with Harvard, in order to be able to have students, graduate students have tandem advisors, one from industry, one from academia, to push forward with this concept that we really need to start pulling industry and academia and government labs together. This really needs to happen if we want to be able to translate basic science eventually into applicable technology.

Mr. LIPINSKI. In the degree program itself, is there anything that you would—advice to give other universities interested in launching their own such programs that perhaps if they don't have the access to a National Lab like Argonne that UC has?

Dr. GUHA. I think that the access to the National Labs that UC has is a huge advantage. We've seen that it helps us attract students, for instance, because these labs have capabilities that are unmatched at universities.

The other part that we focused for the Ph.D. program is, as I mentioned, in pushing forward multidisciplinarity, connecting with computer science. If you look at the faculty at the University of Chicago involved in quantum information sciences, they come from a variety of backgrounds, from physics. My own background is in metallurgical engineering to computer science, nanosciences, nanotechnology, I've worked in these areas over the past decade, has improved the interdisciplinarity of the field. But this takes it one step further so the educational content, we try to reflect that.

Mr. LIPINSKI. I know, Dr. Monroe, you're proposing the National Quantum Initiative. It includes the development in support of four very well-funded quantum innovation labs. I think this is—is this something similar to—do you see these as being similar to the Chicago Quantum Exchange, that concept?

Dr. MONROE. I would say to back up a little bit. At my institute, at the University of Maryland, we probably have the largest cadre of academic and government researchers in quantum sciences in one place, including NIST, LPS which is part of NSA, and the university. We have a computer science center, a quantum science center, and an engineering center is on the way.

But I applaud the efforts at Chicago which is obviously well-situated with Fermi and Argonne Labs in the back yard. And for this National Quantum Initiative, I think we need to have a critical mass of people from different disciplines. It's absolutely critical. Whenever you use your iPhone, you don't know or understand what's inside, and that's why it's useful. We need people to program the higher levels of these devices, and they will not be knowledgeable about every little piece. You just can't. I think I made an analogy to the aircraft engineering. I don't think there's a single person that understands every piece of an F–35. It's too big and complex. A large quantum computer is not as yet complex as that, but it's approaching that. When it gets big, it will be. And so we're going to have to. It's required that this field—and I think I'm echoing everything all the witnesses are saying—that we have people from a variety of fields, including engineering, computer science, physics, all the physical sciences, chemistry, information theory, mathematics.

Mr. LIPINSKI. Okay. Thank you. My time is up so I yield back.

Chairwoman COMSTOCK. I now recognize Mr. Lucas forfive minutes.

Mr. LUCAS. Thank you, Madam Chairwoman. Dr. Crowder, in your testimony you conclude that federal grants in support of core quantum research and development are being eclipsed by other governments. Can you expand on that for a moment?

Dr. CROWDER. Sure. I mean, the United States has put a lot of investment into quantum information science. But if you just look at the estimates that folks like McKenzie have done and just look at the announcements recently by China and by other countries, they are investing more heavily than we are.

I think it's really important, again, from an industry perspective, especially a multi-national company like IBM that has a view of more than just the United States, that we continue to do the basic research for two reasons, one, because of what my colleagues here have stated in terms of just pushing the technology forward but also really to build the skills that are going to be necessary for commercialization. I mentioned it before. There are three types of skills that we see gaps in. Some of them I would say, like FPGA programming or more traditional skills, that maybe are mid-career we can train people to go into.

But quantum information science requires pretty in-depth graduate-level work, and if we do not continue to fund basic research at the graduate and post-doctorate level in this country, we just won't have the skills.

Mr. LUCAS. To continue with that line of thought, and whether it's specific areas of research that are being outpaced in or areas where we should be engaged, that would be vital to our dominance, at the pace we're at right now, looking at what the rest of the world is doing based on the information available to you, at what point do we get behind the curve that we can't catch up if we don't make those investments? Because certainly there comes a point. If you get far enough out, ahead of the rest of the world, then you can't catch up.

Dr. CROWDER. Yeah, as other people have said, I do think we're at a couple inflection points here. We're at the stage now where quantum computing is becoming real. I mean, we put a real quantum computer, albeit small one, on the Internet last May, May 2016, and it's been up and running since then and we've, you know, grown that from 5 qubits to 16 qubits, and we've announced that this year we're building slightly more powerful quantum computers for, you know, commercial availability.

So I think we're at a very interesting inflection point in this technology. If we don't make the investments in both the underlying skills and also as other people have mentioned, the technology of people learning how to use these systems, we will, from an American point of view, fall behind. I can't give you an exact date, but the trajectory isn't sufficient.

Mr. LUCAS. Dr. Monroe, along that similar line, when it comes to research and infrastructure involving light sources or neutron sources, follow up if you would for a moment, expand a bit on how we're faring in that international competition, real or imaginary.

Dr. MONROE. As you've heard today, there are a variety of technologies that are behind successful quantum device, and these are technologies that are themselves maybe not necessarily quantum. I think Dr. Williams mentioned the idea of purifying isotopes of silicon and make it ultra-pure, and through some of our DOE labs, we are world leaders in that area. I think we have a proud history of leading device fabrication in silicon which will play a role in almost every quantum technology, even if it's not based in the bulk of silicon. For instance, in my technology, we use silicon electrodes that are pretty far away, but they need to be machined to be just beautiful. And this happens at Sandia National Laboratory, a DOE laboratory, and no place in the world can really compete at that point. I think the fact that we have many big corporations, IBM, Google, Intel, Microsoft, playing in this field is really the strength we have. And to me, it's really a workforce issue. And I think other countries, from what I see, they can organize in a top-down way because often the industry is their country. They're very linked that way. And in a sense, there are coordinations that can happen that are very fast in some places, particularly China. And I see in the U.S., our system is not or maybe it shouldn't be like that, but the government can play a role I think to better bring together academic research in this field, pure science, the devices, the manufacturing, and the workforce that will be at industry.

Mr. LUCAS. Thank you, Doctor. I yield back, Madam Chair.

Chairwoman COMSTOCK. I now recognize Mr. Veasey for five minutes.

Mr. VEASEY. Thank you, Madam Chair. I wanted to ask Dr. Guha about collaboration and was wondering if you could describe how the private sector partners with National Laboratories on quantum-based technologies and how has this relationship changed as the investments in quantum information science, both public and private, have increased in recent years?

Dr. GUHA. So there is collaboration between the private sector and the public sector in, you know, areas related to quantum information sciences through the large user facilities, for instance, the light sources. Companies like IBM have used our light sources at Argonne. This is just one example. Also through the nanoscience facilities, the NSRCs. That's another channel through which this is—these are also—there are five such user facilities across the U.S. distributed in the DOE labs. And that's another avenue where we collaborate with industry because the Nanoscience Research

Centers possess state-of-the-art capabilities for manipulation of atoms and structures at the nanoscale.

There have been good examples in areas such as battery development, for instance, at Argonne again to give you an example where cathode materials have been developed through basic energy science's funding at Argonne, then through ERE funding, and now these are in major hybrid cars that are sold in the U.S. and worldwide.

So there certainly is a structure and a system for this type of public-private collaboration. And I think this would only increase as we go forward and put more emphasis on quantum information sciences.

Mr. VEASEY. Thank you very much. I also want to ask you about the Department of Energy. As you know, it's home to many scientific user facilities that focus on the fundamental sciences that underpins quantum technologies. How are users taking advantage of the facilities stewarded by the DOE Office of Science to advance our understanding of quantum information science?

Dr. GUHA. So that's a good question. I'll give you another example. For instance, if we go back to the nanoscience research facilities, some of the tools that we are starting to build and starting to equip ourselves with are tools that can deal with single photon measurements to measure correlations between different single photon emitters. So these are tools that basically now start enabling you to figure out how to create and manipulate single quanta of information and try to look at the entanglement between them, which is sort of at the heart of quantum information sciences.

So we are beginning to start getting these tools on line and pulling in users, initially from academia and then from the industry as well hopefully as we go forward. So these are things that are beginning to happen.

Mr. VEASEY. Thank you. Thank you very much. Madam Chair, I yield back my time.

Chairwoman COMSTOCK. I now recognize Ms. Bonamici for five minutes.

Ms. BONAMICI. Thank you very much, Chair Comstock. Thank you to each of the witnesses. Dr. Monroe, you talk in your testimony about the challenges of transition from research to marketplace, and that's an issue that we've discussed many times on this committee, commercialization of research, and you mention workforce challenges and dealing with small companies where there are not yet high-volume applications and the lack of expertise. So that's what you mentioned. Are there policy barriers that we as Congress could address? Are there barriers through policy changes that we could work on?

Dr. MONROE. Thank you for the question. The one I would bring up—and again, I'm opening a can of worms. It's intellectual property laws, and I think my colleague, Dr. Williams from NIST, brought this up. And in my view, to get full engagement of industry, they have to be able to protect their own IP, their own interests in the long run, but they also—I think the reason it could work, having an innovation lab, quantum innovation lab, is that these big industry players, they understand that they're going to get people. They're going to get qualified people that can go back home and then build devices that can be commercial.

So again, I don't know the answer to it. I'm probably not the expert here with regard to IP law. But somehow, to dangle that carrot in front of industry to have their engineers embedded. I will note, by the way, that Intel has an arrangement with the University of Delft in the Netherlands where they do exactly this. And I don't know exactly how this works with regard to IP, but they have embedded engineers that are building silicon devices at Delft. And the researchers there, the academics, they're reaping the benefits of having professionals in place that really know this stuff.

Ms. BONAMICI. Terrific. We can look at that model and also work with our colleagues on the Judiciary Committee on the IP issues. And Dr. Monroe, to follow up your National Quantum Initiative, the way I understand it, you're really talking about four well-funded quantum innovation labs. So I wanted to ask, in that type of model, is there a way that we could address—you know, some of the breakthroughs have come from unexpected places. How would that model be able to work with, for example, the bright faculty and students at lesser-known colleges and universities or the small businesses that are not in the vicinity of one of those innovation labs? What would be the plan to be more broad-reaching than just having the four innovation labs?

Dr. MONROE. Well, I think it would require full engagement of relevant agencies, and I think the science agencies that were in the previous round of witnesses, DOE, NIST, and NSF, are natural to play a huge role in making these hubs happen. And NSF in particular, they deal with blue skies research. They deal with small colleges. They're very good at bringing big science, cutting-edge science, down to even undergraduate institutions. So I think having their engagement will be important.

And I might add, one federal vehicle that also works very well with industry is the SBIR and STTR programs. These are——

Ms. BONAMICI. Right.

Dr. MONROE. —grant programs, largely from the DOD, that can go into industry for more researchy type things.

Ms. BONAMICI. Terrific. And for all the panelists, the title of this hearing is of course about American leadership. And I know it's been addressed and the Chair brought it up and others have as well.

Dr. Monroe, you just mentioned the Intel partnership with Delft. Are there, among the panel there, other examples where we could look at either models, work that's being done in other countries? Where are we seeing leadership efforts that we could either replicate or that we should take note of? Dr. Crowder?

Dr. CROWDER. Yeah. I think one of the things that you see in Europe especially is research institutions deeply partnering with industry participants to provide them with access to quantum technologies. That's one of the things we haven't talked about too much on this panel is not just the underlying quantum technology itself but the algorithms and use cases that you need to develop for that. And you see things going on in the UK, in Oxford, things going on in Germany and some of the research institutions there that I think are really best practices, where they're—I can certainly see a place like Oakridge expanding their test beds to do very similar things to, you know, open up access through their user facilities to these new technologies.

Ms. BONAMICI. Thank you. In my remaining few seconds, Dr. Guha or Dr. Monroe, do you want to add to that?

Dr. GUHA. I think I'd just like to add one more point to what Dr. Crowder said which is that, you know, if you look at China and the funding they are investing, they're putting it in focused centers. And I think there's some benefit to that. And I think we should think about that as well.

If you look at the European funding, it's going more distributed. And I feel that the focused approach, you know, this is something we ought to look at carefully.

Ms. BONAMICI. Thank you. And as I yield back, Madam Chair, I just want to point out in follow up to the prior panel that in South China, the South China Morning Post, they just had an article about their new STEAM school. And a recent study in Korea found that STEAM is a highly effective teaching and learning method.

So as I yield back, I'll point that out to you, Madam Chair, and thank our colleagues.

Chairwoman COMSTOCK. Thank you.

Ms. BONAMICI. Thank you.

Chairwoman COMSTOCK. And I now recognize Representative Tonko for five minutes.

Mr. TONKO. Thank you, Madam Chair. Quantum information science is a rapidly growing field with public and private investments growing across the world. Just how does the United States stack up against international competitors in this field? Who's leading the race in developing the next generation of what may well be revolutionary technologies?

Dr. MONROE. Thank you for the question. I might begin on academic side in that by its nature, academic science is international, and there are many great collaborations. I have some in Europe and so forth. And I would say academically, the science behind QIS is proceeding most rapidly in the U.S. still. China is not far behind and the same can be said for the EU. I think they're all powerhouses in this field.

In terms of the technology development, this is where the U.S. is ahead for now, and I think it's largely driven by industry. We have the industry that the others are struggling to come up with. But I think where China and the EU have an interesting advantage is just how they can make top-down things happen, and it's just the nature of the beast.

We keep returning to China. This is a very capital-intensive field to get this exotic hardware to engineer. It does take a large amount of investments, and I think that China, without the bat of an eye, can just do it.

So this is something I look in the future as maybe an early warning sign that, you know, now is the time to get a head of the curve on that.

Mr. TONKO. Certainly now is not the time to cut into some of these investments, as we've heard?

Dr. MONROE. Yes, I agree with that.

Mr. TONKO. Okay. Do our other doctors have any comments in that regard?

Dr. GUHA. So I agree with Dr. Monroe that the U.S. is leading the race, but the next few years are going to be very interesting, particularly with respect to China. There's two things to note. One, the results on their satellite link that I think is an engineering tour de force. This type of link was first, you know, demonstrated via a DARPA project in 2003 between Boston University and Harvard and a private company, if I remember correctly. But the fact that they're able to do this via satellite is a big deal, and we should take notice of this. And the second is the hiring that's going on in China in the quantum area, in hiring Ph.D. scientists putting huge amounts of investments in starting up labs.

So we really need to take note of this. In the next few years, you know, China has I believe made the decision that they want to wrap up in this area, although the U.S. clearly has the superiority today.

Mr. TONKO. Um-hum. And Dr. Crowder?

Dr. CROWDER. I think my colleagues have said it well. I mean, I think American industry clearly has leadership in this space. I think from an academic point of view the United States, our academic institutions are clear leaders in this space, although in academics and skill development I will say that there is a lot of good work going on worldwide. So there's a lot of skill development happening in Europe, in Canada, and Australia and Japan, as well as in China.

Mr. TONKO. And what would you suggest we need to prioritize in order to secure our competitive edge here in this critical field? You talked about us, you know, holding onto maybe a leading status. But what's most critical for us to do to maintain that or grow it?

Dr. CROWDER. So I think there's two levels here, one, which I touched on before which is we need the skill development from a U.S. economy point of view. I think we do have industry leadership in actually building these systems and the technology behind it, but I do think we need to continue to invest highly in skill development which means investments and basic research. And then the second is we need to make these systems available to U.S. researchers and to U.S. companies. The algorithm development we haven't really touched on her, but there's a lot of possibilities for quantum. But until someone develops the algorithms, those possibilities will not be turned into real business value. There's a lot of work that needs to get done in algorithm development.

Mr. TONKO. Dr. Monroe?

Dr. MONROE. Yeah, thanks for the question. I might add to that that it's a precarious situation for industry or a company to be in a game where they're building a device where we don't actually know exactly what it's going to be used for. This is exactly what happened with conventional computing back in the '50s. It was built for certain purposes but nobody envisioned packing billions of transistors on a watch or an iPhone.

Dr. Kurose in the last session mentioned that quantum computing is not a panacea. It's not going to solve every type of problem, but we need to get these devices out there to users, for users to solve the problem. That may be a difficult argument to make to stockholders in a big company. So that's where I think there is some vulnerability.

Mr. TONKO. Dr. Guha, did you——

Dr. GUHA. I will simply add that, you know, we need to make sure that we continue to have superiority in the basic underlying science behind this field. That's absolutely important. And we should probably set some goals and targets, you know, ten-year goals, 15-year goals, and sort of pull the science along through those targets.

Mr. TONKO. Thank you. I yield back, Madam Chair.

Chairwoman COMSTOCK. Thank you. And I now recognize Mr. Foster for five minutes.

Mr. FOSTER. Thank you, Madam Chair. First, before I go into policy discussions, Dr. Guha, a question about your previous existence. What is the current state of the art for thinox dielectrics versus high-k dielectrics, just in terms of the number of atomic layers?

Dr. GUHA. So the electronic equivalent number of atomic layers is something on the order of, you know, seven angstroms or something, less than a nanometer. It's the electronic equivalent. Physically it's a little thicker but that's what you gain from using a high dielectric constant material.

Mr. FOSTER. Yeah. This has evolved so much since I was designing ICs back in the 1990s. It's amazing what has been accomplished. And I guess there's no clear example of Moore's Law hitting the fence than just the thickness of, you know, the dielectric barriers and mosfets.

Anyway, now back to the policy stuff, you've touched on a lot of issues I was thinking of bringing up having to do with what is the right development model for something like this that requires a long-term investment? I mean, the whole business was jump started by the discovery in principle I believe at Bell Labs that you could actually in principle, theoretically, factor large primes with quantum computing and thereby blow up, you know, the then-current cryptography, which had huge implications.

So the problem there is Bell Labs is gone, right? And they're gone because they existed only because we basically socialized that piece of research that we provided Bell Labs with a monopoly on long distance that provided an income stream to develop a really a wonderful natural resource that only existed because, you know, we gave them a special monopoly. You know, it's a peculiar way to have socialized research. The national labs are really the only, you know, socialized research that we actually have in this country, and it's unique and I think it's necessary for long-term and speculative developments. You simply can't, as you say, sell the stockholders on this.

One of the biggest things that I worry about all the time is intellectual property. You know, this is a huge problem. It's sort of an interesting policy debate because it doesn't—it's something that's not really a moral argument. It's an argument on how you maximize economic and technological progress.

And so are there things that you think are really—you know, if you could have two or three fixes in intellectual property, what would they be? You know, for example, many countries don't allow algorithms to be patented, computer algorithms to be patented. And that's something that's gone back and forth in this country. So how does intellectual property play into the development of, say, quantum algorithms on this? Does our current policy encourage it or discourage it?

Dr. MONROE. Yeah, I will say that in my experience in small business, we're told by our investors you have to get an IP portfolio. And it's almost irrational. I guess as a scientist I find it as a little bit of a nuisance, but I do understand the importance of it because if you don't have it, you will be playing defense against somebody who is just sitting on intellectual property.

So I would not be against tightening different facets of what can be patented or not, mathematic equations——

Mr. FOSTER. As expanding—but saying, you know, if you could patent quantum algorithms for example, you know, would that increase or decrease the amount of interest and the rate of development of these?

Dr. MONROE. My gut feeling is it would decrease. I think it's such an early stage right now that it will maybe scare away others and impede progress in the field.

Mr. FOSTER. Yeah, that would be interesting to talk to, you know, venture capitalists to see if they agree with the same thing because it's a—now, in addition, Dr. Guha touched on the question of whether we centralize or disperse, you know, the centers of excellence. Do we have centers of excellence or do we do, you know, the European model of spreading the technology to a zillion institutions? You know, the obvious—if you see what industry does for things like biotechnology, they just have a very strong clumping effect that occurs naturally, not so much because of the intrinsic merits of where they decide to clump but simply because of the network effects of having a bunch of people nearby that you can, you know, steal employees from each other as you expand and contract.

And so, you know, is this something that we should be fighting against or should we, you know, in the European way of trying to spread out the research or should we just say, okay, we're going to have a clump of this, you know, for example, in the Illinois 11th District would be a fine place? But you know, what are your thoughts on that? And I will skip Dr. Guha which I presume would conclude, would agree with me here.

Dr. CROWDER. Yeah, I think there's two competing forces here. I definitely think that having centers of excellence and concentrating, especially for topical areas, makes a whole lot of sense from a resource point of view.

On the flipside, when I talk to companies about their plans to leverage this, they have the same skill issues that other people have. And what they want is to partner with a local university to do the early research and then so they have someone to hire in two years when this becomes large.

So I do think we need to balance it. I do think there's advantages of having centers of excellence, especially from an access point of view. It doesn't necessarily make sense for everybody to have a user facility for, you know, quantum computing. You should have, you know, a couple user facilities that, you know, other people can get access—other academic institutions can access from. Similarly, I think you need centers of excellence in particular areas so you have a critical mass. But I do think you need regional participation and the academics behind this because you will have companies that need to get skills from regional areas.

Dr. MONROE. Do I have time to add one thing? As a high-energy physicist, you certainly appreciate that CERN and Fermi Lab are these big naturally clumping things. You're studying one problem, and it takes a thousand people to do that.

Quantum computing is not that. I think there are many different technologies. They're wildly different, and I think these innovation hubs can maybe specialize in one at a time at each hub, for instance, that's one model. I think it is clumping, not as much as high-energy physics, but I think we would find a few areas of specialization. One might be more devoted on software, a computer side of things where they don't care about the hardware, and the others will develop particular hardwares.

Mr. FOSTER. Fascinating. Let's see. Do any of you know roughly how many, you know, say photonics Ph.D.s come out of China every year compared to the U.S.? Do you have a feeling for that or just overall? Ph.D.s with relevant skills.

Dr. MONROE. I think they probably beat us on that. I actually don't know the numbers. I shouldn't speculate.

Mr. FOSTER. Okay. I remembered——

Dr. MONROE. There's a lot. There's a lot.

Mr. FOSTER. —seeing a very, in some sub-specialties, at least a very high ratio, and you know, that's a problem. Because the workforce development is huge, and I think it's—anyway, I just want to thank you all for bringing this, attending this very important hearing, and thank the Chair for holding the hearing.

Chairwoman COMSTOCK. Thank you. And I thank this panel of witnesses also for their testimony and expertise. As you can tell, the members were very interested in this topic, and obviously it's a very competitive area where we appreciate all of your insight. I think it will need to be a continuing conversation on how we can continue to be the leaders and remain competitive and the kind of workforce that we're going to need. I think there'll be a lot more questions to ask and issues to develop along this way.

So the record will remain open for two weeks for additional written comments and questions from the members. And the hearing is now adjourned.

[Whereupon, at 12:48 p.m., the Subcommittees were adjourned.]

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