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SUMMARY

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Quantum information science (QIS) combines elements of mathematics, computer science, engineering, and physical sciences, and has the potential to provide capabilities far beyond what is possible with the most advanced technologies available today. Although much of the press coverage of QIS has been devoted to quantum computing, there is more to QIS. Many experts divide QIS technologies into three application areas:

- Sensing and metrology,
- Communications, and
- Computing and simulation.

The government's interest in QIS dates back at least to the mid-1990s, when the National Institute of Standards and Technology and the Department of Defense (DOD) held their first workshops on the topic. QIS is first mentioned in the FY2008 budget of what is now the Networking and Information Technology Research and Development Program and has been a component of the program since then.

Today, QIS is a component of the National Strategic Computing Initiative (Presidential Executive Order 13702), which was established in 2015. Most recently, in September 2018, the National Science and Technology Council issued the National Strategic Overview for Quantum Information Science. The policy opportunities identified in this strategic overview include

- choosing a science-first approach to QIS,
- creating a "quantum-smart" workforce,
- deepening engagement with the quantum industry,
- providing critical infrastructure,
- maintaining national security and economic growth, and
- advancing international cooperation.

The United States is not alone in increasing investment in QIS R&D. This research is also being pursued at major research centers worldwide, with China and the European Union having the largest foreign QIS programs. Further, even without explicit QIS initiatives, many other countries, including Russia, Germany, and Austria, are making strides in QIS research and development (R&D).

The Senate has introduced two bills in the 115th Congress (S. 3143, S. 2998) and the House has introduced one bill in the 115th Congress (H.R. 6227) related to QIS. The first two bills would establish a federal program to accelerate U.S. QIS R&D and create a National Quantum Coordination Office within OSTP. The third bill would establish a Defense Quantum Information Consortium. The House has held three hearings related to QIS. Issues discussed in these hearings included a comparison of U.S. and international QIS R&D, and how to effectively train a QIS-knowledgeable workforce; China's investment in leading-edge technologies, including QIS, and concerns that China may be closing the gap with the United States in advanced technology R&D; and an overview of quantum computers.

This report provides an overview of QIS technologies: sensing and metrology, communications, and computing and simulation. It also includes examples of existing and potential future applications; brief summaries of funding and selected R&D initiatives in the United States and elsewhere around the world; a description of U.S. congressional activity; and a discussion of related policy considerations.

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Introduction

Combining elements of mathematics, computer science, engineering, and physical sciences, quantum information science (QIS) has the potential to provide capabilities far beyond what is possible with the most advanced technologies available today. Quantum science, generally, is the study of the smallest particles of matter and energy; QIS builds on quantum science principles to obtain and process information in ways that cannot be achieved based on classical physics principles. QIS is based on the premise that information science depends on quantum effects in physics.

The advantages to using QIS in certain circumstances can be illustrated by the example of quantum computing. Quantum computing is not just "faster" than classical computing. It is not useful for many types of problems where a classical supercomputer would excel. However, there are certain tasks for which the power of quantum computing is unmatched, such as code breaking. This power is derived from quantum computing's use of "qubits" or "quantum bits."

Whereas classical computing uses "bits" for data processing, quantum computing uses qubits. The practical difference between a bit and a qubit is that a bit can only exist in one of two states at a time, usually represented by a 1 and a 0, whereas a qubit can exist in both states at one time. This is a phenomenon called "superposition" and it is what allows the power of a quantum computer to grow exponentially with the addition of each bit. Two bits in a classical computer provides four possible combinations—00, 01, 11, and 10, but only one combination at a time. Two bits in a quantum computer provides for the same four possibilities, but, because of superposition, the qubits can represent all four states at the same time, making the quantum computer four times as powerful as the classical computer. So, adding a bit to a classical computer increases its power linearly, but adding a qubit to a quantum computer increases its power exponentially—doubling power with the addition of each qubit.

Quantum computing, for all its promise, is still a developing technology (along with other quantum applications). Assembling a working quantum computer is much more difficult than assembling a classical computer. The difficulty is caused by the narrow set of conditions that must exist for a quantum computer to work. For example, the temperature must be exactly $1/100^{th}$ of a degree above absolute zero. Also, the slightest vibration can cause a qubit to lose its superposition. Until systems can be developed to maintain the ideal conditions to maintain a qubit, many quantum systems will remain theoretical in nature.

QIS Applications

Although much of the press coverage of QIS has been devoted to quantum computing, there is more to QIS. Many experts divide QIS technologies into three application areas:

- Sensing and metrology,
- Communications, and
- Computing and simulation.[1]

[1] Some experts further separate computing and simulation into two categories.

Sensing and Metrology

Quantum sensing and metrology include navigation, atomic clocks, gravimeters and gravitational gradiometers, inertial motion units, atomic magnetometers, electron microscopes, technologies to locate subterranean mineral deposits, and quantum-assisted nuclear spin imaging devices.[2] They currently have the largest range of existing and potential commercial products. There are also several products in this category that have been manufactured for decades, making it the most established category.

In its report *Assessment of the Future Economic Impact of Quantum Information Science*, analysts at the Institute for Defense Analysis (IDA) determined that

> new technologies in quantum metrology and sensing offer improved accuracy compared to products based on classical physics or existing quantum technologies. New QIS technologies are being used for position, navigation, and timing; medical imaging; and research.[3]

Some experts believe that the potential markets for these technologies are small because in some cases, traditional technologies remain more attractive due to the higher costs and technical complexity of QIS alternatives.[4] However, others have stated that they believe continued investment and effective coordination between the research community and industry could bring a broad range of QIS-enhanced sensors to the U.S. marketplace by 2021.[5]

Communications

Quantum key distribution (QKD) is a method of securing communications that uses quantum physics, rather than mathematical algorithms, to safeguard data sent over unprotected networks. However, signals traveling over fiber-optic cable weaken at about 60 miles and must be retransmitted. Quantum repeaters *can* extend the distance the signal can be sent, but they significantly increase the complexity of the process. The communications are not only secure, but any eavesdropping attempt will destroy the communication, revealing the eavesdropping attempt.

The Chinese government has been spending heavily on QKD, but many analysts in North America and Europe do not believe that the benefits over existing nonquantum technologies outweigh the costs associated with QKD, making commercial demand difficult to ascertain.[6]

Computing and Simulation

Quantum computing provides an exponentially larger scale than classical computing, which provides advantages for certain applications. Quantum simulation refers to the use of quantum hardware to determine the properties of a quantum system, for example, determining the

[2] Keith W. Crane, Lance G. Joneckis, and Hannah Acheson-Field, et al., *Assessment of the Future Economic Impact of Quantum Information Science*, Institute for Defense Analyses, IDA Paper P-8567, Log: H 17-000362, Washington, DC, August 2017, https://www.ida.org//idamedia/Corporate/Files/Publications/STPIPubs/2017/P-8567.pdf. (Hereinafter, *Assessment of the Future Economic Impact of Quantum Information Science*, IDA.)

[3] *Assessment of the Future Economic Impact of Quantum Information Science*, IDA.

[4] *Assessment of the Future Economic Impact of Quantum Information Science*, IDA.

[5] White House Interagency Working Group on Quantum Information Science, *Advancing Quantum Information Science: National Challenges and Opportunities*, Washington, DC, July 2016, https://obamawhitehouse.archives.gov/blog/2016/07/26/realizing-potential-quantum-information-science-and-advancing-high-performance. (Hereinafter, *Advancing Quantum Information Science*, White House.)

[6] *Assessment of the Future Economic Impact of Quantum Information Science*, IDA.

properties of materials such as high-temperature superconductors, and modeling nuclear and particle physics.

However, the current capabilities of quantum computers limit the size of the problems that they can be used to solve. While significant research has been conducted to date by government laboratories, university departments, and large technology companies, as well as small start-ups, it is unlikely that any commercial quantum computing will be widely available before 2025.

U.S. Government QIS Research History and Funding

The government's interest in QIS dates back at least to the mid-1990s, when the National Institute of Standards and Technology (NIST) and the Department of Defense (DOD) held their first workshops on the topic. QIS is first mentioned in the FY2008 budget of what is now the Networking and Information Technology Research and Development Program and has been a component of the program since then.

In September 2018, the Department of Energy (DOE) announced that it had committed $218 million to 85 research projects lasting from two to five years. Also in September 2018, the National Science Foundation (NSF) announced that it had awarded $31 million in grants to 33 projects. Eight projects receiving a total of $6 million are engineering projects aimed at creating working quantum information systems (applied research). The remaining $25 million will be distributed to 25 basic research projects.[7]

Government QIS basic research is also conducted by NIST, the DOD services, and the Office of the Secretary of Defense. Additionally, the Defense Advanced Research Projects Agency and the Intelligence Advanced Research Projects Activity have funded a series of targeted programs.

U.S. Government QIS Initiatives

QIS is a component of the National Strategic Computing Initiative (Presidential Executive Order 13702), which was established in 2015. The White House has issued two reports on QIS strategy, the first under President Obama and the second under President Trump.

[7] "US Invests $249 Million in Quantum Information Science as White House Unveils Strategic Overview," Physics World, September 28, 2018, https://physicsworld.com/a/us-invests-249m-in-quantum-information-science-as-white-house-unveils-strategic-overview/. (Hereinafter, "US Invests $249 Million in Quantum Information Science," Physics World.)

Advancing Quantum Information Science: National Challenges and Opportunities

In July 2016, the National Science and Technology Council (NSTC),[8] under the purview of the White House Office of Science and Technology Policy (OSTP),[9] issued *Advancing Quantum Information Science: National Challenges and Opportunities*. This report provided a brief description of the QIS disciplines, summarized developments and potential impacts in various fields of technology and areas of basic research, identified impediments to progress and potential approaches to addressing them, surveyed federal investments, and discussed the federal path forward in the context of international and private-sector activity.

The report outlined three principles to guide U.S. government QIS R&D.

- Maintain stable and sustained core programs that can be enhanced as new opportunities appear and restructured as impediments evolve. Sustained core programs will allow established researchers to continue their work, give students confidence that QIS is a field with a future, and provide a solid base for translating laboratory demonstrations into marketable technology.
- Invest strategically in targeted, time-limited programs to achieve concrete, measureable objectives. Targeted, time-limited programs are an effective mechanism for achieving well-defined technical advances and allow quick adaptation to a changing technological landscape.
- Closely monitor the field to evaluate the outcome of federal QIS investments and quickly adapt programs to take advantage of technical breakthroughs as they are made. Continued monitoring is required to ensure that the federal strategy for QIS investment remains effective into the future and to avoid technological surprise.

The report concluded by stating that QIS should be considered a priority for federal coordination and investment, with particular attention paid to identifying and implementing methods to address impediments to progress and maintaining a commitment to keep the United States at the leading edge of QIS developments.

The National Strategic Overview for Quantum Information Science

In September 2018, the NSTC issued *The National Strategic Overview for Quantum Information Science*. The policy opportunities identified in this strategic overview are summarized in **Table 1**.

[8] The National Science and Technology Council is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the federal R&D enterprise. One of the NSTC's primary objectives is establishing clear national goals for federal science and technology investments. The NSTC prepares R&D packages aimed at accomplishing multiple national goals. The NSTC's work is organized under five committees: Environment, Natural Resources, and Sustainability; Homeland and National Security; Science, Technology, Engineering, and Mathematics (STEM) Education; Science; and Technology. Each of the committees oversees subcommittees and working groups that are focused on different aspects of science and technology.

[9] The Office of Science and Technology Policy advises the President in policy formulation and budget development on questions in which science and technology are important elements; articulates the President's science and technology policy and programs; and fosters strong partnerships among federal, state, and local governments, and the scientific communities in industry and academia. The Director of OSTP also serves as Assistant to the President for Science and Technology and manages the NSTC. For more information on OSTP and the NSTC, see CRS Report R43935, *Office of Science and Technology Policy (OSTP): History and Overview*, by John F. Sargent Jr. and Dana A. Shea.

Table 1. The National Strategic Overview for Quantum Information Science: QIS Policy Opportunities

CHOOSE A SCIENCE-FIRST APPROACH TO QIS
• Strengthen federally funded core research programs and use approaches ranging from distributed small grants to centers and consortia where appropriate, to support long-term QIS research. • Foster cross-discipline dialogue and collaboration between quantum-focused researchers, engage the broader scientific community to highlight and share relevant scientific advances, and grow and coordinate the quantum research community. • Establish and utilize a formal coordination body, such as the National Science and Technology Council Subcommittee on Quantum Information Science (SCQIS). • Focus on "grand challenges" as a mechanism for driving advancements in the science and technology of QIS, and encourage federal agencies to identify, prioritize, and coordinate investment in both fundamental and applied challenges.
CREATE A QUANTUM-SMART WORKFORCE FOR TOMORROW
• Encourage industry and academia to create convergent, trans-sector approaches for diverse workforce development to meet the country's QIS needs. • Use and enhance existing programs to increase the size of the QIS-ready workforce. • Encourage academia to consider quantum science and engineering as its own discipline, with needs for new faculty, programs, and initiatives at all levels. • Address education in the area of quantum science at an early stage, including elementary, middle, and high school levels. • Reach out to broader audiences by working with involved agencies and industry to highlight their investments, along with such novel or unconventional approaches as utilizing art, media, and engagement with cultural institutions. • Encourage the QIS community to track and estimate the future workforce needs of quantum industry.
DEEPEN ENGAGEMENT WITH THE QUANTUM INDUSTRY
• Foster the formation of a U.S. Quantum Consortium with participants from industry, academia, and government to forecast and establish consensus on needs and roadblocks, coordinate efforts in precompetitive research, address intellectual property concerns, and streamline technology-transfer mechanisms. • Increase investment in joint quantum technology research centers by partnerships among industry, academia, and government to accelerate precompetitive quantum research and development. • Maintain awareness of how the quantum revolution may affect agency mission spaces and how agencies can nurture the adoption of quantum technologies within the federal government by cultivating potential end-user application spaces.
PROVIDE CRITICAL INFRASTRUCTURE
• Identify critically needed infrastructure and encourage necessary investments by working with government experts and stakeholders, as well as industry and academia. • Encourage agencies to provide the QIS research community with increased access to existing and future facilities and supporting technologies.

• Establish end-user testbed facilities along with training and engagement, thereby allowing federal agencies and stakeholders to explore applications relevant to their respective missions. • Leverage existing infrastructure, including manufacturing facilities that can be repurposed and expanded, to rapidly advance quantum technology development.
MAINTAIN NATIONAL SECURITY AND ECONOMIC GROWTH
• Maintain an understanding of the security implications of the changing science and technology landscape in QIS. • Promote mechanisms, such as the SCQIS, for all government agencies to stay abreast of the defense and security implications of QIS technologies and help balance the benefits of economic growth with new risks created by the technology. • Ensure consistent application of existing classification and export control mechanisms to provide the largest amount of information possible to U.S. universities and industry about actions related to QIS research to encourage economic opportunities, protect intellectual property, and defend applications relevant to national security.
ADVANCE INTERNATIONAL COOPERATION
• Seek to increase international cooperation with industry and government partners. • Ensure the United States continues to attract and retain the best talent, and has access to international technologies, research facilities, and expertise in QIS. • Identify strengths and focus areas, as well as gaps and opportunities, of international actors to better understand the evolving international QIS landscape from both technical and policy perspectives.

Source: The National Strategic Overview for Quantum Information Science, NSTC, September 2018.

According to the report, "following these recommendations, along with detailed planning and coordination made possible by the SCQIS as well as engagement with stakeholders, is crucial for the United States' future success."

International QIS Initiatives

QIS R&D is being pursued at major research centers worldwide, with China and the European Union (EU) having the largest foreign QIS programs. The UK and Canada have also made high-profile investments in QIS R&D, while Australia and the Netherlands have made smaller investments. Even without explicit QIS initiatives, many other countries, including Russia, Germany, and Austria, are making strides in QIS R&D. A report by the Institute for Defense Analysis, *Assessment of the Future Economic Impact of Quantum Information Science,*[10] and witness testimony at congressional hearings have provided information on these initiatives.

China

China designated QIS research as one of four "megaprojects" in its 15-year science and technology development plan for 2006-2020. Additionally, it designated quantum communications and computing as one of six major goals for this period. China's annual funding

[10] *Assessment of the Future Economic Impact of Quantum Information Science*, IDA.

for QIS R&D is estimated at $244 million.[11] In 2017, the country began construction of a national QIS science center. China also actively seeks out QIS experts. Since 2008, China has provided incentives to attract Chinese QIS experts and entrepreneurs, currently living and working overseas, back to China.

Between 2016 and 2018, China was the first to achieve three significant QIS milestones:

- the launch of the world's first quantum satellite, Micius, in August 2016;[12]
- the launch of a long-distance quantum communication landline, between Beijing and Shanghai, in September 2017;[13] and
- the first long-distance quantum videoconference, between the Chinese Academy of Sciences in Beijing and the Austrian Academy of Sciences in Vienna, in January 2018.[14]

European Union

First outlined in the EU's 2016 *Quantum Manifesto*[15] and updated in *The Quantum Technologies Roadmap*[16] in August 2018, the EU's Quantum Technologies Flagship program is a $1.1 billion, 10-year initiative to commercialize the EU's investment in basic QIS R&D. The goals of the initiative are to

- foster a competitive European quantum industry to position Europe as a leader in the future global industrial landscape;
- expand European scientific leadership and excellence in quantum research;
- make Europe an attractive region for innovative businesses and investment in quantum technologies; and
- benefit from advances in quantum technologies to provide better solutions to grand challenges in such fields as energy, health, security, and the environment.

United Kingdom

In 2013, the UK established a five-year, $440 million National Quantum Technologies Program to translate QIS R&D into commercial technologies. In September 2018, the UK announced that it would invest more than $105 million in four UK-based quantum technology development centers over the next five years. Likely research areas may include internet security, vehicle

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[11] "Congress's Quantum Science Bill May Not Keep the US Military Ahead of China," Defense One, September 17, 2018, https://www.defenseone.com/threats/2018/09/congresss-quantum-science-bill-may-not-keep-us-military-ahead-china/151319/.

[12] "At Last America Is Moving on Quantum," *Forbes*, August 20, 2018, https://www.forbes.com/sites/arthurherman/2018/08/20/at-last-america-is-moving-on-quantum/.

[13] "Is China the Leader in Quantum Communications?," *Inside Science*, January 19, 2018, https://www.insidescience.org/news/china-leader-quantum-communications.

[14] "Chinese Satellite Uses Quantum Cryptography for Secure Video Conference Between Continents," *MIT Technology Review*, January 30, 2018, https://www.technologyreview.com/s/610106/chinese-satellite-uses-quantum-cryptography-for-secure-video-conference-between-continents/.

[15] European Union, *Quantum Manifesto*, May 2016, https://time.tno.nl/media/7638/quantum_manifesto.pdf.

[16] European Union, *The Quantum Technologies Roadmap*, August 2018, http://qurope.eu/h2020/qtflagship/roadmap2016.

driving assistance systems, life-saving equipment for search-and-rescue missions, and helping firefighters.[17]

Canada

Canada's QIS program began in 1999 with private investments that established the Perimeter Institute and University of Waterloo as leaders in QIS R&D. Canada's 2018 budget provided $11.5 million (USD) over three years to the Institute of Quantum Computing at the University of Waterloo.

U.S. Congressional Activity

Three QIS-focused bills have been introduced in the 115th Congress. Additionally, the House has held three QIS hearings.

Legislation

The Senate has introduced two bills and the House has introduced one bill related to QIS.

National Quantum Initiative Act (S. 3143, H.R. 6227)

The National Quantum Initiative Act (S. 3143, H.R. 6227) was introduced in the Senate on June 26, 2018, by Senator John Thune and in the House on June 27, 2018, by Representative Lamar Smith. These bills would establish a federal program to accelerate U.S. QIS R&D. Specifically, the bills would establish a National Quantum Coordination Office within OSTP to

- oversee interagency coordination,
- provide strategic planning support,
- serve as a central point of contact for stakeholders,
- conduct outreach, and
- promote commercialization of federal research by the private sector.

The bills are intended to

- support basic QIS research and standards development at NIST, support DOE basic research and establish DOE national research centers, and support National Science Foundation basic research and academic multidisciplinary quantum research and education centers;
- encourage U.S. technology companies to contribute their knowledge and resources to a national effort; and
- address fundamental research gaps, assist in creating a stronger workforce pipeline, and allow the United States to take the lead in developing quantum standards and measures for global use.

H.R. 6227 was reported by the House Committee on Science, Space, and Technology (H.Rept. 115-950) and passed in the House on September 13, 2018; it was received by the Senate and referred to the Committee on Commerce, Science, and Transportation on September 17, 2018. S.

[17] "£80m Funding to Boost UK Quantum Technology Programs," Optics.org, September 13, 2018, http://optics.org/news/9/9/20.

3143 was approved and ordered to be reported with an amendment in the nature of a substitute by the Senate Committee on Commerce, Science, and Transportation on August 1, 2018.

Quantum Computing Research Act (S. 2998)

The Quantum Computing Research Act (S. 2998) was introduced by Senator Kamala Harris on June 5, 2018. The bill would require the Secretary of Defense to establish the Defense Quantum Information Consortium. The consortium would include

- one component composed of members selected by the Chief of Naval Research from among institutions of higher learning and industry partners located in the eastern half of the United States which are recognized for achievement in quantum information science; and
- one component composed of members selected by the Director of the Army Research Laboratory from among institutions of higher learning and industry partners located in the western half of the United States which are recognized for achievement in quantum information science.

The bill would also establish a board composed of

- the Chief of Naval Research and a designee of the Chief;
- the Director of the Army Research Laboratory and a designee of the Director;
- the Assistant Director of Quantum Information Science at the Office of Science and Technology Policy; and
- members of the National Quantum Initiative (NQI).

The board would be responsible for

- awarding grants to consortium members;
- assisting with ongoing research being conducted by consortium members relating to quantum information sciences; and
- facilitating partnerships between consortium members.

Hearings

Three House committees have held hearings on different aspects of QIS.

American Leadership in Quantum Technology

On October 24, 2017, the House Committee on Science, Space, and Technology Subcommittee on Research and Technology and Subcommittee on Energy held a joint hearing on "American Leadership in Quantum Technology."[18] Issues discussed included

- a comparison of U.S. and international QIS R&D and
- how to effectively train a QIS-knowledgeable workforce.

[18] https://science.house.gov/legislation/hearings/american-leadership-quantum-technology.

China's Pursuit of Emerging and Exponential Technologies

On January 9, 2018, the House Armed Services Committee Subcommittee on Emerging Threats and Capabilities held a hearing on "China's Pursuit of Emerging and Exponential Technologies."[19] Issues discussed included

- China's investment in leading-edge technologies, including QIS, and
- concerns that China may be closing the gap with the United States in advanced technology R&D.

Disrupter Series, Quantum

On May 18, 2018, the House Committee on Energy and Commerce Subcommittee on Digital Commerce and Consumer Protection held a hearing on quantum computing as part of its "Disrupter Series."[20] Issues discussed included

- an overview of the uses of quantum computers,
- the advantages of quantum computers over conventional computers,
- potential dangers from quantum technologies,
- barriers to the development of a commercially available quantum computer in the United States, and
- where the United States stands in relation to other nations in developing a commercially available quantum computer.

U.S. Policy Considerations

In its July 2016 report, the NSTC stated that creating a cohesive and effective U.S. QIS R&D policy would require a collaborative effort among government, academia, and the private sector. The report cited five key areas that need to be addressed in crafting an effective policy: institutional boundaries; education and workforce training; technology and knowledge transfer; materials and fabrication; and the level and stability of funding. These topics were reiterated in the DOE report *Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science, and Computing* (2016), and during congressional hearings.

Institutional Boundaries

QIS research is often conducted within institutional boundaries with little coordination. For example, federal departments, and even agencies and offices within a department, have sponsored R&D at a number of universities in different disciplines to address unique federal mission requirements. As a result, coordination and collaboration among these university researchers is difficult. The creation of cross-cutting teams with diverse expertise is seen by many as vital to success. Many observers and researchers contend that partnerships that encourage such collaboration will lead to greater progress than working alone.

[19] https://armedservices.house.gov/legislation/hearings/china-s-pursuit-emerging-and-exponential-technologies.

[20] https://energycommerce.house.gov/hearings/disrupter-series-quantum-computing/.

Education and Workforce Training

Scientists and industry representatives contend that current academic education and workforce training programs are insufficient for continued progress in QIS R&D, which requires a diverse, cross-cutting range of skills and expertise that varies from one application to another. For example, while a deep knowledge of quantum mechanics, taught in physics departments, is required for QIS basic research and applications development, disciplines taught in other departments—such as computer science, applied mathematics, electrical engineering, and systems engineering—are needed as well. Multidisciplinary QIS centers at universities and federal labs (e.g., DOE, NIST) are seen as one possible solution to this problem.

Technology and Knowledge Transfer

Some of the potentially serious impediments to creating successful commercial QIS products include issues related to the complicated nature of licensing of intellectual property from universities and obtaining patents, lack of a strong venture capital environment, and difficulty connecting qualified recent graduates and experienced scientists with companies. Industry and government representatives have noted that some federal programs exist to address these issues, but that challenges remain.

Materials and Fabrication

Advancement of QIS applications depends heavily on the generation of novel quantum materials and on improving the tools needed to fabricate them and package hardware that may currently fill a room into usable forms. These challenges are not yet fully understood, but scientists generally agree that advancement in QIS R&D depends upon solving them.

Level and Stability of Funding

Like other R&D programs, QIS is affected by fluctuations in federal funding. Some assert that such fluctuations have slowed QIS progress, as well as the development of a fully qualified workforce. Some of the funding instability has been attributed to insufficient coordination among federal agencies, which has led to uncertainty in university research programs. This uncertainty may have contributed to promising researchers seeking opportunities outside the United States or being actively recruited by foreign governments or companies.

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