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Federal Quantum Information Science: An Overview

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. This In Focus provides an overview of QIS technologies, including examples of their existing and future applications; brief summaries of funding and selected initiatives in research and development (R&D) in the United States and elsewhere around the world; a description of U.S. congressional activity; and a discussion of related policy considerations.

Technologies and Applications

In quantum computing, rather than *bits* of information that can be encoded as 0 or 1, *qubits* of information can take on the value 0, or 1, or both simultaneously. This greatly enhances computing ability.

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 four application areas: sensing and metrology, communications, computing, and simulation. Others combine computing and simulation as a single category.

- Sensing and metrology—performing navigation, locating mineral deposits, keeping precise time;
- Communications—generating quantum keys for encryption, sending quantum-secure communications (any eavesdropping attempt destroys the communication and the eavesdropping is detected);
- Computing—performing some computations much faster than is possible using conventional high-performance computers; and
- Simulation—determining the properties of materials such as high-temperature superconductors, modeling nuclear and particle physics.

U.S. Government Funding and Initiatives

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. Today, QIS is a component of the National Strategic Computing Initiative (Presidential Executive Order 13702), which was established in 2015. The following year, the National Science and Technology Council (NTSC), under the purview of the White House Office of Science and Technology Policy (OSTP), issued *Advancing Quantum Information Science: National Challenges and Opportunities*. This report provided an overview of QIS technologies and applications, surveyed federal government investment in QIS, and identified issues impeding progress in QIS R&D. More recently, in early 2018, the President recognized QIS as one of several emerging technologies that he sees as key to American prosperity and named an OSTP assistant director for QIS.

The overall annual federal budget for QIS R&D is difficult to calculate across the many departments receiving such funding, but some analyses put that figure between $200 and $250 million. It is also difficult to determine the budget figures that the intelligence community, DOD, and other classified programs have committed to QIS R&D.

Although the federal government has conducted QIS R&D for many years, it has not explicitly made it a national priority, stated any formal federal R&D goals, or established a national quantum initiative or agenda (legislation has been introduced for this purpose). This stands in contrast with the European Union (EU), China, the United Kingdom (UK), and Canada, each of which has made strong statements in support of QIS R&D and supported those statements with explicit funding.

International Funding and Initiatives

QIS R&D is being pursued at major research centers worldwide, with the EU and China 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, other countries, including Russia, Germany, and Austria, are making strides in QIS. A report by the Institute for Defense Analysis, *Assessment of the Future Economic Impact of Quantum Information Science* (2017) and witness testimony at congressional hearings have provided information on these programs.

European Union. Outlined in the EU's 2016 *Quantum Manifesto* and scheduled to launch in 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. Additionally, the program seeks to consolidate and expand European scientific leadership and excellence in QIS R&D; promote a competitive European industry in QIS; and bring QIS R&D, businesses, and investments to the EU.

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 one of six major goals for this period. China's annual funding for QIS R&D has been estimated at $244 million.

On September 29, 2017, China was the first country to achieve two QIS milestones: Operating a long-distance quantum communication landline between Beijing and

Shanghai and conducting the first quantum-encrypted video call. In 2017, the country also 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 who live overseas back to China.

United Kingdom. In 2013, the UK established a five-year, $440 million National Quantum Technologies Program to translate QIS R&D into commercial technologies. The UK spends approximately $1 billion annually on technology research and postgraduate training. QIS technologies account for about 4% of that total.

Canada. Canada's Perimeter Institute and University of Waterloo lead that country's QIS R&D. They received a $56 million award from the Canada First Research Excellence Fund in 2016.

U.S. Congressional Activity, 115th Congress

The House has held three hearings on QIS:

- **American Leadership in Quantum Technology**, House Committee on Science, Space, and Technology Subcommittee on Research and Technology and Subcommittee on Energy, October 24, 2017.
- **China's Pursuit of Emerging and Exponential Technologies**, House Armed Services Committee Subcommittee on Emerging Threats and Capabilities, January 9, 2018.
- **Disrupter Series: Quantum Computing**, House Committee on Energy and Commerce Subcommittee on Digital Commerce and Consumer Protection, May 18, 2018.

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

- **Quantum Computing Research Act (S. 2998),** introduced by Senator Kamala Harris on June 5, 2018. The bill would require the Secretary of Defense to establish the Defense Quantum Information Consortium.
- **National Quantum Initiative Act (S. 3143, H.R. 6227)**, 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.

U.S. Policy Considerations

In its July 2016 report, the NTSC 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 four key areas that need to be addressed in crafting an effective policy: institutional boundaries; education and workforce training; technology and knowledge transfer; 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. Also, as noted earlier, experts express concern that the United States has not yet explicitly made QIS a national priority.

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 universities in different disciplines to address unique federal mission requirements. As a result, coordination and collaboration among university researchers is difficult. The creation of diverse, cross-cutting teams 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.

Education and Workforce Training. Scientists and industry representatives contend that current academic education and workforce training 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 (e.g., computer science, applied mathematics, and electrical engineering) are needed as well. Multidisciplinary QIS centers at universities and federal labs (e.g., DOE, NIST) may be a solution to this problem.

Technology and Knowledge Transfer. Impediments to creating successful commercial QIS products include licensing intellectual property from universities and obtaining patents, lack of a strong venture capital environment, and difficulty connecting qualified graduates and experienced scientists with companies. Industry and government representatives have noted that some programs do exist to address these issues, but that challenges remain.

Materials and Fabrication. Advancement of QIS applications depends on improving the tools needed for the reliable fabrication of quantum materials, such as the ability to miniaturize hardware that may currently fill a room. These challenges are not fully understood, but scientists agree that advancing 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 entities.

QIS R&D Policy There is a consensus among many U.S. scientists and federal agency leaders that the current lack of a unified national policy for QIS may hurt R&D efforts in the long run. However, who would lead this unified effort and how much it could cost is unclear.

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