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Assessment of the Future Economic Impact of Quantum Information Science

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Executive Summary

Quantum information science (QIS) builds on scientific principles unique to quantum science—the study of the smallest particles of matter and energy—to obtain and process information in ways that cannot be achieved based on classical physics principles. Quantum phenomena have been harnessed to enhance the accuracy of sensors and detectors, which has advanced basic science experimentation and produced commercial products. They also hold promise for securing sensitive communications and creating more powerful computers. The pace of basic and applied research in QIS as well as the development and demonstration of technologies employing QIS is increasing. The extent to which the various QIS technologies that are under development will translate into significant commercial markets is, however, an open question.

Researchers from the IDA Science and Technology Policy Institute conducted an economic assessment of the potential shape and size of future markets for QIS technologies. To inform the assessment, we drew on government documents, discussions with stakeholders, and articles on QIS from business, technical, and scientific journals to develop a comprehensive list of potentially commercially viable technologies. We grouped these QIS technologies and their applications into three categories: quantum metrology and sensing, quantum communications, and quantum computing and simulation.

The results of this assessment are intended to improve coordination of Federal expenditures on QIS so as to overcome identified impediments to the development of the QIS products and services we describe.

Technologies

For each category of technology analyzed, we determined what the technology offers to potential buyers, the timescale over which the technology is likely to become commercially available, and the potential size of the market at which it is directed. In addition, we identified current activity in developing these QIS technologies in the United States and around the world, detailing efforts funded by both government and private industry. Summaries of our assessment of technologies in each of the three categories follow.

Quantum Metrology and Sensing

Quantum metrology and sensing is the technology category with the largest array of existing and potential commercial products, which include atomic clocks, gravimeters and gravitational gradiometers, inertial motion units, atomic magnetometers, magnetoencephalography scanners, electron microscopes, and quantum-assisted nuclear spin imaging devices. It is also the most established category in that several products based on quantum phenomena have been manufactured for decades. We 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. However, most potential markets for QIS technologies in metrology and sensing are small. In some cases, traditional metrology and sensing remain more attractive in light of the higher costs and technical complexity of the new quantum devices.

Quantum Communications

Quantum key distribution (QKD) is one component of quantum cryptography, which uses principles of quantum physics, instead of mathematical algorithms, to generate and distribute encryption keys used to safeguard the transmission of data over unprotected networks. While QKD offers a secure solution, because signals traveling over fiber optic cable are attenuated, encrypted messages can be sent only 100 kilometers before they need to be detected and retransmitted. Quantum repeaters hold the promise of extending the link distance for which the signal remains in the quantum domain, though they significantly increase the complexity of the system. Moreover, transmission is only one element in ensuring that communications are secure and is often not the weakest link. We found that the Chinese government has been spending heavily on QKD; many in North America and Europe approach the commercial demand for these technologies with skepticism because existing non-quantum technologies have been satisfactory and less costly.

According to our research, quantum random number generators (QRNGs) and other true random number generators (TRNGs) that are based on physical properties offer an important advantage compared to classical, deterministic methods of number generation because they create randomness through physical processes, both classical and quantum. Only the quantum approach provides a path for absolute unpredictability, in principle; however, the likelihood of predictability for a well-designed random number generator based on physical processes is rarely limited by the source of physical randomness for a well-designed system. The market for QRNGs is currently small; the greatest demand is for lotteries and gaming, and cryptography. The main companies that provide QNRGs are based in Europe, Australia, and the United States, and they currently offer few advantages over TRNGs.

Quantum Computing and Simulation

Quantum computing offers the possibility of computing in an exponentially larger state space than readily accessible with classical computing, allowing possible advantages for certain applications. Quantum simulation refers to the use of quantum hardware to learn the critical properties of a complex quantum system. However, we found that the current capability in quantum computer hardware limits the size of the problems that can be handled and the types of algorithms that can be developed. Despite the substantial current research activities in government laboratories, university departments, large technology companies, and small start-ups, it is unlikely that commercial products in quantum computing will be widely available in the next ten years.

Foreign Government Support and Foreign Industries

U.S. and foreign governments have fostered the development of quantum technologies in several ways: through support of basic and applied research in government and non-government laboratories and universities; through scholarships and fellowships for graduate students, primarily in physics; through grants and subsidized loans to manufacturers; and through purchases of products and services that incorporate quantum technologies. China, the European Union, and the United Kingdom have created national strategies for developing quantum technologies. Other countries have created national programs. In the United States, a large number of agencies fund research in quantum technologies, but our assessment indicates that these programs are not as coordinated as efforts in China and Europe.

We found that companies engaged in developing products that incorporate QIS technologies are located almost exclusively in the developed world. Large and small corporations in Europe and the United States manufacture quantum measuring devices and sensors. Large Japanese and Korean electronics and telecommunications companies have been investing in quantum communications technologies. Chinese firms have also focused on quantum communications technologies, but have confined their activities to the Chinese domestic market. Quantum computing is dominated by the United States, although European companies are also engaged in this sector. U.S. industry is split between small start-ups and research teams, often also small, within technology giants like IBM, Microsoft, Alphabet (Google), and Intel.

Key Findings

The most important findings from our assessments of the commercial potential and viability of QIS technologies are:

1. Markets for quantum metrology and sensing are well-established, but are small (less than $50 million a year) to medium ($50 million to $500 million) in size.
2. Potential markets for inertial navigation systems and reduced interaction electron microscopes are likely to be larger, falling into the $50 million to $500 million range.

3. The market for QKD has been slow to take off because the advantages of quantum keys for security are offset by cost, complexity, and technical limitations (the need to retransmit the keys for separation greater than 100 kilometers).
4. Current commercial quantum computing capabilities are very limited and are likely to remain so for at least the next 10 years, though the introduction of small processors may spur additional algorithm development efforts.
5. Quantum computing and simulations are likely to serve niche markets, like measuring the ground-state energies of specific molecules; they are likely to be used in conjunction with classical computation.
6. The United States is currently ranked the leader in QIS technologies. China is ranked second and has rapidly increased the number of publications in the field, especially in quantum communications.
7. U.S. and European companies are the primary suppliers of quantum metrology and sensing technologies to the world market.
8. Small U.S. start-ups and large technology firms dominate the global quantum computing industry.
9. The immediate commercial potential for QIS technologies appears modest, though continued research may lead to breakthroughs and increase their commercial potential.

Outlook

QIS technology roadmaps have been optimistic about the pace of technology development. For example, a 2002 Advanced Research and Development Activity (ARDA) technology roadmap set aggressive high-level goals for the years 2007 and 2012. It is now 10 years past the original 2007 goals, some of which are starting to come within reach. The 2012 high-level goal of the ARDA roadmap are likely still more than a decade away. Such lags are part of the nature of research, particularly when the problems are as challenging as they are for quantum computing.

QIS technologies are unlikely to generate large, near-term commercial payoffs. However, QIS has and will provide for unique and powerful new technologies, beyond the reach of classical technologies. Over the course of the century, quantum technologies are very likely to be economically important.

Contents

1. Introduction

A. Purpose

The IDA Science and Technology Policy Institute (STPI) conducted this research to provide an economic assessment of the potential shape and size of future markets for quantum information science (QIS) technologies.

For each technology examined, we explain what the technology offers to potential buyers, the timescale over which the technology is likely to become commercially available, and the potential size of the market at which it is directed. This assessment is designed to assist in coordinating Federal expenditures on QIS so as to more efficiently overcome impediments to the development of QIS products and services.

B. Background

QIS builds on unique principles of quantum physics such as superposition, entanglement, and squeezing to obtain and process information in ways that cannot be achieved based on classical physics principles. Quantum phenomena have been harnessed to manufacture sensors and detectors that are more accurate and take laboratory measurements with greater precision. They may eventually be employed to build more powerful computers and provide new technologies for commerce and defense.

The pace of basic and applied research in QIS as well as the development and demonstration of technologies employing QIS is increasing, as noted in a National Science and Technology Council (NSTC) report, and is likely to continue to accelerate in the near future (NSTC 2016). Patents and publications on QIS have grown rapidly, as shown in the NSTC report. Although QIS remains a nascent field, more than 50 companies have received QIS patents, reflecting the growth in the industrial base. Investment in QIS is rising. IBM, Microsoft and Google have quantum research laboratories ("Quantum Computers Are Coming" 2016). In the past 5 years, venture capital has begun to make significant investments in QIS. Venture capital analysts report that 27 disclosed equity rounds for companies developing technologies employing QIS closed between 2013 through mid-2016, nearly four times the number from 2000–2013 ("Quantum Computing" 2016). Despite this interest by commercial entities, QIS has yet to be commercialized on a large scale. Even though basic research shows promise, most QIS technologies are not yet sufficiently reliable, accurate, capable, or low cost to compete with non-quantum substitute technologies. For QIS to become truly commercial outside of existing markets in metrology and sensing, it will have to achieve substantial improvements in performance or cost. This assessment is directed at determining the potential trajectory of these future applications of quantum technologies.

C. Approach

To assess the commercial potential for technologies based on QIS, the STPI team first drew on government documents, discussions with stakeholders, and articles from business, technical, and scientific journals on quantum information science to develop a comprehensive list of potentially commercially viable technologies grouped into three categories: quantum metrology and sensing (Chapter 2), quantum communications (Chapter 3), and quantum computing and simulation (Chapter 4).

Drawing on our review of articles and interviews with practitioners in the area of QIS, we selected several promising technologies in each of the three areas and developed a short description of what the technology does. In particular, we determined whether the technology provides (1) a unique capability; (2) a capability that is better than existing alternatives on the basis of performance, cost, or other metrics used by the business community; or (3) a capability that is simply different than that offered by existing non-quantum alternatives. We drew on interviews and discussions with over three dozen individuals employed by companies, universities, research centers, and government agencies involved in the development of quantum technologies in these areas to garner information on technology capabilities. (The organizations represented by our interviews for this effort are listed in Appendix A.)

We ascertained the likely timescales to market for the products or services generated by each of these technologies and defined *commercial* products or services as those currently available on the market, *short-term* products or services as those expected to become commercially available within the next 5 years, *medium-term* products or services as those likely to become commercially available within 5 to 10 years, and *long-term* products or services as those unlikely to become commercially available within 10 years

We then identified and sized the markets in which these products or services might be sold. Drawing on descriptions of what these products or services provide, we assessed the current markets for analogous non-quantum products and services. For example, we evaluated the current market for position and navigation technologies that do not rely on the global positioning system. We identified the principal customers for each of these markets and grouped them as follows: research (universities and government and commercial laboratories); investment (primarily businesses); government (civilian and military entities); and household. We then assessed likely potential future cost or price points for technologies that draw on QIS and evaluated the likely share of future markets these technologies are likely to capture based on their likely future prices compared to current alternatives. Where we found disagreement about prices or costs among our sources of information, we constructed demand points to form rudimentary demand curves based on two or three points, illustrating the potential range in quantity demanded as prices fall. This analysis was used to categorize each technology in terms of potential future market size: small (less than $50 million in sales per year), medium ($50 million to $500 million per year), or large (over $500 million per year).[1] For each of these products or services, we provide in Chapters 2–4 an overview of the companies currently engaged in developing or selling them. We also describe the structure of the industry in which they operate, including the range and average size of companies, their geographic location by country, and the competitive landscape.

We then identified the role governments play in the development of commercial applications of quantum technologies. We looked at government participation in (1) China, (2) Europe (European Union, Germany, the Netherlands, and the United Kingdom); (3) other foreign countries (Australia, Canada, Japan, Russia, and South Korea), and (4) the United States. In Chapter 5, we describe government programs that support this industry, assess the national industries in terms of size and focus, and evaluate the importance of government support for the industries in these countries.

Chapter 6 provides our findings concerning commercial prospects for selected potential products and services from each of the three groups of quantum technologies. Here, we provide evaluations of the health and strength of the quantum science industries within each of these groups, comparisons of the size and effectiveness of government programs and of foreign industries with those in the United States, and observations concerning U.S. government policy pertaining to the commercializing of technologies employing QIS.

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[1] We use the symbols $ to refer to U.S. dollars (USD), £ to refer to pounds, and € to refer to euros. For other forms of currency, we use the dollar symbol in conjunction with codes from the International Organization for Standardization (ISO) list of currency codes.

2. Quantum Metrology and Sensing

A. Potential Commercial Technologies

To date, metrology and sensing is the sector where quantum technologies have been most successfully introduced into commercial products. It is also the sector with the largest array of existing and potential commercial products. Table 1 indicates the commercial readiness and potential future markets of technologies in this sector.

Table 1. Quantum Metrology and Sensing Technologies

Technology	Technological Readiness[a]	Potential Market
Measurement		
Atomic clocks	Commercial	\$50–\$500 million
Meters for voltage, current, and resistance	Commercial	—
Sensors		
Gravimeters and other atomic interferometers	Commercial	< \$50 million
Quantum inertial motion units	Medium-term	\$50–\$500 million
Atomic magnetometers	Commercial	\$50–\$500 million
Magnetoencephalography	Commercial	\$50–\$500 million
Quantum electron microscopes	Medium-term	\$50–\$500 million
Quantum-assisted nuclear spin imaging	Long-term	< \$50 million
Signal measurement	Medium-term	—

Sources: European Commission (2017) United States Air Force Scientific Advisory Board 2015; interviews.

[a] *Commercial* indicates that products or services from the technologies are currently available; *short-term* readiness means products or services are expected to become commercially available within the next 5 years; *medium-term* readiness means products or services are likely to emerge within 5 to 10 years, and *long-term* readiness means products or services are unlikely to become commercially available within the next 10 years.

B. Atomic Clocks

1. Description and Value of Technology

Atomic clocks measure time by using transitions between the energy levels of atoms of specific elements as a stable frequency reference. To function well as a basis for an atomic clock, these atoms must have stable transition frequencies, be cooled to minimize velocity-induced frequency shifts, have a reliable initial state preparation, and have efficient state detection (Schmidt et al. 2005). Many innovations in these areas have led to orders-of-magnitude improvements in clocks over the last four decades.

Atomic clocks have been in existence for decades and have been developed with varying levels of precision. Here we discuss four types of atomic clocks that meet differing market demands: highly accurate optical lattice and quantum logic clocks, cesium clocks, rubidium clocks, and chip-scale atomic clocks. These clocks vary widely in accuracy, stability (how well an oscillator keeps time over a time interval), aging (change of accuracy and precision over time), and temperature stability (Owings and Ramakrishnan 2014). Prices and applications for these differing types of clocks vary widely.

In the 1950s, scientists at the National Physical Laboratory in the United Kingdom developed atomic clocks using cesium atoms. These clocks were used to set the international standard for the second in terms of frequency in 1967, and they are still used today as the international time standard (Bloom et al. 2014). Cesium clocks are currently based on cesium-133 atoms and have a fractional uncertainty of approximately 10^{-13}. Another standard clock is based on rubidium-87 atoms; these clocks have a fractional uncertainty of 10^{-11} (Table 2).

Table 2. Atomic Clock Precision, Price, Size, and Use

Fractional Precision	Price	Size	Use
10^{-9}	$1,000	2 cm	Short-haul navigation and local communications
10^{-11}	$3,000	15 cm	Local communications hubs and instrumentation level flywheels
10^{-13}	$70,000	1 m	Large-scale communications systems, power grids, GPS space clocks, and local synchronization
10^{-15}	$1,000,000	10 m	Master clocks (long-term synchronization), secure communications, deep space navigation, GPS master clock (ground)

Source: Kitching (n.d.).

In the 1990s, the development of technologies such as ion trapping and frequency combs paved the way for highly accurate quantum logic and optical lattice clocks. In 2014, the National Institute of Standards and Technology (NIST) optical lattice clock became the most accurate clock in the world. Both optical measurement and the lattice design led to this improved accuracy. Optical clocks are generally more accurate than clocks based on microwave standards because they employ higher frequencies; however, optical frequencies have traditionally been more difficult to measure. The lattice design traps many neutral atoms, unlike previous designs, such as the quantum logic clock, that trapped single ions. Because these neutral atoms are trapped in large numbers, clocks using neutral atoms have a high signal-to-noise ratio, making the clocks more stable (Oates 2008). As optical clocks become more stable, they may replace cesium clocks as the international standard. The most recent development in the quest to improve clock accuracy is using specially prepared (squeezed) states to control fundamental quantum noise (Dwyer 2013).

In the early 2000s, the Defense Advanced Research Projects Agency (DARPA) began supporting the development of chip-scale atomic clocks (CSACs) with a focus on reducing the size and cost of atomic clocks. CSACs became commercially available in 2011. These clocks are under 2 cubic centimeters in size, smaller than rubidium clocks, which are about 15 centimeters in length, or cesium clocks, which are about 1 meter in length (Kitching n.d.). They are not only smaller, but also cheaper, albeit less accurate than cesium or rubidium clocks (Rosenband et al. 2008).

2. Current and Potential Markets

Activities that benefit from highly precise clocks include (1) ascertaining position and navigation, especially in locations where radio global positioning systems (GPSs) are unavailable, such as in mines or submarines; (2) establishing the time of financial transactions; (3) synchronizing cell phone transmissions so that calls can be seamlessly shifted from one cell to another; and (4) conducting scientific research. In addition to military uses, non-GPS systems are also used underwater, within buildings, underground, and in other locations where GPS is not available. Clocks, however, are just one component of these systems, which we discuss in the paragraphs that follow. Clocks are also used in conjunction with gravimeters to detect deposits of oil and gas and for scientific experiments. In many of these applications the accuracy and other features of current clocks used are sufficient.

Cesium clocks, rubidium clocks, and chip-scale atomic clocks are all sold commercially for these purposes. Optical lattice clocks and other experimental clocks are currently only used for laboratory applications, some of which include setting or maintaining the national time standard.

The market for cesium atomic clocks is limited. In recent years, demand outside the scientific community for atomic clocks, including traditional cesium clocks, has been small (United States Air Force Scientific Advisory Board 2015). Though recent advances in cesium clocks, such as the optically pumped cesium clock, may become commercially available soon, the market for it is unlikely to exceed the existing market for cesium clocks.

The industry leader, Microsemi Corporation, produces several models of cesium clocks. According to one interviewee, annual sales of its most accurate Microsemi 5071A are in the hundreds of units per year. This model is priced at roughly $75,000, making it expensive compared to non-atomic clocks, even when fairly precise timekeeping is needed. Microsemi also produces less expensive versions of cesium clocks, including an atomic clock primarily for telecom applications priced at roughly $30,000. Microsemi sales of this telecom-grade clock run in the low thousands of units per year, roughly ten times those of the 5071A. According to the same interviewee, Oscilloquartz (a Swiss company that has been acquired by ADVA Optical Networking) has recently developed a prototype of an optically pumped clock that is designed to outperform Microsemi's 5071A by a factor of five. This clock is likely to be priced at roughly $100,000.

Rubidium atomic clocks are widely used in cellular towers. Priced at roughly $3,000, they are substantially cheaper than cesium atomic clocks. Rubidium atomic clocks are also two orders of magnitude less accurate. According to the interviewee, the number of rubidium atomic clocks sold peaked in the early 2000s when approximately 200,000 were produced and sold each year, primarily to cell phone operators. The number sold annually has since fallen as the cell phone industry increasingly relies on GPS for timing. Rubidium atomic clocks are more accurate than CSACs, but they need to be connected to a source of electric power, as they need more power than can be supplied by batteries on an on-going basis. In many developing countries or in remote areas, cell phone towers often run on batteries because the towers are relatively far away from the electric power grid, making GPS or other timing alternatives more attractive than rubidium atomic clocks.

CSACs have found a market in position, navigation, and timing (PNT) and communications, especially for short-haul navigation and local communication applications. CSACs are much smaller than other atomic clocks, making the potential application pool larger, possibly eventually extending to automobiles and smart phones. But the price of CSACs would have to fall substantially to be used in automobiles and smart phones. Currently, CSACs cost roughly $1,000 apiece; to expand the user base, prices would probably have to fall to $100 or lower, according to our interviewee. Currently, annual sales of CSACs appear to be small. According to its 2014 Annual Report, the original manufacturer, Symmetricom, Inc. (since acquired by Microsemi) had sales slightly over $200 million in 2014. CSAC sales appear to have accounted for a small share of these revenues.

3. Industry

While the primary manufacturers of atomic clocks vary by clock type, currently Microsemi and ADVA's Oscilloquartz subsidiary are the overall industry leaders and the two primary manufacturers of cesium atomic clocks. Microsemi, headquartered in Alisa Viejo, California, acquired its atomic clock business in 2013 when it purchased Symmetricom, which had been headquartered in San Jose, California. Before the acquisition, Symmetricom had annual sales of a little over $200 million a year and had been the primary manufacturer of cesium atomic clocks in the world, accounting for the majority of all cesium atomic clocks that have ever been sold. In addition to sales of cesium atomic clocks, Symmetricom sold highly precise time keeping and synchronization technologies, instruments, and solutions (Symmetricom, Inc. 2013). Microsemi, Symmetricom's owner, is now the largest manufacturer of cesium clocks globally, a large manufacturer of rubidium clocks, and one of the only manufacturers of CSACs. Microsemi manufacturers the 5071A Frequency Standard cesium atomic clock, which was initially produced in the 1990s by Hewlett-Packard (now known as HP). Agilent Technologies, an HP spinoff company, produced the clock from 1999 until 2005, when Symmetricom acquired this product line (National Museum of American History n.d.).

In addition to cesium atomic clocks, ADVA's Oscilloquartz subsidiary manufactures frequency sources, such as GPS receivers, Global Navigation Satellite System (GLONASS) receivers, and synchronization solutions (Swatch Group 2012). It provides end-to-end time and frequency synchronization to telecommunications companies. Prior to 2007, Oscilloquartz sold rebranded versions of Symmetricom's cesium clocks primarily in Europe. The company has been manufacturing frequency and timing products for over 60 years. In 2014, the company was purchased by ADVA Optical Networking, a German telecommunications equipment manufacturer, from the Swiss watchmaker Swatch, which had acquired the group around the turn of the last century. In 2016, ADVA reported annual revenue of €566.7 million ($629.04 million USD).[2] Based on information from Swatch from previous years when it owned Oscilloquartz and year-on-year revenue changes for ADVA, sales of Oscilloquartz products contributed modestly to this figure, suggesting that sales by Oscilloquartz were in the range of a few million euros (ADVA Optical Networking 2016).

In addition to Microsemi and ADVA's Oscilloquartz, the following companies manufacture rubidium clocks: Frequency Electronics, headquartered in Long Island, New York; SRS, headquartered in Sunnyvale, California; Spectratime, headquartered in Neuchatel, Switzerland; and Accubeat, headquartered in Jerusalem, Israel. Microsemi is the primary manufacturer of CSACs in the United States. Although Jackson Labs Technologies, Inc., makes its own CSACs for sale, it also sells Microsemi clocks under license. In addition, several Chinese companies advertise sales of atomic clocks, but they do not appear to have a large share of the market.

Frequency Electronics, Inc., headquartered on Long Island, New York, sells time and frequency technologies, primarily for satellite systems, the company's primary market (Frequency Electronics, Inc. 2015). In the 1970s and 1980s, Frequency Electronics sold cesium clocks. Frequency Electronics currently manufactures rubidium atomic clocks, among other time and frequency technologies. Revenues for 2015 were $76.6 million, with

[2] Based on average annual euro-dollar exchange rate in 2016 of 1.11 dollars per euro from the International Monetary Fund's International Financial Statistics database: http://data.imf.org.

sales to military and commercial clients roughly of equal size (Frequency Electronics, Inc. 2015). Frequency technologies appear to be the most important source of revenues, although precision timing is also a core product. Timing includes time pieces based on quartz crystals as well as atomic clocks employing rubidium.

In 2000, DARPA funded researchers at several companies, including Symmetricom, Teleydyne Scientific & Imaging, Honeywell, Strategic Resources, Inc. (SRI), and Sandia National Laboratories, to develop CSACs. Microsemi's version is the only one that has become commercially available even though other companies had built prototypes. For example, Teleydyne Scientific & Imaging, a research and development (R&D) company that focuses mainly on high-speed electronics, microelectromechanical system sensors and actuators, and compound semiconductors, progressed to Phase Four of DARPA's CSAC program and achieved the program's size, power, and stability goals. However, Teleydyne never sold CSACs (Donley 2008). As noted above, annual sales of CSACs appear to be small.

Time and frequency product lines are not major sources of revenue for Microsemi or ADVA Optical Networking. These two companies, along with the companies that produce rubidium clocks, are small to mid-sized companies (National Museum of American History n.d.).

4. Prospects for Clocks

Despite reductions in prices of atomic clocks, especially CSACs, the primary source of demand for clocks of this precision appears to be for position and navigation purposes. In the section on that topic below, we estimate potential demand for position and navigation ensembles, of which clocks are one component.

The key obstacle to greater penetration of atomic clocks has been size and price. While some applications require more accurate clocks (Table 2), the cost of most atomic clocks remains prohibitive for commercial applications when compared to other options, most notably using GPS, which uses atomic clocks, for timekeeping. For example, even though CSAC prices have fallen from roughly $1,500 in 2011 to under $1,000 today, according to an interviewee, this price remains expensive for the vast majority of commercial applications. Although accuracy continues to improve, we do not see signs of additional substantial declines in prices for full-scale atomic clocks. Full-scale atomic clocks, such as cesium and strontium, have been on the market for decades, yet there have been few substantial decreases in prices or size (United States Air Force Scientific Advisory Board 2015). Some companies are trying to design a clock with accuracy of 10^{-13} and at a $5,000–$10,000 price range. Demand for these much more accurate and reliable non-GPS sources of time would have to rise dramatically for the industry to enjoy sharp increases in sales.

C. Gravimeters and Other Atomic Interferometers

1. Description and Value of Technology

Gravimeters employ atomic interferometry, which uses the wave properties of atoms to measure gravitational acceleration, gravity gradients, acceleration, and rotation. These measurements support practical applications, such as navigation and survey. They are also used for fundamental science, including detecting gravitational waves and measuring fundamental constants.

Atomic interferometry is similar to optical interferometry, which uses the wave properties of superimposed photons. In optical interferometry, the superimposed photons are recombined after traveling separate paths, the photons accumulate in constructive and destructive patterns. Changes in these interference patterns indicate a difference in paths. Atomic interferometry uses similar wave properties, but with atoms instead of photons. Lasers cool atoms to millionths of a degree above absolute zero, then pulses of light are used to drive atoms into quantum superposition corresponding to different spatial paths (Müller Group 2017). Two different types of photon pulses, created using either Bragg or Raman transitions, split, steer, and recombine the atoms (Frier 2015). The energy of the atoms determine their de Broglie wavelength. The de Broglie wavelength is inversely proportional to the momentum of the particle and can be used to measure gravitational acceleration and gravity gradients.

It is much easier to produce beams with shorter wavelengths with an atomic beam than with an optical beam. These shorter wavelengths increase the precision of matter-wave interferometers over optical interferometers (which use a longer wavelength). Optical cooling is used to produce a matter beam of a well-defined energy from the cooled atoms. Optical cooling of the matter wave, however, adds a significant amount of complexity to the apparatus. Recently some groups have been experimenting with warm atomic beams so as to eliminate the need for optical cooling (Garrido Alzar 2017).

Some atomic interferometers use Bose-Einstein condensates (BECs). A BEC is a form of matter that consists of atoms that have been cooled to near absolute zero and are all in the same quantum state. BEC interferometers work by suspending a cloud of condensed atoms and shooting a laser into the cloud to create a standing wave (Hardesty 2016). The standing wave separates the cloud into groups of atoms that fall into the troughs of the wave, trapping them at the bottom of a potential energy well. When the laser is turned off, the condensates expand, and their energy shows a pattern that correlates to the accelerations to which the BEC was subject while it was condensed.

This technique is limited by how evenly atoms of a BEC cloud can be separated within the standing wave. For instance, one trough may contain 1,900 atoms while the adjacent one contains 2,100 atoms. Techniques, such as using two condensates with different spins, have been developed to compensate for this unevenness in splitting fractions (Berrada et al. 2013).

Gravimeters employ atomic interferometry to measure variations in gravity. On Earth, gravimeters can be used to find areas where the local density does not match the surrounding density. Areas with higher relative gravity may correlate with denser mineral content, whereas lower gravity areas may correlate with the presence of underground reservoirs, caverns, or soil that is structurally weak compared to the surrounding bedrock.

Gravimetry is useful in research areas such as geophysics and geomorphology. Instruments can be used to study the subsurface structure and to help understand plate tectonics, seismology, and minerology. Researchers in these disciplines are among the primary users of gravimeters.

Atomic gravimeters can be used by geologists to create detailed maps of where and how deep oil and natural gas might be expected to be found. Gravimeters provide better precision than other tools for locating deposits, especially when measurements from several units operating together are employed in unison. Although there is some trial and error in oil well drilling, better gravimetrics could reduce the amount of time and effort wasted on exploratory drilling.

Gravimeters can also be useful for construction projects where it is important to know variations in subterranean structure and density, such as when constructing railroads, large buildings, tunnels, bridges, or pipelines. For example, structures may lean when built over varying ground densities. Quantum gravimeters can also provide water resource managers with additional information about underground water tables (El-Diasty 2016). Other applications include detecting underground archeological artifacts and tunnels, a feature of interest to both construction companies and the military.

Atomic interferometers have a broad range of uses in addition to measuring gravitational acceleration and gravity gradients. For the purposes of basic science, they offer a more precise means to measure fundamental constants than classical experiments. For example, with an accurate value for the ratio of Planck’s constant to the mass of an atom, it would be possible to precisely define the mass of a kilogram in terms of other fundamental constants. The European Space Agency’s Space Atom Interferometer will be used to test the equivalence principle in space as well as other fundamental physics in microgravity (Sorrentino et al. 2011).

2. Current and Potential Markets

Most commercial demand for quantum gravimeters comes from researchers in geophysics and geomorphology and from oil and gas exploration. One company representative we interviewed stated that sales for oil and gas exploration were on the order of ten quantum gravimeters per year at a price of about $450,000 and total sales of less than $5 million a year. A representative we interviewed from another company argued that gravimeters work best when several are spread over a relatively large area for in-depth surveys to locate deposits. Because this approach requires dozens of gravimeters, the representative argued that prices would have to fall to $10,000 per unit for substantial demand to materialize on the part of oil and natural gas exploration companies. This price point is 98 percent less than the current prices we were quoted. The interviewee believed that such price reductions are feasible over the next five years.

Atomic interferometers are also sold for use in basic research, a market that is confined primarily to university and government research laboratories. Demand for atomic interferometers by these institutions is likely to be limited to the one hundred or so laboratories worldwide that have the funds and need for such devices. The price for high-end atomic interferometers tends to be dominated by the auxiliary systems required to run such precise systems; prices are on the order of several hundred thousand to a few million dollars per system. Because research institutes purchase new atomic interferometers only occasionally, not once a year, we estimate potential annual sales to research institutes on the order of a dozen or so a year and potential total revenues of less than $50 million per year.

3. Industry

Some primarily small companies, many of them start-ups, offer commercial technologies based on atomic interferometry; gravimeters appear to be the most developed of the technologies offered. Many of them have connections to military or government research. In most instances, sales have been focused on research institutes and universities. Revenues for these companies involve research and development grants, as well as product sales.

The Stanford University spin-off AOSense is developing atomic optical devices, including gyroscopes, accelerometers, inertial measurement units, gravimeters, gravity gradiometers, and atomic frequency standards using quantum technologies (AOSense, Inc. 2017). The company plans to offer a portable gravimeter to the market within the next five years and is aiming for a price of around $10,000, at which point it would be feasible for military applications and possibly civilian maritime and aviation applications. The French company Muquans is also developing quantum sensors, including the first commercially available absolute quantum gravimeter. This gravimeter is priced around $450,000 and on the order of 10 are sold per year, primarily to research institutes.

Most work in developing atomic interferometers and applications is concentrated in academia and other research programs. In the United States, Stanford University, Yale University, the National Institute of Standards and Technology (NIST), University of Colorado-Boulder, and NASA’s Jet Propulsion Laboratory (JPL) all have groups studying and developing atomic interferometers. In Europe, major groups working on atomic interferometers are located at Humboldt University of Berlin, the *Observatoire de Paris*, and several universities in the United Kingdom that are part of a consortium known as the UK Quantum Technologies Hubs. A few joint European projects are seeking to develop quantum sensors based on atomic interferometry. Australian companies have also been engaged in developing atomic interferometers.

4. Prospects for Gravimeters and Atomic Interferometers

Even if the cost of gravimeters could be reduced to $10,000 compared to current prices of $450,000, the overall market for gravimeters would likely be small. At $10,000 per gravimeter, manufacturers would have to sell 500 gravimeters a year to reach $50,000,000 in sales. In our view, sustained demand by the oil and gas exploration and production industry is unlikely to be that high.

Atomic interferometers have been commercially available and improving over the last 25 years; the true extent of their commercial application has not yet been realized. For most commercial applications, non-quantum solutions have been satisfactory. Higher prices and, in some cases, larger physical sizes and higher power draws of quantum systems compared to non-quantum systems have discouraged adoption of these technologies in many potential civilian markets. These characteristics are likely to continue to limit the size of the markets for these products.

D. Quantum Inertial Motion Units

1. Description and Value of Technology

Position, navigation, and timing (PNT) is another area of application for atomic interferometry, especially when combined with atomic clocks. Precisely measuring the linear and angular accelerations of an object as a function of time, using an initial position as a reference, can yield the object’s current position and velocity. This method of navigation is called *dead reckoning* and can be conducted without external sources of information.

Inherent errors due to bias, drift, noise, and calibration are unavoidable and increase over time, so navigation systems must periodically be synchronized with external information to continue functioning. The amount of time before accuracy degrades beyond a critical level depends on the quality of the sensors. Navigation and timing systems are typically synchronized with GPS, but the vulnerabilities of GPS have highlighted the need for the military to have better inertial PNT services that can provide accurate information for longer periods of time in the event of GPS jamming, spoofing, or satellite loss.

Classical inertial navigation systems use accelerometers that use proof mass to measure a change in acceleration from the inertia of the mass inside the sensor, but this proof mass is subject to manufacturing error. Quantum accelerometers use atoms, which are not subject to manufacturing defects. Their transition states can be measured to determine time, acceleration, magnetic fields, and gravity fields.

Quantum inertial measurement units can provide 10 meters of navigation accuracy for up to an hour and a half, while the best classical systems used by the Air Force can maintain this level of accuracy for about 20 minutes (United States Air Force Scientific Advisory Board 2015). Tactical systems are designed to be small, lightweight, and low power, and they are intended to perform well enough for their applications. As such, they may be reliably accurate for only one minute without updates from an external source of information like GPS. The time period for accurate dead-reckoning navigation is primarily a function of the accuracy of the onboard clock, so quantum PNT systems can extend their period of uncorrected usability longer than classical systems.

Information from additional sensors can enhance inertial navigation systems. When combined with a gravimeter, accelerometers, and gyros, these systems can provide precise inertial navigation for up to two days. Information from magnetic and gravitational maps can also increase the accuracy of inertial navigation systems.

Operating a precise navigation system with no external information is relevant for operating in environments where services of global navigation satellite systems (GNSSs), such as GPS, or signals from other broadcast navigation systems, such as long-range navigation (LORAN), are unavailable. These environments include underground and underwater environments, but more importantly for our discussion, they also include areas where GPS is being jammed or spoofed, making the GPS signal received on the ground very weak. Omnidirectional transmitters with just a few watts of power can disrupt GPS services over an area of a few square kilometers.[3]

2. Current and Potential Markets

While quantum inertial navigation systems could provide unparalleled PNT compared to classical inertial systems, there appears to be relatively little demand for such services outside of military applications. While the military needs to reduce the risk stemming from GNSS denial, commercial and household needs for information on position and navigation are well satisfied by GPS services. In addition to the physical size of these quantum systems, current prices are such that they would need to drop substantially before civilian demand would materialize.

[3] For example, in 2013, Newark Liberty airport experienced a GPS disruption when a truck driver operating a GPS jamming device drove past the airport. These jamming devices are illegal to operate but are relatively cheap: they cost on the order of $100. In another incident, the U.S. Navy accidentally jammed civilian GPS signals in 2007 and caused minor disruptions of services that rely on GPS for time synchronization.

The largest potential military market for quantum PNT systems is for submarines, ships, and airplanes. Submarines must operate underwater without access to GPS. They do not need to navigate exclusively by dead reckoning because they can use visual markers to periodically fix their positions, but they still rely on inertial navigation systems for substantial periods of time. Warships would also benefit from redundant onboard PNT systems to provide an alternative form of timing and navigation to GPS. Both submarines and warships are large enough to hold inertial navigation systems of the current sizes.

If quantum PNT systems can be reduced from their current physical size to packages small enough to be placed into aircraft avionics systems, the market for these products might be relatively large, even if the price for such packages were to run more than one hundred thousand dollars. Precision PNT in GNSS-denied environments is important for unmanned aerial vehicles (UAVs), especially on long-duration flights on low-altitude missions over unusual terrain or above urban areas.

Systems would also have to become smaller for use in manned military aircraft, especially combat aircraft. It would be virtually impossible to install large non-GPS PNT systems on currently operating fighter aircraft because of the difficulty in finding space for such systems. Installing such systems on transport aircraft is more feasible because of the aircraft's larger size and space in the cargo hold.

The U.S. Air Force has expressed interest in developing non-GPS PNT systems. If the U.S. military pursues development of these technologies for limited applications, it would want to keep these systems out of the hands of potentially hostile foreign states; therefore, the market for these technologies would be restricted to the United States and its close friends and allies.

Forecast International projects that 146 new submarines will be procured globally through 2026 (Forecast International 2017, 986). Of this total, 19 would be acquired by the United States. Within NATO, the United Kingdom would procure 4; France, 4; and Spain, 4. Outside of NATO, Sweden and Australia are expected to procure 2 submarines each. In total, the United States and these countries could potentially procure 35 submarines over the next decade.

The company forecasts that 253 naval surface combatants will be procured through 2026 (Forecast International 2017, 1033). Of this total, the United States is expected to procure 97. Within NATO, the United Kingdom is planning to procure 4; France, 6; Italy, 7; and Germany, 4. Outside of NATO, Australia is planning to procure 9 combatants. In total, the United States and its allies are likely to procure 127 naval surface combatants over the next decade.

The company also projects that 780 military transport aircraft will be procured globally through 2024 (Forecast International 2016, 476). Of this total, the United States is projected to procure 112, although this number may include purchases by NATO or other allies; the source is unclear about what countries are included.

Forecast International further projects globally 2,842 military fighter aircraft will be procured through 2024 (Forecast International 2016, 447). Of this total, the United States is projected to procure 1,205, of which 1,052 are variants of the F-35 fighter. Within NATO, Germany is forecast to purchase 108 and France, 8. Outside of NATO, Sweden is projected to procure 86. In total, The United States and its friends and allies may potentially procure 1,407 fighter aircraft over the next decade.

The company forecasts 17,443 UAVs will be procured worldwide through 2023 (Forecast International 2015, 777). It is unclear from the forecasts exactly how many of these are likely to be procured by the United States and its allies, although they might collectively procure more than half this count.

The extent to which these platforms may be equipped with quantum inertial navigation systems depends on how bulky and expensive these non-GPS systems are likely to be. For submarines, the potential benefits of using more precise inertial navigation systems are clear, since submarines operate for long periods without access to GNSS and need reliable navigation for longer periods than classical PNT systems can deliver. Moreover, submarines have much more room than aircraft to house such systems, although space on submarines is constrained. Naval ships would not be constrained by space, but do not need the same level of navigational accuracy as submarines. Aircraft require smaller systems to be installed onboard. It is difficult to imagine how a quantum inertial navigation system could be installed within the space constraints imposed by existing fighter aircraft designs.

Assuming that quantum PNT systems remain bulky and only serve submarines and ships, the market for military systems might run 127 for surface combatants and 35 for submarines for the United States and its allies, or 162 over the next decade (roughly 16 units per year). The total costs of components of complete PNT systems (clocks, gravimeters, and inertial motion sensors) would likely run in excess of $1 million, but at 16 units per year, gross sales of quantum PNT systems for military uses would likely be small, less than $50 million per year. If over the next 20 years the physical size of these systems could be reduced, future generations of military aircraft would likely be designed to incorporate such systems. Assuming that acquisitions of military aircraft by the United States and its friends and allies over the coming decades are similar to projections of procurements for the decade through 2024, fighter aircraft sales would run about 1,300 per decade, or 130 planes per year. Assuming that the size of these systems could be dramatically reduced, the next generation of these aircraft are designed to incorporate them, and prices for quantum systems run more than $1 million, sales of these units in military aircraft could run $130 million to $200 million per year. Quantum PNT systems could provide better information for tunneling and drilling. While gravimeters can help identify deposits for oil and gas exploration, quantum PNT systems could provide more precise information for mining and excavation (not just drilling), tunnel boring, and precise underground information that might be required for large construction projects.

3. Industry

Currently, the U.S. Air Force is leading the development of quantum inertial measurement units, though other organizations are working on the technology. DARPA has made significant progress over the last decade in developing quantum navigation sensors for military applications through their Precise Inertial Navigation System (PINS) program. Other DARPA and Air Force programs aim to significantly reduce the size, weight, and power required for cold atom-based inertial sensors in the near future.

Because of the similarities in the technology, many organizations that are developing cold atom interferometers are also developing some versions of quantum accelerometers and gyroscopes, though none appear to have a fully integrated inertial measurement unit (which requires multiple accelerometers and gyroscopes as well as an atomic clock) on the market at this time. AOSense, Muquans, NIST, JPL, and the UK Quantum Technology Hubs all have quantum acceleration sensors based on atom interferometry technology.

4. Prospects for Quantum Inertial Motion Units

As noted above, demand by the United States and its friends and allies for quantum inertial motion units for military submarines and ships could run roughly 16 units per year. If quantum inertial motion units could be dramatically reduced in size, the potential exists for 130 units a year to be used in next-generation models of military aircraft.

Outside of military applications, demand for quantum PNT systems appears low. If GPS becomes unavailable, we assume that commercial airlines would halt service or revert to the non-GPS radar and radio traditionally used by air traffic controllers. Retrofitting the cockpits of civilian aircraft to include quantum PNT systems would be challenging and expensive.

Deprived of access to GPS, trucking companies would likely do without or, in an extreme case, halt operations. Railway operators might wish to purchase these systems given the requirements for accuracy outlined in the Federal Radionavigation Plan (FRP) for the rail sector (Department of Defense 2014). The FRP requires 2-millimeter accuracy for tectonic monitoring for bridge safety, 2-centimeter accuracy for surveying, and 30-centimeter accuracy for track defect location (Department of Defense, Department of Homeland Security, and Department of Transportation 2014). Moreover, space could be found in locomotives for these systems. However, even though trains do run through tunnels, it is unclear whether they need quantum inertial motion units when other methods offer acceptable alternatives at lower cost.

Some developers of quantum PNT systems believe the arrival of autonomous vehicles will spur a mass market for these devices; however, the added benefit of quantum PNT systems over current and future sensors on vehicles may be relatively small. To a great extent, it is more important to know where an autonomous vehicle is relative to pedestrians, traditional vehicles, and other objects than to know precisely where the vehicle is geographically. Considering the current quality of GPS and the falling costs of commercial lidar and other systems on the market that can help navigate around obstacles, moving or otherwise, the added benefits of quantum PNT may not be enough to interest motor vehicle manufacturers, as current systems are so much cheaper. Advances in artificial intelligence and lower costs of other sensors could further reduce the perceived advantages of quantum PNT systems.

Although quantum PNT systems would enhance existing non-quantum systems in civilian applications, most civilian users consider existing systems adequate. According to most of our sources, the likely incremental cost of quantum enhancements would be higher than most users would be willing to pay. Consequently, quantum PNT systems are unlikely to capture a large share of any of these markets. We estimate the civilian market will be substantially smaller than the military market. The market may be limited to a few units for underground construction; the total civilian market for inertial motion units is unlikely to exceed $50 million annually and will probably be much less.

E. Magnetometry

1. Description and Value of Technology

Magnetometers measure magnetic fields, either the magnitude of the field (scalar magnetometers) or the magnetic vector (vector field magnetometers). While there are many other methods for measuring magnetic fields, the methods used in superconducting quantum-interferometer devices (SQUIDs) and optical atomic magnetometers are the most sensitive. They can measure magnetic fields as weak as a few femto-Teslas (approximately 1 billionth of the Earth's magnetic field) using long measurement times.

Advances in laser pumping technology have spurred the development of new **chip-scale atomic magnetometers**. These magnetometers use optical pumping to establish a macroscopic magnetic moment among a population of atoms, and then measure the precession frequency of the atoms' magnetic moment while exposed to a magnetic field. Small atomic magnetometers are commercially available and, due to their reduced size, weight, and power, can be deployed in situations where traditional magnetometers cannot. For instance, chip-scale atomic magnetometers can be used to conduct magnetic surveys from unmanned aerial systems or be deployed in proximity to the human heart for magnetocardiography.

One vendor of atomic magnetometers has reduced the size and power consumption by a factor of 10 with respect to traditional magnetometers, while maintaining the sensitivity of the instrument. The company will soon release a magnetometer with a sensitivity of 1 pT/√Hz, power consumption of 2 watts, and 15 cubic centimeters in size (Geometrics 2017). The small sensor is intended to be integrated as a component in an instrument and the individual unit cost is about $10,000. By comparison, traditional magnetometers weigh up to 15 kilograms, consume 30 watts, and cost approximately $18,000.

Atomic interferometers can also be used as magnetometers, although commercial atomic interferometry-based magnetometers are not yet available. Building atomic interferometers for magnetometry is challenging because the material near the sensor may have magnetic anomalies that create system noise that is difficult to remove.

Quantum magnetometers can measure the Earth's magnetic field and its anomalies. Mining companies have used magnetometers to locate magnetic ores. They have also been used to detect submarines, to search for unexploded ordinance, to identify hazards for tunnel-boring machines and other construction equipment, as sensors in anti-lock brakes, and for research in heliophysics and planetary science.

Quantum magnetometers have been used to measure biomagnetic fields, including those generated by the brain (see section 2E) and the heart. They are used in nuclear magnetic resonance, in petrology, and solar physics. Advanced research applications include measuring fundamental symmetries of atomic particles (Budker and Romalis 2007).

2. Current and Potential Markets

Chip-scale atomic magnetometers are in demand across several markets, the largest of which is as components for medical equipment. According to one interviewee, the market for magnetic sensors may be $100 million to $200 million because they are primary critical components in a number of diagnostic machines. The same company representative said the market for magnetometers for geophysics is comparatively small, roughly $10 million a year. Security may be a future market for magnetometers, which the interviewee speculated could potentially run $100 million to $300 million annually, since magnetometers could be used to detect signatures of underground tunnels or the presence of explosives and arms. Industrial manufacturing is another possible future market, since magnetometers could be used for quality inspections of manufactured products.

The demand for quantum magnetometers of the precision offered by devices based on atomic interferometry has been relatively low outside of the medical research field. Classical technologies offer low-cost solutions for a wide variety of consumer and exploration applications. Most mineral and other resource exploration can be done with alternative sources of magnetic mapping tools, making it less likely for these companies to invest in more expensive technologies based on atomic interferometry.

3. Industry

The industry developing chip-scale atomic magnetometry is growing rapidly. Both start-ups and well established equipment manufacturers are developing chip-scale atomic magnetometers. University spinoffs have formed companies such as Twinleaf LLC; QuSpin, Inc.; and Southwest Sciences, Inc. Geometrics, Inc., is a major manufacturer of atomic magnetometers and other sensors for geophysical applications. Established companies like Northrop Grumman Corporation, Lockheed Martin Corporation, and Honeywell International, Inc., are also fabricating small atomic magnetometers.

Government research contributes to atomic magnetometry as well. NIST conducts significant research on these devices, and the DARPA program Atomic Magnetometer for Biological Imaging in Earth's Native Terrain (AMBIIENT) is intended to advance small atomic magnetometers, magnetoencephalography scans, and other magnetic sensing technologies for biological applications.

In contrast to some other sectors in quantum metrology and sensing, most companies manufacturing atomic magnetometers are based in the United States, including Twinleaf, QuSpin, Southwest Sciences, Geometrics, Northrop Grumman, Honeywell, and Lockheed Martin.

4. Prospects for Atomic Magnetometry

Atomic magnetometers are already commercially available. If chip-scale atomic magnetometers become more affordable, they could serve a diverse set of markets in the future, including geophysical surveying, medical imaging, security, and manufacturing. One interviewee noted that the potential of these magnetometers in such applications could be upwards of half a billion dollars annually over the short to medium terms. However, competition from non-quantum alternatives on the basis of price has limited demand for more expensive atomic magnetometers and will likely continue to do so.

F. Magnetoencephalography (MEG)

1. Description and Value of Technology

MEG is a well-developed application of magnetometry. It is a non-invasive, painless neuroimaging technique that measures small neuromagnetic fields generated by electric currents from neurons in the brain. MEG provides direct measurements of brain activity, has excellent temporal resolution, has good spatial resolution, offers patients more comfort during the scan than magnetic resonance imaging (MRI), does not use radioactivity or strong magnetic fields, and is quiet during operation (Cleveland Clinic 2016).

MEG scanners use SQUIDs, which are currently the only sensors with sufficient sensitivity to measure neuromagnetic signals from the brain (Hamalainen et al. 1993; Vrba and Robinson 2002). These signals are approximately one-billionth of the strength of the Earth's magnetic field, and require 50,000–100,000 simultaneously active neurons to generate a large enough magnetic field to be detectable by a SQUID sensor (Institute for Learning and Brain Sciences 2016).

Modern MEG scanners contain approximately 300 SQUIDs that are immersed in liquid helium at a temperature of 4.2 Kelvin (K) (Hari and Salmelin 2012; Cleveland Clinic 2016). Such scanners have been used in researching epilepsy; sensory mapping; identifying brain signatures associated with autism, Alzheimer's disease, depression, and other neurologically based disorders; studying sleep; and functional mapping of the brain (Hari and Salmelin 2012; Children's Hospital of Philadelphia 2016; Cleveland Clinic 2016). Figure 1 shows a MEG scanner manufactured by Elekta, a Swedish firm.

Source: Elekta (n.d.).

Figure 1. Elekta's TRIUX MEG Scanner

MEG systems compete with and are used in tandem with other neurodiagnostic tools, such as electroencephalograms (EEGs), functional magnetic resonance imaging (fMRI), and positron emission tomography (PET). Both EEGs and MEG scans provide excellent temporal resolution on the millisecond scale, while PET and fMRI have much longer time scales, ranging from a few seconds to several minutes (Institute for Learning and Brain Sciences 2016). Although both EEGs and MEG scans have lower spatial resolution than PET scans and fMRI, their superior temporal resolution can capture the evolution of localized neural activity (Cohen and Halgren 2009).

Because the magnetic field outside the head is so weak, placing the sensors as close to the head as possible increases the ability of the sensors to pinpoint the location of the neural activity. Because SQUIDs operate at such a low temperature (4.2 K), the means of cooling them also limits placement of the sensor.

Research into using small cells of warm atomic gasses that use optical beams to measure magnetic fields may hold promise for more accurate, lower cost MEG machines (Budker 2007). One research project has developed a four-channel optically pumped atomic magnetometer (Colombo et al. 2016). Although still under development, such a magnetometer would not need liquid helium to operate, potentially reducing the costs of MEG scans substantially.

2. Current and Potential Market

As of 2015, just over 200 MEG systems were installed worldwide (*Nikkei Asian Review* 2016). According to Compumedics Limited, one of the manufacturers of MEG systems, the MEG market is currently about 35 systems a year at an average selling price of $5.5 million each, or roughly $200 million a year (Compumedics 2016). Compumedics projects that the market will grow by 10 percent annually over the next few years, not including China. According to the Institute for Learning and Brain Sciences (2016), a MEG system costs about $3 million. Based on this average price, an annual market of 35 systems a year would generate a little over $100 million of business. In addition to the purchase price, users spend an additional $200,000 in annual maintenance costs (Institute for Learning and Brain Sciences 2016).

The cost of a MEG system is higher than that of other imaging machines, even new top-of-the-line computed tomography (CT) scanner, which costs up to $2.5 million, or an MRI scanner, up to $3 million (Herman 2012; Glover 2014). Like MEG systems, both CT and MRI scanners can cost up to $200,000 per year to maintain (Herman 2012).[4]

Because of their high costs and the difficulties of using a machine that needs liquid helium to operate, MEG systems are still primarily used for research (Cohen and Halgren 2009).

3. Industry

Four companies have manufactured MEG systems in recent years: Elekta AB, CTF MEG International Services LP, Compumedics, and Tristan Technologies, Inc., a U.S. company. Elekta manufactures a wide range of electronic diagnostic and cancer radiation treatment equipment; it had over $1 billion in sales in 2016 (Elekta u.d.). In contrast, Compumedics, which is headquartered in Australia, had sales of 37.5 million Australian

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[4] Prices are available from Block Imaging, “MRI Machine Cost and Price Guide [2017 Update],” https://info.blockimaging.com/bid/92623/MRI-Machine-Cost-and-Price-Guide.

dollars in 2016 (about $27.9 million USD). CTF is a privately held Canadian company that also appears to have substantially less revenue than Elekta. As is the case for many technical equipment manufacturers, manufacturers of MEG scanners are located in more developed countries.

Ricoh Company, a Japanese imaging and electronics company, entered the brain imaging business market when it acquired the MEG production section of Yokogawa Electric in April 2016. Yokogawa Electric stopped manufacturing MEG scanners in 2011, but maintained the production unit until it was sold to Ricoh. Ricoh plans to cut the cost of MEG systems from about 500 million yen (roughly $4.6 million USD, Elekta's approximate unit cost) in half (Nikkei Asian Review 2016).

The industry is split between smaller, specialized, high-technology firms (CTF, Compumedics, and Tristan Technologies) and larger, mid-sized companies dealing in medical or electronics equipment (Elekta and Ricoh). Because of the high cost of research and development for a product like a MEG scanner, market share has gravitated towards Elekta, which benefits from having a global marketing and service network.

4. Prospects for Magnetoencephalography

MEG has been available for several decades. The technique provides a complementary and, in some cases, alternative diagnostic tool to EEG tests, fMRI, and PET scans. As that market grows, demand for MEG systems appears to be rising. Compumedics estimates the current market for MEGs at 35 systems a year with growth of 10 percent per year. The value of this market could run from $100 million to $200 million a year.

The market is competitive. Four manufacturers vie for sales and Ricoh is entering the business with technology purchased from another Japanese manufacturer. In their annual reports Elekta and Compumedics highlight the importance of reducing costs of these machines to expand sales. Thus, the number of MEG systems sold annually may well rise, but prices are likely to fall.

Despite falling prices, demand for MEG systems is limited by the challenges and costs of a machine that needs liquid helium for cooling and by the lower spatial resolution. Replacing SQUIDs with atomic vapor magnetometers while retaining the sensitivity may lower both the initial and operational cost because of the elimination of cryogenic operation.

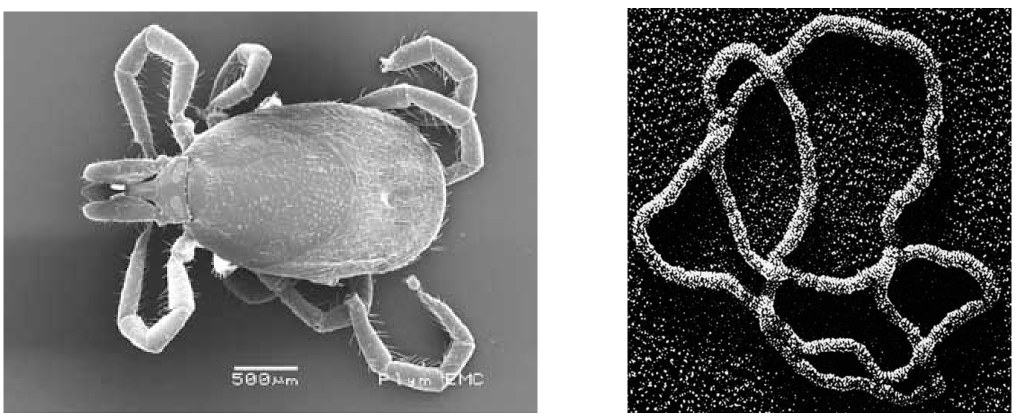
Although manufacturers are likely to see their market shares shift, foreign manufacturers are likely to continue to play a large role in this market. Elekta, a Swedish company, currently has the largest share of the market. Compumedics, an Australian company is enjoying growth. The industry is almost certainly one that will remain global.

In short, MEGs are likely to remain a modest-size niche market over the next two decades. U.S. manufacturers are likely to retain a share of this market, but they are unlikely to become the dominant producers.

G. Electron Microscopy

1. Description and Value of Technology

Very high-resolution images of biological specimens, such as those in Figure 2 of a small arachnid and a strand of deoxyribonucleic acid (DNA), are obtained using scanning electron microscopy in a process that often destroys biological samples, such as proteins. This destruction significantly limits the application of electron microscopy techniques to the life sciences.



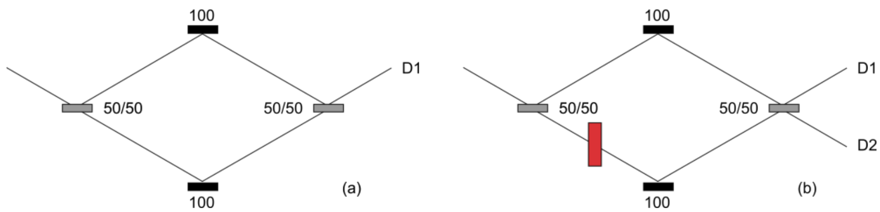
Source: Sheep tick (left): Dartmoor Tick Watch, “Electron Microscope Images, http://www.dartmoorcam.co.uk/dartmoortickwatch/photos/SEM_photos/SEM_photos_Female.htm. Strand of DNA (right): Online Image Arcade, http://imgarcade.com/electron-microscope-dna.html.

Figure 2. Classic Electron Microscopy Images

The smallest resolved feature is on the order of the particle’s wavelength, which depends on its energy. High-resolution imaging requires high-energy particles. High-energy particles damage samples, so delicate structures, such as proteins, cannot be imaged by conventional electron microscopy.

Putnam and Yanik (2009) proposed a novel approach based on an interaction-free mechanism originally discussed for optical interferometry (Kwiat et al. 1995). It may seem counterintuitive that the presence of an object can be detected without having to interact with it in a classical sense, but that is actually possible with quantum mechanics. By minimizing the interaction, it may be possible to image delicate structures without causing damage.

Figure 3 illustrates the detection of an object present in an arm of an interferometer. The portion of the figure labeled (a) is a balanced interferometer. All light from the left in the upper entry port is directed to the upper exit port on the right and detected by sensor D1. Placing a completely opaque object, shown here as a red box in the portion of the figure labeled (b), into the lower arm of the interferometer blocks the lower path and causes the light to exit from both ports on the right with equal probability. Detection of a signal by sensor D2 indicates the presence of an object in the lower arm of the interferometer.

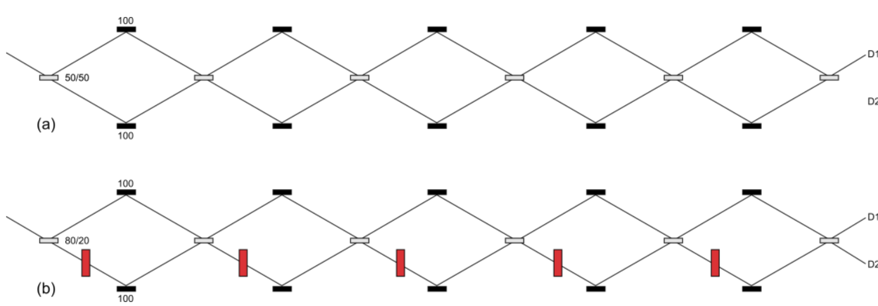


Note: The 50/50 beam splitters (mirrors) transmit half and reflect the other half of the light to the fully reflective mirrors (labeled 100). The lines between the mirrors are the paths the light takes until it is detected (D1 and D2).

Figure 3. Sensing an Object Using Interferometry

This configuration does not reduce the flux of photons (or electrons) needed to determine the opacity of the object in the lower arm. Typically, around 10 electrons per square Angstrom are needed to measure the opacity of the object using an electron microscope. The energy imparted by the flux needed for imaging is sufficient to damage the object and consequently interfere with the measurement. Lowering the flux in this configuration would reduce the quality of the image.

A quantum electron microscope uses quantum effects to reduce electron flux while maintaining image quality. It increases the number of interactions without causing damage. Figure 4 is similar to Figure 3 with the following primary difference. The balanced interferometer is unbalanced by replacing the 50/50 mirror with one of much higher reflectivity, 80/20 in this case.



Source: Derived from Kwiat et al. (1995, Fig. 1).

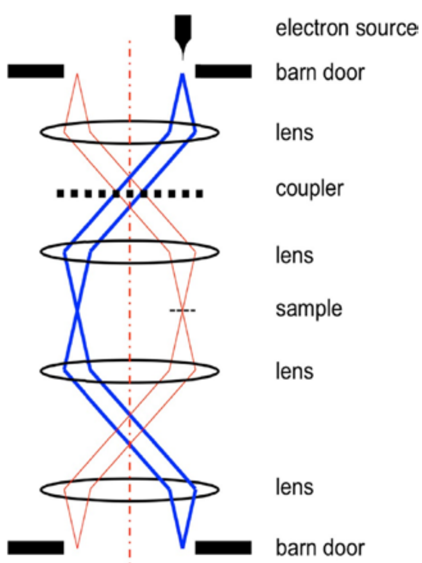
Note: The 50/50 mirror is replaced with a higher reflectivity (80/20), which initially biases the light to the upper arm (eventually it will find its way to the low path). This decreases the likelihood that it will interact with the red sample, located in the lower path. Multiple interactions are depicted in this illustration by repeated stages of interaction. A quantum mechanical analysis of this interaction shows that the presence of the photon from transferring to the lower path and consequently it will be more likely to be detected by D1.

Figure 4. Interaction-Free Object Detection with a Quantum Electron Microscope

First consider the upper case, labeled (a) in Figure 4, where the objects (red boxes) are not present. The effect of having a mirror with higher reflectivity is that the photon's preference is to stay where it is, in either the upper path or the lower path. Eventually, though, the photon will find its way to the other path, and once there, back to the previous (upper or lower) path. The photon moves back and forth in a statistically predictable manner between the two paths, depending on the mirror reflectivity.

Placing an object in the lower arm, labeled (b) in Figure 4, prevents the photon from transferring to the lower path. Classically, the photon would pass through the mirror and be absorbed one out of five encounters on average, but this is not what is observed. The quantum description is that wave function of the photon follows both paths when the object is absent, and the paths interfere at the mirror. However, when the object is present, the lower path is absent and no interference occurs at the mirror, causing the photon to remain on the upper path. This effect was first described and experimentally observed by Kwiat et al. (1995).

This principle is applicable to electron microscopy. While it has not yet been realized, modifications to an electron microscope to accommodate the reduced interaction are realistic. Figure 5 shows one possible approach (Kruit et al. 2016). Two fundamental additions are (1) the barn door and (2) a coherent electron beam splitter (coupler). The barn door provides the resonant interaction. One electron enters the interacting region, the barn door is shut, keeping the electron in the barn (i.e., interacting with the sample). After a number of interactions have occurred, the lower barn door is opened, letting the electron escape and determining which of two spatially separated paths it is on. The beam splitter in this example is provided by scattering off a standing optical wave.



Source: Kruit et al. (2016).

Figure 5. Proposed Scheme for Converting a Conventional Electron Microscope by Scattering the Electron off a Standing Optical Wave for the Coupler

2. Current and Potential Market

The global market for all forms of electron microscopy in 2016 was about $1.2 billion (AATLE 2016). Primary applications are in the semiconductor industry, materials research, and the life sciences. The market for scanning electron microscopy is predicted to grow to $2.2 billion by 2022 (Grand View Research 2016) with pharmaceutical applications, including medicine and life sciences, accounting for 30 percent of all sales. Assuming that quantum electron microscopy could have captured the entire market for medicine and life sciences in 2016 if it had been available, sales would have run $360 million annually. If the market does grow to $2.2 billion in 2022, the market for quantum electron microscopy might reach $660 million annually.

3. Industry

Major manufacturers of electron microscopy equipment include Bruker Corporation, Carl Zeiss AG, FEI, Hitachi High-Technologies Corporation, JEOL Ltd., Leica Microsystems, and Olympus Corporation. Carl Zeiss and Leica Microsystems were historically optical equipment companies that manufactured lenses for glasses and cameras, but have also been engaged in manufacturing scientific equipment. Carl Zeiss had close to €5 billion ($5.5 billion USD) in annual sales in 2015–2016. Sales of electron microscopes fall under its research and quality division, which had sales of close to €1.5 billion in 2015–2016 ($1.7 billion USD). However, electron microscopes account for just a small fraction of those sales. Leica Microsystems is now a division of the large multinational Danaher Company. In contrast to Carl Zeiss, Leica Microsystems is focused solely on microscopes (optical and electron) and scientific equipment.

FEI is primarily a microscope manufacturer. Headquartered in Hillsboro, Oregon, it had sales of $930 million in 2015, before it was acquired by Thermo Fisher Scientific. JEOL, originally the Japan Electron Optics Laboratory Company, like FEI, was primarily a manufacturer of electron microscopes, although it has branched out into industrial and medical equipment. Its sales are also in the $900 million range. Olympus is a large corporation with a wide range of businesses, including optical and electronics. Hitachi High-Technologies is part of Hitachi Ltd., which conducts abroad range of multinational businesses.

The industry is made up of mostly large companies, including Carl Zeiss, Olympus, Hitachi High-Technologies, Leica Microsystems, and FEI, after it was purchased by Thermo Fisher Scientific. However, it also includes medium-sized companies with less than $1 billion in sales, such as JEOL (and FEI, before its acquisition). The electron microscope business is relatively mature compared to many of the other areas involving quantum technologies. New start-ups and small companies are not currently major players in this sector.

The industry is concentrated in Germany, Japan, and the United States. The reputations and global service networks of the divisions engaged in manufacturing electron microscopes of these companies appears to have forestalled the entry of new companies from other countries as have the high cost of purchasing and operating electron microscopes, which encourages buyers to choose an incumbent with a good reputation.

4. Prospects for Quantum Electron Microscopy

Quantum electron microscopy technology is clearly still at an early stage. An international collaboration technology development effort to advance the state of the art and assess the feasibility of such an instrument was begun in 2013 involving the Massachusetts Institute of Technology (MIT), Stanford University, Delft University, and the Max Planck Institute for Optics (Quantum Electron Microscopy 2012). Although one of the project participants claims a prototype may be ready within 5 years, we assume that if the technology is successfully developed, QEM will be available commercially in the mid-term (5–10 years). We estimate that the potential market could be up to $500 million annually.

H. Quantum-Assisted Nuclear Spin Imaging

1. Description and Value of Technology

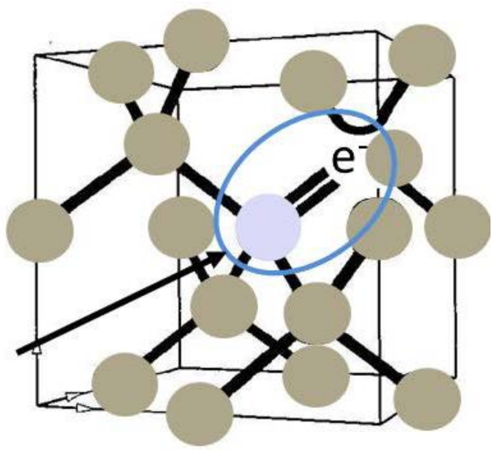
Nuclear spin imaging is a quantum-based technique for optical sensing at (large) molecular length scales. One implementation of nuclear spin imaging is based on nitrogen vacancy (NV) centers, which are particular structural point defects found in diamonds. NVs in diamonds offer a stable, localized electron spin sensor to measure small magnetic fields. The NV center consists of a nitrogen atom and the diamond lattice vacancy.[5] When an electron occupies the vacancy, it is labeled e^- as illustrated in Figure 6. The spin state of the negatively charged NV center has a long coherence time, even at room temperature, and its electronic level structure allows efficient, all-optical spin polarization. Magnetic fields as small as 1 nanotesla have been measured using a diamond NV. In 2005, it was realized a single spin could be used as nanoscale quantum sensors for scanning-probe magnetometry (Maze et al. 2008, 644). The local magnetic field is measured by monitoring changes in the energy levels caused by the Zeeman effect of an optical transition. This is the same way that the magnetic field is measured in atomic vapors, with the advantage in this case being the high localization of the spatial measurement. The influence of the external magnetic field can be limited to the space of a few lattice sites, allowing for spatial resolution in the sub-nanometer range. In 2008, preliminary results indicated that properties of NV centers in diamonds are nearly ideal for this purpose. The crystal field in diamond

[5] The NV center can be employed to create quantum bits (qubits) used in quantum computers.

splits the ground state into three highly coherent states that can be interrogated with optical and microwave fields (Rondin et al. 2014).

In diamond NV centers, photoluminescence can be induced from the spin of the electron through manipulation by electric fields, magnetic fields, or by electro-magnetic radiation. These manipulations create strong photo-luminescent resonances at particular wavelengths (Rondin et al. 2014).

Several potential applications have been demonstrated, including single electron spin detection and imaging and bio imaging (Balasubramanian et al. 2008; Rondin et al. 2014; Staudacher et al. 2013). A driving goal for this research is to perform structural magnetic imaging on individual molecules. At present, resolution is limited to ~5 cubic nanometers, which is the size of a large protein molecule. Improving resolution will require placing the NVs closer to the surface of the diamond without compromising the coherence times of the NV.



Source: Optical Spintronics and Sensing Lab, "Diamond Photonics for Quantum Information Processing," https://sharepoint.washington.edu/phys/research/optospinlab/Pages/Project-Page-Diamond-QI.aspx.

Figure 6. Nitrogen-Vacancy Center (labeled e^-) in a Diamond Lattice

Because the photoluminescence of nuclear spin imaging is created at the atomic scale, this technology provides potential for high-resolution imaging of molecular-level targets such as single proteins under ambient conditions. Existing methods for determining high-resolution protein structure include x-ray crystallography, transmission electron microscopy, and nuclear magnetic resonance. In health care, many pharmaceuticals function by acting on a specific site on a protein. In so doing, they can be effective either by inhibiting the protein function or by locking it into an "on" position. Determining the detailed three-dimensional structure of a protein molecule is therefore critical to new drug development. None of these techniques can image individual protein molecules.

Because of diamond's high biocompatibility and low toxicity, the use of diamond sensors inside of living biological objects is also being explored. Diamond nanocrystals can be coated to preferentially attach to specific sites in a cell and monitor the activities taking place. This technique could be used to study cell-membrane properties and the flows of electrical charge, providing insight into understanding membrane ion-channel operations, which is critical to drug delivery.

2. Current and Potential Market

The primary market for quantum-assisted nuclear spin imaging is likely to be for the research arms of companies or institutions seeking to understand the structure of complex molecules, such as proteins. This market is analogous to, but is unlikely to be as large as, the market for quantum electron microscopy discussed in the previous section. We see purchasers as being primarily research laboratories or companies engaged in pharmaceutical research or potentially research on cancers and other cellular functions. Based on demand for analogous scientific equipment by these potential customers, we believe the market is likely to be less than $50 million per year.

3. Industry

Quantum-assisted nuclear spin imaging is still under development; currently, there are no commercial products or companies engaged in developing commercial versions of these machines. However, if commercial applications become viable, it is highly likely that the current major providers of optical imaging equipment will dominate this field. These include some of the companies, like Carl Zeiss, engaged in manufacturing electron microscopes. They also include Bioptigen, Inc. (North Carolina), Canon, Inc. (Japan), ChemImage Corporation (Pennsylvania), Heidelberg Engineering GmbH (Germany), Headwall Photonics, Inc. (Massachusetts), Michelson Diagnostics Ltd. (United Kingdom), NIDEK CO., LTD. (Japan), Optovue, Inc. (California), St. Jude Medical, Inc. (Maryland), and Topcon Medical Systems, Inc. (California).

In contrast to the electron microscope industry, the optical imaging industry includes more smaller companies and start-ups. However, like the electron microscope industry, companies are located in countries with highly developed scientific equipment industries, such as Germany, Japan, the United Kingdom, and the United States.

4. Prospects for Quantum-Assisted Nuclear Spin Imaging

The first steps in the development of this technology are still being conducted in university research laboratories, and it is therefore far from being a commercial product. Based on our review of the scientific literature and discussions, we believe that if the technology ultimately provides a competitive capability for high-resolution, molecular-level imaging, it will not be available for more than 10 years, making it a long-term technology. As noted above, products would serve the needs of niche, scientific equipment markets. Annual sales are likely to be less than $50 million annually.

3. Quantum Communications

A. Potential Commercial Technologies

Broadly speaking, quantum communications use quantum properties to secure communications. This chapter assesses current and prospective markets for quantum key distribution (QKD), quantum random number generators (QRNGs), and related quantum communications technologies (Table 3).

Table 3. Quantum Communications Technologies

Technology	Technological Readiness[a]	Potential Market
Quantum encryption	Commercial	—
Quantum key distribution	Commercial	\$50–\$500 million
Quantum random number generators	Commercial	< \$50 million
Quantum repeaters	Long-term	—
Quantum satellite transmission	Short-term	—
Long-distance quantum networks	Medium-term	—
Entanglement-based networks	Long-term	—
Quantum teleportation	Long-term	—

[a] *Commercial* indicates that products or services from the technologies are currently available; *short-term* readiness means products or services are expected to become commercially available within the next 5 years; *medium-term* readiness means products or services are likely to emerge within 5 to 10 years, and *long-term* readiness means products or services are unlikely to become commercially available within the next 10 years.

B. Quantum Encryption and Quantum Key Distribution (QKD)

1. Description and Value of Technology

Quantum cryptography uses principles of quantum physics as opposed to mathematical algorithms to generate and distribute encryption keys used to safeguard the transmission of data over unprotected networks. QKD ensures that encryption keys cannot be unknowingly intercepted by an eavesdropper. Since encrypted data are only as secure as the keys used to encrypt them, QKD promises a safe method for both key and data exchange (Quantum-Safe Security Working Group 2014).

An encryption key, which is a string of random bits, allows users to securely share information by encrypting and decrypting messages. To read the message, a key is transmitted to the receiver to unlock the message. The challenge in *key distribution* is to securely transmit the key only to the intended parties. Currently, private and public keys are used to both establish identity (via a certificate from a trusted agent) and exchange a short, symmetric key, which is used to encrypt the bulk of the data using a block cipher, such as the protocol AES256 (Katz and Lindell 2014). The security of this approach is ensured by using large integers that are believed to be computationally intractable to factor and by the cryptanalytic hardness of the algorithms against known cryptanalytic attacks. Computationally intractable indicates that computers cannot decipher the key within a reasonable time (Stebila, Mosca, and Lütkenhaus 2009).

In contrast, *quantum encryption* generates and shares a random bit stream that is as long as the message to be encrypted. This stream can be used only once and then must be discarded. In contrast to current methods, there is no mechanism within quantum cryptography to establish the identity of the parties, even using a trusted agent. Quantum cryptography cannot verify the identity of the parties exchanging keys unless they either have a pre-shared secret key or rely on a non-quantum mechanism, such as public/private keys and certificates.

The largest technical hurdles to widespread use of QKD are distance and the generation rate. In QKD, single-photon quantum states are used to encode the random number. The probability of the photon reaching the end point decreases exponentially with distance. For long distances, fiber links must be regenerated every 100 kilometers or less.

Among the methods for transmitting quantum keys over longer distances are trusted nodes, satellites, and quantum repeaters; all are at varying levels of technical readiness. While for optical communication, repeaters exist to amplify light signals, in quantum communications, quantum information must be converted back to classical information and securely retransmitted. Because the quantum key has to be converted into classical information before being passed onto the next node, it is vulnerable to potential hackers each time this retransmission happens. This back-and-forth between the classical and quantum domain increases the complexity of the system and reduces it assurance.

Because of the need to retransmit and other issues, not all aspects of security are governed by principles of quantum mechanics in quantum cryptography. While quantum cryptography may offer stronger security claims than conventional cryptography, because of these issues it is not clear that the overall security posture of quantum systems is better than the conventional approach. While one interviewer said the security risk is mitigated when QKD is implemented well, others remain concerned.

Trusted nodes for quantum transmission, which can involve a ground-based optical fiber network, are currently in use in China. The planned Beijing-Shanghai network line will use 32 nodes over the 2,000 kilometers between the two cities (Qiu 2014; Courtland 2016). These 32 nodes represent 32 weaknesses in the system.

Satellites could allow information encoded using a quantum key to be transmitted distances longer than 100 kilometers by transmitting the information from one ground station to another via a satellite. China launched the world's first quantum satellite in August 16, 2016 (Xin 2016). It became officially operational as of January 18, 2017 after four months of in-orbit testing (Xinhuanet 2017). Unlike traditional communication satellites that send information through radio waves, China's quantum satellite (QUESS) uses entangled photons to transmit encrypted messages. This quantum satellite system may become commercially ready in China by 2019–2020.

Quantum repeaters are a means to get around the impossibility of reproducing an arbitrary quantum state. Many approaches have been proposed (see Azuma, Tamaki, and Lo 2015), but all are technologically immature and do not show signs of becoming commercially available within the next 10 years. A quantum repeater allows the two parties, separated by an arbitrary distance, to share an entangled state (Munro 2015). The quantum repeater at each hop has two qubits, or quantum memories, such as a trapped ion. One qubit is entangled with the qubit located at the upstream hop and the other is entangled with the one at the downstream hop. Entanglement is accomplished by coupling the photon in the fiber to the qubit. This results in a sequence of entangled states, shared between adjacent hops. As each node measures the state of its qubits, measurement will result in the entanglement present at the measurement node being transferred to the upstream and the downstream node. After all hops have completed their measurement, the result will be the desired final state—a shared entangled state between the endpoints. The quality of this state depends on the quality of the entanglement of all of the intermediate states. For long links, the quality will be low and will impact performance (and security).

Fortunately, the quality of entanglement can be arbitrarily improved by quantum purification. This requires having many entangled states between neighbors at each of the hops. From these poorly entangled pairs a single high-quality entangled state can be distilled. This is done before entanglement swapping. All-optical schemes of producing an entangled state have been proposed (Azuma, Tamaki, and Lo 2015). One interviewee thought quantum repeaters could be commercialized in about 20 years and that they could be a large factor in the overall success of QKD.

2. Current and Potential Market

Commercialized QKD products have been available for over a decade. Switzerland was the first country to use quantum cryptography for a public use. In 2007, QKD was used to securely transfer Swiss election results. QKD is currently used in Switzerland to secure some banking transactions (Marks 2007; ID Quantique 2016a; McMahon 2016). Battelle has installed a 440-mile fiber-optic QKD link between its headquarters in Ohio and its offices in Washington, D.C. (Battelle 2013; "Solice of Quantum" 2013). As previously noted, China is building a 2,000 kilometer quantum encryption network using fiber-optic cables (Qiu 2014) and has launched a quantum satellite to test the transfer of QKD through space (Johnston 2016).

Outside of government-supported activities like those cited above and a few efforts on the part of financial institutions and research institutes like Battelle, QKD has not taken off commercially. Sales could be on the order of $50–500 million annually, based on conversations with companies in the industry. We did talk to a representative of one company that has focused on selling QKD technologies for messages sent between electric power substations along electric power transmission and distribution lines. These messages are currently not protected, though they could also be protected by conventional means. The short distances and relatively simple transmission needs makes this a good market for QKD, because repeater stations are not needed. Prices for QKD systems, like those used to connect substations, are now around $100,000 per unit though there is variation; these prices are likely to fall over time (Russian Quantum Center). However, globally there are 70,000 substations, so linking QKD systems to each of the substations would generate large revenues. Other QKD sales to non-government clients appear to have run a few million dollars or less.

Some market analysts have made optimistic projections of the global quantum encryption market, projecting total annual revenues close to $900 million by 2020 (Global Industry Analysts, Inc. 2015). This projection greatly exceeds any numbers for commercial sales that we have been able to gather. However, in the context of research and development (R&D) expenditures by governments, especially the Chinese government, the difference between the projection and current expenditures does not appear as wide. Global Industry Analysts (2015) projects that about three-fourths of sales would come from research institutions, government agencies, and defense establishments; large corporations and banks would generate about a fifth of these projected sales; and the remainder would be accounted for by small businesses, utilities, and other users.

3. Industry

ID Quantique, a Swiss company based in Geneva, is considered to be the world leader in quantum cryptography. Created in 2001 by four scientists from the University of Geneva, ID Quantique has provided encryption services to both governments and the private sector. The company's encryption algorithm was used in 2007 by the Swiss government to transfer election results from individual polling stations to the main polling data center (Greenemeier 2007). Currently, the company is collaborating with General Electric (GE) and Oak Ridge National Laboratory on a 3-year project aimed at reducing the cost of QKD by making a quantum channel accessible to multiple parties within the United States (Oak Ridge National Laboratory 2017). ID Quantique provided the technology for the first commercial QKD network in the United States, which was installed in 2013 by Battelle (Battelle 2013). In December 2016, ID Quantique partnered with China

Quantum Technologies (QTEC) to bring the company's quantum random number generators and QKD solutions to the Chinese market (ID Quantique 2016b). The joint venture will adapt ID Quantique's technology to the specific needs of the Chinese market and will enable the company to play an integral role in supplying China's incipient quantum communications network with its systems (ID Quantique 2016b). In the past, ID Quantique had charged between $100,000 and $200,000 per QKD system but in recent years, prices have been declining.

A second European company in the QKD space is SeQureNet, based in Paris, France. SeQureNet produces QKD post-processing software. Its main customers are primarily academic institutions. The company is a spin-off from Telecom ParisTech's quantum information team (SeQureNet 2010).

The large Japanese electronics and electrical engineering multinational firm Toshiba Corporation has been exploring QKD. It has participated in a partnership with Cambridge Research Laboratory through its subsidiary, Toshiba Research Europe, to produce a QKD system with bit rates of one million bits per second over a 50-kilometer distance. Toshiba has participated in several QKD field trials, including a 2008 field trial in Vienna, Austria, and more recent field trials in Tokyo in partnership with the National Institute for Information and Communication Technologies (Toshiba Corporation 2017b, 2017c).

There are several small start-ups in the United Kingdom that are focused on quantum secure solutions though they do not produce QKD products. These companies are Quantum Base and Post-Quantum. Quantum Base, a spin-off from Lancaster University, was established in 2014 and is focused on building a portfolio of quantum-enabled digital security products that will increase the level of authentication, identification, and encryption security (Quantum Base 2017). The company currently offers one commercial product, the Quantum-ID (Q-ID), a nanoscale device that creates a unique key based on the specific positions of millions of atoms. The company has seven employees. Second, Post-Quantum, founded in 2009, was a relatively early comer to the quantum technologies industry in the United Kingdom. The company has recently received Series A funding of £8 million (roughly $10 million USD) from VMS Investment Group and AM Partners (Lomas 2016). The small security company currently provides a suite of secure, encrypted communication software that is supposedly hack-proof against quantum computers.[6]

In the United States, MagiQ Technologies, based in Massachusetts, is a quantum information research and engineering technology service provider that is known for offering the world's first commercial quantum cryptography system, the Navajo, in 2003 ("MagiQ Technologies Releases 'Open' Quantum Key Distribution for Researchers Exploring Boundaries of Cryptography" 2003). MagiQ has introduced additional QKD

[6] IPC's Connexus Cloud is a worldwide, private financial markets network that consists of 200,000 users across 6,000 markets in 700 cities (IPC Systems, Inc. 2016).

models, including QPN 8505 in 2006 ("MagiQ Technologies Announces a Significant Increase in Network Security Through First Commercial Exploitation of Decoy State Based Quantum Cryptography Solution"2006). Its primary customers are U.S. government agencies, such as the U.S. Army, Navy, and Air Force; the Department of Energy; NASA; and the Defense Advanced Research Project Agency (MagiQ Technologies 2017). Also in the United States, Qubitekk, Inc., founded in 2012 and located in Vista, California, is focusing on electric utilities. The company recently sold QKD systems to San Diego Gas and Electric and Pacific Gas and Electric (Nanalyze 2016).

QuintessenceLabs is an Australian company specializing in quantum cybersecurity. Commercial products offered by the company include a quantum random number generator, a cloud-based encryption system, and encryption key and policy management systems (QuintessenceLabs 2017). It is also working on a second-generation QKD product using a continuous beam of laser light to generate and detect photons. In January 2017, QuintessenceLabs received additional financial backing from Westpac Banking Group and is looking to expand its global reach in the coming year (Nott 2017). The United States, including the U.S. government and military, accounts for more than half of QuintessenceLabs' customers (McLean 2016).

In China, QuantumCTek is likely the largest QKD company. Located in Hefei Province, the company was founded in 2009 by a physics group at the University of Science and Technology of China. QuantumCTek manufactures the QKD Cipher Machine, which was designed by the physics group. The company is building out China's quantum network (QuantumCTek 2017). In 2014, it joined the Quantum Safe Security Working Group along with ID Quantique and Battelle. A number of smaller Chinese companies, such as Qasky, have also been mentioned in this sector. Chinese government expenditures on QKD and quantum information sciences, more broadly, have provided funding for these companies.

Most of the companies selling QKD technologies are relatively small start-ups. Of the companies mentioned above, only Toshiba is a large multinational company. Several of the companies have specialized in particular applications of QKD, for example, Qubitekk's systems for the electric power grid.

Of the companies listed above, Qubitekk and MagiQ are based in the United States. ID Quantique, Toshiba Research Europe/Cambridge Research Laboratory, SeQureNet, Post-Quantum, and Quantum Base are based in Europe. Quintessence Labs is based in Australia. Despite China's large expenditures and ongoing research efforts in QKD, we identified only two Chinese firms (QuantumCTek and Qasky) engaged in QKD, likely because universities and other research organizations play a large role in the QKD space in China.

4. Prospects for Quantum Key Distribution

According to a U.S. Air Force Scientific Advisory Board study, quantum key distribution would not provide a significant benefit to the Air Force or, for that matter, most other potential customers seeking to secure their information (United States Air Force Scientific Advisory Board 2015, ix). According to the study, QKD provides little advantage over the best classical key distribution alternatives, but significantly increases system complexity. However, as previously noted, one interviewer said this concern could be mitigated if QKD is implemented correctly, though getting to a correct implementation is not an easy endeavor. Further, QKD is only one element of secure communications, and often not the weakest link.

The market for QKD currently appears to lie between $50 and $500 million USD. There was no consensus among interviewees as to whether demand will increase. The U.S. government appears to have reduced expenditures on QKD. The fall or stagnation in interest in QKD appears to stem from this perception that QKD does not provide substantial benefits in terms of greater security. Several interviewees expressed surprise that China continued to invest heavily in the area because of the physical constraints on QKD systems. Others, however, think that China may be able to overcome these constraints, especially that of distance, after which Chinese companies would be able to capture a large share of a potentially expanding market.

C. Quantum Random Number Generation

1. Description and Value of Technology

Quantum random number generation uses quantum principles to generate random numbers that can be used in key generation for cryptographic applications. While random numbers are naturally associated with QKD, they are also needed for conventional cryptographic applications.

Computers are deterministic, meaning that algorithmic output is predictable and repeatable. Random numbers generated with a deterministic algorithm are pseudo-random numbers. Pseudo-random number generators (PRNGs) start with a seed, a string of random bits. While PRNGs are often faster than their quantum counterparts, they are predictable—once the seed and algorithm are known, the sequence can be reproduced. Even though there are methods that introduce unpredictability into PRNGs, PRNGs are not suitable for certain applications (Herrero-Collantes and Garcia-Escartin 2017).

One way to introduce unpredictability into random number generators is to harness randomness in physical systems; these nondeterministic methods are referred to as true random number generators (TRNGs). While one way to generate randomness is to use a physical process, such as using electronic noise present in logic circuits, harnessing randomness in quantum systems provides an alternative approach to generating randomness (Wilber 2013; Stipčević 2011). Examples of quantum phenomena used in quantum random number generators (QRNGs) include radioactive decay or fluctuations in vacuum energy (Herrero-Collantes and Garcia-Escartin 2017; Symul, Assad, and Lam 2011). Because the outcome of a measurement of a quantum state is intrinsically random, QRNGs provide a strong claim that the numbers they generate are truly random (Xiongfeng, Xiao, Zhu, et al. 2016; Stipčević 2011).

TRNGs are sometimes used in cryptography, especially in high-security systems. Random numbers must be unpredictable in cryptography. While there are cryptographically secure PRNGs that use additional criteria, these are often used in conjunction with TRNGs to generate the seed.

Because QKD uses at least one random bit for each secured bit, quantum random number generators must generate random numbers at a much higher rate than needed for other cryptologic approaches. Currently, speeds are often limited to tens of millions of bits per second, which is too slow for some applications. There are no practical limitations on the rate at which random numbers can be generated, so advances in optical integration should increase the rate. Outside of cryptography, current applications include lotteries and gaming industries.

QRNGs produce random numbers differently than other types of generators. However, it is not clear that random numbers generated by quantum processes are inherently more random than random numbers generated by classical physical processes. Because of quantum phenomena, QRNGs are provably random; however, it is not clear how important this advantage over classical alternatives will be.

2. Current and Potential Market

There are at least eight companies that provide commercial QRNGs on the market (Herrero-Collantes 2017). Six of these have publicly accessible company and product information and are described below. We infer that none of these six companies have QRNG sales of more than $1.5 million a year. Assuming the two companies without public websites also have sales of QNRGs that run $1.5 million or less, the total market is unlikely to exceed $12 million annually. One interviewee suggested that the market for QRNGs is smaller, perhaps on the order of $5 million. Currently, the main applications are lotteries and gaming, data center security, simulations, and cryptography. If additional improvements are made on the generation rate, potential applications could expand to include the financial industry or the internet of things. For the financial industry, the generation rate would need to be roughly one to three gigabytes per second for QNRGs to be attractive. With the development of chip-size, high-performance QRNGs, companies may be able to generate faster bit rates, permitting them to penetrate new markets (Xiongfeng, Xiao, Zhu, et al. 2016).

3. Industry

The largest company that sells QRNGs is ID Quantique, which is headquartered in Geneva, Switzerland. (Herrero-Collantes 2017). As discussed above, ID Quantique also sells QKDs (see section B in this chapter). ID Quantique sells Quantis, a QRNG that is available in three models. Quantis ranges in price from €990 euro ($1,100 USD) to €2,990 ($3300 USD). The €990 model has a bit rate of four million bits per second and was introduced to the market in 2005. ID Quantique's most expensive version generates random numbers at a bite rate up to sixteen million bits per second and was introduced in 2010. ID Quantique's featured applications for Quantis include online gaming and lottery companies, data center security, and cryptography (ID Quantique 2017).

QuintessenceLabs and Whitewood Encryption Systems, Inc. are the two largest competitors to ID Quantique that produce QRNGs—other companies manufacture PRNGs. QuintessenceLabs, headquartered in Deakin, Australia, produces the random number generators, qStream and qCrypt-xStream, each with a bit rate of one gigabyte per second. qStream was introduced in 2012. QuintessenceLabs has partnerships with the Centre for Quantum Computation and Communications Technology at University of New South Wales (McLean 2016). Whitewood, headquartered in Boston, Massachusetts, introduced its QRNG, Entropy Engine, in 2015. Entropy Engine's bit rate is 350 million bits per second. In 2016, Whitewood bought Los Alamos National Laboratory Technology's intellectual property relating to quantum communications over optical fiber ("Whitewood Encryption Systems Announces...." 2016). Whitewood only manufactures QRNGs; it does not manufacture commercial QKD systems, though some of the intellectual property that was transferred from Los Alamos National Laboratory was related to QKD (Whitewood Security 2017).

Several smaller companies manufacture QRNGs:

- Micro Photon Devices, headquartered in Bolzano, Italy, produces a QRNG and photon counting devices that it sells to NASA, HP, Novartis, and MIT (Micro Photon Devices 2013).
- PicoQuant, headquartered in Berlin, Germany, sells a QRNG with a bit rate of 150 million bits per second. PicoQuant also sells photon counters, more broadly, pulsed lasers and LEDs, fluorescence spectrometers, and fluorescence microscopes (PicoQuant n.d.).
- qutools, headquartered in Munich Germany, produces a QRNG with a bit rate of 50 million bits per second. In addition to QRNGs, qutools sells entangled photon pair sources, QKD components, and quantum optics components (qutools n.d.).
- Crypta Labs, founded in 2015, is a cybersecurity company focused on developing a quantum random number generator microchip using quantum

properties of light (Crypta Labs 2017). The company announced that it is working on a prototype and will be targeting the transportation, military, and medical sectors for market opportunities.

- Cambridge Quantum Computing, founded in 2014, is an independent company that specializes in developing algorithms, operating systems, and protocols for quantum devices (Cambridge Quantum Computing 2017). In addition, Cambridge Quantum Computing is also working to develop a QRNG, protocols to secure authentication using quantum encryption, and quantum resistant cryptocurrency.

QRNGs represent a large portion of the product lines for QuintessenceLabs and Whitewood, whereas QRNGs are one of several (or more) product lines for the other companies. While some of these companies, such as ID Quantique, have been producing QRNGs for over a decade others, such as QuintessenceLabs and, more recently, Whitewood, have started selling QRNGs more recently.

Of the eight companies listed above, ID Quantique, Micro Photon Devices, PicoQuant, qutools, Crypta Labs, and Cambridge Quantum Computing are located in Europe. QuintessenceLabs is located in Australia, and Whitewood is located in the United States. Of the six companies located in Europe, two are located in Germany, and two are located in the United Kingdom.

4. Prospects for Quantum Random Number Generation

Overall prospects for QRNGs will be determined by whether PRNGs and TRNGs that are not based on quantum phenomena are secure enough. While PRNGs are adequate or better than QRNGs for many applications, the market for QRNGs (or other TRNGs based on physical processes) will likely grow for several reasons. First, the largest driver of the QRNG market will likely be through an expansion into new industries such as the financial industry or data center security. With additional developments in QRNGs, for instance, through wave guide fabrication, the bit rate of QRNGs could rise, increasing the potential customer pool. One advantage of generating randomness through quantum processes instead of through other physical processes is that quantum randomness is provably random; however, it is unclear if this advantage will become an important one.

Second, QRNGs, and TRNGs more generally, may become more important if better factoring algorithms come to fruition. The timeframe for this is unclear because current classical methods are too computationally expensive and Shor's algorithm is far from being able to be utilized to factor very large numbers, as discussed in the next chapter (section C). Classical encryption algorithms that are not susceptible to quantum cryptanalysis have been developed and an effort is underway to select a suitable algorithm.

4. Quantum Computing and Simulation

A. Potential Commercial Technologies

Quantum computing and simulation encompasses the development of both quantum computer hardware and algorithms that can be executed to perform specific tasks on this hardware. The term *quantum simulation* refers to the use of quantum computational techniques to model complex quantum processes that are beyond the capability of classical modeling approaches. Table 4 provides a list of quantum computing technologies arranged into hardware, algorithms, and simulation. All of the technologies required for quantum computing and simulation are in the category of medium- to long-term readiness.

Table 4. Quantum Computing and Simulation Technologies

Technology	Technological Readiness[a]	Potential Market
Hardware		> $500 million
Quantum processors	Medium-term	
Logical qubits (fault tolerant)	Long-term	
Quantum computer design	Medium-term	
Quantum computer fabrication	Long-term	
Algorithms		< $50 million
Quantum error correction	Medium-term	
Fault-tolerant algorithms	Long-term	
Quantum software	Long-term	
Simulation		< $50 million
Practical algorithms	Medium-term	
Nitrogen-fixing	Long-term	

[a] *Commercial* indicates that products or services from the technologies are currently available; *short-term* readiness means products or services are expected to become commercially available within the next 5 years; *medium-term* readiness means products or services are likely to emerge within 5 to 10 years, and *long-term* readiness means products or services are unlikely to become commercially available within the next 10 years.

B. Quantum Computer Hardware

1. Description and Value of Technology

Quantum computing offers the possibility of computing in an exponentially larger state space than that readily accessible with classical computing, which gives quantum computing a possible advantage for certain applications. A quantum computation is governed by the fundamental principles of quantum state evolution and measurement. Information contained in the quantum state is accessed through measurement, and it is this measurement that destroys the state's quantum nature and consequently halts the computation.[7]

As with classical digital computation, quantum computation is realized using bits, but in this case they are quantum bits (qubits). In addition to possessing the classical states of 0 and 1, qubits can be in an arbitrary superposition of 0 and 1.

A classical digital computer performs binary operations on bits that can have a value of 0 or 1. The number of unique states that can be accessed at any instant in time by a classical computer scales as 2^{CB}, where CB is the number of classical bits. A quantum computer based on qubits may exist in a *quantum superposition* of 0 and 1. The amount of information that can be processed in a quantum machine is further increased through *quantum entanglement* in which the properties of one qubit are quantum correlated with other qubits.[8] In general, a quantum computer can access 2^{QB} unique states *simultaneously*, where QB is the number of qubits.[9] A set of entangled qubits is therefore theoretically able to store and process significantly more information than a corresponding set of classical bits.

While superposition (and entanglement with other qubits) gives quantum computation its power, the measurement of a qubit produces only a 0 or a 1, and also destroys any entanglement it may have had with other qubits. Hence, the result of an *n*-qubit computation is a single number that is *n*-bits in length. After measurement, the quantum computation is finished, because the system has been placed in a classical state by the measurement.

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7 This measurement does not include ancilla bits—bits that are designed to eliminate errors—which occur throughout the calculation.

8 *Quantum correlated* in this case simply means that a measurement on one part of the system affects future measurements on the other part of the system in a way that is determined by the non-classical state of the system.

9 Although quantum computing is able to access this much larger space, quantum computing should not be thought of as a form of parallel computing where multiple possible solutions are tried at the same time. This misperception is common in popular media.

The different approaches to constructing a quantum computer are characterized by the technology for the qubits and how they are manipulated (quantum gate operation versus analog couplings):

- *Trapped ion*: The states are determined by the electronic structure of the ions and interactions between ions are mediated by the trap. This is the oldest form of quantum computing. State-of-the-art traps hold and manipulate 15 ions or 15 qubits. Several groups, including National Institute of Standards and Technology (NIST) and several universities are considered the leaders in this technology.

- *Superconducting qubits:* Quantum mechanical tunneling in Josephson junctions allow current to tunnel across an insulating barrier (Clarke 2007). This is the approach being investigated by Google, IBM, and several universities. So far, Google has generated nine entangled qubits, with a near-term goal of 50. Using a similar approach, IBM is aiming to entangle about 50 qubits sometime in the next few years. IBM has made a 5-qubit quantum machine freely available on the Internet for testing (IBM 2017a).

  Superconducting qubits are also used in the quantum annealing machines developed and marketed by D-Wave Systems, Inc. The term quantum annealer refers to the particular type of algorithm that can be implemented on the hardware. While evidence of quantum entanglement has been observed, no clear evidence of computational advantage has been demonstrated for this approach (Mandrà 2017).

  D-Wave's 2000Q model has 2,000 superconducting low-quality qubits,[10] so it is not clear if the 2000Q is a true quantum computer. Of course, from a commercial product standpoint, the computational performance of the machine is more important than its scientific taxonomy.

- *Other approaches:* Less mature approaches that offer promise include qubits based on quantum dots, semiconductor particles, neutral atoms, nitrogen vacancies in diamonds (See Chapter 2, Section H), and photons. Despite their less mature status, these approaches should not be disregarded, particularly those based on silicon.

The key limitation of the present state of quantum computers is the small number of qubits. The number of fully entangled qubits that have been achieved range from five to nine, which represents a very restricted capability. It may be a decade before quantum

[10] *Low-quality* means that the coherence time of the qubit is significantly less that the coherence time for qubits used in quantum gate machines.

computers become available with enough entangled qubits to compete with classical computers in addressing practical problems.

Furthermore, the physical qubits demonstrated to date are not fault tolerant, meaning that they cannot retain the quantum state through the duration needed for the calculation. Logical qubits built from physical qubits are fault tolerant, but the number of physical qubits needed depends on many factors, including the quality of the physical qubits and the properties of the error correction codes. Anywhere from 1,000 to more than 10,000 physical qubits may be needed to produce a single logical qubit suitable for demanding applications (Fower 2012). Most algorithms are discussed in terms of logical qubits, whereas most hardware demonstrations use physical qubits, though often the word “qubit” is used in both cases. We follow this practice in this report unless specifically stated otherwise.

Thus, not only does a quantum computer need to do something useful to be commercially viable, it also needs to do that something better than it can be done using classical computing, particularly because the cost of a classical bit is on the order of one-millionth of a cent, whereas the cost of a physical (not logical) qubit is on the order of $1,000—a difference of 9 orders of magnitude.

Given the likely cost and complexity of quantum computing, the first quantum computers are likely to be paid for, owned, and operated by the Federal government or the national laboratories. As with supercomputers owned and operated by the national laboratories, time on a quantum computer is likely to be made available to qualified users. This is similar to the Platform as a Service (PaaS) in which commercial companies offer access to computer hardware platforms for a fee. The platforms that can be accessed through such cloud services are classical except for the small, free IBM quantum machine mentioned previously.

Computer hardware is only as useful as the software that can be run on it. For now, it is sufficient to say that quantum computers will not outperform classical computers for all applications. For the foreseeable future, it is likely that only a small subset of computational problems will be able to be addressed by quantum computers.

2. Current and Potential Market

At this point in time, quantum computing appears to be focused at specific applications where a quantum approach may be able to solve problems that classical computers are unable to solve in a reasonable length of time. However, all interviewees stated that for all these types of problems, most of the setup, computing, and analysis would take place on classical computers. The computer program would turn to a linked quantum computer for specific operations. Such a model is akin to how supercomputers are currently used: researchers set up their programs on their computers and then reserve time on supercomputers in order to run operations that they would be unable to run on their own machines.

Global sales of supercomputers in 2016 were roughly $4.0 billion (Russell 2017). The market is dominated by a mix of specialized manufacturers, such as Cray, Inc., and large global computing manufacturers and technology companies, such as Dell, Fujitsu, Hewlett Packard Enterprise (HPE), IBM, Lenovo, NEC Corporation of America, Silicon Graphics International (SGI) Corporation, Bull Atos Technologies, and Sugon. At least initially, quantum computers would probably generate a small fraction of the revenues of the supercomputing market, but the market could grow. However, quantum computers are unlikely to become suitable for all the applications for which supercomputers are currently used.

Government purchases dominate the market for supercomputers, and governments often provide researchers with computing time on the machines for free. Looking at this model, the market for quantum computers is likely to be small, with governments or large corporations with special computing challenges choosing to purchase a handful of machines to help solve special types of problems.

3. Industry

Several large companies and a few small businesses are developing quantum computer hardware. D-Wave Systems, headquartered in Hanover, Canada, with offices in California and Maryland is the only company to have sold machines based on quantum computing principles, though any clear observation of quantum speed up remains elusive as of 2017. It has sold 10 D-Wave quantum computers in the last 6 years, including to a NASA-Google consortium, Los Alamos National Laboratory, Lockheed Martin, and Volkswagen. The latest model, the D-Wave 2000Q, is sold for about $15 million (Shah 2017a). Lockheed Martin has continued to purchase subsequent D-Wave systems (Lockheed Martin 2017), upgrading its 128-qubit D-Wave One system to the 512-qubit D-Wave Two in 2013, and upgrading again to the 1000+ qubit D-Wave 2X system in 2015 (D-Wave 2017a). All the D-Wave computers sold have been used for computing research.

Google is seeking to develop a gate-based quantum computer with fully entangled superconducting qubits. Google has recently announced a plan to commercialize small quantum computing devices within the next 5 years (Mohseni et al. 2017). The company has been exploring the potential of quantum computing since 2009, when it first started collaborating with D-Wave Systems (Simonite 2015). In May 2013, the Quantum Artificial Intelligence Laboratory (QuAIL) was created as a joint initiative among Google, NASA, and the Universities Space Research Association (Neven 2013). QuAIL is located at NASA's Ames Research Center and has recently announced that in 2017 it will be updating its D-Wave 2X system to the D-Wave 2000Q system (D-Wave 2017b). To fast-track development, in 2014, Google hired John Martinis, professor of physics at the University of California, Santa Barbara, to head its quantum computing laboratory. Martinis uses superconducting technology to build qubits. In 2015, Martinis and his team successfully ran part of an error-checking and correction program on a 9-qubit chip (Simonite 2015). Martinis' team and Google engineers at QuAIL are attempting to build a 50-qubit device that would be the first to perform a task that today would be infeasible for even the fastest supercomputer (Simonite 2017), though the planned calculation has no practical value (Boxio 2016).

Like Google, IBM has chosen superconducting qubits as the building blocks of its quantum computing initiative. After several decades working on quantum computing, IBM announced in March 2017, a new division named IBM Q, located in New York, which aims to build the industry's first commercially available, universal quantum computer system (IBM 2017b). IBM Q will have approximately 50 qubits, and its systems and services will be made available via IBM's cloud platform (IBM 2017b). IBM hopes to have a larger working prototype within the next 5 years.

In May 2016, IBM launched Quantum Experience, a cloud-based quantum computing service for researchers to run quantum algorithms and experiments remotely on IBM's 5-qubit quantum computer. IBM estimates that about 40,000 users have run over 275,000 experiments on Quantum Experience since its launch. The company recently released a new Quantum Experience application that allows programmers and developers to build interfaces directly between IBM's cloud-based quantum computer and their own classical computers (IBM 2017a).

Microsoft is working on topological quantum computing. The company believes that topological qubits will be more resistant to outside disturbance and interference, allowing them to remain in a quantum state longer, making error correction easier (Linn 2016: Castelvecchi 2017). Microsoft has been working on topological quantum computing since 2005, when it established the research laboratory Station Q under the leadership of Field's mathematician Michael Freedman at the University of California, Santa Barbara (Markoff 2016).

Station Q brings mathematicians, physicists, and computer scientists together to better understand topological properties and how they could be applied to quantum computing (Microsoft 2017). In 2011, Microsoft established Station Q Redmond in Washington State to focus on the development of quantum algorithms. Station Q is now a global consortium working to build not only a quantum computer, but also the software to run on it (Linn 2016; Station Q 2017). Microsoft recently hired four leading researchers in the field to join the growing Station Q consortium and help the company transition from theoretical research to engineering prototypes for commercial applications (Gibney 2016; Linn 2016).

Intel Corporation has been investing in quantum (Shah 2017b). Unlike other companies, Intel is hoping to leverage its expertise in industrial manufacturing of silicon chips to accelerate its research and development on silicon qubits. In 2015, Intel announced a 10-year, $50 million collaborative partnership with QuTech, a quantum research institute of Delft University of Technology, and the Netherlands Organization for Applied Scientific Research (Intel 2015). Intel announced in January 2017 that it was able to successfully layer silicon qubits onto standard wafers currently being used in chip manufacturing (Allendorf 2017). Most of Intel's quantum computing activities are located in Delft, the Netherlands.

IonQ, Inc., is a quantum computing start-up founded in 2015 that specializes in ion trap technology in which qubits are encoded by single ions held by electric and magnetic fields in vacuum traps (Castelvecchi 2017). A recent test that compared trapped ions and IBM's superconducting qubits showed that the trapped-ion system had better accuracy for algorithms that had higher connectivity, but that IBM's superconducting quantum device had faster logic gates (Linke et al. 2017; Pandey 2017).[11]

Like IBM, Rigetti Computing, founded in 2013, is focused on offering quantum computing services over the cloud. As of March 2017, it had raised a total of $64 million in funding for that purpose (Deutscher 2017). The company, located in California, is building a cloud quantum computing platform for artificial intelligence and computational chemistry (Rigetti Computing 2017). Rigetti, like IBM and Google, is using superconducting chips for its quantum computer.

California start-up Qubitekk, located in Vista, California, manufactures devices to generate entangled qubits using photons. One of Qubitekk's advantages over its competitors is its ability to make smaller devices for entangling photons with greater efficiency over time. Qubitekk is planning to release a new, smaller quantum entanglement photon generator that is roughly the size of a stick of gum. While not a quantum computer, such a device might be useful to transport quantum states in the computer.

The industry, which is in a nascent state, consists of several large companies (IBM, Google, and Microsoft) with small quantum computing divisions, and a number of smaller start-ups for which quantum computers are their primary market. There are also a number of basic research activities in quantum computing hardware around the world.

4. Prospects for Quantum Computer Hardware

The key development needed for quantum computers to become commercially viable is having systems with large number of entangleable qubits. While the the minimum

[11] Both the trapped-ion and superconducting quantum device contained five qubits and had similar error rates. Researchers ran a series of quantum algorithms on both platforms to determine accuracy and speed.

number of qubits required is unlcear, many algorithms will need a minimum of 1 million qubits to be useful. Presently, the number of qubits is less than ten, with two of the centers of activity (IBM and Google) aiming for 50 in the near future. But thousands of entangled qubits are likely to be needed for quantum computers to compete with classical computers for useful problems at a minimum. More specifically, the highest technology hurdle facing quantum computers is the lack of a fault-tolerant logical qubit. It will likely take thousands to upwards of a 10,000 physical qubits to make a single logical qubit. The exact number of physical qubits needed will depend on many factors, including the nature of the errors, the performance of the physical qubit, and the choice of quantum error correction codes.

The most likely market for quantum computing hardware in the near- to mid-term is as a small subset of demand for highly specialized computers that are geared for special applications. A number of individuals with whom we spoke argued that quantum computers would be used to solve only one operation in a program housed on classical computers. Users would lease time on quantum computer hardware for specific steps in their analyses, most likely in combination with classical computer processors for input and output of information.

C. Quantum Computer Algorithms

1. Description and Value of Technology

The goal of quantum algorithmic computation is to make the algorithm less complex (fewer operations), resulting in more efficient computation with the intent that computationally difficult problems will be possible on a quantum computer that are not practically feasible through classical computation alone. The properties of quantum computer hardware allow two broad approaches to algorithms, *digital* and *analog*.

The digital version is also called the gate model of quantum computation (Deutsch 1985). Computation in the gate model performs the calculation through a sequence of discrete steps (i.e., unitary transforms) implemented as gates. One challenge for both quantum computing and simulation is the difficulty of producing fault-tolerant logical qubits that can remain in a quantum state for a few hours or a few days at a time so that they can be manipulated. In 2016, researchers from the United States and the Netherlands were able to stabilize qubits for about 400,000 nanoseconds (0.4 milliseconds) using silicon, up from 10 nanoseconds using gallium arsenide (Kawakami et al. 2016). A group of scientists from Australia was able to achieve stabilized qubits for 2.4 milliseconds before they collapsed from their superposition states (Laucht et al. 2017).

A second equally pressing challenge is the need to reduce the rate at which errors occur. Until recently, qubits typically made about one error for every ten computer steps (Gibney 2014). Researchers have shown that it is theoretically possible to use neighboring entangled qubits for error correction (Popkin 2016). Linking entangled qubits together into arrays allows for communication among qubits and faster error correction (Dickerson 2015). Thus far, the largest stabilized array achieved is an array with nine qubits, although this stabilization was insufficiently fault-tolerant for computations of interest (Kelly et al. 2015). Even optimistic researchers expect that it will take at least another 15 to 20 years before arrays consisting of hundreds of qubits can be stabilized long enough to perform substantially meaningful fault-tolerant quantum computations (Gibney 2014; Mueck 2015).

The idea behind *analog* quantum computation is to build a system that imitates the problem and then controls the interaction to continuously evolve the system from the initial to the terminal state followed by a measurement. One commercial example of this approach is the D-Wave Systems quantum computer that implements an Ising model, providing a solution for a system of quantum spin states arranged on a lattice with limited connectivity.

Because the number of algorithms that have been demonstrated on quantum computer hardware is small, quantum computers will be able to address only a small subset of computational problems for the foreseeable future. We discuss the more significant quantum computer algorithms developed thus far below.

a. Shor's Algorithm for Cryptanalysis

Shor's *digital* algorithm (Shor 1997) proves theoretically that a quantum computer can factor large integers with significantly fewer operations than required by a classical computer. Factorization of integers is key to breaking the security of many and the most popular asymmetric crypto systems. For example, to protect information using an RSA cipher, an integer must be employed that is too large to be factored rapidly by the best known approach, the generalized numerical field sieve method. As an illustration, the RSA-768 cipher employs 768 bits, and took two years to factorize on a classical computer (Kleinjung et al. 2010). However, 21 is the largest integer actually factored to date using Shor's algorithm on quantum hardware.[12] While a quantum cryptanalysis capability is of great interest to the intelligence community, there appears to be little interest from commercial markets.

b. Harrow-Hassidim-Lloyd (HHL) Digital Algorithm

The HHL digital algorithm (Harrow, Hassidim, and Lloyd 2009) provides an approach for computing a function f(*x*), where *x* is a vector of length 2^n and is a solution of

[12] The largest integer factored on quantum hardware using any quantum algorithm is 56,153, which was accomplished using a minimization approach (Martin-Lopez et al. 2012). However, the integer 56,153 requires only 16 classical bits and so can easily be decrypted rapidly using a classical computer. It may be a long time before quantum hardware is available for quantum algorithms to factor practical security ciphers.

a large linear set of equations, **A**$x = b$. Significantly, the HHL algorithm solves such systems of equations exponentially faster than classical methods. Some progress has been made in expressing practical problems in the HHL algorithm structure, such as solving linear sets of differential equations (Clader, Jacobs, and Sprouse 2013). However, a significant challenge remains in scaling the use of these algorithms on quantum hardware, with its small number of qubits, in terms of reading and storing the quantity of information associated with vector lengths of input variable *b* for problems of practical interest (Aaronson 2015).

c. Grover's Digital Search Algorithm

Grover's digital algorithm (Grover 1996) performs an unstructured search of *N* objects in a time that scales sublinearly in *N*. Similar to the status of the HHL algorithm, Grover's algorithm has not found practical application at least in part due to the present severe limitation on the amount of information that can be read onto existing quantum computer hardware. In most cases loading the information from a classical source into a quantum computer would take longer than it takes to run the algorithm on a classical computer. In some cases, the data to search could be generated algorithmically. For example, an estimated several thousand logical qubits are required to apply Grover's algorithm to cryptanalysis of a 256-bit cipher (Grassl et al. 2016).

d. Quadratic Unconstrained Binary Optimization (QUBO) Problems

Analog quantum computing algorithms may be better suited than digital algorithms to solving QUBO problems that involve finding the maximum of a quadratic objective function $Z = X`QX$, where *X* is a vector of binary variables (values of 0 or 1), *n* is the length of the vector, *X`* is the transpose of *X*, and *Q* is a symmetric *n*-by-*n* matrix. A variety of practical optimization problems can be translated into the QUBO format. Importantly, QUBO problems can be expressed within the Ising model algorithm structure that the D-Wave quantum annealer solves.

As previously mentioned, the NASA-Google consortium, Lockheed Martin, and Volkswagen are among the companies and institutions that have purchased D-Wave quantum annealers. Examples of applications being investigated include operational planning problems (Rieffel et al. 2015), feature identification, and unsupervised learning (O'Gorman et al. 2015). However, to date, there is little to indicate any algorithms executed on a quantum annealer have yielded performance superior to that already available with classical computing (Aaronson 2017).

2. Current and Potential Market

The global market for quantum algorithms is inextricably tied to the availability of quantum computers. Some programmers may be able to sell tailored programs for the algorithms cited above when quantum computers become available. This is likely to be a niche market in which users write their own applications or a few programmers offer tailored products. It is hard to see how this market would be anything but small.

3. Industry

Because quantum computing algorithms are still nascent, we were unable to identify any companies that have developed commercial software products. Activities involving the study of quantum algorithms are ongoing at Google, IBM, and Microsoft.

Rigetti Computing has set its sights on offering its quantum computing services over the cloud. The company recently launched a beta version of its application programming interface (API), called Forest (Rigetti Computing 2017). The company states that "Forest emphasizes a quantum-classical hybrid computing model, integrating directly with existing cloud infrastructure and treating the quantum computer as an accelerator" (Rigetti Computing 2017).

QC Ware Corporation was founded in 2014 and is focused on developing algorithms and software for quantum computing. QC Ware received seed funding from Airbus Group in 2016 to develop quantum computing applications for aerospace/defense, finance, and cybersecurity domains (PR Newswire 2016). In January 2017, QC Ware and the Universities Space Research Association were awarded a $1 million grant from the National Science Foundation to develop a quantum computing platform-as-a-service that would allow users to access quantum computing resources through the cloud (PR Newswire 2017).

4. Prospects for Quantum Computer Algorithms

The effective development and application of quantum computer algorithms is challenged by the lack of availability of hardware providing sufficient capacity to allow problems of practical size to be addressed. Until that hurdle is overcome, one should recall that the two most famous digital quantum algorithms, Shor's and Grover's, were developed in the late 1990s but have yet to lead to any commercial products. If quantum computers become a reality, we argue that the demand for software and algorithms to run on those computers is likely to be satisfied by programmers employed by the companies that buy these machines or small companies that offer tailored products.

D. Quantum Simulation

1. Description and Value of Technology

Quantum computing provides an opportunity to understand and predict properties of quantum systems. The goal of *quantum simulation* is to predict the desired properties of a quantum system. Quantum computation provides two general means for doing so: (1) numerically solving the equations describing the systems, or (2) building a quantum system that imitates the system of interest and measuring its properties. The first approach uses a gate-based quantum computer, as described in the previous section. The second could use much of the same technology, but the approach would be to use qubits as elementary parts of the system and provide a means for controlled interaction. This approach could be similar to the D-Wave quantum annealer whereby the machine implements an Ising model and provides for a range of interactions between the qubits. As designed, the D-Wave machine embeds a numerical optimization problem into this physical system and encodes the answer in the final state. But the Hamiltonian function describing the interaction in either case is still the two-dimensional Ising model, regardless of whether it is an optimization computation or a quantum simulation.

Because much of the hardware described is similar to that discussed under quantum computer hardware (section B of this chapter), the focus in this section will be on the algorithms specific to quantum simulation. We know that quantum properties cannot be calculated efficiently using classical computation (Feynman 1982). Quantum simulation is important because it is likely that simulation is the only way quantum computations can be undertaken.

a. Nitrogen Fixation

One important example of a potential application of quantum simulation involves nitrogen fixation, the process of converting atmospheric nitrogen (N_2) into organic compounds such as ammonia (NH_3) that are essential for plant growth (Burris 1991). Nitrogen fertilizers have become an integral component of increased crop yields in modern-day agriculture (Garg and Renseigne 2007). The primary sources of nitrogen for agriculture are nitrogen compounds fixed biologically and those manufactured in fertilizer plants (Thomas, Van Bloem, and Schlesinger 2006).

Bacteria that live in nodules in the roots of legumes, clover, and other plants “fix” nitrogenous compounds from atmospheric nitrogen using biochemical processes. The overall reaction for biological nitrogen fixation is:

$$N2 + 8H+ + 8e- \rightarrow 2NH3 + H2$$

Where N_2 is atmospheric nitrogen, H^+ is a hydrogen ion, e− is an electron, and H_2 is hydrogen.

This reaction involves several steps and requires energy to take place. Although the process by which the enzyme nitrogenase catalyzes the reaction has been studied extensively, the catalytic mechanism (i.e., identifying and characterizing each intermediate formed and embedding these intermediates within a kinetic framework that explains their dynamic interconversion) remains unknown (Hoffman et al. 2013).

Industrial nitrogen compounds, such as urea, calcium ammonium nitrate, ammonium nitrate, ammonium sulfate, and ammonia, are manufactured from N_2. U.S. agriculture switched from relying primarily on biologically fixed nitrogen to synthetic nitrogenous fertilizers in the mid-1960s (Houlton et al. 2013). The amount of nitrogen fixed in synthetic fertilizers in developed countries is now probably several times higher than that from biologically fixed nitrogen (Galloway et al. 2004).

Industrial nitrogenous fertilizer plants primarily use the energy-intensive Haber-Bosch process, whereby N_2 reacts with H_2, which is derived predominantly from natural gas (methane), under high temperatures and pressures to produce ammonia (NH_3). The large amounts of nitrogenous fertilizers produced every year using the Haber-Bosch process consume substantial quantities of natural gas, currently about five percent of global consumption (Gibney 2014). If a more energy-efficient process could be designed, modeled on how bacteria fix nitrogen in nodes in the roots of plants, large savings in natural gas and reductions in greenhouse gases emitted during the manufacture of nitrogenous fertilizers could be achieved.

Quantum simulation could help biochemists unlock the biochemical process used by bacteria to fix nitrogen. Complete knowledge of this process could lead to the design and development of a more energy-efficient process to manufacture ammonia. Physicists believe that 400 encoded logical qubits might be sufficient to simulate the industrial nitrogen fixation process, thereby providing key information needed to recreate that process industrially (Gibney 2014). While the number of qubits needed is small compared with the numbers needed for many other quantum computer applications, the number of gate operations may be prohibitively large. The number of gate operations is on the order of 10^{15} logical operations (Reiher 2016), but making the calculation fault tolerant will increase the number of gate operations by several orders of magnitude. More research in quantum simulation algorithms is needed to reduce the complexity of the calculations.

Quantum computers capable of performing this type of calculation are more than 10 years away. The first quantum computers will not have error correction and fewer *physical* qubits than the 400 *logical* qubits needed for this calculation.

b. Ground State Energy

A second example of quantum simulation involves calculating the ground state energy of molecules. One approach that attempts to make use of minimal quantum resources and heavily leverages classical computation, is *quantum-assisted optimization* algorithms (Peruzzo et al. 2013; McClean 2016). These algorithms were designed to make use of quantum processing hardware expected to be available in the near future—processors with 50–100 high-quality physical qubits.[13] Such a processor is not capable of

[13] The term *high quality* means that many gate operation can be performed in a coherence lifetime.

fault tolerant processing. The goal of the algorithm is to find the energy of the ground state by starting in an easily prepared state, evolving that state to become the ground state using a quantum processor, and measuring the energy. The measured energy comes out of the quantum portion of the computation. The parameters that produced the quantum state are varied to reduce the energy and the quantum calculation is repeated. The procedure is repeated until the ground state is determined. Quantum simulation based on this approach was successfully used to calculate the bond disassociation curve of $He\text{-}H^+$, which is the bond energy as a function of atomic separation (Peruzzo et al. 2013). The calculation for a given atomic separation converged using the quantum-assisted optimization algorithm after about 50 iterations. The problem used 4 atomic orbitals. This approach scales as the fourth power of the number of orbitals (Wecker, Hastings, and Troyer 2015), which is computationally challenging for larger problems.

Other quantum simulation approaches have used different variational states in an attempt to simplify the calculation (Wecker, Hastings, and Troyer 2015). For example, estimates have been provided for two Hamiltonian functions: from the Hubbard model and from quantum chemistry. The Hubbard model describes a range of condensed matter phenomena, including superconductivity. For the Hubbard model, 10×10 lattices would require around 200 qubits. Wecker, Hastings, and Troyer set error goals to distinguish competing ground states. They estimated that around 600,000 samples per energy evaluation would be needed. Assuming a gate time of 1 microsecond, this calculation would take several days to complete.

Another approach explored was *quantum chemistry,* which is concerned with ground state energies. Using this approach, Wecker, Hastings, and Troyer estimated that 10^{13} samples would be needed per energy for the Fe_2S_2 molecule for 10^6 energies, bringing the total number of samples to 10^{19}. Each sample would require 10^8 gate executions, bringing the total number of gates in the calculation to 10^{26}. At 1 microsecond per gate, this calculation would take 10^{20} seconds, which is about 200 times the age of the universe.

Because this is an active area of research, it is reasonable to expect that there will be further algorithmic improvements, but it is unlikely such calculations will soon be of practical importance. Elemental quantum processors are being built that should be able to do calculations of ground state energy, and it will then be possible to gain a fuller understanding of those processors' economic viability.

2. Current and Potential Market

a. Nitrogen Fixation

Global sales of synthetic nitrogenous fertilizers are large, running $90 billion in 2016 (Morder Intelligence 2017). Fertilizer production costs are driven by the cost of the industrial plant and the price of natural gas. As previously explained, natural gas is used as a compound in the chemical reaction to create hydrogen gas, a key component in the process of making ammonia (NH_3). It is also used to provide energy for the process. In industrial processes using natural gas to make NH_3, 15 percent of the natural gas (methane, or CH_4) is used as the compound to make the NH_3 and 85 percent is used as energy. In terms of energy consumption, each metric ton of ammonia product consumes 29 million British thermal units, equivalent to 28.6 thousand cubic feet of natural gas,[14] to heat the N_2 and CH_4 to 750 to 800°C at high pressures.

Globally, 140 million tons of NH_3 or its equivalent were manufactured in 2013, which implies that the production of nitrogenous fertilizer consumed 4 trillion cubic feet of natural gas (Heffer and Prud'homme 2016). Using the average price in the United States in 2016 of $3.51 per thousand cubic feet (EIA 2017), the value of the energy used to manufacture this quantity of NH_3 or its equivalent would have been $14 billion in that year. Biological processes for fixing nitrogen work at outdoor temperatures and normal atmospheric pressures. If these biological processes could be mimicked at an industrial plant, manufacturers could save substantial amounts of this energy and hence money. A patent for such a process could capture some of these savings in energy costs in royalty fees.

Technological innovations such as quantum simulation often lead to reductions in prices, but these reductions in price limit the returns that a patent holder might expect. Moreover, biochemists and engineers working on taking a biological process and making it into an industrial process would only be willing to pay a portion of their potential earnings from a patent to pay for analysis of how nitrogenese works in nature. In addition, the information generated by a quantum simulation is likely to be only one piece of the puzzle, as substantial investments in engineering and new plants would also be necessary. The willingness of companies to pay for output from a quantum simulation would be tempered by the cost of trying to obtain analogous information using other techniques. In short, potential revenues from simulations of the biological process for fixing nitrogen are likely to be analogous to payments made for pieces of research in the development of other technologies. In general, companies are reluctant to spend a large share of their R&D expenditures on a single piece of the research process. Accordingly, we argue that prospective payments for quantum simulations for the process of nitrogen fixation are likely to be less than $50 million annually.

b. Ground State Energy

Developing a consistent means of measuring ground state energy for complex molecules would be a valuable tool for chemists. That said, life sciences and chemical companies are likely to either develop their own in-house tools after purchasing a quantum computer or pay specialized quantum computing companies to develop and run simulations

[14] We use 1,015 BTUs per cubic foot of natural gas.

as needed. We argue that this market would be highly specialized and would likely be less than $50 million annually.

3. Industry

We were unable to identify any commercial companies planning to market quantum simulation products.

4. Prospects for Quantum Simulation

Similar to the situation for digital quantum computing, the outlook for quantum simulation is that current capabilities are significantly limited by the available quantum hardware. Only after larger, more capable machines become available will it be possible to effectively assess the usefulness and commercial viability of this technology.

5. Comparisons with Other Countries

A. Introduction

Governments have fostered the development and growth of quantum technologies by supporting basic and applied research in government and non-government laboratories and universities; through scholarships and fellowships for graduate students, primarily in physics; through grants or subsidized loans to manufacturers; and by providing markets for products and services incorporating quantum technologies. In this chapter, we review the goals, types of support, and initial outcomes of recent government programs supporting the development of commercial quantum technologies. We divide the review into four regions: China; Europe (European Union and European countries); other foreign countries (Australia, Canada, Japan, Russia, and South Korea); and the United States. The purpose of this chapter is to provide an assessment of the activities of other governments in the area of commercial applications of quantum information science (QIS).

B. China

1. Government Programs

The Chinese government has made the development of QIS technologies a priority. It has designated quantum research as one of four science megaprojects in its current 15-year National Medium and Long-Term Science and Technology Development Plan (2006–2020) (Ministry of Science and Technology 2006).[15] The central government re-emphasized its commitment to quantum research and development in the 13th Five-Year Plan for Economic and Social Development (2016–2020) by naming quantum communications and computing a key national strategic industry and by designating quantum communications as one of six major science and technology (S&T) development projects within the period to 2030 (National People's Congress 2016).[16] While neither plan disclosed how much the government has spent or plans to spend on quantum research, a study by the Netherlands' Ministry of Economic Affairs estimated that China's annual expenditure on quantum technologies is around $244 million (Heijman-te Paske 2016).

[15] The other three science megaprojects are development and reproductive biology; nanotechnology; and protein science.

[16] The other five major S&T projects are aircraft engines and gas turbines; deep-sea stations; brain science and brain-inspired research; national cyberspace security; and deep space exploration and in-orbit spacecraft servicing and maintenance systems.

The Chinese government has focused particular attention and efforts on advancing technologies in the field of quantum communications, specifically quantum key distribution. The rationale for this investment is unclear. As noted above, several interviewees said that China's investment in quantum communications has surprised them. China currently leads in the number of scientific publications in the field of quantum communications, followed by the United States, the United Kingdom, Germany, and Japan.[17] As discussed above in Chapter 3 Section B, on August 16, 2016, China launched the world's first quantum communication satellite, which is now operational.

China has also invested heavily in quantum computing. Even though there are no national quantum computing initiatives similar in scale to China's quantum communications program, QUESS, Chinese researchers have published more than double the number of scientific articles on quantum computing than they have on quantum communications. China currently ranks second, just slightly behind the United States, based on the total number of articles published on quantum computing from 1965 to 2017. For articles published since 2005, China has published more articles than the United States in every year since 2008. In April 2017, the Chinese Academy of Sciences announced that Chinese scientists are actively working to develop the world's first quantum computer (Chinese Academy of Sciences 2017).

One sign of recent national and regional initiatives to promote quantum research is the construction of the Hefei Comprehensive National Science Center with its Quantum Information and Quantum Science and Technology Innovation Institute (Ministry of Science and Technology 2017; University of Science and Technology of China 2017). The Hefei center is recognized as the "No. 1 Project" to promote scientific and technological innovation in Anhui province. The center will conduct basic research on quantum mechanics and quantum information, technological applications of quantum information, and R&D on core devices (University of Science and Technology of China 2017).

Some of the largest and most important national policies to advance quantum research in China over the long term are the country's preferential incentive programs designed to attract highly regarded Chinese scientists, researchers, professionals, and entrepreneurs who live overseas back to China. These include programs such as the National Science Fund for Distinguished Young Scholars, the Hundred Talents Program, the Thousand Talents Program, the Ten Thousand Talents Program, the Chunhui Program, and the Changjiang Scholars Program (Cao 2008). The Thousand Talents Plan is the most well-known and well-publicized of these policies. Launched in 2008, awardees under the plan receive numerous preferential treatments, ranging from being entitled to assume leadership

[17] STPI staff performed a bibliometric analysis using Elsevier's Scopus database. Search query: TITLE-ABS-KEY ("quantum communication" OR "quantum communications" OR "quantum key distribution" OR "QKD" OR "quantum cryptography"). Publications were limited to articles published between 1965 and 2017. Search result was performed 15 March 2017.

or professional positions at universities, state-owned enterprises, and R&D institutes to receiving a one million Chinese yuan (approximately $145,000 USD) start-up package to guaranteed spousal hires and school admissions for awardees' children (Thousand Talents Plan 2017). Despite criticisms concerning the effectiveness of the Thousand Talents Plan in attracting world-class scientists to China (Cao et al. 2013; Sharma 2013; Hvistendahl 2014), some of the returnees have been distinguished leaders in their fields. For instance, Jianwei Pan, professor of physics at the University of Science and Technology of China (USTC) and Chief Scientist of QUESS, is a Thousand Talents Plan recipient. After receiving his Ph.D. from the University of Vienna in 2001, Dr. Pan returned to USTC and has been instrumental to China's advances and success in the field of quantum communications. China has adopted several such policies to reverse "brain drain" (Achenbach 2017; Waldman 2017). Programs have attempted to attract foreign-born scientists to China as well.

2. China's Quantum Industry

The quantum industry in China is in its infancy. We identified four companies in China employing searches on Google and Baidu that are offering or plan to offer commercial products in quantum technologies—ZTE Corporation in Shenzhen, QuantumCTek in Hefei, Qasky Science and Technology LLC in Wuhu, and a joint-venture between the Alibaba Group Holding Limited and the Chinese Academy of Sciences (CAS) to form a quantum research laboratory in Shanghai.[18] Aside from the Alibaba-CAS partnership, which is focused on quantum computing, the other three enterprises are all focused on bringing quantum communications-related technologies to market. There do not appear to be any public or private endeavors in the fields of quantum simulation or sensing. Given the number of publications China has published over the past decade in the field of quantum computing relative to other countries, there seems to be a dearth of quantum computing start-ups in the country.

ZTE, an international telecommunications equipment provider, claimed that it had created the world's first quantum encryption transport solution based on an optical transport network in September 2016 (ZTE 2016). ZTE also claimed that with the successful launch of QUESS, quantum telecommunication technology is attracting more attention. The company plans to implement quantum encryption transmission by quantum optical transport network equipment but has not specified when this would become publicly available.

[18] More Chinese companies than these four claim to be engaged in developing quantum technologies, but only these four had websites at the time of our research. Because the other companies did not have websites, we were skeptical of their viability and therefore restricted our discussion to these four companies.

Alibaba, China's largest e-commerce company, co-founded the Alibaba Quantum Computing Laboratory with the Chinese Academy of Sciences in July 2015 in an initiative to "realize the practical applications of quantum computing" (Alibaba 2015). The laboratory will be similar in scope to research initiatives by Microsoft, Google, and IBM. Aside from the news release in 2015, no further announcements have been made as to when the laboratory will open, the specific types of research that will be pursued, or how much money will go to funding the laboratory.

QuantumCTek Co., Ltd. heralds itself as China's first and largest producer of network security products and services based on quantum technology (QuantumCTek 2017). The company was initially founded by a research group from the Hefei National Laboratory for Physical Science at Micro-scale at the University of Science and Technology of China. Jianwei Pan, Chief Scientist of QUESS, is also a founder and shareholder of QuantumCTek. Other shareholders of the company include CAS and USTC. The company joined quantum communication pioneers ID Quantique and Battelle in November 2014 to launch the Quantum-Safe Security Working Group, aimed at assessing and countering the growing threat of quantum computers to traditional encryption and key exchange technologies (ID Quantique 2014).

Similar to Alibaba's Laboratory and QuantumCTek, CAS also plays a large role in Qasky Science and Technology LLC. Qasky specializes in quantum cryptography devices, and has a research team that is fully supported by the CAS Key Laboratory of Quantum Information (Qasky 2017). In addition, two of the company's three leaders are academicians at the CAS laboratory.

Given the infancy of China's private venture capital industry, and the difficulty of obtaining bank loans to establish a private company, particularly in risky high-technology sectors, partnerships between industry and research institutions such as CAS and universities are important to advancing China's national innovation system. CAS-industry and university-industry partnerships provide a mechanism for a slightly less risky, more guided approach to translate high-technology research into commercial applications. These partnerships give entrepreneurs access to R&D capabilities provided by highly-trained personnel, high-quality equipment and facilities, and financial support. Partnerships such as the Quantum Laboratory, QuantumCTek, and Qasky allow China to establish a foothold in emerging high-tech industries that might otherwise not take place.

C. Europe

1. Government Programs

a. European Union

By several measures, including articles published, Europe is a major global contributor to research on quantum phenomena. According to the *Quantum Manifesto: A New Era of Technology*, a document written by a group of concerned policy makers, industrialists, and scientists, "Europe still plays a leading role in quantum research" and conducts "world-leading research in quantum computing" (European Commission 2016, 9, 15). This research has been funded in part by the European Commission, which has spent roughly €550M ($600 million) on quantum technologies and research over the last 20 years. The document also provided estimates that the annual budgets of the European Union and its member states for quantum technologies is approximately $515 million (Heijman-te Paske 2016).

The European Union's most recent program in support of quantum technologies is the Quantum Technologies Flagship program, established in April 2016. The Quantum Technologies Flagship is a €1 billion (roughly $1.1 billion USD), 10-year endeavor to translate European Union's investment in basic quantum research into commercialized products in computing, sensing, communication, measurement, and simulation (Kelly 2016). Scheduled to launch in 2018, the program responds in part to the *Quantum Manifesto*'s call for a European Union-wide effort to foster technologies incorporating quantum features. The goals of the Quantum Technologies Flagship program are to (1) consolidate and expand European scientific leadership and excellence in quantum research, (2) kick-start a competitive European industry in quantum technologies, and (3) make Europe a dynamic, attractive region for innovative research, business, and investments in quantum technologies.

b. Netherlands

In 2015, the Dutch government announced that it would invest €135 million (roughly $150 million USD) over a 10-year period to develop a superfast quantum computer (Dutch News 2015). The investment went to QuTech, a quantum computing research center founded in 2013 by the Delft University of Technology and the Netherlands Organization for Applied Scientific Research. QuTech received an additional $50 million in 2015 when Intel announced a 10-year collaborative partnership with the research center to accelerate advancements in quantum computing (Intel 2015). Microsoft, a private partner of QuTech since 2010, announced that it will be expanding its cooperation with QuTech as it establishes its own quantum research laboratory at Delft University of Technology (QuTech 2016). Microsoft's research laboratory will be headed by Professor Leo

Kouwenhoven, founding director of QuTech and one of four leading scientists hired by Microsoft to work on the company's scalable quantum computer project (Linn 2016; QuTech 2016).

c. Switzerland

The Swiss National Science Foundation (SNSF) has funded the Quantum Science and Technology (QIST) initiative, one of 28 National Centers of Competence in Research (NCCRs) (SNSF 2017a). NCCRs are established to promote long-term research networks in areas thought to be of strategic importance to Swiss science, the Swiss economy, and Swiss society. In addition to receiving federal funding, NCCRs are also supported by their home academic institutions and third parties. QIST has been funded from 2010 to 2017; its home institutions are ETH Zurich and the University of Basel and it involves over 34 professors and 300 graduate students (Swiss National Science Foundation 2017b). The main goals of the NCCR QIST are to develop applications in the area of quantum computing and to conduct basic quantum research. The NCCR QIST will have received approximately 117.5 million Swiss francs (roughly $120 million USD) in total funding from 2010 to 2017. In the second phase of research (2015-2018), QSIT is focusing on advances in quantum sensing, engineered quantum states, quantum information and communication, and quantum simulation.

d. United Kingdom

In 2013, the government of the United Kingdom established a 5-year, £270 million (roughly $440 million USD at the time) National Quantum Technologies Program to expedite the transfer of quantum research in the laboratory to commercialized technologies in the marketplace. As part of the program, £120 million (roughly $200 million USD) was used to establish a national network of Quantum Technology Hubs to accelerate quantum technology development. The four hubs are in (1) sensors and metrology;[19] (2) quantum

[19] The sensors and metrology hub includes the universities of Birmingham, Glasgow, Nottingham, Southampton, Strathclyde, and Sussex. The applications areas for sensors and metrology include defense, geophysics, medical diagnostics, construction, naval navigation, data storage masters, health monitoring, gaming interfaces, GPS replacement, data storage products, local network timing, and gravity imaging (U.K. National Quantum Technologies Programme 2017).

enhanced imaging;[20] (3) network quantum information technologies;[21] and (4) quantum communications technologies.[22]

The government of the United Kingdom recognizes that developing a pool of highly skilled talent is essential if the United Kingdom is to maintain its position as a world leader in science and innovation. Like China and Australia, the U.K. government recognizes that the investment in human capital may be even more important than the investment in quantum technologies itself. The Engineering and Physical Sciences Research Council (EPSRC), the United Kingdom's main agency for funding research in engineering and physical sciences, spends around £800 million (roughly $1,010 million USD at 2017 exchange rates) annually on research and postgraduate training to prepare the country for the next round of technological changes (Engineering and Physical Sciences Research Council 2017a). Quantum technologies currently make up 4.24 percent (approximately £196 million or roughly $250 million) of EPSRC's total research portfolio (Engineering and Physical Sciences Research Council 2017b). The largest research area within quantum technologies is *quantum devices, components, and systems*, which accounts for 87 percent of all quantum funding by EPSRC.

In March 2016, the U.K. government announced two investments totaling £204 million (roughly $260 million USD) to support doctoral training over a 2-year period (£167 million or roughly $210 million USD), and to boost quantum research (£37 million, roughly $50 million USD)[23] (Engineering and Physical Sciences Research Council 2016). The government further reaffirmed its commitment to science in March 2016 by announcing that it would invest a record £26.3 billion ($33.5 billion USD) on science over the next 5 years (U.K. Government 2016a).

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[20] Led by the University of Glasgow and including the universities of Bristol, Edinburgh, Heroit-Watt, Oxford, and Strathclyde, this hub is focused on developing ultra-high sensitivity cameras using quantum technologies. Applications include visualizing gas leaks, seeing through smoke, looking around corners, and seeing beneath human skin (U.K. National Quantum Technologies Programme 2017).

[21] This hub is headed by the University of Oxford and includes the universities of Bath, Cambridge, Edinburgh, Leeds, Southampton, Strathclyde, Sussex, and Warwick. The central focus of this hub is on quantum computing. The main project of this hub is the Q20:20 quantum engine, a network of 20 quantum processors that share information via light (U.K. National Quantum Technologies Programme 2017).

[22] Led by the University of York and includes the universities of Bristol, Cambridge, Heroit-Watt, Leeds, Royal Holloway, Sheffield, and Strathclyde, this hub is primarily focused on quantum key distribution and is looking for ways to make market-ready technologies smaller, less expensive, and more easily incorporated into existing systems and infrastructures. Secure mobile banking is one application that would be of interest to this hub (U.K. National Quantum Technologies Programme 2017).

[23] Of the £37 million investment in quantum research, £25 million was for new equipment, and the rest was allocated for training of research personnel.

2. National Quantum Industries

a. Switzerland

ID Quantique, one of the better known quantum technology companies in the world, offers a variety of quantum communication services and products, including quantum network encryption, quantum key generation, and quantum key distribution. The company has worked with the financial industry, enterprises, and a variety of government organizations. (See Chapter 2 on Quantum Communications for more information on ID Quantique.)

b. United Kingdom

The United Kingdom is home to several small-scale quantum technology start-ups, most of which are focused on quantum encryption or quantum cryptography technology. These companies include Quantum Base, Crypta Labs, Post-Quantum, and Cambridge Quantum Computing. (See Chapter 2 on Quantum Communications for more information on these companies.) As previously noted, several large multinational corporations have established quantum research laboratories in the United Kingdom, including Toshiba Corporation, HP, and Hitachi Ltd.

D. Other Foreign Countries

1. Government Programs

a. Australia

The Australian federal government launched its National Innovation and Science Agenda in December 2015 to "enable Australia to seize the next wave of prosperity by embracing new ideas through innovation and science" (Australian Department of Industry, Innovation and Science 2017). The agenda is a comprehensive suite of 24 initiatives worth $1.1 billion Australian dollars (AUD) (roughly $820 million USD) that will be enacted over the course of 4 years (Australian National Innovation and Science Agenda 2017). As part of the agenda, the Australian government is investing $25 million AUD (roughly $19 million USD) in the Center for Quantum Computation and Communication Technology over the next 5 years to support the development and advancement of quantum computing in Australia. This government investment is part of a larger $70 million AUD (roughly $52 million USD) partnership with the University of New South Wales (UNSW), the Commonwealth Bank of Australia, and Telstra to build the world's first scalable silicon-based quantum computer.[24] The investment is focused on enhancing Australia's research on silicon-based quantum computing, an area which Australia is reputed to have a two- to three-year lead over the rest of the world (Australian Department of Industry, Innovation and Science 2016).

On a local level, the government of the Australian Capital Territory (ACT) granted the Australian National University (ANU) $375,000 AUD (roughly $280,000 USD) in November 2016 for a collaborative quantum-encrypted satellite communications project involving UNSW and ANU spin-off companies Quintessence Labs and Liquid Instruments (ANU 2016). The goal of the project is to demonstrate secure space quantum communication links via satellites between the Advanced Instrumentation Technology Center at Mount Stromlo and the UNSW Canberra optical telescope (ANU 2016; Baker 2016). In addition, researchers at UNSW are collaborating with those at the National University of Singapore to launch Australia's first quantum satellites by 2019. The satellites will be equipped with Australian-developed quantum technologies such as cold-atom sensors for precision timing, navigation, and positioning measurements; and quantum communication technologies for transmitting information between satellites in space or between satellites and ground stations via light (Gough 2017).

Australia's quantum research community is also receiving international financial support for its research in quantum computing. The University of Sydney, as part of an international consortium, was awarded a multimillion-dollar grant from the United States Office of the Director of National Intelligence in May 2016 to help deliver a logical qubit using trapped ions (University of Sydney 2016). The grant is a part of the larger LogiQ program, which belongs to the U.S. government agency Intelligence Advanced Research Projects Activity (Strom 2016).

b. Canada

In September 2016, the University of Waterloo received $76 million Canadian dollars (CAD)—roughly $57 million USD—through the Canada First Research Excellence Fund to support Canada's Transformative Quantum Technologies initiative. The initiative is aimed at advancing the development of quantum technologies in areas such as medicine, navigation, sensing, and the development of new materials (Canada First Research Excellence Fund 2016).

Canada's 2017 budget designated funding of $158 million CAD (roughly $119 million USD) to support organizations such as the Institute for Quantum Computing and the Premier Institute for Theoretical Physics. An additional $10 million CAD (roughly $8

[24] UNSW is contributing $25 million, and Telstra and the Commonwealth Bank of Australia are contributing $10 million each.

million USD) was appropriated to the Institute for Quantum Computing over the course of two years to strengthen innovation and economic growth (Government of Canada 2017).

c. Japan

Japan established the National Institutes for Quantum and Radiological Science and Technology (QST) in April 2016 to promote advances in quantum science and technology. QST is operating on approximately $487 million USD per year (National Institutes for Quantum and Radiological Science and Technology 2017). In addition to QST, Japan's Ministry for Education, Culture, Sports, Science and Technology intends to establish an R&D center that would focus specifically on optical and quantum sciences (Ministry of Education, Culture, Sports, Science and Technology 2016).

d. Russia

The Russian government has funded a long-standing effort to develop technologies based on quantum phenomena through the Russian Academy of Sciences. More recently, it created the Russian Quantum Center (RQC), a project of the government-sponsored Russian Innovation Hub, part of the activities of the Skolkovo Foundation (Johnson 2013). The RQC is to have a director and eight to ten full-time researchers. To achieve its goal of taking Russia to the forefront of quantum technology, the RQC has created three channels through which researchers can collaborate with the program: (1) researchers working on-site and the center's facilities in Skolkovo; (2) principal investigators who work on-site in Skolkovo during the course of the projects they are leading and return to their home institutions when the projects are completed; and (3) external members who participate in research funded by the RQC, but conduct the research in their home laboratories.

e. Singapore

The Center for Quantum Technologies (CQT) at the National University of Singapore was established in 2007 by Singapore's National Research Foundation (NRF) and Ministry of Education. The Center received $158 million Singapore dollars (SGD) in 2007 (roughly $125 million USD) to fund its operations for up to 10 years and in 2014, CQT received an additional $36.9 million SGD (about $30 million USD) from the NRF to fund its core operations (Center for Quantum Technologies 2017b). The center was Singapore's first Research Center of Excellence and is focused on conducting both theoretical and experimental research in quantum theory, developing quantum technologies, and constructing quantum devices for cryptography and computation (Center for Quantum Technologies 2017a). In addition, Singapore's NRF, together with the National Natural Science Foundation of China, recently announced a joint funding program to support cooperation between Singaporean and Chinese researchers focused on quantum technologies (National Research Foundation 2017).

Singapore launched the nano-satellite Galassia, built by CQT researchers, in December 2015. The satellite carried a payload containing the basic components used in quantum communications and quantum computing (National University of Singapore 2015). CQT researchers are working on future satellites that will allow them to send entangled photons to satellites and back to Earth as well as to other satellites (National University of Singapore 2016). Like China, Singapore is planning on building a global quantum network (National University of Singapore 2016). CQT researchers are primarily working with CubeSat nanosatellites, which are small devices that can be launched relatively cheaply by riding on conventional spacecraft (National University of Singapore 2016), commonly referred to as a *piggyback launch*.

2. National Quantum Industries

a. Australia

Australia is home to a handful of small quantum technology start-ups. As discussed in Chapter 3, QuintessenceLabs is engaged in creating quantum key distribution (QKD) products. Compumedics Limited is a small company that manufactures MEG scanners. QxBranch, a U.S.-Australian start-up that resulted from a 2014 partnership between Lockheed Martin and Shoal Engineering, is a private defense technology firm based in Adelaide (Dodd and Smith 2016). The company provides a variety of services including developing and testing commercial applications for quantum computing, risk analysis, machine learning, and software development. Though the company is small in size and employs only about 20 individuals, it has a presence in many areas around the world (QxBranch 2017). The company's executive team is headquartered in Washington. D.C.; its technical team is based in Adelaide; and it has established offices in the United Kingdom and Hong Kong. Despite being a relatively new start-up, QxBranch is already working with Swiss bank UBS to develop quantum algorithms for use in foreign-exchange trading and arbitrage ("Here, There, and Everywhere" 2017).

b. Canada

As discussed in Chapter 4, D-Wave Systems has built and sold several quantum annealers. Founded in 1999, D-Wave now has over 150 employees and claims to be the world's first quantum computing company (D-Wave 2017c). D-Wave was the leading patent applicant in the 2014 worldwide patent analysis for quantum computing technologies and held almost twice as many patent families as its closest competitor (Intellectual Property Office 2014). In March 2017, Virginia Polytechnic Institute (more commonly known as Virginia Tech) and D-Wave announced a partnership to create a permanent quantum computing center at Virginia Tech's Hume Center for National

Security and Technology to provide researchers from the U.S. intelligence community and the Department of Defense with greater access to quantum computing (D-Wave 2017d).

1QBit, a quantum computing software company, was founded in 2012 and has had a long-standing partnership with D-Wave since 2014. In 2016, 1Qbit and D-Wave partnered with financial industry experts to launch Quantum for Quants, an online community for financial experts and quantum computing professionals to discuss how quantum technology can be applied to the finance industry (D-Wave 2016). The company has also developed a software development kit to enable traditional software developers to build quantum-ready applications (1Qbit 2017).

Michael Lazaridis, co-founder of BlackBerry and former Chief Executive Officer at D-Wave Systems, has been one of Canada's biggest supporters and investors in quantum research. Lazaridis founded the Perimeter Institute for Theoretical Physics in 1999 and the Institute for Quantum Computing (IQC) at the University of Waterloo in 2002. To date, he has donated more than $170 million CAD (roughly $128 million USD) to Perimeter and more than $100 million CAD (roughly $75 million USD) to IQC (Quantum Valley Investments 2017a). Perimeter has nine research fields, four of which are quantum-based (Perimeter Institute 2017).[25] IQC is focusing its attention and research on three main applications: quantum computing, quantum communications, and quantum sensing (Institute for Quantum Computing 2017a). Within these three broad categories, IQC is conducting research on quantum error correction, quantum algorithms, quantum information theory, quantum complexity, quantum information processing, and quantum cryptography (Institute for Quantum Computing 2017b).

In 2013, Lazaridis teamed up with BlackBerry's co-founder Doug Fregin to establish the Quantum Valley Investment Fund in Ontario, Canada (Hardy 2013).[26] The initial size of the fund is $100 million CAD (roughly $75 million USD). It targets QIS projects that could lead to commercial technologies and applications (Quantum Valley Investments 2017b).

c. Japan

Japan has several multinational corporations that have invested in quantum telecommunications, quantum computing, and quantum sensing. These corporations are among the world leaders based on number of patents in quantum technologies.

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[25] Perimeter's nine research fields are: quantum fields and strings; quantum foundations; quantum gravity; quantum information; condensed matter; cosmology; mathematical physics; particle physics; and strong gravity.

[26] The term "Quantum Valley," in reference to Silicon Valley, has been used to refer to the innovative, technological hub for quantum technologies developing in Ontario.

Toshiba Corporation has focused its R&D on quantum cryptography and to a lesser degree on quantum computing. The company started conducting basic research in quantum cryptography in 2003 (Toshiba Corporation 2015). Toshiba's Quantum Information Group (QIG) is based at its Cambridge Research Laboratory in the United Kingdom, part of Toshiba Research Europe Limited. The laboratory is working on ways to apply quantum mechanics to information technology (Toshiba Corporation 2017a). In a 2014 worldwide patent analysis, Toshiba ranked as the world's third largest patent applicant in quantum telecommunication technologies and quantum computing technologies and tenth in quantum sensing technologies (Intellectual Property Office 2014).[27] The analysis found that many of Toshiba's patent families for both quantum telecommunications and quantum computing were focused on quantum dots as a source of entangled photon pairs (Intellectual Property Office 2014). Toshiba has also sought intellectual property protection for optics technology, quantum repeaters, error correction, and a method to select a pre-agreed quantum communication protocol (Intellectual Property Office 2014). Toshiba's nine patent families in quantum sensing were all related to improving and using superconducting quantum interference devices (SQUIDs) (Intellectual Property Office 2014).

Most of Toshiba's advances in quantum research have been in the realm of quantum communications. In 2014, Toshiba announced that it had developed and successfully demonstrated the world's highest speed quantum encryption system (Toshiba Corporation 2014). The company claimed that it had sent 878 gigabits of secure data over 45 kilometers of fiber optic cables between the Otemachi and Koganei regions of Tokyo over the course of 34 days for an average transmission speed of 300 kilobits per second (Toshiba Corporation 2014). In 2015, Toshiba embarked on a two-year verification program to test its quantum cryptographic communication system by transmitting genomic data from the Toshiba Life Science Analysis Center to the Tohoku Medical Megabank Organization seven kilometers away (Toshiba Corporation 2015). The two-year program is set to conclude in August 2017. In October 2016, Toshiba and British Telecommunications showcased the United Kingdom's first secure quantum communication system. The two companies have been working together over the past two years at Toshiba's Cambridge Research Laboratory on how to integrate quantum security measures into traditional fiber optic communication networks (Toshiba Corporation 2016). In addition, Toshiba and British Telecommunications are building a quantum communication network linking

[27] Patents were limited to applications with a date range between 2004 and 2013. Patents at the application stage are also included. Patents applicants included in the analysis may not necessarily be granted the patents for which they are applying. Patents were searched using the *Thomson Reuters* World Patent Index (WPI) and the European Patent Office EPODOC databases. The two databases together contain patent information for the majority of leading industrialized countries and patent organizations including the World Intellectual Property Organization, European Patent Office, and the African Regional Industry Property Organization. For full information on methodology, see Intellectual Property Office (2013).

Cambridge, Bristol, London, and Adastral Park in the United Kingdom (Toshiba Corporation 2016). The project is part of the United Kingdom's Quantum Technology Program.

Like Toshiba, Hitachi has an established research laboratory housed at the University of Cambridge. The laboratory focuses on both experimental and theoretical research on quantum computing, QKD, and spintronics (Hitachi Cambridge Laboratory 2017). Hitachi ranked as the largest patent applicant in the world for quantum sensing technologies (Intellectual Property Office 2014). The company's patents in quantum sensing have been mainly focused on inventions relating to improving SQUID components, fabrication, and methods of use (Intellectual Property Office 2014). Hitachi ranked as the eighth largest patent applicant for quantum telecommunication technologies.

Nippon Electric Company (NEC) is a multinational information technology company established in 1899. It currently employs almost 100,000 individuals worldwide. NEC is the world leader in the number of patents related to quantum telecommunications (Intellectual Property Office 2014). NEC's quantum telecommunication patents are primarily focused on QKD and quantum encryption devices (Intellectual Property Office 2014). In September 2015, the University of Tokyo, NEC, and Fujitsu Laboratories announced that they had achieved QKD at a record distance of 120 kilometers using a single-photon emitter (Takemoto 2015). NEC's Internet of Things (IoT) Devices Research Laboratories is working to develop a quantum dot sensor array that can be used in satellites to collect data on the natural environment such as on vegetation and soil (NEC 2017).

Nippon Telegraph and Telephone (NTT) Corporation, a telecommunications company, has four research groups devoted to quantum research. NTT's research group on quantum optical state control is focused on harnessing quantum properties of light for information processing and communications. The research group's activities include performing quantum communications experiments, exploring quantum state control techniques, and conducting quantum simulations using ultra-cold atomic gases (NTT Corporation 2017a). The company's theoretical quantum physics research group is focused on QKD; techniques for quantum communication, repeaters, and computation; and hybrid quantum systems (NTT Corporation 2017b). The quantum optical physics research group studies how to control exciton spin in low dimensional structures (Nippon Telegraph and Telephones 2017c). NTT's quantum solid state physics research group is focused on quantum phenomena in semiconductor nanostructures including the spin and charge dynamics of quantum dots (NTT Corporation 2017d). The four quantum research groups together employ 38 doctoral-level researchers.

NTT ranked as the second largest patent applicant in the world for quantum computing technologies and fourth largest for quantum telecommunications technologies (Intellectual Property Office 2014).

d. South Korea

SK Telecom Company, Ltd., South Korea's largest telecommunications company, has invested heavily in quantum communications. In late 2015, SK Telecom entered a research and education partnership with Florida Atlantic University to jointly conduct quantum physics research for applications in cryptography, hardware engineering, and quantum computing (Galoustian 2015). In 2016, the company invested in ID Quantique to have exclusive rights to bring ID Quantique's next generation of quantum random number generators to market (ID Quantique 2016c). In February 2017, SK Telecom and Nokia Corporation announced that the two companies have entered into a cooperative agreement to establish interoperations between SK Telecom's QKD system and Nokia's next-generation optical transport system (SK Telecom 2017a). Also in February 2017, SK Telecom and Deutsche Telekom established the Quantum Alliance to ensure secure communications in the age of quantum computing (SK Telecom 2017b). The two telecom companies announced that they will be working to recruit network operators, network equipment makers, device manufacturers, and software vendors to join the Quantum Alliance's mission to ensure that communications remain secure in the future (SK Telecom 2017b).

E. United States

In contrast to several of the other governments discussed in this chapter, the U.S. government does not have a formal strategy for R&D on quantum technologies, although several documents propose a call to action on the topic. Quantum computing is one component of Executive Order No. 13702, which launched the National Strategic Computing Initiative (Executive Office of the President 2015). Since then, the National Science and Technology Council (NSTC) released *Advancing Quantum Information Science: National Challenges and Opportunities* (NSTC 2016) and the Office of Science and Technology Policy (OSTP) hosted a forum on QIS on October 18, 2016 (Carim and Polk 2016).

Despite the lack of a formal national strategy, the U.S. government supports a wide range of QIS technologies through a large number of programs and institutions. We did not find a single repository of information about all the quantum activities funded by the U.S. government. Rather, we compiled information on U.S. government activities by reviewing programs by various Federal agencies, U.S. government laboratories, and other institutions that are engaged in QIS.

1. Government Programs

a. U.S. Air Force Research Laboratory (AFRL)

The Information Directorate of the AFRL established the Quantum Communications Laboratory and the Quantum Information Science Laboratory. The Quantum Communications Laboratory is focused on the integration of quantum data encryption and QKD with transmission of data at high rates. The main goal of the Quantum Information Science Laboratory is to construct systems that allow for secure and highly efficient data analytics.

The Air Force Office of Scientific Research (AFOSR), the fundamental research arm of AFRL, supports two quantum programs: Quantum Electronic Solids and Quantum Information Science (AFOSR 2017). The primary emphasis of the Quantum Electronic Solids program is on superconductors, metamaterials, and nanoscopic electronic components and devices. The Quantum Information Sciences program is focused on using quantum properties to enhance the capabilities of the Air Force beyond what can be accomplished by classical systems in areas such as position, navigation, and timing, sensing, quantum networks, and complex materials (AFOSR 2017).

b. Army Research Office (ARO)

ARO is the fundamental research arm of the Army Research Laboratory. The ARO Quantum Information Sciences program supports work that includes quantum sensing, PNT, computation, and communications (ARO 2017).

c. Defense Advanced Research Projects Agency (DARPA)

DARPA has three programs focused on various aspects of quantum technologies. The Quiness program is concerned with the development of quantum communications systems, particularly focusing on technologies that can enable high-rate, long-distance quantum communications (DARPA 2017a). An overarching goal for Quiness is to develop a quantum network that would allow for secure, point-to-point communications by the Department of Defense. The Quantum-Assisted Sensing and Readout program is focused on quantum sensing with applications to imaging and PNT (DARPA 2017b). The Quantum Orbital Resonance Spectroscopy program is aimed at developing novel, non-invasive, neuro-diagnostic capabilities using quantum photonics to better assess traumatic brain injuries and post-traumatic stress disorders (DARPA 2017c).

d. Intelligence Advanced Research Projects Agency (IARPA)

IARPA’s Quantum Enhanced Optimization project involves a multi-year research effort to develop special-purpose quantum algorithms and hardware with a focus on hard optimization problems (IARPA 2017). Practical applications include more rapid training of machine learning algorithms, circuit fault diagnostics on larger circuits than possible today, and faster optimal scheduling of multiple machines on multiple tasks. The overall goal is to generate solutions on quantum annealers at a speed that is 10,000 times faster than can be accomplished on classical computers. Another program is IARPA's LogiQ, which seeks to extend the lifetime of a qubit, a necessary step in the quest for a fault-tolerant, logical qubit.

e. Los Alamos National Laboratory (LANL)

LANL's Quantum Institute (QI) was established in 2002 and focuses on quantum computing and quantum cryptography (LANL 2017a). In the area of quantum computing, QI researchers are collaborating with researchers from the University of New South Wales, the California Institute of Technology, and the University of Maryland to construct a quantum computer as a solid-state device (LANL 2017b). In the area of quantum cryptography, QI researchers are working on the development of a cryptography system that can be used to transmit quantum keys between Earth-orbiting satellites and ground stations (LANL 2017c). The Department of Energy provides funding and oversight for LANL.

f. National Aeronautics and Space Administration (NASA)

The Quantum Artificial Intelligence Laboratory (QuAIL) is a joint effort by NASA, the Universities Space Research Association, and Google to explore the potential for quantum computers to solve problems that are difficult or impossible to solve on classical supercomputers. Formed in 2013, QuAIL is hosted at NASA's Ames Research Center. The primary research interest of QuAIL is the theoretical and empirical development of quantum annealing approaches to difficult optimization problems of relevance to NASA (NASA 2017).

g. National Science Foundation (NSF)

NSF has two primary programs that focus on quantum technologies. The Quantum Information Science program supports theoretical and experimental research that explores quantum applications for new computing paradigms and that push the frontiers of quantum-based information, transmission, and manipulation (NSF 2017). The Advancing Communication Quantum Information Research in Engineering program has the primary goal of advancing the technologies necessary for secure communications (NSF 2016).

h. National Security Agency (NSA)

The primary interests of NSA are cryptanalysis (i.e., code breaking) and ensuring the security of critical governmental systems. While NSA does not make details public, it is reasonable to assume that the agency supports work on the development of quantum communications, computer hardware, and algorithms.

i. Office of Naval Research (ONR)

The basic research component of ONR supports its Quantum Information Sciences Program, which focuses on the security implications of QKD for the maritime environment, and quantum computer algorithms that directly support naval functions (ONR 2017a). ONR’s Atomic, Molecular, and Quantum Physics Program funds work in quantum-based PNT and sensing (ONR 2017b).

j. Sandia National Laboratories

Sandia National Laboratories has invested roughly $76 million in internal research funds over an 11-year period to fund research on quantum sensing, quantum communications, and quantum computing under a variety of programs, including its Computing and Information Science program. As with LANL, the Department of Energy provides funding and oversight for Sandia National Laboratories.

2. U.S. Quantum Industry

The United States has a vibrant industry engaged in developing, manufacturing, and selling QIS technologies. The large number of small companies, especially start-ups such as IonQ, Inc., Rigetti Computing, and QC Ware Corporation, are especially notable in quantum computing (see Chapter 4), but many smaller companies, some of which have been in business for quite some time, are active in developing and manufacturing sensors, clocks, and electron microscopes. Many small companies have also been active in developing instruments and equipment that support QIS, such as lasers and mechanisms to cool atoms.

Some of the largest U.S. technology companies, notably Google, Microsoft, IBM, and Intel, also have quantum programs, primarily in quantum computing (again, see Chapter 4). In the defense industry, Lockheed Martin is funding research on quantum technologies. In most instances, these programs are not large, generally employing 20 or fewer researchers. None has yet developed marketable products. But these larger companies see medium-term prospects for developing marketable computing products (within 5 to 10 years).

F. Comparisons across Countries

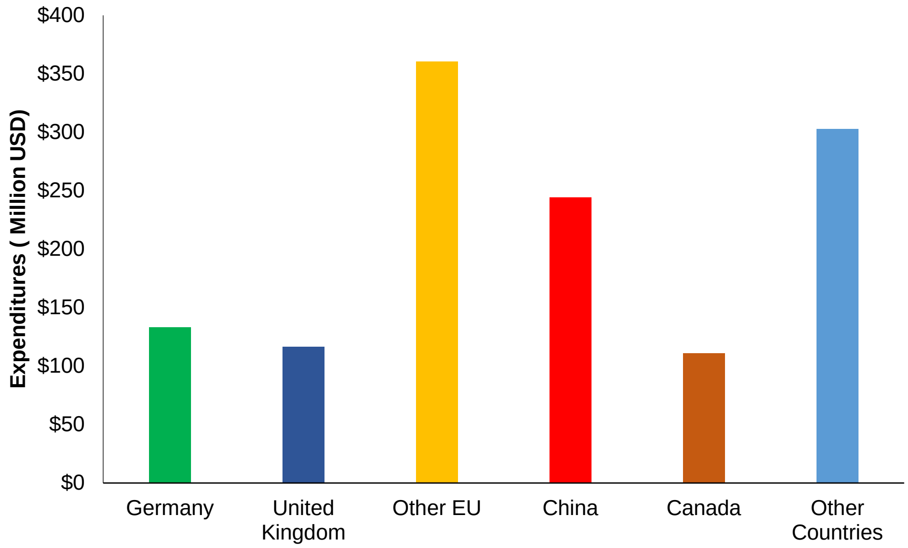
1. Government Programs

In recent years several countries or entities, most notably China, the European Union, and the United Kingdom, have developed national strategies or programs aimed at accelerating research on QIS technologies. Other countries, such as Australia, Canada, and Switzerland, have been supporting research on QIS technologies through specific initiatives or research centers. The United States funds quantum research through a large number of Federal agencies, but does not have a comprehensive national strategy or initiative pertaining to QIS technologies.

A number of governments have substantially increased funding for research on quantum technologies over the past few years. Because the agencies that fund quantum research in the United States are so disparate (including the Department of Defense and intelligence agencies as well as science and technology agencies), we were unable to find a precise aggregate number for U.S. government spending on quantum research. Using partial data, a report by the government of the Netherlands found that the U.S. government spends more on quantum research than any other country (Figure 7) (Heijman-te Paske 2016; U.K. Government Office for Science 2016). According to the report, the European Union spends the second largest amount on quantum research in the world, $361 million a year on average between 2013 and 2015, followed by China ($244 million on average).[28] Canada and the United Kingdom each spent about half of the estimated average annual spending by China on quantum science and technology between 2013 and 2015, $111 million and $117 million, respectively (Figure 7). Despite spending more than the European Union and China on quantum research, the U.S. government has been criticized for lack of stability in funding (Costello 2017).

Based on overall scientific publications on quantum science, China is currently ranked as the global leader, followed by the United States, Germany, and the United Kingdom (U.K. Government Office for Science 2016). Based on the results of a search on quantum communications in Elsevier's Scopus database of peer-reviewed literature, China has had almost twice as many scientific articles published between 1965 and 2017 on the topic than the United States, its nearest contender (Figure 8). The results of a similar search on quantum computing indicate that the United States was the global leader in terms of number of scientific articles published on the topic between 1965 and 2017, followed by China (Figure 8). However, if we limit the count to those articles published since 2008, researchers in China have published more articles on quantum computing than have researchers in the United States (Figure 9).

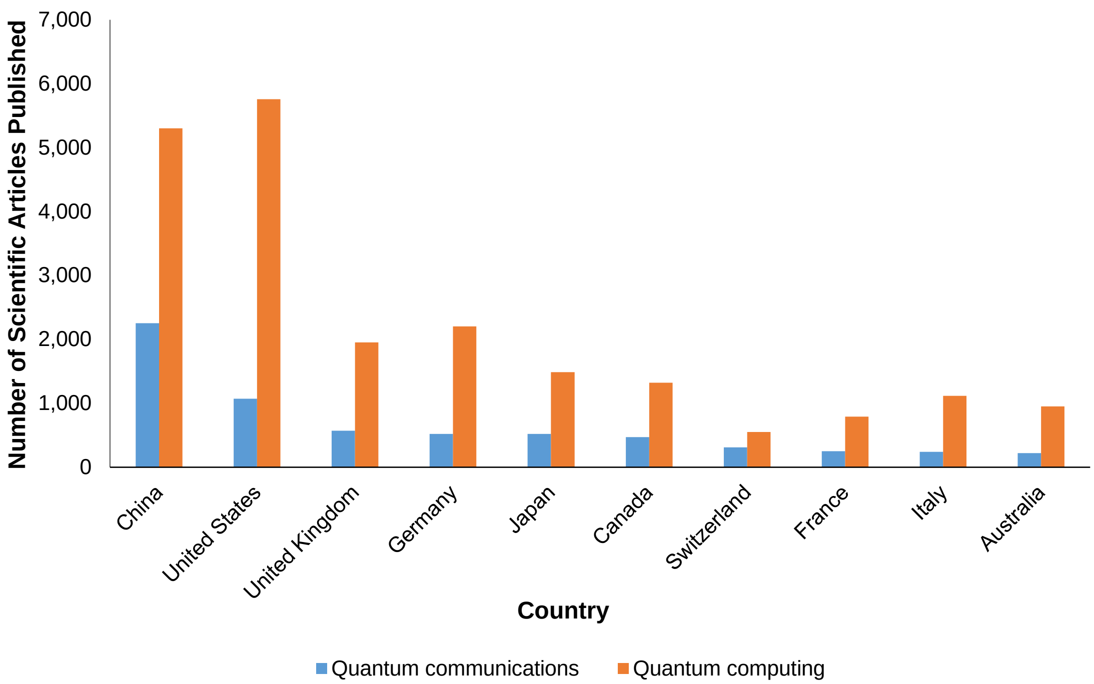
[28] Based on a 2016 study conducted by the U.K. Government Office for Science, China ranks number two in the world in spending on quantum science and technology.



Source: Heijman-te Paske (2016).

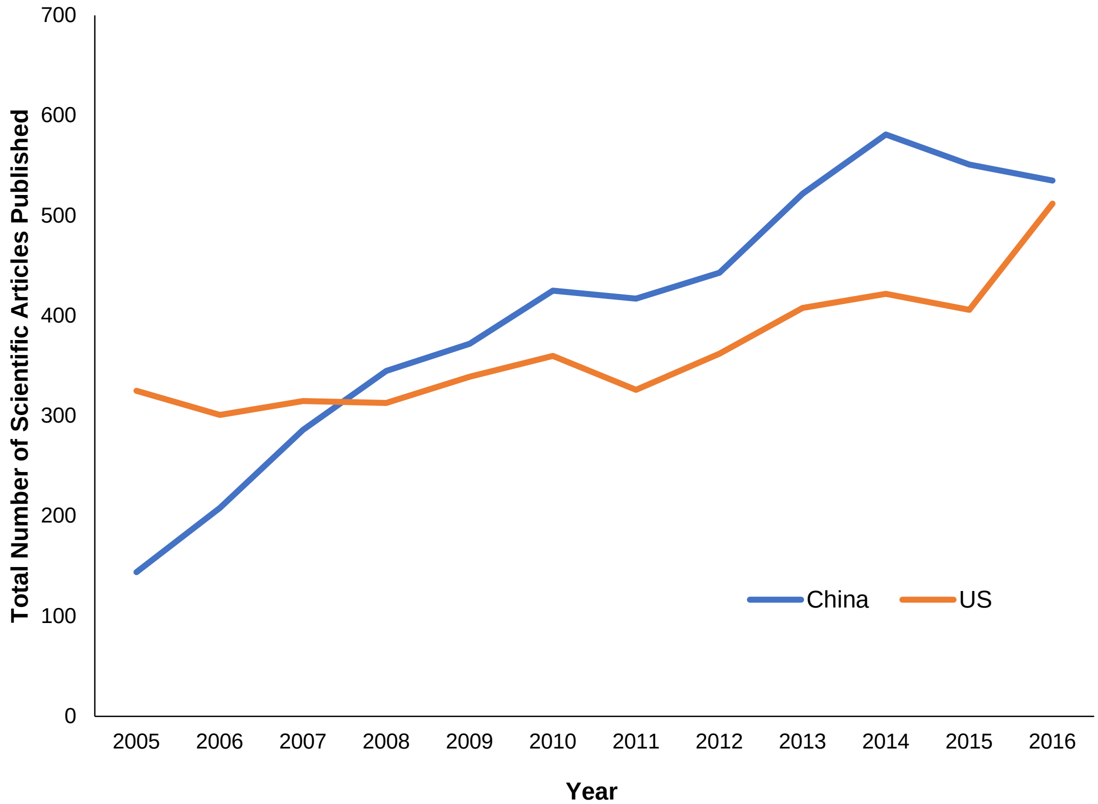
Note: Conversion from euros to U.S. dollars based on the 2015 yearly average currency exchange rate published by the International Monetary Fund (IMF n.d.).

Figure 7. Foreign Government Expenditures on Research and Development on Quantum Technologies in 2015



Source: Quantum computing data retrieved from Elsevier's Scopus database on April 14, 2017, using the search query: TITLE-ABS-KEY("quantum comput*" OR "qubit" OR "quantum simulat*"). Quantum communications data retrieved from Scopus using the search query: TITLE-ABS-KEY("quantum communication" OR "quantum communications" OR "quantum key distribution" OR "QKD" OR "quantum cryptography").

Figure 8. Total Number of Articles Published between 1965 and 2017 on Quantum Computing and Quantum Communications by Country



Source: Quantum computing and simulation data retrieved from Elsevier's Scopus on April 14, 2017 using the search query: (TITLE-ABS-KEY("quantum comput*" OR "qubit" OR "quantum simulat*") AND (LIMIT-TO (DOCTYPE,"ar "))).

Figure 9. Total of Quantum Computing and Simulation Articles Published by China and the United States, 2005–2017

A British assessment of national programs supporting quantum technologies ranked countries based on number of publications, total government expenditures on quantum research, and number of patent applications for quantum technologies. The assessment ranked the United States number one, followed by China, the United Kingdom, and Germany (Table 5). Looking at Europe as a whole, the continent ranks highly. China was the world leader in overall scientific publications on quantum research, followed by the United States (U.K. Government Office for Science 2016).

Table 5. World Ranking of Countries in Quantum Science and Technology

Country	World ranking based on spending	World ranking based on scientific publications	World ranking based on patent applications	Total world ranking
United States	1	2	1	1
China	2	1	2	2
Germany	3	3	6	3
United Kingdom	4	4	4	3
Japan	8	5	3	5
Canada	5	6	5	5
Australia	6	11	7	7
France	9	8	10	8
Italy	11	9	12	9
South Korea	17	10	8	10

Source: U.K. Government Office for Science (2016).

2. National Quantum Industries

The three sets of QIS technologies examined in this report vary greatly in terms of the composition and geographical concentration of the industries that manufacture these products. Metrology and sensing consists of a substantial number of niche markets. The companies that produce these products are located exclusively in highly technologically advanced economies. U.S., European, and Japanese companies dominate these markets. In the subsectors of clocks, gravimeters, and atomic interferometers, most companies are small, although several smaller companies have been acquired by larger companies, in some cases, large multinationals. In contrast, manufacturers of electron microscopes tend to be manufactured by large firms with divisions specializing in scientific equipment or optics. Large U.S., German, and Japanese companies dominate the electron microscope sector. In the market niches of cesium atomic clocks and MEG scanners, one producer dominates the markets, a U.S. company and a Swedish company, respectively.

European and Japanese companies appear to be most active in quantum communications, although several U.S. companies, including MagiQ, are engaged in quantum cryptography, European and U.S. companies have been offering commercial quantum cryptography applications for quite some time. The large Japanese and Korean electronics and telecommunications companies have development programs in quantum communications. Although China has been active in this area, most of is activity appears to occur in government-sponsored research institutes, not in Chinese companies.

U.S. companies lead in quantum computing, although European firms are also engaged in this area. The U.S. quantum computing industry is characterized by a large number of small start-ups financed by venture capital funding and research programs by large technology companies, most notably Google, IBM, Intel, and Microsoft, as well as Lockheed Martin. Some start-ups have substantially larger teams than the teams in the larger corporations working on quantum computing, which tend to be smaller than 20 researchers, sometimes much less so. Much of the activity in quantum computing is concentrated in the western United States, particularly California. A number of smaller companies in Europe are also developing software or components for quantum computing.

Despite the substantial funding for QIS research in China and the large number of publications by Chinese researchers, Chinese companies have not made inroads in international markets. The Chinese industry is dominated by partially state-owned companies or state research institutes. All four companies engaged in developing quantum communications listed in this report are partially owned by the Chinese central government. Three of the companies (i.e., Alibaba Quantum Computing Laboratory, QuantumCTek, and Qasky) partner with the Chinese Academy of Sciences. Although ZTE is a private company, two of its largest shareholders are state-owned enterprises. These companies have not made major sales outside of China, perhaps because of Chinese export controls on these technologies.

Government programs play important roles in supporting private industry in quantum communications and quantum computing. Australia, the European Union, and the United Kingdom have large government programs designed to encourage the development of QIS technologies and companies. In Australia, the federal government has partnered with an academic institution (University of New South Wales) and two private institutions (Commonwealth Bank of Australia and Telstra) to develop a quantum computer. The European Union and the United Kingdom have encouraged public-private partnerships as an instrument to encourage the development of industry in these areas (Council of the European Union 2016; U.K. National Quantum Technologies Programme 2017). The U.S. government is also an important source of funds for U.S. companies in these two areas.

6. Findings

Previous chapters presented our assessments of the commercial viability of the various quantum technologies considered. For each technology examined, we explained what the technology offers to potential buyers, the timescale over which the technology is likely to be technologically ready (commercially available now or short-term, medium-term, or long-term readiness), and the potential size of its likely market (small, medium, or large). In this chapter, we present our most important findings from those assessments in the areas of quantum metrology and sensing, quantum communications, and quantum computing and simulation.

A. Quantum Metrology and Sensing

Markets for quantum metrology and sensing are well-established, but are generally small (less than $50 million a year) to medium ($50 million to $500 million) in size.

Quantum metrology and sensing encompass the widest range of technologies and applications among the three categories of quantum technologies we examined. These applications range from clocks to gravimeters to inertial motion units to medical imaging equipment. These are also the most well-established technologies. Electron microscopes, which are based on quantum principles, have been manufactured for over 80 years.

Almost all the new technologies in quantum metrology and sensing compete with products based on classical physics or existing quantum technologies. Although the new technologies, such as more recent atomic clocks and atomic interferometers, offer higher measurement accuracy, we frequently found that existing technologies have been "good enough," making it difficult for these new quantum technologies to capture market share from existing products, especially as the new technologies usually cost more. Atomic clocks and interferometers tend to be more expensive, heavier, and bulkier than traditional technologies for PNT that use non-GPS systems. Consequently, markets for products based on new quantum technologies tend to be small to medium in size. Where the cost of quantum sensors has fallen close to the cost of traditional sensors, as with atomic magnetometers, the greater sensitivity of quantum sensors holds promise for making inroads into existing markets.

Potential markets for inertial navigation systems and reduced interaction electron microscopes fall into the medium market range of $50 million to $500 million.

Buyers of new quantum sensor technologies tend to have special needs for higher accuracy. For example, rather than commercial companies, buyers of quantum inertial navigation systems are frequently from the research, defense, or intelligence communities. In the event GPS systems should become unavailable, the U.S. military would need a non-GPS backup system. Because of the importance in ensuring that PNT is always available, military demand for quantum inertial navigation systems as a backup to GPS could run $150 million to $250 million a year.

The largest potential markets for sensing equipment appear to be for MEG scanners, other medical imaging equipment, and reduced-interaction electron microscopes. The medical and quantum electron microscope markets are likely to be of medium size, from $50 million to $500 million in annual sales. MEG scanners and quantum electron microscopy enable levels of precision in measurement for diagnostic tests and for research in the life sciences that is impossible with traditional measurement devices. Quantum electron microscopy has the potential for a wide variety of applications that can be advanced through non-destructive imaging of biological molecules, something that is impossible with traditional electron microscopes for many samples of interest.

The structure of the industries that manufacture quantum sensing and measurement equipment varies by market niche. In more established markets like those for atomic clocks, MEG scanners, and electron microscopes, incumbents have a strong advantage. In these markets, large scientific and medical equipment companies with sales of a few billion dollars a year tend to have a few product lines featuring quantum technologies. In other market niches, small companies, often start-ups, dominate. Sales of these companies are often on the order of a few million dollars per year.

B. Quantum Communications

The market for quantum key distribution (QKD) has been slow to take off because the advantages of quantum keys for security are offset by cost, complexity, and technical limitations (the need to retransmit the keys for separation greater than 100 kilometers).

QKD offers the possibility for cryptographic security guaranteed by the laws of physics rather than pseudo-random keys generated by computer programs and shared via protocols whose security rests on computationally intractable problems, which is currently the case. However, QKD is constrained by distance and the speed with which quantum keys can be generated and distributed. It is significantly more complicated and costly than current solutions. Because of these disadvantages, wide-scale commercial adoption of QKD is unlikely for the foreseeable future, although government security agencies have made small purchases. QKD has found niche markets in transmitting information between substations on the electric power grid. Between government markets and specialized niche markets, the total market for QKD could run from $50 million to $500 million annually, based on conversations with companies in the industry.

China has been on the forefront of quantum communications, whereas U.S. interest in QKD has declined.

China appears to be the current global leader in quantum communications. It launched the world's first quantum satellite in August 2016 and is about to complete a 2,000 kilometer quantum communication network linking Beijing and Shanghai. The Chinese industry is funded and controlled by the Chinese government. In the United States, research funding for quantum applications has shifted from QKD to other quantum technologies, like quantum computing, which are deemed more promising.

The market for quantum random number generators (QRNGs) is small, offering few advantages over classical alternatives.

The market for QRNGs is much smaller than that for QKD, and it is largely concentrated in gaming applications, cryptography, and data center security. QRNGs compete with true random number generators (TRNGs), which are based on non-quantum physical processes, as well as with deterministic pseudo random number generators (PRNGs) that use classical computation. One problem with QRNGs is that they are slow and therefore have difficulty in meeting commercial demand for random numbers for some encryption protocols, particularly ones used in QKD. Some remain optimistic that if the bit rate increases, demand for QRNGs will grow, perhaps by the financial industry, but this will be largely in support of QKD. We estimate that the overall size of the market for QRNGs is small, less than $50 million annually.

C. Quantum Computing and Simulation

Current commercial quantum computing capabilities are very limited and are likely to remain so for at least the next 10 years, though the introduction of small processors may spur additional algorithm development efforts.

Quantum computing is limited by the absence of both hardware and algorithms. Quantum computing will have commercial viability if and when its capability is both useful and exceeds classical computation capability. Quantum processors of 50 to 100 high-quality physical qubits will be available within the next 5 years. These qubits will not be fault tolerant, however. Consequently any quantum algorithms based on logical qubits will not be viable, except in simple cases, so this capability is unlikely to be of much commercial interest. Because of U.S. government interest in specific applications, we do expect research to continue and progress will be made toward fault-tolerant quantum computing.

Quantum computing and simulations are likely to serve niche markets, like computation of ground-state energies of specific molecules. They are also likely to be used in conjunction with classical computers.

Perhaps the most appealing application of quantum computing lies in quantum simulation, for example, finding the ground-state energies of specific molecules. The viability of this approach has been demonstrated for simple molecules that are still within the reach of classical computation. The most important outstanding concern is if the models within computational reach have sufficient fidelity for molecules under investigation. Quantum simulations need high precision, and the number of runs to achieve this precision may be prohibitive. Both algorithm development for quantum simulation and its verification on real quantum computing hardware will remain an active area of research.

Optimization using quantum annealing has been shown to be viable. However, it has not yet demonstrated a clear, compelling advantage over classical computational methods. As with other quantum computing technologies, the approaches are reaching a scale where this may be changing. Many optimizations designed for quantum annealers are for small, extremely hard problems, which may not have important commercial applications. Most optimization problems for commercial use are large and moderately hard.

Quantum algorithms have been explored for more than 30 years; fewer than 200 have been written and many of these have little or no commercial utility. Many of these quantum algorithms are similar. The commercial viability of quantum computing will be intimately tied to the future development of more commercially important algorithms.

D. Comparisons with Other Countries

The United States is currently ranked the leader in QIS technologies. China is ranked second and has rapidly increased the number of publications in the field, especially in quantum communications.

Europe also ranks highly in publications, patents, and companies engaged in developing QIS technologies. The European industry is much more similar to the U.S. industry than to China's, which is dominated by state-run laboratories and state-controlled companies that appear to sell their products only to the Chinese government.

Several countries have national strategies for developing QIS technologies; the United States does not.

China, the European Union, and the United Kingdom have strategies for developing QIS technologies. Australia and Switzerland have national programs as well. The United States government does not have a national strategy for QIS, despite the substantial sums of money it spends on quantum research.

One of the sharpest differences between the United States and China has been in the importance ascribed to quantum communications.

China has made quantum communications a priority among QIS technologies. As noted in Chapter 2, it has launched a quantum satellite and is constructing a quantum communications network connecting Beijing to Shanghai. Chinese researchers lead the world in publications on quantum communications. The European Union, Japan, Switzerland, and the United Kingdom have also given quantum communications technologies, especially QKD, more prominence than has the U.S. private sector, but they have not given it the high level of priority that China has. Despite the less prominent role that QKD plays in the U.S. quantum industry, the U.S. government remains highly concerned about the potential for quantum systems to provide keys for securing information. Interviewees, all based in North America and Europe, have expressed measured skepticism: many see little to no current or future demand for QKD. In contrast, in 2016, the National Security Agency announced that quantum-resistant cryptography is essential to protecting U.S. critical infrastructures, though there are many options beyond using QKD to address this need.

Companies developing and selling quantum technologies are concentrated in the developed countries of North America, East Asia, Europe, and Australia.

The companies developing and selling quantum technologies operate in a global market place. Although the types of firms vary by market niche, small companies engaged in developing quantum technologies, many of them start-ups, are prevalent in Europe, Canada, and Australia, as well as in the United States.

Quantum metrology and sensing are characterized by more established firms, as those are the technologies that are the best established commercially. In several instances, smaller, established firms manufacturing atomic clocks or atomic interferometers have been absorbed by larger scientific equipment and optical companies in Germany, Japan, and the United States. Large Japanese and Korean electronics and telecommunications companies have quantum communications programs, although they do not yet sell commercial products. Chinese companies in this area tend to be state controlled and have not yet attempted to sell products to the rest of the world, perhaps for reasons of Chinese national security.

The United States holds a clear lead globally in quantum computing. The U.S. industry is bifurcated into a number of small start-ups and programs in large technology companies like Google, IBM, Intel, and Microsoft. These programs are, however, relatively small, in general employing less than two dozen researchers, fewer than some start-ups. Some European companies, especially in the United Kingdom, are also engaged in quantum computing.

The culture of entrepreneurship in the United States has been an important factor in the development of U.S. businesses engaged in developing QIS technologies.

U.S. start-ups have been especially prominent in quantum computing. U.S. government grants have played an important role in sustaining these and other companies engaged in developing QIS technologies. Formal public-private partnerships appear to have played a larger, more formal role in Australia, the Netherlands, Switzerland, and the United Kingdom than in the United States. In China, the industry appears to be dominated by the government, with state research institutes playing a major role in building quantum systems like quantum satellites.

E. Outlook

Previous Quantum Information Science roadmaps have been quite optimistic about technology development. A 2002 Advanced Research and Development Activity (ARDA) technology roadmap set aggressive high-level goals for 2007 and 2012. Two of the 2007 goals were to “encode a single qubit into the state of a logical qubit,” and “perform repetitive error correction on the logical qubit.” The 2012 goal was to “implement a concatenated quantum-error correcting code” (ARDA 2004, 4). It is now 10 years down the road from the original 2007 goals and these goals may finally be within reach of IARPA’s LogiQ program, which is scheduled to end in the 2020 timeframe. The fault-tolerant logic qubits envisioned in the 2007 goals of the ARDA roadmap are likely still more than a decade away. This is simply the nature of research, particularly when the problems are as challenging as they are for quantum computing.

The immediate commercial potential for QIS technologies appears to be modest.

QIS remains one of the most active areas in physics. Companies in the United States and elsewhere are developing new technologies based on advances in QIS, most of which serve small- to medium-sized markets. Thus, although QIS technologies do contribute to U.S. economic output, it is unlikely that the QIS industry will become a major economic sector within the next 10 years.

Despite our caution about large near-term commercial payoffs from QIS technologies, we expect QIS will continue to generate unique, powerful new technologies. A century from now, quantum technologies are almost certain to be economically important.

Appendix A.
List of Organizations Represented in Interviews

Table A-1. Names and QIS Technology Category of Organizations Represented in Interviews

Organization	QIS Technology Category
Companies	
µQuanS	Metrology and Sensing
AOSense, Inc.	Metrology and Sensing
ColdQuanta, Inc.	Metrology and Sensing
EvolutionQ	Communications
Geometrics	Metrology and Sensing
ID Quantique	Communications
IonQ, Inc.	Computing and Simulation
Microsoft	Computing and Simulation
Qubitekk	Metrology and Sensing, Communications
QxBranch	Computing and Simulation
Rigetti Computing	Computing and Simulation
Telestra	Computing and Simulation
Zyvex Labs	Metrology and Sensing
Research Organizations	
Duke University	Computing and Simulation
JILA	Sensing and Metrology, Communications, Computing and Simulation
Stanford University	Metrology and Sensing
University of Birmingham, United Kingdom	Metrology and Sensing
University of California, Berkeley	Metrology and Sensing
University of Glasgow	Metrology and Sensing
Government Organizations	
Defense Advanced Research Projects Agency (DARPA)	Metrology and Sensing
NASA Jet Propulsion Laboratory	Metrology and Sensing
Innovate UK	Metrology and Sensing
National Institute of Standards and Technology (NIST)	Metrology and Sensing, Communications, Computing and Simulation

Appendix B.
List of Selected QIS Companies

Table B-1. Alphabetical List of Selected QIS Companies

Company Name	Country	QIS Technology Category
µQuanS	France	Sensing and Metrology
1Qbit	Canada	Computing and Simulation
Accubeat	Israel	Sensing and Metrology
Anyon Systems	Canada	Computing and Simulation
AOSense, Inc.	United States	Sensing and Metrology
Bruker Corporation	United States	Sensing and Metrology
Cambridge Quantum Computing	United Kingdom	Computing and Simulation
Carl Zeiss	Germany	Sensing and Metrology
ColdQuanta	United States	Sensing and Metrology
Compumedics	Australia	Sensing and Metrology
Crypta Labs	United Kingdom	Communications
CTF MEG International Services LP	Canada	Sensing and Metrology
D-Wave	Canada	Computing and Simulation
Elekta	Sweden	Sensing and Metrology
EvolutionQ	Canada	Communications
FEI	United States	Sensing and Metrology
Frequency Electronics	United States	Sensing and Metrology
Geometrics	United States	Sensing and Metrology
Google	United States	Computing and Simulation
Hitachi High-Technologies Corporation	Japan	Sensing and Metrology
Honeywell	United States	Sensing and Metrology
IBM	United States	Computing and Simulation
ID Quantique	Switzerland	Communications
Intel	United States	Computing and Simulation
InVisage	United States	Quantum Film
IonQ	United States	Computing and Simulation
JEOL	Japan	Sensing and Metrology
Leica Microsystems	Germany	Sensing and Metrology
Lockheed Martin	United States	Computing and Simulation
MagiQ	United States	Communications
Micro Photon Devices	Italy	Communications

Company Name	Country	QIS Technology Category
Microsemi	United States	Sensing and Metrology
Microsoft	United States	Computing and Simulation
Northrop Grumman	United States	Sensing and Metrology
Olympus Corporation	Japan	Sensing and Metrology
PicoQuant	Germany	Communications
Post-Quantum	United Kingdom	Communications
Qasky	China	Communications
QC Ware	United States	Computing and Simulation
Quantum Base	United Kingdom	Communications
QuantumCTek	China	Communications
Qubitekk	United States	Sensing and Metrology, Communications
QuintessenceLabs	Australia	Communications
QuSpin	United States	Sensing and Metrology
qutools	Germany	Communications
QxBranch	United States	Computing and Simulation
Ricoh	Japan	Sensing and Metrology
Rigetti Computing	United States	Computing and Simulation
SeQureNet	Europe	Computing and Simulation
Southwest Sciences	United States	Sensing and Metrology
Sparrow Computing	Denmark	Computing and Simulation
Spectratime	Switzerland	Sensing and Metrology
Stanford Research Systems	United States	Sensing and Metrology
Toshiba	Japan	Communications
Tristan Technologies	United States	Sensing and Metrology
Twinleaf	United States	Sensing and Metrology
Whitewood	United States	Communications
Zyvex Labs	United States	Sensing and Metrology

Note: This list is based on the companies listed in this report, were mentioned in interviews, or came up in prior research. Therefore, it may not be comprehensive.

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Glossary

Atomic interferometer	device in which atom waves are made to interfere with each other; it may be used to measure accelerations due to gravity or other forces (Joint Quantum Institute)
de Broglie wavelength	a particle's de Broglie wavelength is defined as Planck's constant divided by the particles momentum
Entanglement	a condition in which two particles are inherently linked even though they may be separated; if one particle is measured, the result of the other is implied (Joint Quantum Institute)
Femto-Tesla	a unit of measurement of the strength of a magnetic field
Geomorphology	the study of the physical features of the surface of Earth and their relation to its geological structures
Gravimeter	a type of accelerometer that measures the local gravitational field of Earth
Haber-Bosch process	an industrial process for producing ammonia from nitrogen and hydrogen, using an iron catalyst at high temperature and pressure
Hamiltonian	is an operator corresponding to the total energy of the system
Inertial navigation	using a computer, motion sensors, and rotation sensors to calculate the position, velocity, and acceleration of a system without the need for external references.
Ising model	a mathematical model of ferromagnetism
Josephson junction	an electrical device in which two superconducting metals are separated by a thin layer of insulator, across which an electric current may flow in the absence of a potential difference
Lidar	a detection system that works on the principle of radar, but uses light from a laser
Metrology	metrology is the science of measurement and seeks to define standard, international units of measurement
Magnetometer	a magnetometer is a device that measures the direction, strength, or relative change of a magnetic field at a particular location
petrology	study of the origin, history, occurrence, structure, chemical composition, and classification of rocks

Planck's constant	a constant that gives the unvarying ratio of the energy of a quantum of radiation to its frequency
Quantum computing	use of quantum mechanical phenomena such as superposition and entanglement to perform operations on data
Quantum correlated	a measurement on one part of the system that affects future measurements on the other part of the system in a way that is determined by the non-classical state of the system
Quantum cryptography	uses principles of quantum physics as opposed to mathematical algorithms to generate and distribute encryption keys used to safeguard the transmission of data over unprotected networks
Quantum dots	semiconductor particles, many types of which emit light of specific frequencies if electricity or light is applied to them
Quantum information science (QIS)	an area of study that builds on uniquely quantum principles such as superposition, entanglement, and squeezing to obtain and process information in ways that cannot be achieved based on classical principles
Quantum key distribution (QKD)	uses quantum properties to send an encryption key between two parties. Because of quantum mechanics, QKD ensures that encryption keys cannot be unknowingly intercepted by a third party
Quantum random number generator (QRNG)	uses quantum phenomena to generate entropy to generate random numbers. QRNGs are unlike other pseudo random number generators (PRNGs), which are deterministic, and other true random number generators (TRNGs) that use other physical processes to generate entropy because QRNGs are provably random.
Quantum repeaters	a means to get around the impossibility of reproducing an arbitrary quantum state and allow two parties, separated by an arbitrary distance, to share an entangled state. In optical communications, repeaters amplify light signals; for quantum use, quantum information must be translated to classical information and are error prone. Quantum repeaters provide an alternative.
Quantum simulation	refers to the use of quantum hardware to simulate quantum processes
Qubit	the quantum version of a bit used in classical computing; unlike a bit, which may have a value of 0 or 1, a qubit may assume a superposition of these two states (Joint Quantum Institute)
Raman effect	inelastic scattering of a photon by molecules that are excited to higher vibrational or rotational energy levels

Squeezing	squeezing of light is an entanglement of states so as to reduce the noise of the light below the standard quantum limit in a given component (RP Photonics Encyclopedia)
Superposition	a condition in which a quantum system can be in multiple states simultaneously; the correct state is unknown until the system is measured (Joint Quantum Institute)
Zeeman effect	splitting of the spectrum line into several components by the application of a magnetic field

Abbreviations

ACT	Australian Capital Territory
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AMBIIENT	Atomic Magnetometer for Biological Imaging in Earth's Native Terrain
ANU	Australian National University
ARDA	Advanced Research and Development Activity
ARO	Army Research Office
AUD	Australian dollar
BEC	Bose-Einstein condensate
C	Celsius
CAD	Canadian dollar
CAS	Chinese Academy of Sciences
CB	classical bit
CSAC	chip-scale atomic clock
CQC	Cambridge Quantum Computing
CQT	Center for Quantum Technologies
DARPA	Defense Advanced Research Projects Agency
DOE	Department of Energy
EEG	electroencephalogram
EPSRC	Engineering and Physical Sciences Research Council
EUR	Euro
fMRI	functional magnetic resonance imaging
FRP	Federal Radionavigation Plan
GE	General Electric
GNSS	global navigation satellite system
GPS	Global Positioning System
HHL	Harrow-Hassidim-Lloyd
IARPA	Intelligence Advanced Research Projects Activity
IDA	Institute for Defense Analyses
IQC	Institute for Quantum Computing
JPL	Jet Propulsion Laboratory

K	kelvin
LANL	Los Alamos National Laboratory
LED	Light-Emitting Diode
LORAN	long-range navigation
MEG	magnetoencephalography
MIT	Massachusetts Institute of Technology
MRI	magnetic resonance imaging
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NCCR	National Center of Competence in Research
NEC	Nippon Electric Company
NIST	National Institute of Standards and Technology
NQIT	Network Quantum Information Technologies
NRF	National Research Foundation
NSA	National Security Agency
NSF	National Science Foundation
NSTC	National Science and Technology Council
NTT	Nippon Telegraph and Telephone
NV	nitrogen vacancy
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
PET	positron emission tomography
PNT	Position, Navigation, and Timing
PRNG	pseudo-random number generators
RQC	Russian Quantum Center
QI	Quantum Institute
QIG	Quantum Information Group
QIS	quantum information science
QIST	Quantum Science and Technology
QKD	quantum key distribution
QRNG	quantum random number generator
QST	National Institutes for Quantum and Radiological Science and Technology
QTEC	Quantum Technologies
QuAIL	Quantum Artificial Intelligence Laboratory
qubit	quantum bit

QUBO	Quadratic Unconstrained Binary Optimization
QUESS	Quantum Experiments at Space Scale
R&D	research and development
SGD	Singapore dollar
SNSF	Swiss National Science Foundation
SQUID	superconducting quantum-interferometer device
STPI	Science and Technology Policy Institute
TRNG	true random number generator
UAVs	unmanned aerial vehicles
UNSW	University of New South Wales
USD	U.S. dollars
VC	Venture Capital

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14. ABSTRACT

Quantum information science (QIS) builds on scientific principles unique to quantum science—the study of the smallest particles of matter and energy—to obtain and process information in ways that cannot be achieved based on classical physics principles. Quantum phenomena have been harnessed to enhance the accuracy of sensors and detectors, which has advanced basic science experimentation and produced commercial products. They also hold promise for securing sensitive communications and creating more powerful computers. The extent to which the various QIS technologies that are under development will translate into significant commercial markets is, however, an open question. This report explores what new and emerging quantum technologies offers to potential buyers, the timescale over which the technology is likely to become commercially available, and the potential size of the market at which it is directed. In addition, it identifies current activity in developing these QIS technologies in the United States and around the world, detailing efforts funded by both government and private industry. QIS technologies are unlikely to generate large, near-term commercial payoffs. However, QIS has and will provide for unique and powerful new technologies, beyond the reach of classical technologies. Over the course of the century, quantum technologies are very likely to be economically important.

15. SUBJECT TERMS

future markets; QIS; quantum communications; quantum computing and simulation; quantum information science; quantum metrology and sensing

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