MAY 2023

Quantum Technology

Applications and Implications

By James A. Lewis and Georgia Wood[1]

Introduction

Quantum physics is the "study of matter and energy at the most fundamental level." Quantum technologies exploit the properties identified by quantum physics to provide new capabilities in computing, communications, and sensing.

While quantum phenomena have been studied for decades, important technologies based on those phenomena have only appeared relatively recently. Some of these technologies will offer significant advantages for business and national security. Others will create new risks for encryption and stealth. This makes quantum an important topic for policymaking and an important area for cooperation between the United States and its allies. This paper, written to introduce a general audience to the topic, looks at key quantum technologies, timelines for deployment, and national policies for quantum innovation.

The principles of quantum physics can be perplexing and often counterintuitive, with terms like "spooky" or "entanglement" used to describe how quantum physics works. While a basic understanding of those principles is important for evaluating progress and potential, the more immediate policy questions are how to accelerate research, how to develop new quantum technologies, and how to use (or in some cases, protect against) these technologies' different applications.

Quantum research is carried out by universities, government labs, and companies in more than a dozen countries. The infrastructure for research and services includes quantum computers and the specialized chips they use, new kinds of sensors, quantum communication devices, and unique software, since the software needed for quantum computing is very different from conventional computing software. Quantum is more than computing, also having applications for sensing, encryption, and communications. The number of companies offering quantum technologies and services is growing rapidly. Some quantum applications, like sensing, will enter into widespread use before quantum computers do, and some

1. The authors would like to thank Shawn Rostker for his research assistance and Jonah Force Hill for his comments on this paper.

quantum applications are closer to entering commercial use than others.

Quantum Computing

Quantum computing often gets the most attention among the applications. Quantum computing uses quantum physics to solve problems at speeds not possible with classical computers. The basis of quantum computing is the "qubit" (short for "quantum bit"). Conventional computers use "bits," which can represent either "1" or "0." In contrast, qubits can simultaneously represent 1, 0, or any value in between. This property (called "superposition") allows a quantum computer to perform many operations simultaneously and in parallel, allowing for computations millions of times faster than those of classical computers.

This will make quantum computing an exceptional new research tool for all sciences. Quantum computing will improve data analysis and accelerate the performance of machine learning algorithms for research and business. While financial services companies are investing in quantum computing as it could give them an edge in making investment decisions for **derivatives** and **calculating** market risk. Quantum computing's security applications include being able to "break" secure encryption, perform complex simulations, and allow the analysis of massive datasets for improved threat detection and decisionmaking.

Quantum computing requires special chips that are different from conventional semiconductors (although there is research underway to allow quantum chips to be made using the advanced techniques used now for conventional silicon-based chips). These special chips are what make quantum computers faster and more capable. Quantum chips are expensive (one estimate is **$10,000 a qubit**, compared to under $200 for a conventional chip) and they require a host of specialized support equipment. The first quantum chip was made by the National Institutes of Standards and Technology (NIST) in 2009, and there is now a race to develop computers that use multiple quantum chips; the more chips and the more qubits on a chip, the faster the processing of data. The largest quantum processors now have **a few hundred qubits.**

This race has led to a contest of sorts in the pursuit of **"quantum supremacy,"** where a quantum computer can perform calculations that no conventional computer could ever do. There are disputes over whether quantum supremacy has been achieved, but it is a useful initial threshold for identifying performance.

One obstacle to quantum computing is the need to improve qubits so they are less prone to making calculation errors due to "noise," which can be anything from radio signals to **disturbances in the Earth's magnetic field.** Shielding a quantum chip from noise helps. Another solution to the noise problem is to create error correction software that can fix qubit errors. Quantum chips themselves need to be simplified to allow each chip to contain multiple qubits without the complex wiring now required, since error correction requires the ability to use multiple qubits simultaneously. While some experts believe these problems are insolvable, others are more confident that further research can overcome them in the next 10 to 15 years.

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Despite this, quantum computing is in use now (primarily for research). Given the need for specialized support equipment and the fragility of qubits, it is not currently feasible to install a quantum computer on every desk; however, internet-enabled computers can allow researchers to use quantum computing capabilities without requiring physical access. This is also known as "quantum-as-a-service." Since quantum computers are complex, high maintenance, and expensive, quantum-as-a-service allows researchers and companies to access quantum computers owned, operated, and maintained by another company—often using cloud services or over the internet—without needing to own the hardware. Quantum-as-a-service is already used by universities and a few national programs (like **Germany**) for research.

Quantum's Effect on Cryptography and Communications

Cryptography is the process of using complex mathematical formulas to encode data and make it unreadable until it is decoded. Encryption is widely used in online commerce, finance, and national security systems. Quantum computers, with their immensely greater speeds, will be able to perform calculations to rapidly decrypt messages once considered secure. They will also have the **ability** to solve complex math equations at much faster rates than traditional computers, allowing them to "break" the encryption, creating a new threat to existing software and services.

Any system using the public key cryptography found widely in commercial applications will be vulnerable to decryption by quantum computers. While this is not possible now, many countries are pursuing the capability, and it is likely that advanced adversaries like China are collecting and storing encrypted data now for decryption later, when quantum computers are available. This "store now, decrypt later" threat is particularly concerning as some U.S. government data can remain **sensitive for decades**.

Given these risks, NIST has led a process to create post-quantum cryptography (PQC). PQC algorithms will provide the basis for commercially available quantum-resistant cryptography. They are expected to be standardized in 2024. Transitioning to PQC will not be the first time a change of encryption standards has been implemented. In 1977, the National Bureau of Standards (NBS) **adopted** the Data Encryption Standard (DES), but by the late 1990s, researchers were able to **break** DES encryption. This prompted NIST to **develop** the Advanced Encryption Standard (AES) in 2001. That experience showed that changing encryption standards is a lengthy process, since new products based on the standards have to be created and then deployed across the economy, and a similar process will shape the PQC transition.

The implementation of PQC also faces further obstacles. The PQC algorithms most likely to be adopted have varying technical attributes, including different key lengths and processing times. These features make the implementation of PQC more extensive than the previous transition from DES to AES. NIST predicts that without large-scale implementation planning, it could be decades until most of the vulnerable public-key systems incorporate PQC. The National Security Agency has recommended moving to NIST’s post-quantum cryptographic algorithms (once they are standardized) as the best way to secure against the decryption threat.

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Quantum Communication

Quantum communication applies the properties of quantum physics to provide better security and improved long-distance communications. Quantum communication provides two advantages for security. First, in conventional digital communication, messages are encrypted and decrypted using keys and transmitted as classical bits (zeros or ones). Quantum key distribution (QKD) allows the creation of encryption keys that are encoded and transmitted using qubits, making them more difficult to break.

Second, qubits are incredibly sensitive. Any attempt to disrupt or even just observe them will force qubits to collapse. This means that if an outside observer tries to intercept or monitor communications that use QKD, their activity will be immediately noticed by the message recipient. Quantum communications therefore hold the potential to protect transmitted data and make it very difficult for eavesdroppers to evade detection.

Wide deployment of quantum communications technology is still years away. QKD has been demonstrated over fiber optic cables, radio, and satellite relays. However, fiber optics can transmit QKD over only short distances, and space-to-ground demonstrations have been **inconclusive**. Each medium requires the development of additional technologies before it can be commercially viable.

China is attempting to develop quantum communications using projects like the **Micius satellite** program (initially undertaken in cooperation with an **Austrian university**). China launched Micius in 2016 and reported that it achieved the world’s first quantum encrypted teleconference in 2017. However, there were security concerns with the satellite itself. In 2020, Chinese researchers announced they had resolved these problems, relying more on secure ground technology to work in collaboration with the satellite, and said their new method increases the security of QKD to an “unprecedented level.”

Quantum Sensing

Quantum sensing allows for extremely precise measurements. The technology can capture high-resolution and highly sensitive measurements at the level of individual atoms, providing greatly improved accuracy. Quantum sensing technologies have a broad range of applications, including healthcare and medical research, environmental monitoring, construction, energy, navigation, and defense. They are resistant to electromagnetic interference and jamming. Their more sensitive and precise measurements provide greater reliability than conventional sensors.

Quantum sensing offers the possibility of more precise and secure navigation. Critical civilian, commercial, and military systems rely on GPS and the Precision Navigation and Timing (PNT) data it provides. GPS is often the only source of PNT data for many critical infrastructure systems (including finance and electrical power), making them potential targets for GPS interference. Using quantum sensing could eliminate these vulnerabilities. Quantum sensing also allows for high-precision navigation without the use of GPS. Unlike GPS, quantum navigation would not depend on an external signal, making it resistant to jamming. Quantum sensors can measure the Earth's gravitational and magnetic fields to detect minute changes in motion and electromagnetic impulses. Sensitive gravitometers (instruments that measure the Earth's gravitational field) and magnetometers can measure anomalies and compare them to existing data and allow precise navigation without the need for satellite communications.

There are several hurdles to achieving reliable quantum navigation, given the complexity and delicate calibration of the necessary sensors. These include needing lower cost, smaller size and weight, and improved power components. Miniaturization also poses challenges, as miniaturizing sensor platforms tends to reduce their sensitivity, raising a barrier to effective applications.

Quantum sensing also has implications for intelligence, surveillance, and reconnaissance capabilities. The U.S. Army Research Lab developed a technique known as "ghost imaging" that uses the quantum properties of light to detect distant objects through the use of weak illumination beams. These beams are capable of penetrating atmospheric conditions and are weak enough to avoid detection by the imaged target in many cases, making it a potentially useful tool for covert operations. Another technique known as quantum illumination could improve the stealth detection capabilities of quantum radar. This technique is thought to be able to obtain a higher signal-to-noise ratio than non-quantum sensors, which is ideal for detecting low-reflectivity targets amid high-noise backgrounds, such as stealth bombers during flight. Chinese researchers are working on a **quantum radar system** that can detect stealth aircraft, but some experts question how successful China has been. Quantum sensors could also make it easier to **detect submarines** and China claims to have made progress in developing powerful quantum sensors for submarine detection.

Biomedical research provides further unique opportunities for quantum sensing. The ability to measure the electromagnetic fields of the brain, heart, or other organs to study the impact of medical treatments could lead to more effective drug development and to potential cures for some diseases. Quantum sensors will allow researchers to obtain data from the electromagnetic field of a patient's brain that could be compared to a healthy brain, enabling them to better understand the impact of certain drugs.

Quantum sensing also has applications for medical diagnostic imagery. One example is that traditional sensing devices are not effective on children because they are often too big and require the subject to remain still during the scan. However, breakthroughs in quantum sensing could change that, with the ability to detect and diagnose without requiring the patient to remain still. Some quantum devices are already being deployed in hospitals.

Timelines for Quantum

One question that always comes up in discussions of quantum technology is: "How soon?" Skeptics say that quantum technology is decades away from realization. This skepticism is misplaced. First, the pace of innovation has increased in the last decade, given the data science and computing tools available today to assist research and development (R&D). Second, the arrival time for quantum varies by application. Some sensor technologies are close to commercial deployment, while high-performance quantum computing applications are likely years away. It is important to understand that while computing, sensing, and communications applications all leverage quantum science, they are different technologies with different timelines.

When it comes to quantum computing, robust technology that will outperform conventional computers is more than a decade away, but less intensive computing applications are entering use now. Decryption using quantum computers, one of the most sensitive applications provided by computing, is also probably **years** away from deployment, with the caveat of not fully knowing what progress competitors such as China may have made. As for quantum communications, relevant technologies are still in the development phase. The Government Accountability Office estimates that fiber optics for QKD will require another decade to mature, while satellite QKD communications may be available sooner. In contrast, some quantum sensing applications for biomedical research, construction, or enhanced imaging are commercially available, or (as in the case of navigation) will be so in a few years.

Quantum Research Is Global

Quantum technology holds significant potential for global innovation, even before quantum computers are fully deployed. Many countries have recognized the potential of quantum technology and are investing in it to develop computing, communication, and sensing capabilities. This includes both government and private sector research investments. Quantum technologies are still research-intensive and leading science and technology powers are spending hundreds of millions of dollars to fund R&D. As of 2022, nine countries and the European Union have announced spending more than a combined $30 billion on quantum programs (see Appendix B), and the U.S. private sector spends more than many countries.

Governments can encourage quantum technologies through national R&D programs and accompanying funding. A variety of national strategies for quantum research have been established in recent years by the United States, China, the United Kingdom, Canada, and others (see Appendix A).

As quantum applications are developed, policymakers will need to identify how best to promote further research, create global markets, and take advantage of the commercial and security benefits quantum technologies provide. One immediate policy problem for quantum technology is technology transfer. Export controls are an important tool in the Biden administration's policy against China. The White House hopes to slow Chinese advancements in critical technologies by limiting access to supply chains in partnership. The administration is exploring controls on emerging technologies, including quantum. There are concerns that U.S. advancements in quantum science could improve Chinese military capabilities—the Department of Commerce cited this when it placed three Chinese organizations on the **Entities List** in 2021.

However, there are also concerns that quantum technology is at too early a stage to implement restrictions without damaging innovation. A recent report from RAND analyzed U.S. and Chinese industrial bases in quantum technology and came to the conclusion that "export controls would prematurely limit the exchange of scientific ideas, slowing down technological progress." The analysis notes the importance of a **global quantum "ecosystem"** in early-stage development, the harmful impact of export controls on small startups, and the potential damage from a lack of regulatory clarity.

While the United States should limit China's access to quantum technologies, it also needs to expand cooperation with partners. Commitments to collaborate on quantum are linked to initiatives like the Quad and AUKUS. Equally importantly, the United States needs to build a global market for quantum applications to incentivize private sector development and innovation. On balance, an overly restrictive approach to technology transfer that goes beyond China and makes it difficult to work with research partners or develop new markets for quantum technologies will do more harm than good to the quantum effort in the United States—as shown by earlier experience with satellite and encryption controls, where overly expansive export controls damaged U.S. technology companies.

Moving Ahead

Quantum technologies will create immense opportunities in ways that will reshape research, business, and security, as well as accelerate innovation. There are seven broad recommendations for policy:

1. **Increase support for research**. This can be accomplished through more than just additional funding (although, since China may outspend the United States, funding cannot be ignored). Support could also take the form of tax incentives and supportive regulations in associated markets, like autonomous vehicles. This support should include funds for basic research but also programs to nurture startups, develop use cases and applications, build public infrastructure, and promote investment collaboration domestically and overseas.

2. **Bolster technological cooperation with allies and partners**. The United States is already working collaboratively with allies on quantum technologies and their implementation and should accompany this with appropriate agreement on policies and standards for quantum technologies. The United States should also work with allies to develop common policies on technology transfer. Ill-timed or badly designed technology transfer restrictions will slow the United States by cutting off access to the global quantum research community and by strangling the commercial market for quantum applications and the willingness of entrepreneurs to enter the quantum market.

3. **Accelerate the transition to PQC to stay on the projected timeline of quantum computers**. It took almost a decade for the transition from DES to AES, and since it may not be 10 years before cryptographic systems are vulnerable to a quantum computer, a failure to plan now for transition to PQC could be exceptionally damaging.

4. **Use federal funding to increase researcher access to quantum-as-a-service (including allied researchers)**. The Department of Energy Quantum User Expansion for Science and Technology (QUEST) program is a good start that can be expanded to include allies. Quantum computing is sufficiently different that increased access will provide necessary experience and innovation.

5. **Develop standards and regulations to ensure the safe and responsible development and deployment of quantum technologies**. This includes establishing standards for the performance and reliability of quantum tech, as well as regulations governing the use of this technology in critical industries such as finance, transportation, energy, and telecommunications. This can be done in partnership with allies and partners using AUKUS, U.S.-EU Trade and Technology Council, and other mechanisms.

6. **Review existing intellectual property rules and regulations for their application to a quantum computing world**. Quantum computing may pose significant challenges for intellectual property protection, since the ability to quickly process vast amounts of data could potentially lead to the rapid discovery of new drugs, materials, and other scientific breakthroughs.

7. **Invest in quantum skills and workforce**. Government, academic institutions, and corporations will need to invest in education and workforce programs to provide individuals with the skills and knowledge needed to work in this exciting and rapidly evolving field. As the quantum industry continues to grow, there will be a significant demand for skilled workers. ■

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This report is made possible through funding from SandboxAQ.

Appendix A

SELECTED NATIONAL STRATEGIES

United States: In 2018, the U.S. Congress passed the **National Quantum Initiative Act**, which allocated $1.2 billion for government spending on quantum tech and created the National Quantum Coordination Office within the White House to coordinate efforts on quantum throughout the federal government. The National Quantum Initiative Act sought to increase U.S. leadership on quantum and drive a whole-of-government approach to accelerate its R&D. The act is up for reauthorization in 2023, and Congress is **focusing** on expanding fundamental science provisions, pivoting to use-case R&D, supporting test beds for start-ups, and expanding workforce development in its reauthorization.

The White House released **National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems in 2022**. The memorandum seeks to accelerate U.S. leadership on quantum computing while safeguarding federal networks against its potential encryption risks. The immediate goal is to **mitigate** much of the risk posed to encryption by 2035. A first step is for the heads of all Federal Civilian Executive Branch agencies to complete an inventory of their systems to discover where they are vulnerable to quantum computing.

The memorandum has laid out requirements for the transition to QRC to take place after NIST finalizes the QRC standards (expected in 2024). The Office of Management and Budget will provide a migration plan for agencies within one year after NIST completes its work. NIST is directed to work with the private sector and the Cybersecurity and Infrastructure Security Agency is to work with sector risk management agencies and state and local governments on the transition. All of these actions are accompanied by various reporting requirements on progress. The **Quantum Computing Cybersecurity Preparedness Act,** passed in December 2022, codified many of the provisions from the memorandum.

These efforts are accompanied by R&D initiatives. The U.S. government has been funding quantum R&D since at least the early **2000s**, and the memorandum lays out steps to create a cohesive national strategy for quantum promotion and technology protection. This includes the **Entanglement Exchange**—a partnership with like-minded countries to accelerate quantum and connect researchers and professionals globally. The omnibus **CHIPS and Science Act of 2022** included several quantum-related provisions, from workforce development to improving accessibility to quantum technology for U.S. researchers.

China: China declared quantum to be a key priority in its **14th Five-Year Plan**. In 2017, the government announced the creation of a National Laboratory for Quantum Science for further R&D initiatives, and China has been making significant investments in quantum, mainly from government sources, with total spending of least at **$4 billion**. Chinese investments span a range of quantum technologies but are largely focused on military applications (such as sensing, decryption, and secure communications). Notably, at **$260 million**, its private sector investments lag in comparison to those in the United States, Canada, and the United Kingdom.

United Kingdom: In March 2023, the government published its **National Quantum Strategy**, outlining its plan to promote quantum R&D and realize the potential of these technologies over the next 10 years. The strategy commits £2.5 billion (over $3 billion) to developing quantum technologies between 2024 and 2034. It also outlines specific metrics for the United Kingdom to achieve success in quantum, including goals for market share, private equity investment, and academic outputs.

Canada: In January 2023, Canada announced its **National Quantum Strategy** to become a world leader in quantum computing, safeguard against the potential risks of quantum technologies, and enable the adoption of quantum sensing. In order to implement these steps, the government allocated CAD $360 million ($267 million) to research, talent development, and the commercialization of quantum products.

Japan: In 2020, Japan **launched** its Quantum Technology and Innovation Strategy, with three main objectives: to accelerate innovation, conduct basic research, and expand international collaboration (in particular with the United States and the European Union). The strategy seeks to create technology roadmaps for innovation, establish quantum hubs, and increase multilateral and bilateral agreements on quantum. Building on this, in 2022 Japan launched its Vision of Quantum Future Society, which seeks to integrate quantum technology into classical systems to solve societal challenges, create opportunities for industry, and promote quantum use through testbeds. The strategy hopes to enable economic growth, drive sustainability, and empower resilient societies through advancements in quantum.

European Union: In 2018, the European Union announced its **Quantum Technologies Flagship**, a research conglomerate aimed at bringing together academic institutions, industry, and the public sector to accelerate EU leadership and innovation. The group has a €1 billion ($1.1 billion) budget over 10 years to support researchers, mainly focused on computing, simulation, communication, and sensing. The European Union also adopted the **Council Regulation on establishing the new European High Performance Computing Joint Undertaking** (EuroHPC JU) in 2021, an initiative that will draw funds from EU-wide programs and the private sector to create a €7 billion ($7.5 billion) investment in high-performance computing. EuroHPC JU hopes to build quantum computers by 2025 and aims to make Europe a leader in quantum computing.

India: In 2023, India's Union Cabinet **approved** the National Quantum Mission, providing over $730 million in funding for R&D to establish India as a global quantum leader. It aims to use quantum to support national priorities (e.g., **Digital India** and **Make in India**). This initiative will fund quantum programs until 2031, and the targeted technologies include quantum computing, sensing, and communication. To accomplish its goals, the mission will create four thematic hubs at universities and research institutes focused on basic and applied research.

Russia: As a part of Russia's broader data economy **program** that seeks to develop high technology markets domestically, the government announced a **$790 million** quantum investment for 2019-2024. This funding aims to provide Russian researchers with tools to develop practical quantum applications, focusing on computing and simulation, communication, and sensing. Russia **announced** progress on the initiative in 2021, stating that the goal of having a quantum computer with cloud access (quantum-as-a-service) by 2024 is still on track. This funding builds on previous initiatives, including the government-**supported** Russian Quantum Center and related state-backed research **labs**. Much of Russia's practical work on quantum has focused on quantum communication. In 2019, Russia **claimed** its QKD technology is "ready for industrial integration" and that Russia wants to work with international partners on creating global QKD networks. The goal is to create a QKD network in Russia to connect Chinese and European infrastructures. However, these Russian claims are likely overstated.

Australia: In May 2023, Australia announced its **National Quantum Strategy**, an initiative to position Australia as a leader in the global quantum industry by 2030. There are five central themes of the strategy–investing in R&D, accessing key quantum infrastructure, expanding the workforce, advancing standards that reflect national interests, and building a trusted and inclusive ecosystem. While the strategy does not directly commit additional quantum funding, it notes that it signals areas the government may invest in the future.

Appendix B

GLOBAL FUNDING

Below is a table of funding highlights by the top quantum spenders, combining both private and public sector investment efforts. While these are not comprehensive numbers, they provide a glimpse into the countries most focused on developing quantum technologies for future applications. The government spending data (all in USD) combines a variety of public commitments to quantum investment, as cited in the table's footnotes.

Country	Private Sector Investment (as of 2022)	Government Spending (as of 2022)	Projected Government Spending	Estimated Total
China	**$260 million**	**$9.7 billion**	Not Available	$10.0 billion[1]
European Union	Not Available	**$1.1 billion**	**$7.5 billion**[2]	$8.7 billion
United States[3]	**$3.7 billion**	**$2.9 billion**[4]	**$844 million**[5]	$7.4 billion
United King-dom	**$890 million**	**$1 billion**	**$3.1 billion**	$5 billion
Germany	**$100 million**	**$1.9 billion**[6]	**$1.2 billion**[7]	$3.2 billion
Canada	**$700 million**	**$748 million**	**$270 million**	$1.7 billion
Japan	Not Available	**$1.1 billion**	**$607 million**	$1.7 billion
France	**$420 million**	**$565 million**[8]	**$565 million**	$1.6 billion
Australia	Not Available	**$311 million**	**$725 million**	$1.0 billion
Netherlands	Not Available	**$853 million**	Not Available	$853 million
Russia	Not Available	**$790 million**	Not Available	$790 million
India	Not Available	Not Available	**$730 million**	$730 million

Endnotes

1 Numbers from the Chinese government are difficult to assess and state announcements can be unreliable. This number is the most agreed upon estimate.

2 This projection includes both private and public spending.

3 This consists of the Quantum Economic Development Consortium, as well as new QIS R&D activities. Agencies reported actual budget expenditures for Quantum Information Science (QIS) R&D of $449 million in FY 2019, $672 million in FY 2020, and $855 million in FY 2021, followed by $918 million of enacted budget authority for QIS R&D in FY 2022, and a requested budget authority of $844 million for QIS R&D in FY 2023.

4 Spending since 2019.

5 Budget request for FY 2023.

6 Previous government frameworks committed $650 million. Coronavirus stimulus bill earmarked $2.4 billion to be spent by 2025, allocating $600 million a year.

7 Coronavirus stimulus bill earmarked $2.4 billion to be spent by 2025, allocating $600 million a year.

8 Earmarked $2 billion between 2021-2025.