JCOTS

JOINT COMMISSION ON TECHNOLOGY & SCIENCE

Snapshot

Quantum Information Science & Technology (QIST)

May 2025

How to read this report

This snapshot is organized into four sections:

- The **Introduction** gives an overview of the topic, explains several important concepts in quantum physics, and outlines the relevance of QIST to policy and policy makers;
- **Key concepts** provides definitions for important terms used throughout the report;
- The **Policy Issues** section highlights and explains several issues related to QIST that might be of interest to policy makers because they sit at the intersection of technology and its societal impacts;
- Finally, the **Policy Considerations** section raises several questions for policy makers to explore in developing policy solutions or formulating questions for future studies.

The snapshot can be read as a continuous document, or readers can skip to sections of interest. Important takeaways are summarized at the end of each of the Policy Issues and in the conclusion, in the Policy Considerations section.

Introduction

Advances in the field of quantum physics have led to the emergence of **Quantum Information Science and Technology (QIST)** – the use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information. Quantum physics deals with properties at atomic and subatomic scales. QIST encompasses applications in computation, networking, sensing, and measurement. Experts project that QIST may eventually perform significantly better than non-quantum, or "classical" technologies, a leap in performance known as **quantum advantage**. QIST holds the potential to revolutionize medical and pharmaceutical research, supercharge Artificial Intelligence (AI), enable unbreakable encryption, and much more, likely exceeding our ability to predict today.[1]

Recent advances have fueled growing public and private investment in QIST research and development. The United Nations has declared 2025 the "International Year of Quantum Science and Technology" in a recognition of the importance of the field.[2] McKinsey reported that the private sector had invested more than $8.5 billion in QIS technologies in 2024.[3] As QIST progresses rapidly, it is accompanied by waves of hype that alternately overstate or understate its potential benefits and risks.[4] QIST has experienced a long evolution, and although it is many years away from the practical applications that often capture headlines and imaginations, some QIST innovations are on the precipice of breakthroughs that could profoundly transform society.

QIST is a fusion of quantum mechanics and information science that began in earnest in the 1980s when theoretical physicist Richard Feynman proposed that the unique properties of quantum physics could be used to solve computation problems beyond the capacity of classical computers.[5] Because things at the quantum scale behave differently than they do at the scale of larger objects, quantum information science opens up new possibilities for performing calculations, encoding information, and even understanding the world around us.

This snapshot provides an overview of QIST, with particular emphasis on the policy-relevant issues that QIST raises, rather than on the underlying science and theory, although this introduction will provide a brief overview of key quantum concepts. QIST is a complex field in which fundamental theoretical and empirical debates remain among scientists and scholars,[6] but it is hardly too early to consider the risks and rewards of investing in QIST and the societal opportunities and harms that public policy will need to address.

Overview of Quantum Properties

Although this snapshot will go on to focus on the applications and implications of QIST for policy, it will be helpful to start with a basic overview of several aspects of quantum mechanics that make QIST possible.

The behavior of particles at the atomic and subatomic levels cannot be explained by the laws of classical physics, which govern larger objects we encounter in everyday life. Many of the principles of quantum mechanics are therefore counterintuitive, made all the more complicated by what is known as the **observer effect**, which describes how the act of observing (or measuring) a quantum system can interfere with the system itself, rendering measurement outcomes probabilistic.[7] In quantum physics, particles do not have definite, predictable qualities. They exist in a probabilistic state, occupying many possible positions and conditions at once until they are measured. Real-world applications of quantum information science depend on reliable measurement of quantum effects, so the observer effect is a significant challenge for QIST that researchers and developers are racing to address. It also marks a fundamental difference with classical physics, which is based on the precise measurement of observable phenomena. (For an example of classical physics, think of Galileo's apocryphal experiment, where he dropped objects of different weights from the Tower of Pisa, observing that they fall at the same rate and revealing the universal force of gravity.)[8]

On a theoretical level, quantum physics has raised profound questions about the nature of reality: is the universe deterministic (predictable) or probabilistic (uncertain)? On a practical level, there are still many things about quantum physics that remain mysterious, even to quantum researchers, and the field is continuously developing with new insights. Nonetheless, what is already known about quantum behavior has unlocked new possibilities in the field of information science. Information science in the digital age has long been predicated on the precise manipulation of predictable electromagnetic signals that follow the rules of classical physics, but quantum physics opens up the potential to leverage the inherent uncertainty in quantum systems to encode, transmit, and protect information in entirely new ways.

A key property of quantum particles is **superposition**, which describes a quantum system before it is measured, when—colloquially speaking—it exists in multiple states at once. This multiplicity of states can only be expressed in terms of probabilistically.[9] Superposition is crucial to QIST, in which information is encoded in quantum bits, or **qubits**, which can represent 0 or 1 or any value in between. Classical bits are binary and can only represent 0 or 1.[10] By harnessing superposition, quantum computers can perform complex operations beyond the capacity of classical computers.[11]

Another key property of quantum systems is **entanglement**, which refers to a phenomenon where two or more quantum particles become linked, so that the state of one particle is dependent on the state of the other(s), regardless of the distance between them.[12] This property is essential to quantum communication, and it also helps quantum computers perform complex calculations faster. **Quantum interference** refers to the ability of quantum systems to interact in ways that either amplify or cancel out certain probabilities.[13] Interference can be used to nudge quantum systems toward particular outcomes, and quantum algorithms leverage this property to perform calculations.[14]

However, quantum states are fragile, and getting quantum systems to stay in superposition or entangled states is difficult. Environmental factors like thermal or electromagnetic interactions can cause **decoherence**, where quantum systems lose their quantum properties and behave more like classical systems.[15] When environmental **noise** causes quantum systems to decohere, they lose information, which undermines quantum technologies that depend on the unique properties of quantum behavior to work.[16]

Then, there is also the problem of the observer effect described above, in which attempting to measure a quantum system can make the system **collapse**. When a quantum system collapses, it exists in a single, definitive state after having existed in many possible states (superposition).[17] In quantum computing, a qubit in superposition that can represent 0 or 1 or anything in between will collapse into simply 0 or 1. All the other possible states—and information—are lost. Reading a result from a quantum computer is complicated because if the system collapses at the wrong time, the calculations can be faulty or useless.[18]

The field of QIST today is highly concerned with how to manipulate quantum systems reliably. Developing effective and useful quantum technologies depends on reducing errors caused by decoherence and environmental noise and on developing stable systems that can maintain superposition and entanglement to achieve desired outcomes.[19] The field has seen major advances in these areas (more on this below), but many of the projected applications of quantum technologies remain theoretical while these fundamental hardware and measurement issues are unresolved.

Quantum Technologies

QIST applies the principles of quantum mechanics to the storage, processing, transmission, and security of information. It combines quantum physics, computer science, information theory, and engineering to harness quantum effects (like superposition and entanglement) and develop new technologies. QIST encompasses several applications that can broadly be grouped into three categories: quantum computing, quantum sensing, and quantum communication.

Quantum computing uses the properties of quantum systems to perform calculations. In non-quantum, or "classical," computing, calculations use bits, which represent 0 or 1. An operation can only be performed on bits one-at-a-time. Quantum computing uses qubits, which have the unique properties of superposition and entanglement, meaning that they can represent 0 or 1 or any value in between, enabling quantum computers to perform different kinds of calculations than classical computers are capable of. However, quantum computing is currently limited by the sensitivity and fragility of qubits.[18] Qubits are subject to noise and decoherence, leading to high error rates in contemporary quantum computer prototypes, known collectively as **Noisy Intermediate-Scale Quantum (NISQ)**.[20]

Researchers are actively exploring how to produce fault-tolerant quantum computers, and there are several proposed strategies for reducing errors, including increasing the number of qubits and developing sophisticated algorithms.[21] In order to solve the kinds of complex problems that many researchers hope quantum computing will be able to tackle, computers will need to use thousands or millions of qubits. Today's quantum computers operate with tens to hundreds of qubits, and increasing the number of qubits also increases the risk of noise and decoherence.[22] To date, quantum computing has only demonstrated the capacity to solve very specific mathematical problems, but its potential applications include aiding drug discovery, assessing financial risks, optimizing logistics and transportation routes, enhancing artificial intelligence models, breaking classical encryption, and more.[23]

Quantum sensing is a field of precision measurement, enabled by quantum mechanics and the ability to detect the smallest disturbances at atomic and subatomic levels. While many quantum applications depend on stabilizing or gaining greater control over quantum states, quantum sensing exploits the inherent fragility of quantum systems. It uses sensors to detect rapidly changing quantum states to measure, image, or identify physical things.[24] This might explain why quantum sensing is widely considered the most promising near-term quantum technology – unlike quantum computing, which relies on maintaining and manipulating fragile quantum states, quantum sensing exploits this inherent fragility to take precise readings of quantum systems.

In fact, many so-called **first-generation quantum technologies** are in the field of quantum sensing. These technologies use quantum mechanics to measure time (atomic clocks), generate precise images (MRI), and navigate challenging terrain, such as under water (accelerometers).[25] In magnetic resonance imaging (MRI), for instance, an intense magnetic field is used to manipulate the internal property, known as "spin," of protons present in molecules in the body. When the protons return to their original state, they emit electromagnetic signals that the machine interprets into images, effectively allowing it to "see through" the body.

Likely real-world applications of quantum sensing include advances in medical imaging; precise detection of defects in materials, like bridges or buildings; enhanced radar and sonar; and the development of new navigational tools for hard-to-access terrains, such as underwater or underground. Quantum sensing has many potential military and security applications, enabling unprecedented stealth detection of submarines and aircraft, for instance. It could pass through previously impenetrable barriers to reveal physical things behind walls, inside bunkers, and more. It is also a key part of secure quantum communication.[26]

Quantum communication uses quantum mechanics to transmit information and keep it secure. It integrates some aspects of quantum sensing and quantum computing. Quantum communication relies on the same quantum properties of superposition, entanglement, interference, and so on. For example, the observer effect (measuring a system disturbs the system) underpins the security of quantum communications, rendering it easy to detect attempts to intercept or eavesdrop on quantum transmissions.[27] This is the basis of **quantum key distribution (QKD)**, an encryption technique that relies on quantum properties, rather than algorithmic complexity used in classical key-based encryption. Today's encryption keys are hard to crack because of their mathematical difficulty. Quantum encryption, by contrast, is impossible to crack because it is based on the fundamental measurement principles of quantum mechanics.[28] The killer app of quantum communication is information security—it could make the transmission of information impervious to cyber threats, including from quantum computer attacks.

Another quantum communication application is what is often called "quantum networking" or the "**quantum internet**." The quantum internet would not be a substitute for the internet as we know it. Instead, it would be a specialized network to enable the exchange of information across quantum sensing and computing devices over large distances. Among other things, it could support quantum key generation and validation, the integration of classical and quantum computers, further developing of the QIST field.[29]

QIS Technologies	Summary	Stage of Development
Quantum computing	A type of computing that harnesses the principles of quantum mechanics to encode, store, process, and transmit data. It does this by manipulating qubits, which can represent more information than a classical bit (which can represent 0 or 1). Quantum computing takes advantage of quantum properties, like superposition and entanglement, to perform operations beyond the capability of a classical computer.	Early stage, with some notable advances toward quantum advantage in controlled experiments.
Quantum sensing	A field of precision measurement, enabled by quantum mechanics and the ability to detect the smallest disturbances at atomic and subatomic levels. It exploits the inherent fragility of quantum systems, measuring the changes in quantum states to do things like image physical things or detect hacking.	Advanced stage, with some commercially available technologies and the potential to develop more applied technologies in the near future.
Quantum communication	A field of information security that uses quantum mechanics to transmit information using "information-theoretic secure" encryption. It integrates some aspects of quantum sensing and quantum computing to secure communication using quantum states, rather than complex mathematical equations, as classical encryption does.	Intermediate stage, with some limited real-world deployment and continued testing.

Quantum technologies are at various stages of development, and many of the real-world applications and social and economic impacts remain distant prospects today. Nonetheless, QIST is at a point where investment and policy can significantly shape the future of the field – who develops it, who benefits from it, and how it is used.

Key Concepts

Data fusion: The process of integrating multiple sources of data to produce a more comprehensive representation of information, often combining data from different sensors, systems, or datasets.

Decoherence: A phenomenon in quantum mechanics that describes the loss of coherence or the superposition of a quantum state, typically due to the interaction of a quantum system with its surrounding environment. It is a significant hurdle in developing quantum computers because processing information requires measuring the state of qubits, but the act of measuring can cause the qubit to decohere and lose crucial information.

Encryption: The process of converting information into a secret code to conceal its meaning. Classical encryption relies on the computational difficulty of certain mathematical problems, while quantum encryption leverages the laws of quantum physics to achieve secure communication. One of the challenges in quantum encryption involves transmission across long distances, which introduces environmental factors that can cause quantum states to decohere.

Entanglement: A unique quantum phenomenon where multiple particles become interconnected and share a relationship that cannot be explained by classical physics; they are inextricably linked, regardless of the physical distance separating them. Entanglement is essential for achieving quantum advantage.

First-generation quantum technology: This term refers to the early-stage technologies that harness quantum mechanics, including established technologies like atomic clocks, MRI, and quantum random number generators.

Noise: Any disturbance to a qubit's environment, such as heat, light, thermal vibrations, electromagnetic radiation, Earth's magnetic field, cosmic rays, or neighboring qubits, among others.

Noisy Intermediate-Scale Quantum: This term refers to a class of quantum computing devices that are not yet fault-tolerant but may still execute computations that outperform classical computers under specific conditions. They are considered "noisy" because they are susceptible to environmental noise, making it difficult to maintain quantum states.

Observer effect: The phenomenon in quantum mechanics where the act of observing or measuring a quantum system can influence the state of the system or disturb the system. This interaction causes the system to "collapse" into a single state, losing information.

Post-quantum encryption (PQE): Also known as quantum-safe encryption, this type of encryption aims to create algorithms that are resistant to both classical and quantum computational attacks, based on mathematical problems that are believed to be more difficult for quantum computers to solve than the problems that underpin classical encryption.

Quantum advantage: The point when quantum computers can solve certain computational problems more efficiently than classical computers.

Quantum communications: A technology that uses quantum mechanics to encrypt and transmit data.

Quantum computing: A type of computation that uses the principles of quantum mechanics to process information by manipulating different states of qubits—such as superposition, interference, and entanglement—to perform calculations.

Quantum Information Science (QIS): The use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information. (*Definition from NQI Act; P.L. 115-368; codified at 15 U.S.C. §§8801 et seq.*)

Quantum internet: The quantum internet is a next-generation network that uses quantum signals – typically entangled photons – to transmit information with ultra-high security, enabling things like networked quantum computing. The quantum internet is likely to have specialized applications that enhance quantum computing and quantum communications capabilities.

Quantum Key Distribution (QKD): A method of securely exchanging cryptographic keys between two parties using the principles of quantum mechanics, ensuring that any eavesdropping attempt can be detected. It leverages quantum properties like superposition and entanglement to protect the key from interception.

Quantum sensing: A field that uses quantum effects to measure or sense physical things by harnessing quantum properties and effects to acquire data from the smallest perturbations at atomic and subatomic levels, which allows for precise measurements of subtle phenomena.

Quantum system collapse: When a quantum system is measured, it collapses into one of many possible outcomes. Before measurement, the system is in a superposition of all potential states, but upon measurement, it takes on a definite state. Collapse is probabilistic, so each possible outcome has a certain probability associated with it.

Qubit: The basic data unit in quantum computing, a quantum bit. Qubits must be initialized and manipulated to perform quantum computation. There are several different kinds of qubits: superconducting qubits, quantum dot qubits, trapped ion qubits, photonic qubits, topological qubits, neutral atom qubits, and defect spins in solids, such as the nitrogen-vacancy center in diamond.[30]

Superposition: A fundamental concept in quantum mechanics that describes the state of a quantum system before it is measured. In quantum computing, superposition allows a qubit to represent 0, 1, or any value in between, allowing a quantum computer to compute directly with quantum probabilities, thereby simultaneously considering a multitude of solutions.

Topological qubit: A type of qubit that encodes information using the topological properties of quantum states, rather than the physical properties like charge or spin typically used in other types of qubits. The main advantage of topological qubits is their robustness: unlike other qubits, which can easily lose their quantum state due to environmental factors, topological qubits are theoretically immune to decoherence. (See “Qubit” above for other kinds of qubits.)

Milestones and Timeline

There have been several notable advances in QIST in recent years, alongside significant investment by the federal government and several large technology companies in quantum research and development.

IBM is a longtime quantum leader, and in 2022, it announced a 433-qubit computer, setting a record at the time.[31] The following year, it launched a partnership with the University of Tokyo and University of Chicago to develop a supercomputer by 2033.[32] According to IBM's quantum roadmap, it will deliver a fully error-corrected quantum computing system by 2029.[33] IBM hosts a cloud-based quantum processor that is available to the public, called the IBM Quantum Experience, along with an open-source programming language, Qiskit, for interacting with its cloud-based quantum prototype infrastructure.

In December 2024, Google announced that it had developed a quantum computer capable of completing a calculation in minutes that would be virtually impossible for classical computers using a specialized chip called Willow.[34] Google is conducting quantum research in several areas, including on "quantum AI," harnessing quantum computing to accelerate more powerful artificial intelligence systems. Its roadmap for development aims to produce commercial computers by 2030,[35] although its published timeline is less specific.[36] Meanwhile, Microsoft announced this year that it had achieved a breakthrough in creating a **topological qubit**—a type of qubit that is theoretically less prone to errors.[37] Although, this announcement has been met with some skepticism in the academic community.[38] The quantum research and development ecosystem includes a wide range of suppliers and smaller commercial competitors, from chip manufacturers, like NVIDIA, to startup companies, like PsiQuantum.

There have also been recent investments in quantum communication. The European Union launched the EuroQCI initiative in 2019, which aims to develop a secure quantum communication infrastructure across Europe by securing existing communication networks with satellite-based quantum key distribution (QKD).[39] China has also invested heavily in QKD, having launched the world's first QKD satellite in 2016. In 2020, China demonstrated that the satellite could secure transmissions over thousands of kilometers.[40] China has also established a QKD connection between Beijing and Shanghai over fiberoptic cable.[41] There are other experimental QKD networks in Japan and the UK.[42]

Ultimately, although QIST has witnessed some noteworthy advances in recent years, and companies that have invested in quantum are optimistic about timelines for real-world applications, realistic estimates for developing commercial QIST are more tentative. Quantum sensing holds the most near-term promise, while other QIS technologies that have grabbed headlines in recent years have longer horizons.

Societal Impacts and Policy Implications

QIST holds the potential to transform society, but it presents both opportunities and risks, accompanied by significant costs in research and development. Quantum computing could revolutionize industries like medicine, materials science, and climate change. Quantum cryptography promises unbreakable encryption, greatly enhancing digital security in an era of increasing cyber threats. But QIST technologies could also introduce unprecedented threats, particularly to cybersecurity and human rights. Quantum technologies could eventually break current encryption methods, jeopardizing the security of sensitive data across various sectors if they are not adequately prepared. An although a more distant prospect, QIST could enable new powers of surveillance with advances in quantum-powered AI, imaging, and sensing.

QIST could also lead to significant job displacement in industries reliant on current computing systems, demanding workforce reskilling and updated educational standards. Additionally, due to the extremely high bar of entry for QIST development – requiring specialized hardware and software and large financial investments – the sector is poised to deepen many existing societal inequalities and concentrate market power, as only a small number of countries and companies with the necessary resources can compete in this field. This could profoundly deepen technological divides and destabilize global security. Therefore, even at this early stage, it is worth considering the policy implications of QIST – who will benefit, who will lose, and what these dynamics mean for society.

Policy Issues

In the last few years, there have been several important pieces of legislation and investment in the U.S. at the federal level in QIST, and some states have tapped into federal funding to support investments in quantum. Virginia institutions have received competitive federal grants for quantum research, but the Commonwealth lags behind some other states in the region, such as Maryland, in investing in a robust quantum research ecosystem.

Congress passed the National Quantum Initiative Act in 2018, which established a coordinated national strategy to support quantum research, development, and commercialization. Actual budget expenditures on QIST between 2019 and 2021 were close to $2 billion for activities led by federal agencies, such as NIST, NSF, DOD, and NASA, in collaboration with academia and industry.[43] NIST subsequently established the Quantum

Economic Development Consortium (QED-C), a membership organization made up of private and public sector stakeholders with an interest in growing the quantum industry.

In 2019, and then again in 2020, the National Defense Authorization Act authorized the DOD to increase QIST readiness for defense, and the 2022 CHIPS and Science Act, further built on the NQI Act by instructing the Department of Energy to establish research, education, and fellowship programs focused on quantum computing, among other things.[44] There are currently five National QIS Research Centers based at national laboratories that collaborate with universities,[45] and some states are also investing in quantum hubs. Colorado, New Mexico, and Wyoming are establishing a regional hub with over $40 million in CHIPS grant funding and an additional $127 million in contributions from Colorado and New Mexico.[46]

In the mid-Atlantic region, Maryland is a quantum leader and home to an early quantum computer company, IonQ. This year, Maryland's Governor Wes Moore announced a $1 billion public-private partnership with the University of Maryland and IonQ, dubbed the "capital of quantum" initiative.[47] Academia and industry collaborate across state borders, and Virginia has benefited from these quantum investments and collaborations. The Commonwealth is home to some of the nation's leading quantum research, particularly through programs at Virginia Tech,[48] George Mason University,[49] and University of Virginia,[50] which have attracted competitive federal funding. The region also hosts a U.S. Army Cyber Command presence at Fort Meade and Fort Belvoir, the 91st Cyber Brigade of the Virginia National Guard,[51] and the Office of Naval Research, which has a Quantum Information Science program.[52] Cyber Fortress, a training and technology evaluation exercise held annually in Virginia, focuses on defending critical infrastructure and increasingly integrates emerging technologies, such as post-quantum encryption (PQE), to anticipate future cyber threats.[53]

The state has not made significant public investments in QIST, however, and although Virginia boasts strong credentials in theoretical research, in comparison, the capacity to conduct experimental research is limited. Only one company in the *Quantum Insider* 2024 list of quantum leaders – Quantum Computing Incorporated – is headquartered in Virginia.[54] Although, there are other quantum or quantum-adjacent companies with a presence in the Commonwealth, including MITRE, Boeing, Amazon, and Micron. Experts consulted during the background research for this report highlighted Virginia's particular strength in bridging basic research and quantum education, from K-12 through higher education.

While these state and federal initiatives demonstrate growing recognition of QIST's strategic importance, they represent only the first steps toward a comprehensive national quantum strategy. The landscape of quantum policy extends beyond funding and institutional frameworks to encompass a complex set of interconnected challenges that sit at the intersection of science and society. The next section turns to five specific policy issues: security and privacy, scaling AI, research and development, supply chain resilience, and workforce preparedness.

Each of these issues presents distinct opportunities and obstacles for policymakers seeking to promote ethical and responsible innovation in a frontier field.

Security and Privacy

QIST holds the potential to both dramatically enhance and endanger security and privacy at the level of the individual, organizations, and the state. One of the most commonly cited policy issues associated with QIST is the possibility of quantum computers breaking classical encryption and jeopardizing sensitive information held by individuals, governments, and corporations.[55] This capability would also threaten tools widely used by human rights defenders, activists, and citizens of authoritarian regimes, who often rely on encrypted platforms maintained by volunteers or non-profits that lack the scale of financial investment in QIST industries. Moreover, if adversarial countries achieve quantum advantage before the United States and its allies, this could threaten national security. It is worth noting that some experts think the risk to classical encryption is overstated, since quantum cryptography would require large, fault-tolerant systems that are still only possible theoretically, suggesting that widespread quantum attacks could be decades away, or even impossible.[56]

However, companies and governments are attempting to pre-empt this risk by investing in **post-quantum encryption (PQE)**, or "quantum-safe" encryption, which is built on mathematical problems believed to be too difficult for quantum computers to solve. Apple already advertises PQE for its messaging platform, iMessage,[57] and twelve companies, including Microsoft and AWS, have joined a NIST-initiated effort to migrate their protocols to PQE through a dedicated National Cybersecurity Center of Excellence program aimed at establishing and testing nationwide standards.[58]

Quantum sensing, by far the most established quantum technology in the near term, also raises a number of privacy and security issues. Because of its ability to detect the most subtle and minute changes in quantum states, quantum sensing has the potential to see through barriers, around corners, and even into the body in new ways.[59] Traditional conceptions of privacy have evolved in a world without quantum technologies, where the physical integrity of things—from buildings to bodies—serves as a protection and a legally recognized boundary against unwarranted incursions. Quantum sensing raises questions about the limitations of existing privacy laws and norms.[60] At the same time, quantum sensing holds the potential to improve the human condition by identifying life-saving faults in materials, such as bridges and roads, or by monitoring and addressing environmental changes or damage. It could also bolster national security by enhancing stealth detection and navigation tools used by the military.

Quantum communication, which uses quantum mechanics to encrypt and transmit information over long distances, introduces yet more security and privacy issues. As with previous generations of secure communication technologies, QIST could result in newly siloed communication channels, deepening the diplomatic fault lines between allies and enemies.[61] Due to the high financial threshold that this technology requires, as well as the hardware and software development needed to implement quantum communication, a stark divide could emerge between countries or companies with the resources to implement it and those without. In addition, quantum communication could make lawful surveillance harder, enabling criminals to evade law enforcement attempts to intercept or eavesdrop on conversations or transmissions. The dual-use nature of QIS technologies illustrates a need for shared norms and practices in their development and deployment so that even as the privacy and security landscape changes, privacy and security protections are upheld.

In summary:

- **Encryption:** QIST poses risks to security and privacy, particularly through the potential of quantum computing to break classical encryption, threatening sensitive data, human rights tools, and national security, though experts suggest widespread quantum attacks may be a long way off.
- **PQE:** Although encryption-breaking quantum computers do not yet exist, governments and companies are preparing for a quantum future by investing in post-quantum encryption (PQE), which is a kind of encryption based on algorithms that would be very hard for even quantum computers to break.
- **Privacy:** QIST offers dual uses that can both enhance and erode privacy and security. Quantum sensing, for instance, offers unprecedented military stealth detection capabilities alongside privacy threats, such as advanced imaging capabilities. This potential may require a shoring up of privacy norms and laws.

Scaling AI

Quantum-enhanced artificial intelligence presents another key policy issue that brings together the power and perils of QIST with those of AI. Although this application of QIST is still under development and possibly only a distant prospect, experts recognize that if quantum computers become more reliable, the application of quantum processing to machine learning will follow.[62] The fusion of quantum computing and AI illustrates the fact that quantum computing and classical computing do not exist in separate siloes. Quantum research harnesses innovative work in classical computing to achieve gains and breakthroughs, such as using AI to reduce quantum errors, and classical computing techniques, like machine learning and AI, can be bolstered by quantum capabilities.[63] So, rather than quantum superseding and replacing classical computing, the future is likely to include many quantum-augmented computing advances. There is potential for significant technological synergy: QIST could boost the existing applications of AI and realize some of its loftier promises, while AI could help bring fault-tolerant quantum computing to fruition.

As a result, QIST holds the potential to amplify the risks and opportunities of AI – a technology that already has far-reaching impacts on everyday life and is currently subject to piecemeal, and often untested, regulation globally. Among the opportunities, quantum technologies could increase the efficiency and speed of AI training, resulting in reductions in costs and environmental impacts.[64] Among the risks, however, QIST could amplify many of the known harms and vulnerabilities of AI, such as bias, hallucinations, data leakage, and more.[65]

Concerns about quantum-enhanced AI largely focus on risks of digital repression and surveillance, enabled by new powers of **data fusion** – the process of combining data from multiple sources to produce new information or insights.[66] QIST could scale AI by powering machine learning that leverages quantum properties (e.g. superposition and entanglement) to analyze high-dimensional datasets without the need to simplify, clean, or eliminate data.[67] Data fusion is already a feature of AI systems, which can process vast amounts of information, identifying patterns and making predications. Quantum-enabled data fusion could facilitate more precise pattern recognition and prediction, exacerbating many of the well-documented harms resulting from applying AI to complex social problems.

Data fusion is already at work in law enforcement technologies and social scoring systems, which evaluate individuals based on their behaviors, activities, and interactions within a social context, often using data from online platforms, social networks, or real-world interactions. The most notable example is China's social credit system.[68] Quantum-enhanced AI could supercharge predictive applications like these, possibly eroding the line between intent and action: could someone be arrested for a crime the data suggests they might commit in the future? This technological capability could also widen the gap between those with the means of conducting quantum surveillance and those who are not well equipped to challenge these practices.

Ultimately, quantum-enhanced AI faces many near- and intermediate-term challenges stemming from the fundamental hurdles in realizing reliable, error-free quantum computing. The hurdles must be surmounted before it can become a viable technology. However, the quantum industry is developing rapidly along many tracks simultaneously, including toward eventual machine learning, AI, and deep learning applications. Scaling AI with quantum technologies could heighten AI risks and profoundly deepen an existing technologically powered privacy divide in which privacy is a privilege,[69] available only to those who can afford the premium of the most advanced technological protections against data collection and data fusion.

In summary:

- **Limitations:** Quantum-enhanced AI is not imminent and would first require some significant advances in quantum computing, which currently faces formidable technical challenges.
- **Data fusion:** Data fusion refers to the integration of several different data sources to make inferences and is already a feature of classical AI. Quantum-powered AI could amplify the social risks of data fusion, exacerbating AI harms.
- **Inequalities:** The integration of QIST and AI raises concerns about digital repression, predictive policing, and social scoring systems, while potentially widening the gap between those with access to quantum surveillance tools and those unable to challenge such practices.

Research and Development

Research and development (R&D) of QIST constitutes an important policy issue because of the field is still in its early development. To date, government support has been essential to QIST R&D, given the high financial costs and associated risks. Government investment has funded basic research and helped to overcome hurdles, such as the distant horizon for commercialization and the many as-yet undetermined applications of QIST. There is an inherent tension between balancing investments in fundamental science, which is needed to achieve quantum advances, and investments in specific technology development, which offers the greatest opportunity for real-world applications and commercialization. QIST experts highlight a need for exploratory basic research in order to advance the field as a whole.[70]

Although private QIST companies do invest in basic research, the private sector is best positioned to make big bets on commercially promising technologies, and those investment choices will inevitably shape – and possibly constrain – the field. Governments have already played an important role in spurring basic, exploratory research, and this public sector investment as generally seen as essential to developing a diversified quantum industry at the cutting-edge of innovation. [71] Publicly funded research also helps to facilitate open knowledge sharing, which allows researchers to benefit and build on one another's findings.[72] When cutting edge research predominantly or wholly takes place in the private sector, knowledge sharing is often curtailed by the imperative to protect commercial IP. Further, government involvement in QIST research gives the public sector policy levers beyond regulation or legislation to encourage QIST development and incentivize responsible innovation.

In addition to public investment, international collaboration has been key to QIST breakthroughs. Like other fields of scientific research, international collaboration and global knowledge networks have powered the industry. Around half of original, peer-reviewed QIST research published by U.S. scientists between 2018 and 2022 involved international collaborators.[73] The U.S. also lacks the talent pipeline to support QIST, prompting the U.S. Subcommittee on Quantum Information Science of the National Science & Technology Council to recommend using existing international talent recruitment pathways, such as education- and skills-based visas, to attract people with high-level skills to the U.S. Developing shared global principles and practices in QIST also helps advance the field via the cross-pollination of ideas and shared norms based on transparency, rigor, and competition.[74]

Additionally, building and maintaining international collaborations in QIST helps to counteract the potential geopolitical risks of QIST development, in which new political and economic tensions over technological advances could lead to broader trade or military conflicts. Some recent collaborative efforts have included bilateral agreements with countries like Australia, Switzerland, and the UK; a roundtable launched by the National Quantum Coordination Office (NQCO); the Department of Education's QIS Research Centers, which include other countries like Canada and Italy as full partners; and other agency-level initiatives led by the NSA, NIH, and NASA, among others. International coordination around QIST has also focused on establishing standards of transparency, accountability, and ethics that aim to unite global stakeholders in a shared sense of responsibility for quantum technologies that pose many potential social, economic, and political risks.[75]

Finally, QIST R&D faces damaging cycles of hype that risk setting unrealistic market and policy expectations. The industry has proven vulnerable to overstated claims of QIST capabilities and overly optimistic roadmaps to commercialization. As a result of QIST hype, the field is at risk of falling prey to either of two extremes: a quantum race or a quantum winter. In a quantum race, QIST researchers sprint rapidly toward quantum breakthroughs in order to achieve an advantage over commercial or geopolitical competitors. At this end of the spectrum, the frantic drive to innovate and take technologies to market can lead to cutting corners on quality checks and ethical considerations. In a quantum winter, at the other end of the spectrum, investment and research stagnate because hype is followed by discouraging setbacks in research and development. Such winters slow progress toward potentially revolutionary technologies, and cycles of hype and disappointment also fuel public distrust in technology and science.[76]

The potential for these problematic outcomes, fueled by quantum hype, points to a clear need to cultivate responsible journalism, science communication, and education around QIST – in particular, involving and educating the public on key QIST concepts and policy issues. Open science has been vital to advances in QIST to date, but beyond the research community, open dialogue with the public about QIST is a key component of responsible innovation and policymaking.[77]

In summary:

- **Role of government:** The development of QIST relies heavily on government support for basic research due to high costs, uncertain applications, and long commercialization timelines.
- **International collaboration:** International collaboration has been essential for advancing QIST by addressing talent shortages and mitigating geopolitical risks through efforts establishing shared standards of transparency, ethics, and open science principles.
- **Hype cycles:** Managing cycles of hype and unrealistic expectations through responsible communication is crucial to avoiding the problematic extremes of a “quantum race” or a "quantum winter," which could lead to cutting ethical corners or stalling scientific progress, respectively.

Supply Chain Resilience

Closely related to R&D is the issue of securing a reliable supply chain for quantum technology. Emerging QIST supply chains are both specialized and highly global, relying on critical components sourced from various suppliers across the world, ranging from the materials needed for superconductors to human talent and expertise.[78] For example, QIST research is actively exploring several different ways of producing qubits for quantum computers, including using superconductors, photons, neutral atoms, and more. Each of these methods requires different materials and expertise to create and control qubits, and it is not yet clear which kind of qubit will be best for certain applications. Exploring several possible avenues of inquiry simultaneously requires a resilient supply chain that can support both basic and applied research. International cooperation has been the primary way to address these complex needs. However, dependence on international supply chains introduces risk.

In a 2022 survey of quantum computing commercial entities, 60% of respondents expected disruptions in the quantum supply chain in coming years.[79] Given the privacy and security risks posed by many QIS technologies, countries are adopting export controls to exert more influence over the availability of materials for QIST research.[80] Sweeping tariffs imposed recently by the U.S. on China and other countries have also ignited a wave of retaliatory trade restrictions that is likely to impact supply chains for specialized technology. In response to

American tariffs, China, which produces over 90 percent of the world's rare earth elements, placed prohibitive restrictions on the rare earth exports needed for many electronics, including QIS technologies.[81]

No single country today possesses all the resources needed to achieve quantum advantage or develop real-world applications for QIST. With the potential for quantum advantage to create new geopolitical tensions and instability, international collaboration has not only helped secure essential supply chains but mitigate some of these risks. Alongside developing strategies for domestic quantum supply chain resilience, the international nature of the quantum ecosystem points to a need for ongoing collaboration on trade and global norms around ethical and responsible quantum research, development, and commercialization.

In summary:

- **Vulnerabilities:** The quantum supply chain is highly susceptible to disruptions and bottlenecks because it is dependent on global trade and international talent. Many countries are exploring ways to bolster their own domestic supply chains.

- **Technical and normative innovation:** Given the global nature of QIST supply chains, there is a need to bolster domestic supply chains where possible while also continuing to collaborate internationally on trade and normative frameworks that govern the ethical and responsible development of quantum technologies.

Workforce Preparedness

QIST R&D requires specialized skills and talent, and if quantum technology begins to play a more central role in the global economy, there will be wider transformations in society with far-reaching impacts on jobs. Even at this early stage of development, there are signs of skills shortages across the quantum workforce.[82] Some of these challenges are not new, and promoting STEM education in K-12 and beyond has been a national priority for decades.[83] Cultivating the required human capital requires education and training at every level, and some QIST-focused programs are already emerging. Virginia Tech researchers run an online summer school for high school students on quantum science and have established a QIST undergraduate minor degree,[84] and last year, George Mason University received a $1.2 million NSF grant to examine how to prepare more students for the quantum workforce and prepare the next generation of quantum educators.[85] The National Q-12 Education Partnership, a collaboration among the federal government and numerous industry partners, also creates educational resources for K-12 students and makes resources available for free.[86]

In addition, QIST workforce skills go beyond traditional science and math education. QIST development will also depend on strong interpersonal and collaborative skills to maintain and expand the essential scientific collaborations that have made QIST possible up to this point. The field requires so-called "soft" skills alongside training in the scientific method, mathematics, and coding. As QIS technologies become more integrated into everyday life, there will be complex societal and ethical questions to tackle – questions that cut across a wide range of disciplines, from the humanities to the hard sciences. Other fields, such as the biomedical sciences, have benefited from such a multidisciplinary approach to research ethics, and similar efforts are underway in the field of artificial intelligence. As with these other industries, QIST would benefit from cultivating a segment of the workforce that can communicate effectively with the public. Good science communication can help mitigate cycles of hype and build public trust. Scientists, policy makers, and others will need to develop a level of fluency in QIST that renders this complex, and often seemingly obscure field, more accessible and legible to wider audiences.

Workforce resilience will depend on this multi-disciplinary and multi-dimensional approach to QIST education and training. Although QIST will not transform every job, and many QIST applications will be highly specialized, it will likely have wide-reaching, unanticipated impacts. Like the digital revolution before it, QIST may usher in an imperative for broader societal awareness and literacy and a need for multidisciplinary expertise.

In summary:

- **Education:** Addressing workforce challenges in QIST requires cultivating specialized STEM skills, starting with K-12 education and extending through higher education. In this area, Virginia is already distinguishing itself with the potential to do more.
- **Diverse skills:** Effective science communication and public engagement are essential to building trust, mitigating hype cycles, and fostering societal understanding of QIST, emphasizing the need for humanities and social science skills alongside STEM education.
- **Engaging society:** Like the digital revolution, QIST's integration into the global economy could drive transformative societal impacts, necessitating broader quantum literacy among the public and policies that foster ethical and responsible applications of QIS technologies for public benefit.

The final section of this snapshot, **policy considerations,** will offer several questions for policy makers to consider regarding the policy issues discussed above. The questions could prompt an exploration of possible policy solutions or lead to research questions for further study by the Commission.

Policy Considerations

- **Security and privacy:** Quantum technologies could expand surveillance capabilities and challenge encryption methods, necessitating a reevaluation of privacy laws and norms. The dual-use nature of QIS technologies raises important concerns about inequalities that might emerge and the tradeoffs between security and privacy.

  Key questions:

  - *Who will benefit and who will lose in the development, deployment, and commercialization of QIST? What are the likely impacts on privacy at the level of the individual, organization, or state?*
  - *What existing privacy protections already extend or could be expanded to cover QIST?*
  - *How could the Commonwealth gather information about the state of quantum preparedness across different sectors and coordinate an integrated state action plan?*
  - *How could the Commonwealth incentivize migration toward quantum-resistant encryption protocols in the public, private, and non-profit sectors?*
  - *What oversight or enforcement mechanisms might be needed to ensure that QIS technologies do not put citizens at risk?*

- **Scaling AI:** QIST could amplify the risks associated with AI, such as digital repression, surveillance, and bias, by enhancing data analysis and accelerating AI model training. As technology advances, the need for effective regulations and standards to mitigate these harms becomes more urgent.

  Key questions:

  - *What guidelines, regulations, or standards are needed to establish innovation-friendly safeguards for the development and deployment of QIST-enhanced AI?*
  - *What AI policies are needed today to prepare for a quantum future?*
  - *How are other states dealing with the potential for QIST-enhanced AI?*

- **Research and development:** QIST research and development is a national priority, requiring both public funding and private investment, along with international collaboration to set common frameworks and standards. Ensuring transparent and responsible research is crucial to avoid misuse, geopolitical tensions, and unintended consequences.

Key questions:

- *How could Virginia boost local QIST R&D, such as cultivating a robust research ecosystem that builds on existing centers/programs of excellence?*
- *What investments can/should Virginia make in QIST R&D? What opportunities for federal funding could the state pursue under a re-authorized NQI Act?*
- *What responsible innovation approaches can/should be employed in QIST? What is the role of the private and public sectors in embedding responsible R&D?*

- **Supply Chain Resilience:** The QIST supply chain is highly global, with both raw materials and talent dispersed across the world. There are many risks to the quantum supply chain, pointing to a need to both shore up domestic supply strategies and work collaboratively to develop global norms around QIST R&D.

  Key questions:

  - *What role does and should Virginia play in U.S. quantum supply chain resilience?*
  - *What analysis is needed of current supply chain dynamics?*
  - *How could Virginia contribute to collaborative norm-setting on quantum research and development, regionally and nationally?*

- **Workforce preparedness:** QIST faces challenges from talent shortages and limited coverage in STEM curricula, and may usher in future workforce transformations, such as job loss. Workforce preparedness will likely require multidisciplinary skills, public awareness and literacy, and collaboration among academia, industry, and government.

  Key questions:

  - *How can Virginia effectively forecast the evolving short- and long-term QIST workforce needs?*
  - *What specific policies or funding could help Virginia build a sustainable and adaptable domestic QIST workforce?*
  - *How could the Commonwealth support existing efforts and pilot new initiatives to train QIST educators and researchers?*
  - *How could quantum principles be incorporated into K-12 education standards?*

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