Quantum Can’t Be Business as Usual

Issues for the Reauthorization of the National Quantum Initiative Act

By Sujai Shivakumar, Charles Wessner, and Thomas Howell

Quantum technologies are at an inflection point—from research and development to practical commercial and military applications. As Freeke Heijman, cofounder of the Dutch quantum umbrella organization Quantum Delta NL, expresses it: “Given that there is a solid scientific foundation underpinning the potential of quantum technology, the question is not if it will happen but when.”

U.S. policy may be at an inflection point as well. Given that this transition will happen, is the United States taking the measures necessary to ensure it takes the lead? The question could not be timelier, particularly given the upcoming reauthorization of the National Quantum Initiative Act (NQIA). To address this potential turning point, this paper identifies policies and actions that government, academia, and industry should address right now.

From Science to Application

While it offers significant commercial opportunities, quantum computing poses new challenges for policy. To begin with, the technology is not widely understood. Quantum computing and quantum communications exemplify a field of computing, based on the principles of quantum theory, that seeks to explain the nature of matter and energy at the atomic and subatomic level. However, reflecting the lack of broad understanding of its scientific underpinnings, some promoters hail quantum computing as a font of spectacular technological breakthroughs, while others disparage it as an overhyped phenomenon that is fostering yet another investment bubble.

The initial skepticism with respect to quantum computing may reflect the fact that it is based on a number of esoteric, difficult-to-grasp concepts. For the purposes of clarity, some key notions are defined below.
• “Superposition” refers to the ability of quantum systems to exist in multiple states simultaneously.

• “Qubits” are computing units that employ superposition to encode information in two states—0 or 1—but, unlike a classical bit or switch, qubits can also be in a superposition of 0 and 1. Physical qubits can be made from different types of media, including superconductors, trapped ions, and photonic light-based processors. The computational power of a quantum computer increases exponentially (relative to a binary-based computer) with the addition of more qubits.

• “Entanglement” refers to a state in which “two or more quantum objects in a system can be intrinsically linked such that measurement of one dictates the possible measurement outcomes for another,” regardless of how far apart the two objects are in physical space. This phenomenon holds the promise of completely secure communications, for example between satellites and ground stations.

• “Decoherence” refers to the degradation of superposition and entanglement, which can occur over time as a result of qubits interacting with the environment, including temperature changes and other factors. Decoherence is perhaps the principal technical hurdle to the practical application of quantum technology.

While quantum concepts remain counterintuitive to many, they have been validated throughout the twentieth century. In October 2022, three scientists were awarded the Nobel Prize in Physics for their experimental work in superposition and quantum physics, which has “laid the foundation for a ‘new era of quantum technology’,” including quantum computing and communications.

**Bracing for New Applications**

The startling practical applications of quantum information science (QIS), including their potential military and intelligence advantages, are only beginning to become apparent, but some have already attracted the attention—and in some cases alarm—of policymakers and businesses around the world.

Notably, experts are concerned that sophisticated quantum computers could decrypt information stored on encrypted systems. A May 2022 Biden administration National Security Memorandum warns that “a quantum computer of sufficient size and sophistication . . . could jeopardize civilian and military communications, undermine supervisory and control systems for critical infrastructure, and defeat security protocols for most Internet-based financial transactions.”

Application of quantum concepts to sensors—which is the basis of atomic clocks and is close to implementation in other applications—could enhance the effectiveness of military intelligence, surveillance, and reconnaissance (ISR), enabling improved submarine detection and the detection of concealed underground structures, troop concentrations, and nuclear weapons. Ultrasensitive quantum accelerometers may be used for navigation where GPS is not available—such as underwater, underground, or in scenarios in which GPS systems fail.

Some observers believe that quantum technologies will enable dramatic advances in machine learning—a subdiscipline of AI—leading to more accurate and effective autonomous weapons systems. Quantum-based communications systems could enable secure communications impervious to covert interception by adversaries, as interception would destroy the message and could reveal the interceptor’s existence.
QIS can be used to simulate the properties of materials and to model nuclear and particle physics, and the commercial potential of these simulations is now being exploited. The Mercedes-Benz group, for example, is working with IBM to determine how QIS can simulate new materials—a development that could lead to more efficient car batteries. In addition, biomedical scientists are examining how quantum computing can help them apply algorithms and machine learning in many areas of biology, such as protein design and molecular biology.

These applications may only be the start. In October 2022, a Dutch research team disclosed that they had placed a record number (six) of silicon spin qubits on a chip, a feat that suggests it may be possible to mass-produce qubits like semiconductor chips.

**The Emerging Competitive Landscape**

Reflecting the multifaceted potential of quantum, the private sector in the United States and abroad is making major commitments to develop commercially relevant products and processes, frequently with substantial governmental support.

AWS, Google, Honeywell (through its controlling stake in Quantinuum), IBM, Cisco Systems, Microsoft, and other large U.S.-based information technology firms are building quantum computers and components. IBM unveiled a 433-qubit chip in November 2022 and plans to release a 1,121-qubit device in 2023, and over 200,000 IBM clients are already using the company’s quantum devices.

The United States is not alone. China’s Baidu has reportedly launched a 10-qubit quantum computer based on superconducting technology, and the country’s Origin Quantum sold its 24-qubit Wuyuan computer to an undisclosed buyer.

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Numerous start-ups and small- to medium-sized companies around the world are also investing in developing the equipment, components, software, and materials that will be needed to support the manufacturing of a broad range of QIS-based products.

A number of quantum computing companies are now publicly listed, including IonQ, Quantum Computing, Inc., D-Wave, and Rigetti. U.S.-based Zvyex Labs recently announced the development of an extremely precise lithography system for fabricating quantum chips, producing line-widths smaller than the deep ultraviolet and extreme ultraviolet systems currently used in semiconductor fabs. Meanwhile, an Australian firm, Silex Systems, launched a pilot facility in 2022 to demonstrate the production of ultra-purified silicon wafers supporting the fabrication of qubits. And the French start-up Quandela, with support from the government’s CEA-Leti research institute, will begin manufacturing photonic chips for application in QIS beginning in 2023.
Large information technology firms are teaming up with start-ups and smaller companies that specialize in QIS to combine the resources of the major players with the innovations of the smaller firms. In this vein, Germany’s Infineon has joined with Oxford Ionics—a UK firm developing microwave controls for qubit gate operations—a combination that leverages Infineon’s precision semiconductor manufacturing resources. Honeywell has joined with Cambridge Quantum, a UK-based quantum software firm founded in 2014, to form Quantinuum, which currently employs 370 scientists and engineers developing QIS technologies. And in October 2022, Quantinuum announced the formation of an alliance with Japan’s Mitsui & Co. Ltd. to collaborate in the delivery of quantum computing to Japan and East Asia.

Major corporations are also pursuing opportunities in QIS outside the traditional information technology realm. In 2022, HSBC paired with IBM to explore quantum computing applications in the financial services sector. Goldman Sachs is reportedly developing quantum optimization algorithms to price assets according to the risks inherent in particular types of stocks and bonds. Airbus reportedly has over 200 employees investigating QIS applications, and in August 2022, it signed a deal with the quantum computing company IonQ to explore applications of QIS in aerospace, including themes such as fuel efficiency and cargo loading.

With respect to space applications, the European Space Agency (ESA) has announced a plan for a consortium of 20 companies to launch a quantum satellite in 2024, with ground-to-space communications based on quantum key distribution (QKD) technology, exchanging encryption keys known only between shared parties. Singapore’s aerospace company SpeQtral-1 plans to launch a QKD-based satellite in 2024, in partnership with the European company Thales and with support from Singapore’s Office for Space Technology and Industry. Richard Branson’s Virgin Orbit plans five QKD satellite launches beginning in 2023, in partnership with the UK firm Arqit Quantum.

National and Regional Programs to Support the Development and Deployment of Quantum Technology

While quantum computing originated in the United States (with the work of physicist Richard Feynman and mathematician Peter Shor, among others), there is no guarantee that the United States will lead the world in this potentially revolutionary technology. U.S. government programs in this field still focus primarily on research, while governments in other countries place more emphasis on creating and supporting quantum-based industries, processes, and commercial products.

Europe in particular, which enjoys deep scientific competency, appears to be making rapid strides. In 2018, the European Union launched the Quantum Technologies Flagship initiative, committing 1 billion euros to support hundreds of quantum researchers across Europe. In addition, pursuant to the European High Performance Computing Joint Undertaking, the European Commission (EC) plans to build state-of-the-art pilot quantum computers based purely on European technology in 2023, to be located at six centers across Europe for use by industry and academia. The European Quantum Communication Infrastructure Initiative, launched in 2019, further commits all EU member states to the creation of a quantum communications infrastructure covering the entire European Union, and a number of industry consortia are pursuing various aspects of this effort.
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At the national level, the German government pledged 2 billion euros to support the development of quantum technologies in 2021. Of this total, the Ministry for Education and Research (BMBF) will administer about 1.1 billion euros through 2025 to build a competitive quantum computer in Germany and create an “associated ecosystem” for potential users. Germany’s Ministry of Economic Affairs and Climate Action (BMWK) is reportedly providing 740 million euros in support of various quantum computing projects, including the construction of a quantum cloud computing service. At the same time, a number of major German companies (including Volkswagen, Infineon, BASF, Merck, BMW, and others) have formed a consortium, the Quantum Technology and Application Consortium (QUTAO), to bring quantum computing to the level of large-scale industrial application.

The government of the United Kingdom has pledged to spend 2.5 billion pounds over the next 10 years pursuant to a new “Plan for Quantum,” more than doubling the 1 billion pounds already allocated to quantum computing in the National Quantum Technologies Programme. The nearly complete National Quantum Computing Centre in Oxfordshire will play a key role in the new plan, which will also feature distributed research hubs around the country.

Significantly, China has reportedly committed $15 billion to public investments in quantum technology—more than the rest of the world’s governments combined, although this number may be somewhat overestimated. In any event, China’s sprawling promotional effort has seen the development of a number of quantum computing prototypes based on superconducting technology, including Zhuchongzhi 2.1, a 66-qubit machine that became operational in 2021, which—according to a Chinese government source—was able to perform large-scale random quantum circuit sampling about 10 million times faster than the fastest supercomputer in operation at the time. There are also reports that Chinese research institutes are developing a quantum communications network using satellites in low- and medium-to-high-earth orbits.

In March 2023, Japan’s Riken research institute, which is largely supported by public funding, made the country’s first homegrown quantum computer available for research. A 100-qubit machine will reportedly be ready by 2025, and Fujitsu, working with Riken, hopes to debut a 1,000-qubit quantum computer in 2026. In 2021, a number of major Japanese companies, including Hitachi, Toyota, and NTT, formed the Quantum Strategic Industry Alliance for Revolution (Q-STAR) to explore new applications for quantum technology. Among other themes, Q-STAR is working with Japanese logistics companies to create quantum software that can determine the best transportation options based on cost, type of vehicle, and traveling time.

Israel’s Innovation Authority is providing $33 million to five Israeli companies to develop two quantum processors—one based on superconducting technology and one based on ion trap technology—with sizes in dozens of qubits. The five-company consortium represents the largest single project in the Innovation Authority’s history.
In sum, other nations of the world see the mastery of this technology as critical to their future economic prospects and to their national security in a challenging geopolitical context.

The U.S. Response

The U.S. government has not been inactive. It has been interested in QIS since the mid-1990s, when the National Institute of Standards and Technology (NIST) and the Department of Defense (DOD) convened workshops on the subject and over time laid out a substantial federal policy architecture for developing and exploiting U.S. capabilities in quantum computing.

Building on this, in December 2018, Congress enacted the National Quantum Initiative Act (Pub L. No. 115-368), which authorized federal agencies to establish consortia and research centers to enable QIS R&D and mandated the coordination of QIS programs across the government and in conjunction with industry and academia. Federal agencies have received progressively higher levels of budget authority for QIS activities in each fiscal year, with $877 million requested for FY 2022. Following this push, four federal QIS coordinating or advisory bodies have been established, including the Subcommittee on Quantum Information Science.

Significant quantum developmental efforts are also under way in over a dozen federal agencies, most notably at NASA, NIST, the DOD, and the Department of Energy (DOE), as well as within the intelligence community. The DOD’s QIS programs, which have been underway for many years, are implemented pursuant to the National Defense Authorization Act. In early 2023, DARPA initiated “Underexplored Systems for Utility-Scale Quantum Computing” (US2QC) to determine whether any revolutionary or underexplored approaches to quantum computing are capable of reaching utility-scale operation faster than conventional predictions.

In May 2022, President Biden signed a National Security Memorandum seeking to promote U.S. leadership in QIS to address the potential threats quantum computers could pose to U.S. encrypted systems and data. An ancillary executive order issued concurrently moved the National Quantum Initiative Advisory Committee—originally established under DOE auspices—under direct White House authority. The recently enacted CHIPS and Science Act of 2022 authorizes increased federal outlays for QIS efforts at the DOE, NIST, and the National Science Foundation (NSF).

Reflecting emerging geostrategic considerations, the Biden administration recently issued an executive order that will restrict outbound U.S. investments to China in sensitive advanced dual-use technology sectors, including quantum computing. Echoing this new U.S. stance, European Commission president Ursula von der Leyen indicated in a March 30, 2023, address that the European Union needed to rethink its relations with China and determine whether exports or investments with respect to certain strategic dual-use technologies, including quantum computing, “are in our own security interests.” The United States and the European Union have begun to coordinate with respect to quantum computing policy in the bilateral EU-U.S. Trade and Technology Council (TTC), a working group addressing digital trade issues in a geostrategic context.

Challenges for the Federal Response

Achieving Scale and Commitment: Even with the increasing attention of White House officials, substantial outlays from Congress, and the development of agency programs, there remain concerns as
to whether the federal effort is adequate in its focus and scale. While some observers draw on the historic analogies of the Manhattan and Apollo projects to capture the significance and focus of the quantum undertaking, it is worth noting that those earlier efforts had clearly defined endpoint targets. Developing quantum technologies is more akin to a race without a finish line, requiring a significant commitment of resources and national will over an undefined long term. It will also require new thinking about procurement and the education and training systems needed to buttress this extended effort.

**Focusing beyond Cryptography:** Another concern centers on whether current U.S. government thinking on QIS places too much attention on cryptography to the detriment of other major potential applications. It is important that no one application, however critical, dominate the U.S. research agenda. Still, reflecting the centrality of these concerns, in December 2022, Congress passed the Quantum Computing Cybersecurity Preparedness Act to provide a framework for the migration of U.S. government information technology systems to post-quantum cryptography.

**Revising Curricula and Training:** U.S. university physics curricula frequently do not address quantum physics and its potential applications. As one critic puts it, “rather than expose students to quantum phenomena, most physics curricula today are designed to start with the physics ABCs—riveting topics such as strings on pulleys and inclined planes.” This is starting to change as coursework on quantum topics is being introduced at institutions such as UCLA, the University of Wisconsin, and the University of Pittsburgh. Ohio recently became the first state to introduce quantum training in its K–12 science curriculum.

**Building the Quantum Workforce:** While there is no central repository of information about the landscape of the U.S. QIS workforce, an NSTC report released in February 2022 concluded from a review of available and anecdotal evidence that “there appears to be a talent shortage at all levels.”

**Attracting and Retaining Foreign Talent:** Fewer than 5 percent of U.S. doctorate degree holders in relevant fields focus on quantum science. In addition to doctoral level researchers, workers with skills in quantum hardware manufacturing and software development are in great demand. Many U.S. graduates with relevant degrees in physics and engineering are foreign nationals who are educated at leading U.S. universities and then required by the U.S. immigration system to leave the country upon graduation. To address the trained workforce challenges described here, in addition to greatly expanded programs to grow the domestic workforce, a “quantum carve-out” is needed in U.S. immigration policy—one that would enable QIS graduates to remain in the United States with a path to permanent resident status. Quantum-trained engineers are simply too rare and too valuable to be pushed out of the United States’ nascent quantum ecosystem. Similarly, it is essential that any new export controls provide a “deemed export exclusion” so that qualified foreign nationals are free to work within the U.S. industrial sector.

**Building the Domestic Skilled Talent Pipeline:** Reflecting the recent emergence of the discipline, there is a general lack of awareness within the U.S. education system of the employment opportunities available in quantum research and industry. There is also no efficient pipeline for transitioning graduates into jobs (though recently adopted best practices in semiconductor training, such as those from the National Institute for Innovation and Technology, may prove applicable). In the semiconductor industry, this challenge was successfully addressed in the 1980s through the
establishment of the Semiconductor Research Corporation (SRC), an industry-funded consortium enabling commercially relevant microelectronics research at U.S. universities, which later received government matching funds as well. Individual companies in the quantum field have already begun some programs, but the scale and scope of these efforts is currently too small. Cooperative efforts similar to the SRC, backed by government cost share for quantum-related fields, should be initiated.

**Building the Skilled Technical Workforce:** Beyond this, there are numerous positions in quantum-related fields—perhaps as much as half of the workforce—that will not need deep QIS competencies but must possess relevant skills in areas such as coding, materials science, data analysis, circuit design, optical materials, and mechanical engineering. Research centers, universities—including second- and third-tier institutions—and the best community colleges need access to quantum hardware (single-photon detectors, dilution refrigerators, cryostats, measurement equipment, etc.) to enable hands-on applied research and training. Because this equipment is expensive, there is a clear federal role in creating sharing arrangements and in serving as a first adopter for new equipment. In a promising step, the NSF now has a new organization to address the challenges in QIS and other emerging technologies, the Directorate for Technology, Innovation and Partnerships (TIP); still, the potential of this new directorate needs to be rapidly realized and its resources sustained.

**Building Partnerships:** Given that most existing federal agencies simply lack the autonomy, the culture, and the mandate necessary to pursue high-risk and high-potential research strategies, the United States may need to add a specialized and well-funded complement to DARPA’s portfolio—or perhaps even an ARPA-E type effort—as well as funding mechanisms and trials to de-risk the adoption of innovative quantum technologies by federal organizations.

Of note here is the Quantum Economic Development Consortium (QED-C), a public-private partnership that is designed and available for collaboration with any government agency that wishes to partner with the quantum business community. Established with support from the National Institute of Standards and Technology (NIST) it is a part of the federal strategy for advancing QIS, as called for by the National Quantum Initiative Act enacted in 2018.

According to recent testimony by Bob Sutor, an executive at the U.S. quantum computing products maker ColdQuanta, there is currently a shortage of federal support to help small companies transition promising QIS technologies to the stages of prototyping and scale-up production capability. **The Small Business Innovation Research program (SBIR),** while widely used by quantum firms, is regarded by some as too rigid in terms of timeframes and maximum grant sizes for it to accommodate the requirements of QIS; both those issues can and should be addressed administratively or within a similar quantum-focused system.

**Facilitating International Partnerships:** Transatlantic cooperation in the development of quantum technologies is essential for the advancement of this rapidly evolving field. With the United Kingdom, Europe, and the United States at the forefront of quantum research, cooperative efforts to pool resources, expertise, and knowledge in order to address major challenges may enable faster progress and breakthroughs in pre-competitive technologies. Collaboration between UK, EU, and U.S. companies, universities, and research institutions can not only help accelerate the development of quantum technologies but also help create a common framework for quantum standards and regulation that could
well prove crucial for transatlantic competitiveness. Concretely, there is an opportunity to enhance transatlantic collaboration by emulating initiatives like the Defense Innovation Accelerator for the North Atlantic (DIANA) to facilitate the successful industrialization of defense related quantum technologies.

**Expanding Capital:** A June 2022 study by McKinsey reported that funding for quantum-focused start-ups doubled from $700 million in 2020 to $1.4 billion in 2021. However, the same study found that more recently “the rate of new quantum start-ups coming to market globally has started to slow,” reflecting factors such as the shortage of talent and the relative immaturity of the quantum hardware sector needed to support commercial quantum applications.

Indeed, the quantum hardware makers that are necessary to support this nascent industry are frequently small, artisanal businesses that require long lead times to make small batches of equipment. Many lack the steady drumbeat of orders that would enable them to scale up to assembly-line operations, hence the importance of early public sector adopters and available early-stage finance to help firms cross the “valley of death.” Fundamentally, successful companies don’t thrive on venture capital; they thrive on customers.

Perhaps reflecting these factors, access to patient capital is cited as a bottleneck to the commercialization of quantum technologies. That challenge is linked to the long lead times that may be required to generate revenue from the sale of quantum products, lead times that do not normally mesh with the business models of venture funds.

**Finding Early Adopters—the Role of Federal Procurement:** One source of customers should be the federal government. Federal procurement of integrated circuits by NASA and the DOD in the early years of the semiconductor industry drove the industry up the learning curve in reliability and performance and drove down costs rapidly. Focused federal procurement—especially coupled with the use of Other Transaction Authority (OTA) mechanisms to speed acquisition and development—might well play a similar, powerful role in enabling the commercial introduction of quantum tools, software, materials, and systems to address national missions and help meet the growing challenge of deployment by friends and adversaries.

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**Looking Ahead**

What is clear is that the United States needs to launch a much larger, multifaceted effort to support the development of quantum-based technologies—one with substantially increased funding, backed by new or enhanced policy tools and expanded domestic and international partnerships to support early applications and accelerate research progress. With the NQIA up for reauthorization in 2023, now is the time to put in place the federal policies necessary to ensure U.S. leadership in this critical emerging technology. The competition in the quantum domain is fierce from both friends and adversaries. Delays and half measures are genuine threats to the United States’ future growth and security.
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