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Quantum Computing: Concepts, Current State, and Considerations for Congress

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SUMMARY

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Congress passed and the President signed into law the National Quantum Initiative Act (NQI Act; P.L. 115-368; codified at 15 U.S.C. §§8801 et seq.) in December 2018 to accelerate quantum research and development (R&D) for the economic and national security of the United States and ensure the continued U.S. leadership in quantum information science and its technology applications. Since the enactment of the NQI Act, researchers have made progress in quantum R&D. The authorization of funding for several federal R&D activities under the NQI Act is set to expire at the end of FY2023.

In the NQI Act, Congress defined the term *quantum information science* as “the use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information.” Quantum computing, one of technology applications of quantum information science, uses a quantum bit, or qubit, as its basic data unit, to harness quantum properties such as superposition and entanglement. By generating and manipulating qubits, a quantum computer is capable of performing certain calculations significantly faster than conventional, non-quantum computers, known as classical computers, leading to new ways to solve some complex problems that were previously unsolvable. Researchers have demonstrated the potential for quantum computing applications in areas such as cryptography, machine learning, and scientific and engineering research, particularly using modeling, optimization, and simulation.

The NQI Act is the primary federal law that supports R&D activities in quantum computing. It has been amended by the National Defense Authorization Act (NDAA) for FY2022 (P.L. 117-81) and the CHIPS and Science Act (Division B of P.L. 117-167). The current act contains four titles, directing (1) the President to implement an NQI Program with a 10-year plan to accelerate quantum R&D, invest in and coordinate fundamental federal R&D activities, and partner with industry and universities to advance goals and priorities in the NQI Program; (2) the National Institute of Standards and Technology (NIST) to carry out specified R&D activities and convene a stakeholder consortium to identify the future measurement, standards, cybersecurity, and needs for a robust quantum industry; (3) the National Science Foundation (NSF) to carry out a basic research and education program and award grants to establish Multidisciplinary Centers for Quantum Research and Education; and (4) the Department of Energy (DOE) to administer a number of programs, including a basic research program, National Quantum Information Science Research Centers, a program to accelerate innovation in quantum network infrastructure, and the Quantum User Expansion for Science and Technology program. The authorization of funding for the following activities under the NQI Act is set to expire in September 2023: NSF’s five university-based Quantum Leap Challenge Institutes, DOE’s five national lab-led research centers, and NIST’s R&D activities, including the industry-led Quantum Economic Development Consortium.

Since the enactment of the NQI Act in 2018, researchers have made notable advances in quantum computing in three areas: demonstrating that a quantum processor could execute a complex computational task much faster than a classical supercomputer in an experiment; demonstrating the mitigation of calculation errors caused by the loss of information held by qubits—a major outstanding challenge to quantum computing—in an experiment; and scaling up quantum computing processors, thus enhancing their power and potential reliability.

Some experts argue that sustained federal R&D investment is necessary to accelerate progress toward practical quantum computing and to maintain the leading role of U.S. researchers and institutions globally. There is less consensus, however, on the specific role the federal government should play in quantum R&D and how resources and support should be specifically targeted and prioritized.

Congress faces policymaking in three areas. First, Congress may decide whether and how to reauthorize or expand federal R&D activities and support under the NQI Act. Second, Congress may choose whether to set policy priorities to ensure U.S. leadership in quantum computing, including (1) accelerating the development of practical quantum computers with near-term, useful applications; (2) supporting the development of an accessible, sustainable, and secure supply chain and domestic manufacturing capabilities; and (3) facilitating the development of a quantum-literate workforce. Congress may also consider whether to set policy priorities to protect national security interests in quantum computing by addressing risks; in particular, the anticipated compromise of current cryptographic systems that protect sensitive data and communications among government agencies, financial institutions, health service providers, and others.

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This report uses one particular quantum information technology—quantum computing—to explain concepts such as quantum superposition, entanglement, and qubit, and the current state of the field, including recent technical milestones. The report also provides an overview of relevant federal laws—the NQI Act as well as quantum provisions in annual National Defense Authorization Acts (NDAAs) and the CHIPS and Science Act. Finally, the report discusses current policy issues that Congress may opt to consider: (1) reauthorizing federal R&D activities under the NQI Act; (2) ensuring continued U.S. leadership in quantum computing through accelerating near-term applications, developing a robust supply chain, and facilitating workforce development; and (3) assessing and protecting national security interests with advances in quantum computing.

Concepts of Quantum Computing

Congress has defined some key terms related to quantum computing in federal law. In the NQI Act, the term *quantum information science* means "the use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information."[1] In the Quantum Computing Cybersecurity Preparedness Act (P.L. 117-260), the term *quantum computer* means a computer that "uses the collective properties of quantum states, such as superposition, interference, and entanglement, to perform calculations."[2] In addition to these statutory definitions, reports issued under the National Quantum Initiative Program established in the NQI Act use the term *quantum information science and technology* (QIST) to refer to the understanding and applications of quantum information science to design new types of computers, networks, and sensors that "enable new speed, precision, or functionality."[3]

Specifically, quantum computing—part of the umbrella concept of QIST—is an emerging computing paradigm that harnesses the principles of quantum mechanics to represent, store, process, and transmit data.[4] In quantum computing the basic data unit is a quantum bit, or *qubit*,

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[1] 15 U.S.C. §8801(6).

[2] Section 3(9) of P.L. 117-260.

[3] National Quantum Initiative, *About the National Quantum Initiative: QIS—Quantum Information Science*, at https://www.quantum.gov/about/#QIS. See also National Quantum Initiative Advisory Committee, *Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science*, June 2023, p. 3, at https://www.quantum.gov/wp-content/uploads/2023/06/NQIAC-Report-Renewing-the-National-Quantum-Initiative.pdf.

[4] See **Appendix A** for the explanation for the terms of quantum networking and quantum sensing.

the equivalent of a *bit* in conventional, non-quantum computers (also called classical computers).[5] A quantum computer's data processing power is largely contingent upon the effective and efficient generation and manipulation of qubits.[6] Scientists have physically created and controlled qubits using superconducting materials and devices,[7] or tiny objects such as atoms, electrons, trapped ions, or photons.[8]

Unlike a classical bit that can represent only one piece of information, *either* 0 *or* 1, a qubit can represent more mathematically-rich information by being in a superposition, which can be expressed as a combination of a certain probability of being in 0 and a certain probability of being in 1.[9] Qubits can be entangled with one another, so that a quantum computer can manipulate a group of qubits in a single operation, unlike in classical computing where the same operation needs to be performed on each bit individually.[10] Computer algorithms specially designed to take advantage of these unique qubit properties of superposition and entanglement will allow quantum computers to perform multiple tasks simultaneously and certain calculations significantly faster than classical computers, leading to new ways to solve some complex problems that are intractable for classical computers at any scale (even high-performance supercomputers).[11]

In short, as the number of qubits increases linearly, the information that the qubits are capable of carrying grows exponentially. In classical computing, doubling the number of bits only doubles its computational power to handle data. See **Appendix A** for the explanation for the terms of quantum, quantum mechanics, quantum superposition, and quantum entanglement.

Resolving computationally complex problems typically requires dealing with a large number of variables that interact in complicated ways, with multiple possible and uncertain outcomes.[12] Solving these problems requires a vast amount of computing resources and is time-consuming. Examples include modeling the behavior of individual atoms in a molecule; simulating all possible interactions when two objects collide with each other; optimizing a set of routes for a fleet of vehicles to deliver packages to customers in different locations; factoring a large composite integer into a product of prime numbers in cryptographic algorithms; and identifying fraud patterns in financial transactions. Researchers have demonstrated the potential for quantum computing to solve complex problems in areas such as cryptography, machine learning, and scientific and engineering research, particularly using modeling, optimization, and simulation (e.g., for the study of quantum physics, chemistry, and material science, and for new drug

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[5] A bit, short for "binary digit," represents a binary code of either 0 or 1. Letters, numbers, symbols, images, and audio signals are encoded in combinations of bits to represent and store information in classical computers. See Injosoft AB, *ASCII Characters*, at https://www.ascii-code.com/characters.

[6] Amazon AWS, *What Is Quantum Computing*, Quantum Technologies, 2023, at https://aws.amazon.com/what-is/quantum-computing/. See also Martin Giles, "Explainer: What Is a Quantum Computer?," *MIT Technology Review*, January 29, 2019, at https://www.technologyreview.com/2019/01/29/66141/what-is-quantum-computing.

[7] Olivier Ezratty, "Perspective on Superconducting Qubit Quantum Computing," *The European Physical Journal A*, vol. 59, no. 94 (May 2023), p. 1, at https://doi.org/10.1140/epja/s10050-023-01006-7.

[8] Microsoft, *Explore Quantum: Types of Qubits*, Azure Quantum, at https://quantum.microsoft.com/en-us/explore/concepts/types-of-qubits.

[9] See Microsoft, *Explore Quantum: Superposition*, Azure Quantum, at https://quantum.microsoft.com/en-us/explore/concepts/superposition.

[10] Microsoft, *Explore Quantum: Entanglement*, Azure Quantum, at https://quantum.microsoft.com/en-us/explore/concepts/entanglement.

[11] Microsoft, *Explore Quantum: The Qubit*, Azure Quantum, at https://quantum.microsoft.com/en-us/explore/concepts/what-is-a-qubit. See also California Institute of Technology (Caltech), *What Is Quantum Computing?*, Caltech Science Exchange Series: Quantum Science and Technology, at https://scienceexchange.caltech.edu/topics/quantum-science-explained/quantum-computing-computers.

[12] IBM, *What Is Quantum Computing?*, at https://www.ibm.com/topics/quantum-computing.

development).[13] However, there are practical implementation challenges such as maintaining a qubit's superposition and correcting calculation errors (discussed in the following sub-section, "Increasing Quantum Computing Reliability"), leading to uncertainty about whether and when quantum computing could be broadly deployed and applied.

The Current State of Quantum Computing

Since the enactment of the NQI Act in 2018, researchers have made notable advances in quantum computing in three specific areas.

Demonstrating Quantum Advantage

In October 2019, a research team led by scientists from Google's quantum group reported that a quantum processor with 54 qubits took about 200 seconds to complete a specially designed computation; an equivalent computation would take a state-of-the-art classical supercomputer approximately 10,000 years. The researchers claimed that their experiment demonstrated a milestone for quantum computing—the first computational task executed much faster on a quantum processor than on a classical processor. This achievement also demonstrated so-called "quantum advantage" or "quantum speedup" over classical computing.

In April 2023, another research team led by the same Google group reported that a second generation of its quantum processor, with 70 qubits, performed a more complex task than the one reported in 2019. According to the researchers' estimate, the same task would take about 47 years for the Frontier supercomputer at Oak Ridge National Laboratory—the fastest classical computing system in the world at the time.[14] The researchers claimed that such a computational task was beyond the capabilities of many existing classical supercomputers.[15]

Despite these successes, some experts argue that researchers have thus far only demonstrated quantum advantage over classical computers in solving mathematical proofs and that quantum advantage may not have practical value beyond academic research.[16]

Increasing Quantum Computing Reliability

To make quantum computing broadly applicable in solving practical problems, researchers have recognized the need for technical advances to increase the reliability of quantum computers.[17] Many researchers agree that a major outstanding challenge to quantum computing is "noise,"

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[13] Michael Brooks, "Quantum Computers: What Are They Good For?," *Nature*, vol. 617 (May 2023), pp. S1-S3, at https://doi.org/10.1038/d41586-023-01692-9.

[14] Alexis Morvan et al., "Phase Transition in Random Circuit Sampling," *arXiv*, 2304.11119 (April 2023), p. 5, at https://doi.org/10.48550/arXiv.2304.11119. Frontier remained the fastest classical computing system in the world as of June 2023. See Top500, "TOP500," 61st edition, June 2023, at https://www.top500.org/lists/top500/2023/06/.

[15] Alexis Morvan et al., "Phase Transition in Random Circuit Sampling," *arXiv*, 2304.11119 (April 2023), p. 1, at https://doi.org/10.48550/arXiv.2304.11119.

[16] Michael Brooks, "Quantum Computers: What Are They Good For?," *Nature*, vol. 617 (May 2023), pp. S1-S3, at https://doi.org/10.1038/d41586-023-01692-9. See also Matt Swayne, "Google Claims Latest Quantum Experiment Would Take Decades on Classical Computer," *The Quantum Insider*, July 4, 2023, at https://thequantuminsider.com/2023/07/04/google-claims-latest-quantum-experiment-would-take-decades-on-classical-computer/.

[17] Frank Arute et al., "Quantum Supremacy Using a Programmable Superconducting Processor," *Nature*, vol. 574 (October 2019), pp. 505–510, at https://doi.org/10.1038/s41586-019-1666-5.

which can affect the accuracy of calculations made by a quantum computer.[18] Noise refers to 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.[19] Qubits are highly susceptible to noise, which can cause the loss of information it holds.[20] Error rates are generally higher in quantum computers than in classical computers.[21]

Noise introduces errors in quantum calculations that are difficult to correct[22] and limits the number of qubits a quantum computer can have.[23] Solutions to this challenge include developing fault-tolerant quantum processors or running fully error-corrected quantum algorithms. Both approaches require at least tens of thousands of qubits,[24] well beyond the capacity of current quantum processors.[25]

Some promising recent research results point to the possible development of techniques that may help reduce error and increase reliability. In June 2023, a team led by IBM quantum researchers presented the results of an experiment to "controllably manipulate" quantum noise, demonstrating success in an experimental setting.[26] Google's quantum research group reported in February 2023 that its researchers were able to demonstrate that increasing the number of qubits can lower the error rate of calculations in a quantum computer.[27] The researchers admitted that the improvement on the error rate in their experiment was still small, and error rates needs to drop much more to realize the potential of solving problems beyond the reach of classical computers.[28] Some experts argue that progress so far has mitigated, but not fully corrected, calculation errors, and only full quantum error correction can truly enable reliable quantum computing.[29]

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[18] Youngseok Kim et al., "Evidence for the Utility of Quantum Computing Before Fault Tolerance," *Nature*, vol. 618 (June 2023), pp. 500–505, at https://doi.org/10.1038/s41586-023-06096-3.

[19] Juan Moreno, Grant Salton, and Tim Chen, *Noise in Quantum Computing*, AWS Quantum Technologies Blog, September 8, 2022, at https://aws.amazon.com/blogs/quantum-computing/noise-in-quantum-computing/. See also Adam Zewe, *A Technique for Making Quantum Computing More Resilient to Noise, Which Boosts Performance*, Science X, March 22, 2022, at https://phys.org/news/2022-03-technique-quantum-resilient-noise-boosts.html.

[20] Adrian Cho, "No Room for Error," *Science*, July 9, 2020, at https://www.science.org/content/article/biggest-flipping-challenge-quantum-computing.

[21] Adam Zewe, *A Technique for Making Quantum Computing More Resilient to Noise, Which Boosts Performance*, Science X, March 22, 2022, at https://phys.org/news/2022-03-technique-quantum-resilient-noise-boosts.html.

[22] David Castelvecchi, "IBM Quantum Computer Passes Calculation Milestone," *Nature*, vol. 618 (June 2023), pp. 656-657, at https://doi.org/10.1038/d41586-023-01965-3.

[23] Michael Brooks, "Beyond Quantum Supremacy: The Hunt for Useful Quantum Computers," *Nature*, vol. 574 (October 2019), pp. 19-21, at https://doi.org/10.1038/d41586-019-02936-3.

[24] David Castelvecchi, "IBM Quantum Computer Passes Calculation Milestone," *Nature*, vol. 618 (June 2023), pp. 656-657, at https://doi.org/10.1038/d41586-023-01965-3.

[25] Youngseok Kim et al., "Evidence for the Utility of Quantum Computing Before Fault Tolerance," *Nature*, vol. 618 (June 2023), pp. 500–505, at https://doi.org/10.1038/s41586-023-06096-3.

[26] Ibid.

[27] Google Quantum AI, "Suppressing Quantum Errors by Scaling a Surface Code Logical Qubit," *Nature*, vol. 614 (February 2023), pp. 676-681, at https://doi.org/10.1038/s41586-022-05434-1.

[28] Davide Castelvecchi, "Google's Quantum Computer Hits Key Milestone by Reducing Errors," *Nature*, February 22, 2023, at https://doi.org/10.1038/d41586-023-00536-w.

[29] David Castelvecchi, "IBM Quantum Computer Passes Calculation Milestone," *Nature*, vol. 618 (June 2023), pp. 656-657, at https://doi.org/10.1038/d41586-023-01965-3.

Achieving Quantum Advantage for Practical Problems

Some experts have suggested focusing on the development of quantum computers that provide practical quantum advantage, beyond simulating and testing quantum hardware.[30] Practical quantum advantage means using quantum computers to reliably tackle useful, real-world problems that leading classical supercomputers cannot address. It will require a large-scale quantum computer with thousands, hundreds of thousands, or even millions of qubits, depending on factors such as the type of problem, the algorithm, and the architecture of the quantum hardware.[31] Quantum processors at this scale do not yet exist.

To achieve practical quantum advantage, leading industry players have set their R&D roadmaps to scale up quantum processors with qubits. In November 2022, IBM announced a 433-qubit processor based on superconducting technology.[32] The company claimed that it was on track to deliver a 1,000-qubit processor by the end of 2023.[33] In May 2023, IBM launched a $100 million partnership with the University of Tokyo and the University of Chicago, aiming to develop a quantum supercomputer by 2033 powered by 100,000 qubits,[34] which it predicts will allow the supercomputer to perform some useful tasks with practical quantum advantage.[35]

Researchers at Google believe that scaling up qubits also helps to improve quantum error correction—the required feature of general-purpose quantum computers.[36] Google is reportedly working toward a 1,000-qubit processor and expects to achieve this milestone as early as 2025.[37] It hopes to demonstrate a useful, error-corrected quantum computer with one million qubits within a decade.[38]

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[30] Andrew J. Daley et al., "Practical Quantum Advantage in Quantum Simulation," *Nature*, vol. 607 (July 2022), pp. 667-676, at https://doi.org/10.1038/s41586-022-04940-6. See also John Preskill, "Quantum Computing in the NISQ Era and Beyond," *Quantum*, vol. 2 (July 2018), pp. 79-99, at https://doi.org/10.22331/q-2018-08-06-79.

[31] John Preskill, "Quantum Computing in the NISQ Era and Beyond," *Quantum*, vol. 2 (July 2018), pp. 79-99, at https://doi.org/10.22331/q-2018-08-06-79; Michael E. Beverland et al., "Assessing Requirements to Scale to Practical Quantum Advantage," *arXiv*, 2211.07629 (November 2022), at https://doi.org/10.48550/arXiv.2211.07629; Craig Gidney and Martin Ekerå, "How to Factor 2048 Bit RSA Integers in 8 Hours Using 20 Million Noisy Qubits," *Quantum*, vol. 5 (April 2021), pp. 433-464, at https://doi.org/10.22331/q-2021-04-15-433; and Google, "Our Focused and Responsible Approach to Quantum Computing," at https://ai.google/static/documents/approach-quantum-computing.pdf.

[32] IBM, "IBM Unveils 400 Qubit-Plus Quantum Processor and Next-Generation IBM Quantum System Two," November 9, 2022, at https://newsroom.ibm.com/2022-11-09-IBM-Unveils-400-Qubit-Plus-Quantum-Processor-and-Next-Generation-IBM-Quantum-System-Two.

[33] IBM, "The IBM Quantum Development Roadmap," 2022, at https://www.ibm.com/quantum/roadmap.

[34] IBM, "IBM Launches $100 Million Partnership with Global Universities to Develop Novel Technologies Towards a 100,000-Qubit Quantum-Centric Supercomputer," May 21, 2023, at https://newsroom.ibm.com/2023-05-21-IBM-Launches-100-Million-Partnership-with-Global-Universities-to-Develop-Novel-Technologies-Towards-a-100,000-Qubit-Quantum-Centric-Supercomputer.

[35] Jay Gambetta and Matthias Steffen, "Charting the Course to 100,000 Qubits," *IBM Research Blog*, May 21, 2023, at https://research.ibm.com/blog/100k-qubit-supercomputer.

[36] Google Quantum AI, "Suppressing Quantum Errors by Scaling a Surface Code Logical Qubit," *Nature*, vol. 614 (February 2023), pp. 676-681, at https://doi.org/10.1038/s41586-022-05434-1. See also Sankar Das Sarma, "Quantum Computing Has a Hype Problem," *MIT Technology Review*, March 28, 2022, at https://www.technologyreview.com/2022/03/28/1048355/quantum-computing-has-a-hype-problem/.

[37] Google, "Our Focused and Responsible Approach to Quantum Computing," at https://ai.google/static/documents/approach-quantum-computing.pdf.

[38] Google Quantum AI, "Our Quantum Computing Journey," at https://quantumai.google/learn/map.

Federal Law Concerning Quantum Computing

Since the NQI Act was enacted in December 2018,[39] it has been amended by the National Defense Authorization Act (NDAA) for FY2022 (P.L. 117-81) and the CHIPS and Science Act (Division B of P.L. 117-167).[40] In addition to these amendments, the CHIPS and Science Act, the American COMPETES Act (Title XV of P.L. 116-260), and the NDAAs for FY2019 (P.L. 115-232), FY2020 (P.L. 116-92), FY2021 (P.L. 116-283), FY2022 (P.L. 117-81), and FY2023 (P.L. 117-263) contain other provisions pertinent to R&D activities in quantum computing. This section summarizes highlights of those provisions.

Highlights of Federal Laws Concerning Quantum Computing

NQI Act, as amended

The act contains four titles, directing

- the President to implement an NQI Program to develop a 10-year plan to accelerate development of quantum information science and technology applications, invest in fundamental federal R&D activities and quantum workforce, coordinate federal R&D activities, partner with industry and universities, and leverage existing federal investments to advance goals and priorities set in the NQI Program;[41]
- the National Institute of Standards and Technology (NIST) to carry out specified R&D activities and convene a consortium of stakeholders to identify the future measurement, standards, cybersecurity, and needs for a robust quantum information science and technology industry;[42]
- the National Science Foundation (NSF) to carry out a basic research and education program on quantum information science and engineering and award grants to establish Multidisciplinary Centers for Quantum Research and Education;[43] and
- the Department of Energy (DOE) to administer a number of programs, including a basic research program on quantum information science, National Quantum Information Science Research Centers, an R&D program to accelerate innovation in quantum network infrastructure, and the Quantum User Expansion for Science and Technology (QUEST) program.[44]

CHIPS and Science Act

In addition to amendments to the NQI Act, the act contains the following provisions:

- DOE shall establish an Advanced Computing Program, in which DOE shall maintain foundational research programs, including on quantum computing.[45] In addition, DOE shall support the Computational Science Graduate Fellowship program to facilitate collaboration between graduate students and researchers at the National Laboratories and the development of a diverse and inclusive computational research workforce in a range of relevant areas, including quantum computing.[46]
- NSF shall continue the Federal Cyber Scholarship-for-Service Program that provides scholarships to students who pursue degrees or certifications in relevant fields, including quantum computing.[47] In addition, NSF shall annually update a list of key technology focus areas to guide activities conducted by the newly established

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[39] For more background information of the NQI Act, see CRS Report R45409, *Quantum Information Science: Applications, Global Research and Development, and Policy Considerations*, by Patricia Moloney Figliola.

[40] Division B of P.L. 117-167 has been commonly referred to as the CHIPS and Science Act, while it may also be cited as the "Research and Development, Competition, and Innovation Act" (Section 10001 of P.L. 117-167).

[41] 15 U.S.C. §8811.

[42] 15 U.S.C. §8831.

[43] 15 U.S.C. §§8841, 8842.

[44] 15 U.S.C. §§8851-8854.

[45] 42 U.S.C. §18642(e)(1)(A).

[46] 42 U.S.C. §18642(j)(1).

[47] 15 U.S.C. §7442(b)(1).

NSF Directorate for Technology, Innovation, and Partnerships (TIP); the initial list identified by Congress included "quantum information science and technology."[48]

American COMPETES Act

The Department of Commerce and Federal Trade Commission shall (1) complete a study on the state of the quantum computing industry and its impact on the U.S. economy; (2) conduct a survey of the marketplace and supply chain of quantum computing; and (3) submit to Congress a report that contains results of the study and survey and policy recommendations regarding quantum computing.[49]

Title XLI "Federal Permitting Improvement" of the FAST Act, as amended

Federal agencies shall improve the federal permitting process for a covered project that requires federal authorization or environmental review involving construction of infrastructure for relevant activities, including R&D in quantum information science and technology.[50]

Section 2 of the Export-Import Bank Act of 1945, as amended

The Export-Import Bank of the United States shall establish a Program on China and Transformational Exports to support the extension of loans, guarantees, and insurance with competitive rates, terms, and other conditions compared with those established by China or a covered country to advance U.S. leadership or support U.S. innovation, employment, and technological standards through direct exports in transformational areas, including quantum computing.[51]

James M. Inhofe NDAA for FY2023

- The Department of Defense (DOD) shall submit to Congress a plan for investments to support the development of novel processing approaches for defense applications; the term *novel processing approaches* means emerging computational techniques, including "utility scale quantum computing," and associated algorithm and hardware development needed to implement such techniques.[52]
- NSF shall made awards to support research, including "the implications of quantum computing on applications of distributed ledger technologies, including long-term protection of sensitive information (such as medical or digital property)."[53]
- The Director of National Intelligence shall develop a plan, including an assessment to support engineering, research, and development at covered higher education institutions in computer science, including quantum computing.[54]
- Congress authorized an appropriation of $20 million for the DOD Applied Research program on the "trapped ion quantum computer."[55]

NDAA for FY2022

In addition to amendments to the NQI Act, the act contains the following provisions:

- DOD shall establish a set of activities and an assistance program to accelerate the development and deployment of dual-use quantum technologies.[56]
- Congress authorized an appropriation of $100 million for the DOD Research, Development, Test, and Evaluation program for "quantum computing acceleration."[57]

William M. (Mac) Thornberry NDAA for FY2021

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[48] 47 U.S.C. §19107(a), (c)(3).

[49] Section 1501(d) of the Consolidated Appropriations Act, 2021 (P.L. 116-260).

[50] 42 U.S.C. §4370m(6)(A), as amended by P.L. 117-173.

[51] 12 U.S.C. §635(l)(1)(B)(v), as amended by Section 402(a) of the Further Consolidated Appropriations Act, 2020 (P.L. 116-94).

[52] Section 233(a) and (d) of the James M. Inhofe NDAA for FY2023 (P.L. 117-263).

[53] Section 5913(c)(1)(D) of the James M. Inhofe NDAA for FY2023 (P.L. 117-263).

[54] Section 6812(a)(1), (2)(A) of the James M. Inhofe NDAA for FY2023 (P.L. 117-263).

[55] Line 014 in Section 4201 of the James M. Inhofe NDAA for FY2023 (P.L. 117-263).

[56] Section 229 of the NDAA for FY2022 (P.L. 117-81). The term *dual-use* means products, services, standards, processes, or acquisition practices, respectively, that are capable of meeting requirements for military and nonmilitary applications (10 U.S.C. §4801(2)).

[57] Line 015 in Section 4201 of the NDAA for FY2022 (P.L. 117-81).

- Each military department shall annually identify a list of technical problems and research challenges that are likely to be addressable by quantum computers available for use within the next one to three years; and establish programs and enter contracts to provide functional quantum computing capabilities available in private sectors to government, industry, and academic researchers.[58]
- DOD shall assess threats and risks posed by quantum computing technologies to critical national security systems and develop recommendations for securing these systems against quantum computing code-breaking capabilities.[59]
- The National Nuclear Security Administration shall commission the National Academy of Sciences to review the future of computing to meet national security needs; the review shall include quantum computing architectures and hybrid combinations of classical and quantum computing architectures.[60]

NDAA for FY2020

- Each military department shall establish or designate a defense laboratory to engage with public and private sector organizations to enhance and accelerate the R&D and deployment of quantum information sciences, technologies, and systems.[61]
- DOD shall establish a process to ensure that DOD policies relating to emerging technology, including quantum computing, are formulated and updated as such technology is developed by DOD.[62]

John S. McCain NDAA for FY2019

DOD shall establish the Defense Quantum Information Science and Technology Research and Development Program.[63]

Federal R&D Investments in Quantum Information Science and Technology

Actual budget expenditures for federal QIST R&D activities at federal agencies totaled nearly $2 billion between FY2019-FY2021, or an average of $667 million per fiscal year.[64] These expenditures supported R&D activities conducted by NIST, NSF, DOE, DOD, the Department of Homeland Security (DHS), and the National Aeronautics and Space Administration (NASA).[65] These agencies reported an enacted budget authority of $918 million for FY2022 for QIST R&D activities, and a requested budget authority of $844 million for FY2023.[66] A large portion of the budget expenditures and budget authorities are for activities authorized in the NQI Act, as shown in **Table 1**.

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[58] Section 214 of the William M. (Mac) Thornberry NDAA for FY2021 (P.L. 116-283).

[59] Section 1722(a) of the William M. (Mac) Thornberry NDAA for FY2021 (P.L. 116-283).

[60] Section 3172(a), (b)(2)(B) and (C) of the William M. (Mac) Thornberry NDAA for FY2021 (P.L. 116-283).

[61] Section 220(4) of the NDAA for FY2020 (P.L. 116-92).

[62] Section 232(a), (d)(2) of the NDAA for FY2020 (P.L. 116-92).

[63] Section 234 of the John S. McCain NDAA for FY2019 (P.L. 115-232).

[64] National Science and Technology Council, Committee on Science, Subcommittee on Quantum Information Science, *National Quantum Initiative Supplement to the President's FY2023 Budget*, January 2023, p. 3, at https://www.quantum.gov/wp-content/uploads/2023/01/NQI-Annual-Report-FY2023.pdf.

[65] Ibid., p. 6.

[66] Ibid., p. 3. The *National Quantum Initiative Supplement to the President's FY2023 Budget* also listed quantum activities at the Intelligence Advanced Research Projects Activity and National Security Agency, but did not appear to include them in the budget authority figures presented above.

Table 1. R&D Activities Authorized in the NQI Act, as Amended

Agency	Funded Activities	Total Authorized Amount	Statutory Reference
For FY2019-FY2023			
NIST	(1) To conduct authorized R&D activities under the NQI Program, including to support and expand basic and applied R&D; train scientists; carry out research for the development and standardization of quantum cryptography, networking, communications, and sensing and their applications; provide technical assistance to other agencies for the development of quantum networking standards; and establish collaborations with public and private sector entities. (2) To convene a stakeholder consortium to identify needs for a robust QIST industry.[a]	Up to $400 million from appropriations for NIST	15 U.S.C. §8831
NSF	To award grants to establish up to five Multidisciplinary Centers for Quantum Research and Education to conduct basic research and education activities, including advancing quantum information science and engineering, supporting curriculum and workforce development, and fostering innovation by bringing industry perspectives.[b]	Up to $250 million from appropriations for NSF	15 U.S.C. §8842
DOE	To establish and operate up to five National Quantum Information Science Research Centers to conduct basic research to accelerate scientific breakthroughs in QIST and support DOE's quantum information science basic research program.[c]	Up to $625 million from appropriations for DOE	15 U.S.C. §8852
For FY2023-FY2027			
DOE	To carry out an R&D program to accelerate innovation in quantum network infrastructure—any facility, expertise, or capability that enables the development and deployment of scalable and diverse quantum network technologies.	$500 million from authorized appropriations for DOE's Office of Science	15 U.S.C. §8853
DOE	To establish and carry out the Quantum User Expansion for Science and Technology Program (QUEST program) to facilitate access to quantum computing hardware and clouds in the United States for research purposes.	$165.8 million from authorized appropriations for DOE's Office of Science	15 U.S.C. §8854

Source: The NQI Act, as amended (P.L. 115-368; codified at 15 U.S.C. §§8801 et seq.).

Notes:

a. In September 2018, NIST signed a cooperative R&D agreement with SRI International to lead the "Quantum Economic Development Consortium" (QED-C), with a goal of expanding U.S. leadership in global quantum R&D and the emerging industry in quantum computing, networking, and sensing. For the list of QED-C members, see https://quantumconsortium.org/members/.

b. See **Table B-1** in **Appendix B** for the list of five NQI Act-funded NSF quantum research and education centers, called Quantum Leap Challenge Institutes (QLCI).

c. See **Table B-2** in **Appendix B** for the list of five NQI Act-funded DOE national quantum information science research centers.

Policy Considerations for Congress

Congress may be interested in considering policy issues surrounding the reauthorization of funding for several R&D activities under the NQI Act, which is set to expire at the end of

FY2023. The funded programs and activities include NSF's five university-based Quantum Leap Challenge Institutes, DOE's five national lab-led research centers, and NIST's R&D activities such as the industry-led Quantum Economic Development Consortium (QED-C) (see **Table 1**, **Table B-1**, and **Table B-2**).

Many experts contend that sustained federal investment in QIST R&D generally is necessary to accelerate progress toward practical quantum computing and to maintain a leading role of U.S. researchers in quantum computing R&D globally.[67] There is less consensus, however, on the specific role the federal government should play, if any, in QIST R&D and how resources and support should be specifically targeted and prioritized to accelerate R&D in the field. Areas for possible congressional action include the following:

Reauthorizing Federal R&D Activities Under the NQI Act

When contemplating reauthorization, Congress may wish to consider the following options:

1. Whether to reauthorize and continue funding the existing NSF and DOE research and education centers and NIST activities, perhaps for a duration aligned with the sunset date of December 21, 2029, when the authority to carry out the National Quantum Initiative in the NQI Act expires.[68]
2. Whether to increase the number of centers that NSF and DOE are authorized to support. The current maximum number is five for each agency.[69]
3. Whether the current model of supporting national-level, large-scale centers is sustainable and effective to deliver practical quantum computers; whether to broaden federal support to include other research and education institutions, startups, small and medium-sized R&D enterprises, and individual principal investigators; and whether to widen the focus of support from basic to applied science and engineering research focused on making and testing scalable quantum systems and developing quantum software.[70]
4. Whether to expand the NQI Act-authorized activities conducted by NIST, NSF, and DOE to include other agencies, such as NASA, DHS, the National Institutes of Health (NIH), and the National Telecommunications and Information Administration (NTIA).
5. Whether to prioritize particular aspects of quantum computing, networking, sensing, and their applications. While quantum computing is the most anticipated and most challenging quantum technology, quantum networking—which may be implementable for some near-term applications—has important implications for the development of advanced information infrastructure, where the United States faces substantial competition from other countries such as China.[71]

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[67] See Testimony of Charles Tahan, Assistant Director of Quantum Information Science and Director of the National Quantum Coordination Office, the White House Office of Science and Technology Policy, in U.S. Congress, House Committee on Science, Space, and Technology, *Advancing American Leadership in Quantum Technology*, hearings, 118th Cong., 1st sess., June 7, 2023.

[68] See 15 U.S.C. §8815(a).

[69] See 15 U.S.C. §§8842(a), 8852(a)(1).

[70] See National Quantum Initiative Advisory Committee, *Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science*, June 2023, p. 10, at https://www.quantum.gov/wp-content/uploads/2023/06/NQIAC-Report-Renewing-the-National-Quantum-Initiative.pdf.

[71] See Testimony of Celia Merzbacher, Executive Director of QED-C, SRI International, in U.S. Congress, House (continued...)

6. Whether to encourage and provide oversight of quantum R&D collaboration and coordination among federal agencies, national laboratories, academia, industry, and entities in allied countries. For example, a bipartisan bill introduced in the 118th Congress, S. 2450, would amend the NQI Act to "ensure the coordination, and avoid unnecessary duplication," of DOE and NSF activities authorized under the NQI Act. It would also direct QED-C to conduct a study of the impediments to collaboration between NSF research and education centers, DOE research centers, industry, and academia.[72]
7. Whether to direct any agency that conducts authorized and funded R&D activities to report its progress to Congress at some regular interval.[73] Among the current authorized activities established in the NQI Act, there is one statutory reporting requirement: NIST shall submit a report to congressional oversight committees summarizing QED-C findings.[74]

Ensuring Continued U.S. Leadership in Quantum Computing

As discussed in the section "The Current State of Quantum Computing," researchers in the United States, many supported by federal programs, have made substantial progress in quantum computing R&D since the enactment of the NQI Act. This has helped establish U.S. leadership in this still nascent but promising field. To ensure and strengthen U.S. leadership, Congress may wish to consider three policy priorities when addressing quantum computing.

Accelerating the Development of Practical Quantum Computers with Near-Term Applications

The current global competition in quantum computing is essentially a race to achieve practical quantum advantage and solve practical problems. This requires breakthroughs in quantum error correction and scaled-up quantum processors with a larger number of qubits.

A bipartisan bill in the 118th Congress, the Quantum Sandbox for Near-Term Applications Act of 2023 (S. 1439/H.R. 2739), would amend the NQI Act by directing the Department of Commerce (DOC), in coordination with NIST, to establish a public-private partnership "focused on quantum computing application development acceleration for quantum, quantum communication, quantum sensing, and quantum-hybrid computing near-term use cases."[75] To carry out this mandate, the bill says DOC should, acting through NIST, engage with QED-C, national laboratories, federally funded R&D centers, and other members of the U.S. quantum computing ecosystem.[76]

Another bill, the Leveraging Quantum Computing Act (H.R. 3987), would engage federal agencies "to identify potential use cases with respect to which quantum computing could advance

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Committee on Science, Space, and Technology, *Advancing American Leadership in Quantum Technology*, hearings, 118th Cong., 1st sess., June 7, 2023.

[72] Sections 1(a) and 3(b) of S. 2450, 118th Congress. Other bills that would provide for interagency R&D coordination in quantum computing include H.R. 2980 and H.R. 2988 in the 118th Congress.

[73] Some Members of Congress have also called for an independent study to assess the progress made by the NQI Program, "with respect to quantum sensing, communications, computing, and workforce development for near-term development and quantum applications." See Section 3(a)(2) of S. 2450, 118th Congress.

[74] 15 U.S.C. §8831(b)(3).

[75] The term *near-term use case* means an application that can be developed and deployed in less than 24 months. Section 405 of S. 1439/H.R. 2739, 118th Congress.

[76] Section 405 of S. 1439/H.R. 2739, 118th Congress.

the missions of such agencies, including through on-premises, cloud-based, hybrid, or networked approaches."[77]

Additionally, Congress may wish to consider targeting federal support toward specific priorities. To accelerate near-term applications of quantum computing, an option could be to direct federal agencies to support the development and testing of quantum algorithms and fault-tolerant quantum processors, and the development of computer networks to allow researchers and developers to access quantum computing resources through cloud computing services.

Supporting the Development of a Quantum Supply Chain

To build quantum computers at scale, industry has identified the strategic priority of developing an accessible, sustainable, and secure supply chain and independent manufacturing capabilities that can foster a healthy and stable quantum computing ecosystem. According to an industry survey commissioned by QED-C in June 2022, "key raw materials" and "key manufacturing/assembly equipment" were thought to be the top two "most likely causes of a [quantum computing] supply chain interruption in the next three years."[78]

Quantum computing technologies are not mature enough to provide certain and sufficient market demand to have an established and extant supply chain.[79] Different approaches to the physical implementation of quantum computing may lead to a variety of, as yet unknown, mineral, material, and equipment requirements,[80] some of which may be under the control of non-allied countries.[81]

To address these issues, S. 2450 would direct DOC, through NIST and in consultation with DOE, to (1) determine the manufacturing capabilities to produce reliable quantum components and systems at scale and the gaps in access to such capabilities; and (2) establish a Manufacturing USA institute that provides an end-to-end manufacturing ecosystem addressing quantum computing, sensing, and networking and supports the development of a resilient quantum supply chain.[82]

Other options for Congress could include the following:

- Directing a federal agency or body, such as the National Quantum Coordination Office, to study and report on the global quantum computing supply chain and identify risks and security concerns.
- Establishing proactive policies to avoid similar supply chain and manufacturing issues faced by the classical computer chip industry. These may include directing

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[77] Section 2(a) of H.R. 3987, 118th Congress.

[78] Bob Sorensen and Tom Sorensen, *Special Analysis: Challenges and Opportunities for Securing a Robust U.S. Quantum Computing Supply Chain*, Hyperion Research, LLC, HR4.0024.04.15.2022, June 2022, p. 7, at https://quantumconsortium.org/mp-files/qed-c-special-analysis-us-quantum-computing-supply-chain-issues.pdf/.

[79] National Quantum Initiative Advisory Committee, *Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science*, June 2023, p. 7, at https://www.quantum.gov/wp-content/uploads/2023/06/NQIAC-Report-Renewing-the-National-Quantum-Initiative.pdf.

[80] Bob Sorensen and Tom Sorensen, *Special Analysis: Challenges and Opportunities for Securing a Robust U.S. Quantum Computing Supply Chain*, Hyperion Research, LLC, HR4.0024.04.15.2022, June 2022, p. 1, at https://quantumconsortium.org/mp-files/qed-c-special-analysis-us-quantum-computing-supply-chain-issues.pdf/.

[81] National Quantum Initiative Advisory Committee, *Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science*, June 2023, p. 15, at https://www.quantum.gov/wp-content/uploads/2023/06/NQIAC-Report-Renewing-the-National-Quantum-Initiative.pdf.

[82] Section 2(b) of S. 2450, 118th Congress. For more information on Manufacturing USA institutes, see CRS Report R46703, *Manufacturing USA: Advanced Manufacturing Institutes and Network*, by John F. Sargent Jr.

and funding federal agencies to support material science and computer engineering research dedicated to developing additional domestic quantum computing capacity, and to programs that support the establishment and maintenance of domestic quantum manufacturing capabilities.

- Imposing export controls for critical quantum computing materials and components.

Facilitating Workforce Development for Quantum Computing

Many experts maintain that training, recruiting, and retaining talent are important for sustaining U.S. leadership in quantum computing hardware and software R&D.[83] The National Science and Technology Council Subcommittee on Quantum Information Science has recommended four strategic actions: (1) understanding the workforce needs in the QIST ecosystem; (2) introducing broader audiences to QIST through public outreach; (3) enhancing QIST-specific education and training opportunities; and (4) making careers in QIST and related fields more accessible and equitable.[84] In the abovementioned QED-C industry survey, respondents identified a potential skilled workforce shortage in the United States in optical, mechanical, and electronics engineers, and software developers.[85]

In the CHIPS and Science Act, Congress has authorized $8 million per year for FY2023-FY2026 for NSF to carry out QIST workforce development activities, including (1) commissioning the National Academies of Sciences, Engineering, and Medicine to conduct a study to evaluate and make recommendations for the workforce; and (2) making awards to carry out the Next Generation Quantum Leaders Pilot Program to educate and train K-12 students and teachers in the fundamental principles of quantum mechanics.[86]

Congress may wish to consider policies to encourage domestic high school and college students to participate in related STEM (science, technology, engineering, and mathematics) education courses and programs that are foundational to QIST.[87] Quantum computing relies upon knowledge and research in a number of disciplines (e.g., quantum physics, mathematics, chemistry, electrical engineering, software engineering, bioengineering, computer science and engineering, and information science, among others). Courses and curricula in relevant fields may help develop a quantum-literate workforce in general and prepare students with necessary knowledge and skillsets to work in quantum computing in private and public sectors.

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[83] Mitch Ambrose, "Expansion of National Quantum Initiative Pitched to Science Committee," *American Institute of Physics*, June 22, 2023, at https://ww2.aip.org/fyi/expansion-of-national-quantum-initiative-pitched-to-science-committee.

[84] National Science and Technology Council, Committee on Science, Subcommittee on Quantum Information Science, *Quantum Information Science and Technology Workforce Development National Strategic Plan*, February 2022, p. v, at https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf.

[85] Bob Sorensen and Tom Sorensen, *Special Analysis: Challenges and Opportunities for Securing a Robust U.S. Quantum Computing Supply Chain*, Hyperion Research, LLC, HR4.0024.04.15.2022, June 2022, p. 9, at https://quantumconsortium.org/mp-files/qed-c-special-analysis-us-quantum-computing-supply-chain-issues.pdf/.

[86] 42 U.S.C. §19261(d), (f).

[87] For an introduction to STEM education in general, see CRS Report R45223, *Science, Technology, Engineering, and Mathematics (STEM) Education: An Overview*, by Boris Granovskiy.

Protecting National Security Interests in Quantum Computing

Some quantum computing technologies may pose risks to national security if they were to be obtained by adversaries of the United States and other malign actors.[88] For example, using quantum algorithms,[89] a practical quantum computer could potentially compromise the cryptography currently used to protect sensitive data communications among government agencies, financial institutions, health service providers, and others.[90] In general terms, modern cryptography is based on the idea that the intractability of certain mathematical problems provides a reliable approach to enforcing policies for accessing digital data—only someone who holds the authenticated "key" can immediately access the encrypted data; anyone else must first solve a problem, such as factoring the products of large prime numbers.[91] This problem is designed to be impossible to complete within a reasonable time even using (existing, classical) supercomputers, and the difficulty of the problem guarantees the security for a cryptosystem. Some experts claim that a future fault-tolerant quantum computer with millions of qubits could solve such a problem in hours.[92]

Experts on the National Quantum Initiative Advisory Committee have urged the federal government and industry to work together to simultaneously accelerate progress in QIST, and develop and deploy new encryption algorithms and standards resistant to quantum attacks (also known as "post-quantum cryptography," or PQC).[93] Some industry leaders have committed to keeping the government and public informed of their R&D progress toward a practical quantum computer capable of undermining existing encryption.[94]

Since 2016, NIST has worked on its PQC standardization process, which selects cryptographic algorithms that can be implemented on classical computers to protect information that may become vulnerable with the advent of quantum computers.[95] NIST expects that these algorithms could replace current cryptosystems "to prepare for the eventuality that large-scale quantum

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[88] National Quantum Initiative Advisory Committee, *Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science*, June 2023, p. 13, at https://www.quantum.gov/wp-content/uploads/2023/06/NQIAC-Report-Renewing-the-National-Quantum-Initiative.pdf.

[89] Peter W. Shor, "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer," *Proceedings of the 35th Annual Symposium on Foundations of Computer Science*, Santa Fe, NM, November 1994, pp. 124-134, at https://doi.org/10.1137/S0097539795293172.

Shor's quantum algorithm demonstrated how to factorize large integers in polynomial time, "which is an exponential speed-up over the best classical algorithms." See David Joseph et al., "Transitioning Organizations to Post-Quantum Cryptography," *Nature*, vol. 605 (May 2022), pp. 237-243, at https://doi.org/10.1038/s41586-022-04623-2.

[90] David Joseph et al., "Transitioning Organizations to Post-Quantum Cryptography," *Nature*, vol. 605 (May 2022), pp. 237-243, at https://doi.org/10.1038/s41586-022-04623-2.

[91] Ibid.

[92] Google, "Our Focused and Responsible Approach to Quantum Computing," p. 7, at https://ai.google/static/documents/approach-quantum-computing.pdf.

[93] National Quantum Initiative Advisory Committee, *Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science*, June 2023, p. 13, at https://www.quantum.gov/wp-content/uploads/2023/06/NQIAC-Report-Renewing-the-National-Quantum-Initiative.pdf.

[94] Google, "Our Focused and Responsible Approach to Quantum Computing," p. 8, at https://ai.google/static/documents/approach-quantum-computing.pdf.

[95] NIST, *PQC Standardization Process: Announcing Four Candidates to be Standardized, Plus Fourth Round Candidates*, July 5, 2022, at https://csrc.nist.gov/News/2022/pqc-candidates-to-be-standardized-and-round-4.

computers become a reality."[96] The agency anticipates finalizing the standard by 2024.[97] In May 2022, the Biden Administration issued the National Security Memorandum (NSM) on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems (NSM-10), which stated that "the United States must prioritize the timely and equitable transition of cryptographic systems to quantum-resistant cryptography, with the goal of mitigating as much of the quantum risk as is feasible by 2035."[98]

In December 2022, Congress passed and the President signed into law the Quantum Computing Cybersecurity Preparedness Act (P.L. 117-260). Congress found a potential for adversaries of the United States "to steal sensitive encrypted data today using classical computers, and wait until sufficiently powerful quantum systems are available to decrypt it."[99] It directed the Office of Management and Budget to issue guidance on the migration of federal information technology systems to PQC and submit to Congress a report on PQC and a report on the progress of agencies in adopting PQC standards.[100] The law codifies NIST's ongoing work on PQC standards, but does not apply to any national security systems.[101]

Breaking classical cryptography systems is one highly anticipated use of quantum computing. Congress may wish to consider options to safeguard national security interests, in addition to the abovementioned initiatives and legislative efforts regarding PQC. These options may include whether to

- prioritize federal support for the development of large-scale, practical quantum computers that are capable of implementing quantum algorithms to break existing encryption;
- further support R&D in quantum cryptographic algorithms and standards that can be implemented on quantum computers and to establish new, secure quantum data communications;
- require the disclosure by quantum computer developers when they make substantial progress in breaking existing cryptography systems;
- direct resources to develop a quantum-ready national security workforce;
- strengthen export controls for quantum computing hardware, software, and network equipment, and intellectual property protections for relevant technologies and processes;
- oversee technology transfers and commercialization involving dual-use quantum applications, including cryptography, drug discovery, virus study, and new material development; and

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[96] NIST, *Call for Proposals: Post-Quantum Cryptography (PQC)*, January 3, 2017, updated August 14, 2023, at https://csrc.nist.gov/Projects/post-quantum-cryptography/post-quantum-cryptography-standardization/Call-for-Proposals.

[97] NIST, *Post-Quantum Cryptography (PQC): Workshops and Timeline*, August 14, 2023, at https://csrc.nist.gov/Projects/post-quantum-cryptography/workshops-and-timeline.

[98] White House, "National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems," National Security Memorandum/NSM-10, May 4, 2022, at https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/04/national-security-memorandum-on-promoting-united-states-leadership-in-quantum-computing-while-mitigating-risks-to-vulnerable-cryptographic-systems/.

[99] Section 2(a)(4) of P.L. 117-260.

[100] 6 U.S.C. §1526(a)(1), (e)(1), (2).

[101] 6 U.S.C. §1526(e)(1)(c) and Section 5 of P.L. 117-260.

- enforce the review of foreign investments in U.S. entities and U.S. investments in non-partner countries in security-related quantum computing technologies and products.

Appendix A. **Key Terms of Quantum Computing Explained**

Quantum Networking

Quantum computing, quantum networking, and quantum sensing are closely related to one another. Quantum computing is discussed in the main text of this report. Quantum networking (also called quantum communications) refers to building fast and secure data communication networks that use quantum phenomena such as superposition and entanglement (discussed below) to encode, send, receive, and store information among interconnected quantum devices.[102] Some experts assert that the ultimate goal of quantum networking is building and scaling a quantum-enhanced and protected, full-scale global internet, or *quantum internet*, not replacing but complementing the existing internet (i.e., a network of networks of classical computing devices).[103] A quantum internet could be used to connect quantum computers to enable distributed computing services, similar to the ideas of cloud computing and parallel computing for classical computers.[104] Network-enabled quantum computing could unleash even more computing power than individual quantum computers.[105]

Quantum Sensing

Quantum sensing refers to the development of quantum-based instruments capable of measuring physical quantities, such as time, temperature, distance, gravity, and electric and magnetic fields, with more sensitivity and precision than conventional sensors such as seismometers, microscopes, or magnetic resonance imaging (MRI) devices.[106] Quantum sensing may have a variety of potential applications, including medical imaging; imaging of molecular structures such as proteins; radio signal receiving and amplification in wireless communications; navigation;

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[102] Caltech, *Quantum Science and Technology: Terms to Know*, Caltech Science Exchange Series, at https://scienceexchange.caltech.edu/topics/quantum-science-explained#terms-to-know.

[103] U.S. Department of Energy (DOE), Office of Science, From Long-Distance Entanglement to Building a Nationwide Quantum Internet: Report of the DOE Quantum Internet Blueprint Workshop, February 2020, p. 10, at https://www.energy.gov/sites/prod/files/2020/07/f76/QuantumWkshpRpt20FINAL_Nav_0.pdf. See also Andrew Nellis, "The Quantum Internet, Explained," University of Chicago News, Explainer Series, December 8, 2022, at https://news.uchicago.edu/explainer/quantum-internet-explained.

[104] DOE, Office of Science, *From Long-Distance Entanglement to Building a Nationwide Quantum Internet: Report of the DOE Quantum Internet Blueprint Workshop*, February 2020, p. 11, at https://www.energy.gov/sites/prod/files/2020/07/f76/QuantumWkshpRpt20FINAL_Nav_0.pdf.

Cloud-based quantum computing, called *blind quantum computing*, could take advantage of secure quantum networking to enable the delegation of sensitive computational tasks to remote, powerful quantum computers in the cloud (see ibid.). In parallel quantum computing, a network of quantum computers could simultaneously work on different, smaller tasks broken down from a large, complex problem, further improving the performance of quantum computing (see Andrew Nellis, "The Quantum Internet, Explained," *University of Chicago News*, Explainer Series, December 8, 2022, at https://news.uchicago.edu/explainer/quantum-internet-explained).

[105] Gaurav Batra et al., "Shaping the Long Race in Quantum Communication and Quantum Sensing," McKinsey & Company, *Advanced Electronics Practice Series*, December 2021, pp. 3, 5, at https://www.mckinsey.com/~/media/mckinsey/industries/advanced%20electronics/our%20insights/shaping%20the%20long%20race%20in%20quantum%20communication%20and%20quantum%20sensing/shaping-the-long-race-in-quantum-communication-and-quantum-sensing.pdf.

[106] Caltech, *Quantum Science and Technology: Terms to Know*, Caltech Science Exchange Series, at https://scienceexchange.caltech.edu/topics/quantum-science-explained#terms-to-know. See also C. L. Degen, F. Reinhard, and P. Cappellaro, "Quantum Sensing," *Reviews of Modern Physics*, vol. 89, no. 3 (July-September 2017), p. 035002-1, at https://journals.aps.org/rmp/pdf/10.1103/RevModPhys.89.035002.

environmental monitoring; physical infrastructure monitoring; energy consumption monitoring; geographical surveying; and fundamental research.[107]

Quantum computing, networking, and sensing technologies can exist independently, but synergies may arise as these technologies mature.[108] For example, quantum networking may enhance quantum computing and facilitate quantum sensing, and quantum sensing may enable new quantum computing applications, particularly in artificial intelligence.

Quantum

The term refers to either the smallest possible discrete unit of energy that can occur in nature, or a tiny object (e.g., an electron, proton, or neutron in an atom, or a photon of light) that carries such a single unit of energy. At the atomic and subatomic scale, physical properties such as energy are not continuous but rather exist in specific discrete amounts. These properties are called "quantized."[109]

Quantum Mechanics

The term refers to the mathematical laws and principles of quantum physics, which describes the behavior, properties, and interactions of quantum. These quantum objects behave often in ways that are unfamiliar and may be counterintuitive and surprising. Many phenomena occurring at the quantum scale cannot be explained by classical physics, which describes nature's behavior at much larger scales that people experience in everyday life.[110] Yet those quantum phenomena are essential for QIST.

Quantum Superposition

In quantum mechanics, superposition refers to the fact that an object at the quantum scale (e.g., an electron) can exist in an undetermined state.[111] This state can be expressed by a combination of possibilities of multiple definite states in which the object may exist.[112] For example, an electron could be in a superposition state with probabilities of two spinning directions—40% of the chance it is spinning downward and 60% of the chance it is spinning upward. It does not mean that the

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[107] Gaurav Batra et al., "Shaping the Long Race in Quantum Communication and Quantum Sensing," McKinsey & Company, *Advanced Electronics Practice Series*, December 2021, p. 4, at https://www.mckinsey.com/~/media/mckinsey/industries/advanced%20electronics/our%20insights/shaping%20the%20long%20race%20in%20quantum%20communication%20and%20quantum%20sensing/shaping-the-long-race-in-quantum-communication-and-quantum-sensing.pdf.

[108] Ibid., pp. 8-9.

[109] Quantum Physics Lady, *What Is the Difference Between Quantum Mechanics and Quantum Physics?*, Encyclopedia of Quantum Physics, June 28, 2019, at https://quantumphysicslady.org/what-is-the-difference-between-quantum-mechanics-and-quantum-physics/.

[110] Caltech, *Quantum Science and Technology: Terms to Know*, Caltech Science Exchange Series, at https://scienceexchange.caltech.edu/topics/quantum-science-explained#terms-to-know.

A classical object consists of millions or billions of atoms. Its behavior is described by classical physics in ways that may be intuitive. For example, its states (e.g., location, orientation, velocity, etc.) are definite, even if it is not observed and measured.

[111] Quantum Physics Lady, *Superposition, Quantum*, Encyclopedia of Quantum Physics: Glossary, June 13, 2019, at https://quantumphysicslady.org/glossary/quantum-superposition/. In an atom, an electron orbits the nucleus like planets orbiting a star.

[112] Caltech, *What Is Superposition and Why Is It Important?*, Caltech Science Exchange Series: Quantum Science and Technology: Superposition, at https://scienceexchange.caltech.edu/topics/quantum-science-explained/quantum-superposition.

electron is in both directions simultaneously; rather, it is in a quantum state that can be only expressed mathematically.

Once a quantum object is measured and interacts with its environment (e.g., other objects, light, vibration, or heat), the superposition state will "collapse" into a particular state.[113] This collapse is called *quantum decoherence*. Preventing decoherence, so that quantum computers can continue to employ superposition to make reliable calculations, is a major challenge in realizing quantum computing.[114]

Superposition is one of the fundamental attributes of quantum computers that differentiate them from classical computers. It is an inherently quantum property, not included in classical physics, because classical objects are large enough that they always exist in a single definite state. Quantum computing harnesses this unique property to enable an object at the quantum level to carry more information than a single given state can represent. For example, while two classical bits can represent only a pair of data at a time from the four possible combinations of 0|0, 0|1, 1|0, and 1|1, two qubits can represent possibilities of these four combinations at the same time.[115] Following this trajectory, as the number of qubits increases linearly, the information that the qubits are capable of carrying grows exponentially. In classical computing, however, doubling the number of bits only doubles its computational power to handle data.[116]

Quantum Entanglement

In quantum mechanics, entanglement describes a phenomenon in which two or more quantum objects, when entangled, behave in a correlated way and remain so even if they are physically separated by a large distance.[117] Because of this correlation, measuring the state of one object in the group instantaneously determines the state of other objects in the group.[118]

For example, two electrons might be in superposition states and entangled—one with 40% of the spin-down probability and 60% of the spin-up probability, and the other with 70% spin-down and 30% spin-up. If the first electron is observed and found spinning upward, the superposition state of the second electron will instantaneously collapse. Without a direct observation on the second electron, its state is determined spinning downward. Like superposition, entanglement has no explanation in classical physics, but it is essential to enabling quantum computing and networking.[119]

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[113] Microsoft, *Explore Quantum: Superposition*, Azure Quantum, at https://quantum.microsoft.com/en-us/explore/concepts/superposition. Watch an animated visualization of quantum superposition at Physics Reimagined, *Quantum Superposition of States and Decoherence*, Quantum Research: State Superposition, YouTube video, 2023, at https://toutestquantique.fr/en/superposition/.

[114] Martin Giles, "Explainer: What Is a Quantum Computer?," *MIT Technology Review*, January 29, 2019, at https://www.technologyreview.com/2019/01/29/66141/what-is-quantum-computing.

[115] Microsoft, *Explore Quantum: The Qubit*, Azure Quantum, at https://quantum.microsoft.com/en-us/explore/concepts/what-is-a-qubit.

[116] Martin Giles, "Explainer: What Is a Quantum Computer?," *MIT Technology Review*, January 29, 2019, at https://www.technologyreview.com/2019/01/29/66141/what-is-quantum-computing.

[117] Caltech, *What Is Entanglement and Why Is It Important?*, Caltech Science Exchange Series: Entanglement, at https://scienceexchange.caltech.edu/topics/quantum-science-explained/entanglement.

[118] NASA, Jet Propulsion Laboratory, *Particles in Love: Quantum Mechanics Explored in New Study*, February 12, 2016, at https://www.jpl.nasa.gov/news/particles-in-love-quantum-mechanics-explored-in-new-study.

[119] Microsoft, *Explore Quantum: Entanglement*, Azure Quantum, at https://quantum.microsoft.com/en-us/explore/concepts/entanglement.

Appendix B. **NQI Act-Funded R&D Centers**[120]

In February 2019, NSF issued a Program Solicitation for Quantum Leap Challenge Institutes (QLCI), which are “large-scale interdisciplinary research projects that aim to advance the frontiers of quantum information science and engineering.” Research at these institutes would focus on topics such as quantum computing, networking, and sensing. According to NSF, the program is “consistent with the scope of NSF multidisciplinary centers for quantum research and education” as authorized and funded in the NQI Act.[121] NSF thereafter awarded grants to create and support five QLCI, as shown in **Table B-1**.

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[120] In addition to ten NQI Act-funded quantum R&D centers, DOD has designated four defense QIST R&D centers under the authorization of the NDAA for FY2020: the National Security Agency’s Laboratory for Physical Sciences (LPS) Qubit Collaboratory (LQC), Air Force Research Laboratory (AFRL), Naval Research Laboratory (NRL), and Army Research Laboratory (ARL). See National Quantum Initiative, *Getting the Science Right: QIS Centers*, at https://www.quantum.gov/science/.

[121] NSF, *Quantum Leap Challenge Institutes (QLCI) Program Solicitation*, NSF 19-559, February 2019, at https://www.nsf.gov/pubs/2019/nsf19559/nsf19559.htm.

Table B-1. NSF Quantum Leap Challenge Institutes (QLCI)

Name	Total Intended Award Amount	Primary Place of Performance	Congressional District	Overall Goal	Start Date	End Date (Estimated)
QLCI for Present and Future Quantum Computing	$24.9 million	University of California-Berkeley	CA 12	"To help bring about the quantum computer," particularly "the realization of large-scale quantum computation."	9/1/2020	8/31/2025
QLCI for Hybrid Quantum Architectures and Networks	$25 million	University of Illinois at Urbana-Champaign	IL 13	To carry out fundamental research and engineering to develop "a multi-node, full-stack system, ranging from quantum processor design and control to a high-level software application interface."	9/1/2020	8/31/2025
QLCI for Enhanced Sensing and Distribution Using Correlated Quantum States	$25 million	University of Colorado at Boulder	CO 02	To build scalable and programmable quantum sensing systems with genuine quantum advantages	9/1/2020	8/31/2025
QLCI for Robust Quantum Simulation	$25 million	University of Maryland College Park	MD 04	To build "a well-controlled, well-characterized quantum system that can reliably simulate the behavior of matter at small scales."	9/1/2021	8/31/2026
QLCI for Quantum Sensing in Biophysics and Bio-engineering	$25 million	University of Chicago	IL 01	To create "biocompatible quantum sensors" to extract new information and gain control over biological processes."	9/1/2021	8/31/2026

Source: NSF, *Quantum Leap Challenge Institutes (QLCI)*, at https://new.nsf.gov/funding/opportunities/quantum-leap-challenge-institutes-qlci.

In January 2020, DOE's Office of Science issued a Funding Opportunity Announcement (FOA) for the creation of National Quantum Information Science Research Centers (NQISRCs), which would "accelerate the transformational advances in basic science and quantum-based technology needed to assure continued U.S. leadership" in QIST.[122] Since then, DOE has funded five NQISRCs, each led by a DOE national laboratory, as shown in **Table B-2**.[123] The goal of the NQISRCs is "to create and to steward the ecosystem needed to foster and facilitate advancement" of QIST.[124] Scientists and engineers at the centers work on designing and building (1) powerful quantum computer, (2) unhackable communication networks, (3) ultrasensitive instruments and sensors, and (4) groundbreaking new materials.[125]

Table B-2. DOE National Quantum Information Science Research Centers

Name	Lead Institution	Primary Goal
Next Generation Quantum Science and Engineering (Q-NEXT)	Argonne National Laboratory	To create an ecosystem to deliver quantum interconnects, establish national foundries, and demonstrate communication links, networks of sensors, and simulation testbeds.
Co-design Center for Quantum Advantage (C^2QA)	Brookhaven National Laboratory	To deliver quantum computer systems that achieve quantum advantage for scientific computations in high-energy, nuclear, chemical, and condensed matter physics.
Superconducting Quantum Materials and Systems Center (SQMS)	Fermi National Accelerator Laboratory	To enable construction and deployment of superior quantum computing and sensing systems.
Quantum Systems Accelerator (QSA)	Lawrence Berkeley National Laboratory	To design quantum algorithms, devices, and engineering solutions to deliver certified quantum advantage in scientific applications.
The Quantum Science Center (QSC)	Oak Ridge National Laboratory	To overcome key roadblocks in quantum state resilience, controllability, and scalability of quantum technologies.

Source: DOE, Office of Science, *National QIS Research Centers*, at https://science.osti.gov/Initiatives/QIS/QIS-Centers.

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[122] DOE, Office of Science, *National Quantum Information Science Research Centers: Funding Opportunity Announcement (FOA)*, DE-FOA-0002253, March 17, 2020, at https://science.osti.gov/-/media/grants/pdf/foas/2020/SC_FOA_0002253.pdf.

[123] Hannah Adams et al., *How the Five National Quantum Information Science Research Centers Harness the Quantum Revolution*, Argonne National Laboratory, August 26, 2022, at https://www.anl.gov/article/how-the-five-national-quantum-information-science-research-centers-harness-the-quantum-revolution.

[124] DOE, Office of Science, *National QIS Research Centers*, at https://science.osti.gov/Initiatives/QIS/QIS-Centers.

[125] DOE, Office of Science, *National QIS Research Centers At-A-Glance*, at https://science.osti.gov/-/media/QIS/pdf/QuantumBrochure2021.pdf.

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