NATIONAL QUANTUM INITIATIVE SUPPLEMENT TO THE PRESIDENT'S FY 2025 BUDGET

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

December 2024

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The NSTC Subcommittee on Quantum Information Science was established by the National Quantum Initiative Act and coordinates Federal R&D in quantum information science and related technologies under the auspices of the NSTC Committee on Science. The aim of this R&D coordination is to maintain and expand U.S. leadership in quantum information science and its applications over the next decade.

About this Document

This document is a supplement to the President's 2025 Budget request, and serves as the annual report for the National Quantum Initiative called for under the National Quantum Initiative Act.

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Table of Contents

About the National Science and Technology Council ii

Abbreviations and Acronyms 2

Executive Summary 3

1 Introduction 4

2 Budget Data 6

3 QIS R&D Program Highlights 10

3.1 The National Institute of Standards and Technology (NIST) 11

3.2 The National Science Foundation (NSF) 16

3.3 The Department of Energy (DOE) 20

3.4 The Department of Defense (DOD) 26

3.5 The National Aeronautics and Space Administration (NASA) 31

3.6 The National Security Agency (NSA) 33

3.7 The Intelligence Advanced Research Projects Activity (IARPA) 35

3.8 Concluding remarks for QIS R&D Overview 36

4 QIS Policy Areas 37

4.1 Choosing a Science-First Approach to QIS 37

4.2 Creating a Quantum-Smart Workforce for Tomorrow 43

4.3 Deepening Engagement with Quantum Industry 49

4.4 Providing Critical Infrastructure 51

4.5 Maintaining National Security and Economic Growth 54

4.6 Advancing International Cooperation 56

5 Summary and Outlook 60

Abbreviations and Acronyms

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
ARL	Army Research Laboratory
ARO	Army Research Office
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
DOT	Department of Transportation
ESIX	Subcommittee on Economic and Security Implications of Quantum Science
FBI	Federal Bureau of Investigation
FFRDC	Federally Funded Research and Development Center
IARPA	Intelligence Advanced Research Projects Activity
IC	Intelligence Community
IWG	Interagency Working Group
LPS	National Security Agency Laboratory for Physical Sciences
NASA	National Aeronautics and Space Administration
NDAA	National Defense Authorization Act
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NQCO	National Quantum Coordination Office
NQI	National Quantum Initiative
NQIAC	National Quantum Initiative Advisory Committee
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSA	National Security Agency
NSF	National Science Foundation
NSTC	National Science and Technology Council
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
OUSD(R&E)	Office of the Undersecretary of Defense for Research and Engineering
PQC	Post-Quantum Cryptography
QED-C	Quantum Economic Development Consortium
QIS	Quantum Information Science
QIST	Quantum Information Science and Technology
R&D	Research and Development
SCQIS	Subcommittee on Quantum Information Science
USPTO	United States Patent and Trademark Office
USDA	United States Department of Agriculture

Executive Summary

Quantum information science (QIS) is the convergence of two foundational fields underpinning modern technology: quantum mechanics and information theory. This new field is starting to yield transformative new capabilities in computing, sensing, and networking with the potential to improve the Nation's prosperity and security. Investments in fundamental QIS research are laying a foundation for the technologies of the future and opening new frontiers in science. The Administration is committed to advancing critical and emerging technologies, including QIS, as reaffirmed in the Office of Management and Budget and Office of Science and Technology Policy Priorities Memorandum for Research and Development (R&D) for the Fiscal Year (FY) 2025 Budget.

The National Quantum Initiative (NQI) Act was enacted in December 2018 to accelerate American leadership in QIS technology. The NQI Act authorizes U.S. Federal departments and agencies (hereafter, "agencies") to establish centers and a consortium and carry out new programs to foster QIS R&D. The NQI Act calls for the coordination of QIS R&D efforts across the Federal Government, as well as with industry and the academic community.

The Administration has made significant contributions to the NQI over the last year, including holding two roundtables on post-quantum cryptography, publishing the first post-quantum cryptography standards, and publishing the National Science and Technology Council strategy on *Advancing International Collaboration in Quantum Information Science and Technology*. In addition, the NQI Advisory Committee report on *Growing American Leadership in Quantum Networking* was published.

In line with the *National Strategic Overview for QIS*, the United States is making substantial and sustained investments in QIS R&D to explore a range of applications and nurture a culture of discovery. Major efforts funded by several agencies are recognized in this report, as well as overviews of agency efforts to make further progress on cross-cutting QIS policy topics. Examples of such topics include overcoming fundamental science and engineering challenges, increasing the workforce capacity, engaging with industry, investing in infrastructure, maintaining economic and national security, and encouraging international cooperation.

This is the fifth annual report on the NQI Program and budget, as required by Section 103(g) of the NQI Act. It reports investments in the NQI Program, building upon the establishment of the NQI research centers, the Quantum Economic Development Consortium, and new QIS R&D activities. Agencies reported budget expenditures for QIS R&D of $456 million in FY 2019, $690 million in FY 2020, $851 million in FY 2021, $1,041 million in FY 2022, and $1,036 million in FY 2023, followed by $1,006 million of enacted budget authority for FY 2024 and a requested budget authority of $998 million for FY 2025.

While the development of QIS technologies is at an early stage, now is a critical time to develop the fundamental scientific knowledge, infrastructure, and workforce needed for the creation of new applications and use cases for QIS technologies, grow the marketplace, and foster an ecosystem for basic, applied, and translational research in QIS. QIS could have profound and positive impacts on society and the way each agency accomplishes its mission. Agencies are ensuring that all Americans have the opportunity to benefit from participation in QIS, including through efforts that expand the quantum workforce to ensure it reflects the whole of society. Agencies are also taking steps to spur innovation while ensuring that new technologies and capabilities are adequately protected.

1 Introduction

Quantum information science (QIS) builds on quantum mechanics and information theory to explore applications in computation, networking, sensing, and measurement. In some cases, the performance of QIS technologies may be vastly superior to that of traditional, classical technologies. The world is on the cusp of a second quantum revolution. This technological progress is built on key QIS discoveries in the 1980's, pioneering QIS experiments in the 1990's, growth in quantum engineering capabilities in the 2000's, and the development of commercial activities currently underway. The potential for innovations based on QIS - and the associated implications for jobs and security - motivated the U.S. Government to enact the National Quantum Initiative (NQI) Act to accelerate QIS research and development (R&D) and training opportunities.[1]

Box 1.1

COORDINATING BODIES SUPPORTING THE NATIONAL QUANTUM INITIATIVE

The Subcommittee on Quantum Information Science (SCQIS) coordinates Federal R&D in QIS under the auspices of the National Science and Technology Council (NSTC) Committee on Science. The SCQIS is co-chaired by the Office of Science and Technology Policy (OSTP), National Institute of Technology (NIST), National Science Foundation (NSF), and Department of Energy (DOE). Interagency discussions and recommendations by the SCQIS aim to strengthen U.S. leadership in QIS and its applications over the next decade. SCQIS members are listed in the front matter.

The Subcommittee on Economic and Security Implications of Quantum Science (ESIX) of the NSTC is co-chaired by OSTP, the Department of Defense (DOD), DOE, and the National Security Agency (NSA). In parallel with the SCQIS, ESIX works to ensure that the economic and security implications of QIS are understood across the agencies, while providing a national security perspective on QIS-related R&D policy.

The National Quantum Initiative Advisory Committee (NQIAC) is the Federal advisory committee called for in the NQI Act to advise the administration on ways to ensure continued American leadership in QIS. The NQIAC is tasked to provide an independent assessment of the NQI Program and to make recommendations for the President and the Subcommittees to consider when reviewing and revising the NQI Program. The NQIAC is comprised of leaders in QIS from industry, academia, and the Federal Government. In 2022, an Executive Order on Enhancing the National Quantum Initiative Advisory Committee reconstituted the NQIAC as a Presidential advisory committee.[2]

The National Quantum Coordination Office (NQCO) is located in OSTP within the Executive Office of the President to carry out the daily activities needed for coordinating and supporting the NQI Program. The NQCO is tasked with providing technical and administrative support to the SCQIS, ESIX, and the NQIAC, overseeing interagency coordination of the NQI Program, serving as the point of contact on Federal civilian QIS activities, ensuring coordination among the consortium and quantum centers, and conducting public outreach. The NQCO staff consists of Federal employees on detail assignments from across the Federal Government. NQCO staff are listed in the front matter.

The NQI Act became law in 2018 "to provide for a coordinated Federal program to accelerate quantum R&D for the economic and national security of the United States." The NQI Act authorizes NIST, NSF,

[1] National Quantum Initiative Act (hereinafter "NQI Act") (Pub. L. 115-368), 15 U.S.C. § 8801 et seq. For the NQI Act with amendments made as of October 2022 see, https://www.quantum.gov/wp-content/uploads/2022/08/NQIA2018-NDAA2022-CHIPS2022.pdf

[2] https://www.federalregister.gov/documents/2022/05/09/2022-10076/enhancing-the-national-quantum-initiative-advisory-committee

and DOE to strengthen and expand QIS programs, centers, and establish a consortium The NQI Act also calls for the coordination of QIS R&D efforts across the U.S. Government, including the civilian, defense, and intelligence sectors. To guide these actions, the NQI Act designated several responsibilities to the SCQIS, the NQCO, and the NQIAC.

Concurrently, the Defense Quantum Information Science and Technology (QIST) R&D Program, as established and then modified by the FY 2019 and FY 2020 National Defense Authorization Acts (NDAAs), respectively, continues DOD's decades-long history of QIS R&D.[3] [4] [5] The FY 2022 NDAA amended the NQI Act to codify the ESIX Subcommittee and articulate its specific responsibilities.[6]

The CHIPS and Science Act of 2022 further amended the NQI Act, authorizing additional activities for NIST, DOE, and the SCQIS.[7] Altogether, the NQI Program provides an overarching framework to strengthen and coordinate QIS R&D activities across agencies, industry, and the academic community. See Box 1.1 for an overview of the different NQI coordinating bodies.

The *National Strategic Overview for QIS* continues to be the overarching strategy for the NQI. It recommends strengthening the United States' approach to QIS R&D by focusing on six areas: science, workforce, industry, infrastructure, security, and international cooperation.[8] These policy pillars are further developed in additional reports available on www.quantum.gov. The *National Strategic Overview for QIS* and the ongoing SCQIS and ESIX Subcommittee activities build upon earlier Federal QIS R&D coordination via interagency strategies such as the early efforts described in the 2009 NSTC report on *A Federal Vision for QIS* and the 2016 NSTC report on *Advancing QIS*.[9] [10] U.S. QIS R&D efforts are also informed by numerous Federally-funded workshops led by the QIS R&D community.[11]

The NQI annual reports describe key activities and the Federal budgets used to support these efforts. Mechanisms to strengthen core programs and coordinate QIS R&D efforts across the Federal Government are also described, as is progress made by the quantum consortium, centers, and institutes established as part of the NQI.

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[3] As described in the NQI Act, ''quantum information science'' (QIS) means the use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information. QIST refers to technologies that leverage QIS. Both QIS and QIST are used throughout this report.

[4] John S. McCain National Defense Authorization Act for Fiscal Year 2019 (Pub. L. 115–232) § 234, 10 U.S.C. § 2358 note

[5] National Defense Authorization Act for Fiscal Year 2020 (Pub. L. 116-92) § 220

[6] National Defense Authorization Act for Fiscal Year 2022 (Pub. L. 117-81) § 6606 (amending the NQI Act to add a new section 105), 15 U.S.C. § 8814a

[7] Research and Development, Competition, and Innovation Act (division B of the law commonly referred to as the CHIPS and Science Act (Pub. L. 117-167)) §§ 10661 and 10104(b) (amending NQI Act to add new sections 103(h), 201(a)(3)-(5), and 403-404), 15 U.S.C. §§ 8813(h), 8831(a)(3)-(5), and 8853-8854

[8] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

[9] https://www.quantum.gov/wp-content/uploads/2020/10/2009_NSTC_Federal_Vision_QIS.pdf

[10] https://www.quantum.gov/wp-content/uploads/2020/10/2016_NSTC_Advancing_QIS.pdf

[11] https://www.quantum.gov/publications-and-resources/publication-library/

2 Budget Data

The U.S. Federal budgets for QIS R&D presented here summarize FY 2019 – FY 2023 actual expenditures, FY 2024 estimated expenditures, and FY 2025 budget requests. The U.S. QIS R&D budgets increased substantially since FY 2019, with efforts catalyzed by the NQI Program.

Figure 2.1 shows overall Federal budgets for U.S. QIS R&D activities aggregated across several agencies including NIST, NSF, DOE, DOD, the Department of Homeland Security (DHS), and the National Aeronautics and Space Administration (NASA). Much of the growth in QIS R&D budgets since 2019 is for NQI activities such as the establishment of a quantum consortium by NIST, the NSF Quantum Leap Challenge Institutes (QLCI), the DOE National Quantum Information Science Research Centers (NQISRCs), expansion of the DOD QIS research program, and the coordination and strengthening of core QIS programs across agencies. Sustained investment in U.S. QIS R&D will position American universities, industry, and Government researchers to explore quantum frontiers, advance QIS technologies, and develop the required workforce to continue American leadership in this field and the related industries of the future.

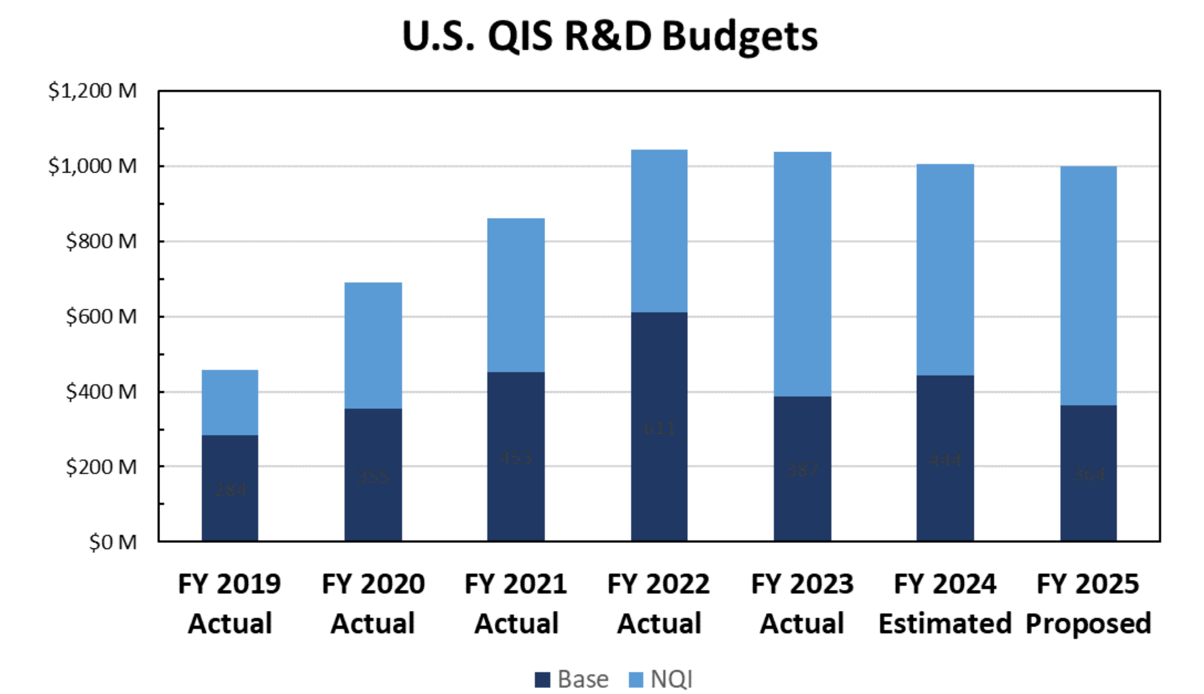

Figure 2.1: U.S. R&D budgets for QIS since the inception of the NQI Act. The bar heights represent the total budget for each fiscal year (FY 2019 – FY 2023 actual expenditures, FY 2024 estimated expenditures, and FY 2025 budget request). The portion of each bar marked "NQI" identifies funding allocated for NQI Act-authorized activities; this additional funding is on top of the budgets for baseline QIS R&D activities.

Budget distributions over five different NQI Program Component Areas (PCAs) are discussed below. These PCAs are used by the Office of Management and Budget (OMB) to collect and analyze budget data. They are consistent with the classification introduced in the *National Strategic Overview for QIS* and those used in previous annual reports on the NQI Program.

NQI Program Component Areas

- **Quantum Sensing and Metrology (QSENS)** refers to the use of quantum mechanics to enhance sensors and measurement science. QSENS can include the use of superposition and entanglement, non-classical states of light, new metrology regimes or modalities, and advances in accuracy and precision enabled by quantum control, for example with atomic clocks.
- **Quantum Computing (QCOMP)** activities include the development of quantum bits (qubits) and entangling gates, quantum algorithms and software, digital and analog quantum simulators using programmable quantum devices, quantum computers and prototypes, and hybrid digital-analog quantum computing, as well as quantum-classical computing systems.
- **Quantum Networking (QNET)** includes efforts to create and use entangled quantum states that are distributed over distances and shared by multiple parties for new information technology applications and fundamental science; for example, networking of intermediate scale quantum computers (modules) for enhanced beyond-classical computing capabilities.
- **QIS for Advancing Fundamental Science (QADV)** includes foundational efforts to invoke quantum devices and QIS theory to expand fundamental knowledge in other disciplines; for example, to improve understanding of biology, chemistry, computation, cosmology, energy science, engineering, materials, nuclear matter, and other aspects of fundamental science.
- **Quantum Technology (QT)** catalogues several topics including work with end-users to deploy quantum technologies in the field and develop use cases, basic R&D on supporting technologies for QIS engineering, *e.g.,* infrastructure and manufacturing techniques for electronics, photonics, and cryogenics, and efforts to understand and mitigate risks raised by quantum technologies, *e.g.,* post-quantum cryptography (PQC).

Figure 2.2 shows budget allocations by NQI PCA for FY 2019 – FY 2025 using a “layer-cake” bar chart for each year. A final breakdown for the budget data presented in Figure 2.3 shows QIS R&D budgets by agency, which includes the total QIS R&D budgets for five agencies prominently engaged in NQI activities: NASA, NIST, DOE, DOD, and NSF.

The data presented in Figures 2.1-2.3 show an increased and sustained investment in QIS R&D across the Federal Government and across each PCA since 2019. This is in alignment with each agency’s mission and a coordinated Federal program to accelerate QIS R&D. The budget data were provided by agencies directly to OMB as part of a routine QIS crosscut reporting process to enable coordinated monitoring and implementation of the NQI Program.

The NQCO is not accounted for in this budget data because its support is derived from employees on detail from NQI Act agencies who staff the office. To date, DOD, DOE, NIST, NSA, and NSF have detailed staff to the NQCO.

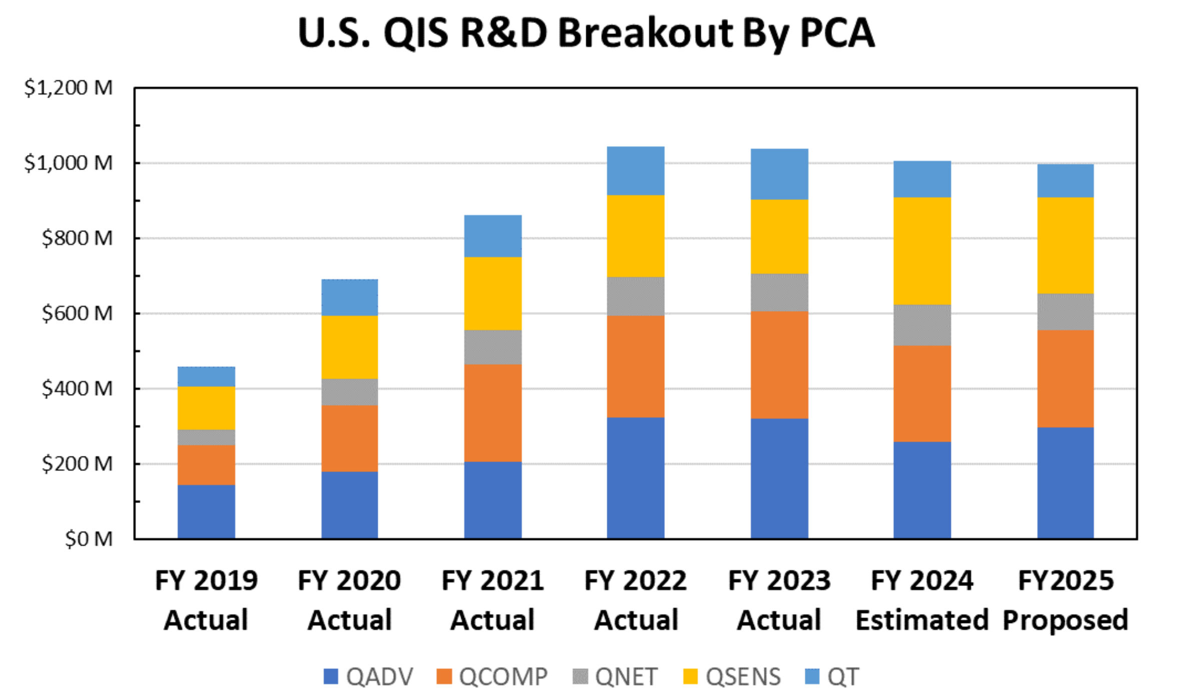

Figure 2.2: U.S. QIS R&D Budget allocations by NQI Program Component Area (PCA) for FY 2019 – FY 2023 actual expenditures, FY 2024 estimated expenditures, and FY 2025 requested budgets.

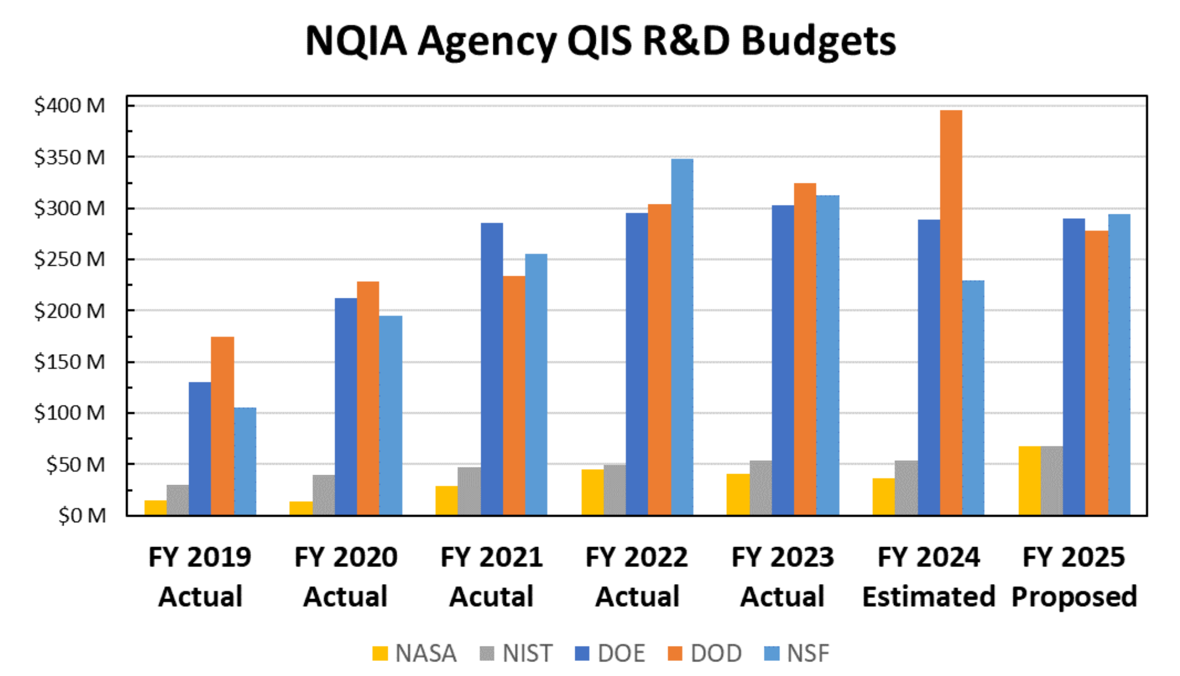

Figure 2.3: QIS R&D Budgets for five agencies engaged in NQI activities showing FY 2019 – FY 2023 actual expenditures, FY 2024 estimated expenditures, and FY 2025 requested budgets.

The next sections describe how agencies use these budgets to advance QIS R&D. The NQI provides a framework to strengthen and coordinate QIS R&D activities across Federal agencies, and also promotes engagement with industry, academia, National Laboratories, and Federally Funded Research and Development Centers (FFRDCs). As illustrated in Figure 2.4, investments made in fundamental QIS research, education, training, and workforce development across agencies are reinforcing and complementary, strengthening their collective efforts. The resulting ecosystem accelerates American leadership in QIS by simultaneously promoting discovery, exploration, and efforts to develop the market, supply chain, infrastructure, and the capacity to utilize quantum technologies.

Section 3 summarizes QIS R&D programs at select agencies and Section 4 tracks progress on key policy topics identified in the *National Strategic Overview for QIS*.

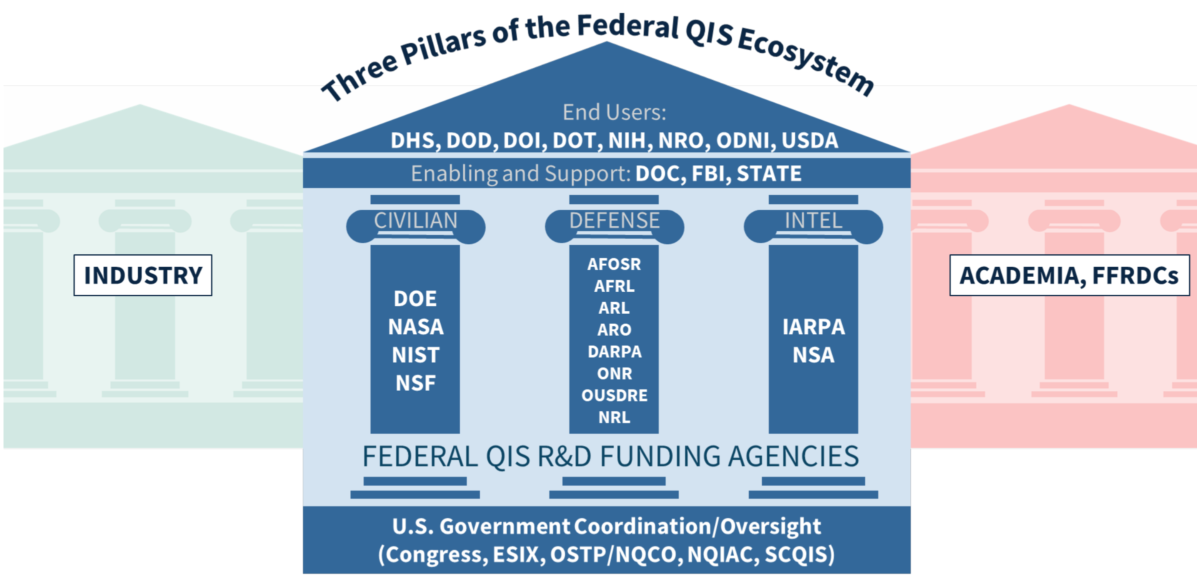

Figure 2.4: Federal QIS R&D funding agencies can be seen as three pillars that support the Federal QIS ecosystem. Civilian science agencies (DOE, NASA, NIST, NSF) stand alongside DOD science agencies (AFOSR, AFRL, ARL, ARO, DARPA, ONR, OUSD(R&E), NRL) and the intelligence community science agencies (IARPA, NSA) to collectively contribute to QIS R&D efforts. Within the Federal Government, support enabling the QIS ecosystem also comes from DOC (BIS, EDA, ITA, USPTO), FBI, State, and potential end users including DHS, DOD, DOI, DOT, NIH, NRO, ODNI, and USDA. Authorization, coordination and oversight are provided by Congress, ESIX, OSTP/NQCO, the NQIAC, and the SCQIS. Pictured here as separate houses, Industry, Academia, and FFRDCs are also critically important for QIS R&D.

3 QIS R&D Program Highlights

In this section, QIS R&D activities are described by agency, including NIST, NSF, DOE, DOD, NASA, NSA, and the Intelligence Advanced Research Projects Activity (IARPA), to provide a more complete description of the U.S. QIS R&D enterprise. While each agency works independently on their respective missions, the collective efforts are crucial for American leadership in QIS. Activities described here accelerate the exploration of basic science and the development of new technologies, with efforts coordinated through coherent policy goals as discussed in Section 4.

QIS R&D highlights are featured throughout this report to illustrate the range of discovery and technical achievement of agency programs. In many cases, the results are supported by multiple agencies.

Box 3.1

Highlight: Logical qubit encoding with arrays of trapped neutral atoms

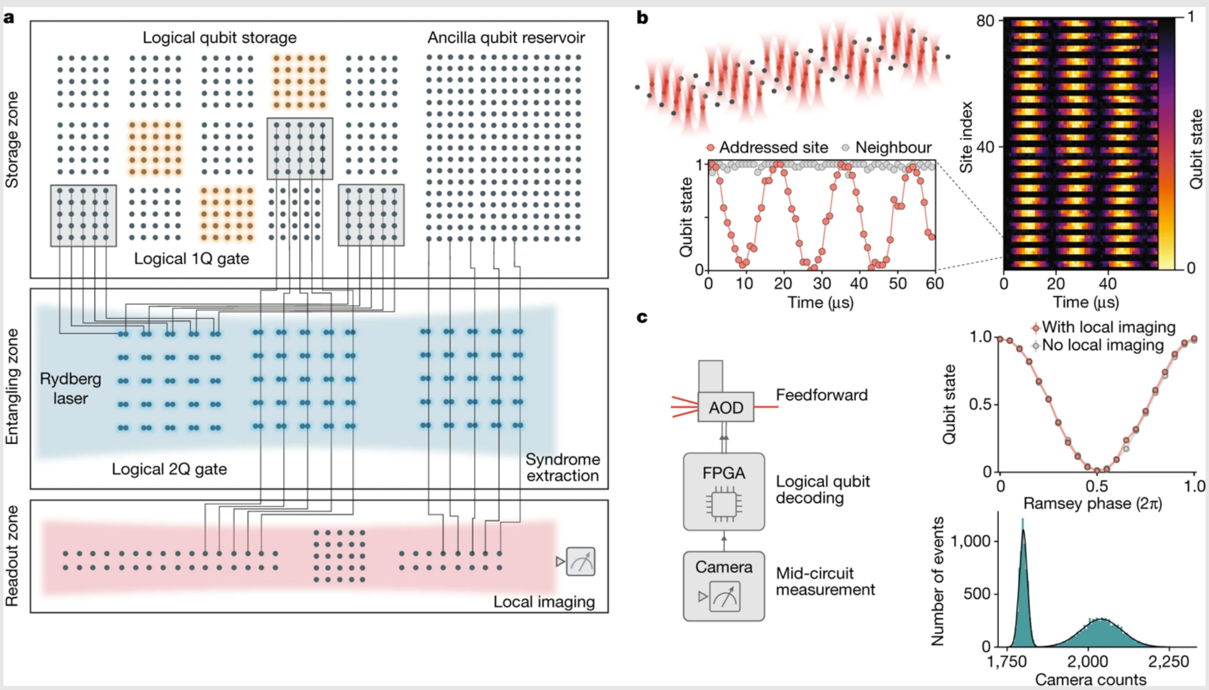

Figure.3.1: Schematic of a neutral-atom based quantum processor and key operations, including single qubit rotations, mid-circuit readout and real-time processing of quantum information.[12]

A pioneering demonstration of quantum algorithms with 48 logical qubits using a few hundred individual physical qubits and several hundred logical quantum gates was performed by researchers in academia, Government, and industry.[13] These experiments demonstrate the key ingredients of scalable error correction and quantum information processing with logical qubits encoded using trapped neutral atoms. The logical qubits were used to carry out operations which outperform the individual (*i.e.*, physical) qubits in neutral-atom arrays by implementing fault-tolerant gates. The output was less error prone than if the qubits had not encoded the information into logical states. Improving the error rates of quantum computers is key to reaching reliable large-scale quantum computation. This research was funded in part by DARPA, IARPA, NSF, ARO, and industry partners.

[12] Image reproduced with permission from doi.org/10.1038/s41586-023-06927-3

[13] 'Logical quantum processor based on reconfigurable atom arrays,' doi.org/10.1038/s41586-023-06927-3

3.1 The National Institute of Standards and Technology (NIST)

NIST promotes U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. Quantum effects set fundamental limits on measurement precision and therefore, by necessity, NIST has been a global leader in QIS R&D. The emerging U.S. quantum industry faces many technical challenges as it seeks to unlock the transformative potential of QIS. Scaling and connecting quantum systems, improving device performance and robustness, growing the talent pool to perform this work, and developing technical standards that enable businesses to succeed are some of the ways in which NIST is promoting innovation and industrial competitiveness in QIS. More broadly, NIST conducts open, world-class research touching upon all elements of the national QIS agenda, with an emphasis on precision metrology and cybersecurity.[14] NIST advances QIS through its core technical programs on quantum sensing, computing, networking, enabling technologies, risk mitigation, and foundational science, including at its joint institutes – JILA,[15] the Joint Quantum Institute (JQI),[16] and the Joint Center for Quantum Information in Computer Science (QuICS).[17] NIST established and supports an industry-led consortium, the Quantum Economic Development Consortium (QED-C), working to accelerate the growth of the U.S. quantum industry via community building, collaboration, and commercialization.[18] The NIST FY 2025 budget request identified quantum science as one of five strategic focus areas that will position NIST to drive innovation in support of America's economic security in the coming decades.[19]

QIS R&D activities supported by NIST include:

- NIST continues to develop its foundational and applied QIS research programs on quantum-enhanced sensing and precision measurement, quantum networking and communications, quantum computing and simulation, fundamental physics, key enabling technologies, and applications of quantum technologies in chemistry, biology, healthcare, and security.
- In support of time standards and Position-Navigation-Timing (PNT) applications, NIST grew its activities on optical atomic clocks, including optical-lattice, trapped-ion, and nuclear-transition clocks.
- In support of efforts to improve the performance and robustness of quantum technologies, NIST continued to develop its program on integrated photonics for QIS and expanded activities in quantum networking metrology, Rydberg sensors, cryogenic electronics, and quantum characterization theory. NIST continued to emphasize support for early-career researchers as part of an internal strategy for growing the NIST quantum workforce.
- NIST continues to engage with the U.S. quantum industry through cooperative research and development agreements (CRADAs) to address specific technology gaps, and more broadly with the industry-led QED-C, which now has participation from more than 180 companies and over 250 member organizations in total. This year, NIST supported the establishment of QED-C's R&D program to address QIS industry needs for photonic integrated circuits and a series of workshops to examine use cases in five key application areas. This year, QED-C also began an R&D program on control and readout electronics for quantum systems and held a workshop on integrated photonics for quantum applications.

[14] https://www.nist.gov/topics/quantum-information-science
[15] https://jila.colorado.edu/
[16] https://jqi.umd.edu/
[17] https://quics.umd.edu/
[18] https://quantumconsortium.org/
[19] https://www.commerce.gov/sites/default/files/2024-03/NIST-NTIS-FY2025-Congressional-Budget-Submission.pdf

- NIST performs workforce development activities through partnerships with higher-education institutions at its joint institutes, its Professional Research Experience Program (PREP), its Summer Undergraduate Research Fellowship (SURF) program, and through its National Research Council (NRC) Postdoctoral Fellowship program.
- NIST has continued its long history of QIS research collaboration with NSF, DOE, DOD, and the IC. For example, NIST researchers contribute to many of the NSF and DOE quantum centers, notably Quantum Systems through Entangled Science and Engineering (Q-SEnSE), Quantum Systems Accelerator (QSA), Superconducting Quantum Materials and Systems Center (SQMS), and the Institute for Robust Quantum Simulation (RQS).
- NIST advanced its post-quantum cryptography (PQC) program to secure U.S. public key infrastructure in preparation for the possibility of a cryptanalytically-relevant quantum computer, and hosted its fifth conference on PQC Standardization. NIST released the first three finalized post-quantum encryption standards on August 13, 2024.[20]
- NIST utilizes its state-of-the-art cleanroom facilities for the fabrication of QIS devices, including superconducting circuits, ion traps, nano-mechanical structures, integrated photonic circuits, and spin-qubit devices. NIST's Center for Nanoscale Science and Technology in Gaithersburg, MD is a national user facility. It provides broad access to a comprehensive fabrication tool set, including advanced capabilities for lithography, thin-film deposition, and nanostructure characterization, as well as support from expert staff. NIST's Boulder Microfabrication Facility provides state-of-the-art microfabrication and imaging capabilities to meet the needs of NIST researchers and their external collaborators. The NIST on a Chip program leverages these facilities to develop accurate and readily deployable measurement technologies for industry and Government users, without the need for NIST's traditional measurement services.[21]
- NIST works collaboratively with its peer National Metrology Institutes (NMIs) around the world on quantum metrology, including methods for the dissemination of the International System of Units, or SI. NIST engaged with Joint Technical Committee 3, a new joint committee of the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) on standardization in the field of quantum technologies.
- This year, NIST engaged in discussions with international partners on potential QIS collaboration and cooperation, including with Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, India, Ireland, Israel, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Netherlands, New Zealand, Norway, Poland, Portugal, Republic of Korea, Romania, Singapore, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. The NIST Foreign Guest Researcher Program enabled researchers from around the world to work collaboratively with NIST scientists.

NIST QIS R&D activities highlights:

- (June 13, 2023) NIST researchers demonstrated a new chip-scale atomic beam clock. This tiny atomic clock could bring stable timing to places where GPS is unavailable and could be used for quantum sensing applications.[22]
- (June 14, 2023) NIST researchers at QuICS studied concatenating bosonic error-correcting codes with qubit codes to boost the error-correcting power of the original qubit codes. Improving error correction is vital to achieving practical large-scale quantum computing.

[20] https://www.nist.gov/news-events/news/2024/08/nist-releases-first-3-finalized-post-quantum-encryption-standards
[21] https://www.nist.gov/noac
[22] https://www.nist.gov/news-events/news/2023/06/new-tiny-atomic-beam-clock-could-bring-stable-timing-places-gps-cant-reach

- (June 21, 2023) NIST researchers announced that they had laid groundwork for future ultra-precise timing links to geosynchronous satellites by demonstrating quantum-limited optical time transfer over 300 km between two mountaintops in Hawaii.[23]
- (July 18, 2023) NIST researchers at QuICS and JQI reported a study on the quantitative connections between the entanglement present in certain quantum systems to the computational complexity of simulating those systems. The researchers discovered that quantum computers run on just the right amount of connectivity.[24]
- (August 1, 2023) NIST researchers demonstrated a new quantum-based primary standard for measuring ultra-low gas pressures that uses the loss rate of two species of magnetically trapped ultracold atoms. In addition to the cold-atom measurement of pressure being primary, portable versions of the technology have the potential to replace common classical ultra-high-vacuum (UHV) pressure gauges.[25]
- (October 25, 2023) NIST researchers, in collaborations with colleagues at the Jet Propulsion Laboratory (JPL), developed and demonstrated a nanowire single-photon camera with 400,000 pixels, breaking the previous record of 20,000 pixels, and with an architecture that is both scalable and tolerant of fabrication defects.[26]
- (January 24, 2024) NIST researchers at JILA observed dynamical phases of model Bardeen-Cooper-Schrieffer (BCS) superconductors in a cavity-QED simulator. This work highlighted the potential for quantum simulators to be used to engineer unconventional superconductors.[27]
- (February 9, 2024) NIST announced a new IEC/ISO Joint Technical Committee on Quantum Technologies (JTC3) and invited participants to engage with the U.S. National Committee Technical Advisory Group.[28]
- (March 07, 2024) NIST researchers described a protocol for characterization of low-noise cryogenic microwave amplifiers, which are ubiquitous in superconducting quantum computing. Noise performance characterization methodologies, being inconsistent and sometimes misleading, have hampered development of the technology and its applications.
- (March 18, 2024) NIST researchers at QuICS determined precision bounds on continuous-variable state tomography using “classical shadows.” The work addressed a central challenge of quantum state tomography – estimating quantum states accurately with few measurements.
- (April 17, 2024) NIST researchers have demonstrated a protocol for amplifying the strength of a broad class of quantum interactions through squeezing. This amplification results in a speedup of dynamics, and it is a new approach to improving the fidelity of quantum operations.
- (April 23, 2024) NIST researchers modified a common type of cryostat to cool faster and with less energy. Cryostats are a key quantum-enabling technology, and rapid cooldown and low energy consumption are necessary for large-scale practical deployment.[29]
- (May 8, 2024) NIST researchers at JILA demonstrated an atomic boson sampler based on a neutral atom array. Quantum interference of many atoms was used to overcome technical limits of other approaches to this quantum computing technique.[30]

[23] https://www.nist.gov/news-events/news/2023/06/nist-lays-groundwork-future-ultra-precise-timing-links-geosynchronous
[24] https://www.nist.gov/news-events/news/2023/10/partially-unraveling-entangled-mystery
[25] https://www.nist.gov/news-events/news/2023/08/nist-demonstrates-new-primary-standard-measuring-ultralow-pressures
[26] https://www.nist.gov/news-events/news/2023/10/nist-team-develops-highest-resolution-single-photon-superconducting-camera
[27] https://www.nist.gov/news-events/news/2024/02/scientists-observe-long-predicted-superconductor-property-using-quantum
[28] https://www.nist.gov/news-events/news/2024/02/new-iecisо-joint-technical-committee-quantum-technologies-inviting
[29] https://www.nist.gov/news-events/news/2024/04/big-quantum-chill-nist-scientists-modify-common-lab-refrigerator-cool
[30] https://jila.colorado.edu/news-events/articles/interference-many-atoms-and-new-approach-boson-sampling

- (May 2, 2024) NIST researchers at JILA demonstrated quantum simulation of magnetism and recoil phenomena akin to the Mössbauer effect, using momentum-exchange interactions in an atom interferometer. This work highlights the strength of cold atoms in cavities as a platform for quantum simulation.[31]
- (May 9, 2024) NIST researchers demonstrated entangled photon pair generation in an integrated silicon carbide platform, a promising candidate for scaled quantum information processing.
- (July 10, 2024) NIST researchers at JILA reported an optical atomic clock with a record-breaking low (8×10^{-19}) systematic uncertainty in fractional frequency.[32]
- (July 29, 2024) NIST researchers have demonstrated coherent coupling and non-destructive measurement in a trapped-ion quantum processor. Controllable coupling is central to scaling quantum systems for practical quantum information processing and simulation.[33]
- (September 4, 2024) NIST researchers at JILA demonstrated a new type of clock based on nuclear energy levels. This work heralded a next-generation platform for precision metrology and fundamental physics studies.[34]

[31] https://jila.colorado.edu/news-events/articles/twisting-and-binding-matter-waves-photons-cavity
[32] https://www.nist.gov/news-events/news/2024/07/worlds-most-accurate-and-precise-atomic-clock-pushes-new-frontiers-physics
[33] 'Coherent coupling and non-destructive measurement of trapped-ion mechanical oscillators' doi.org/10.1038/s41567-024-02585-y
[34] https://www.nist.gov/news-events/news/2024/09/major-leap-nuclear-clock-paves-way-ultraprecise-timekeeping

Box 3.2

Highlight: Towards large-scale integration of quantum dots and photonic structures

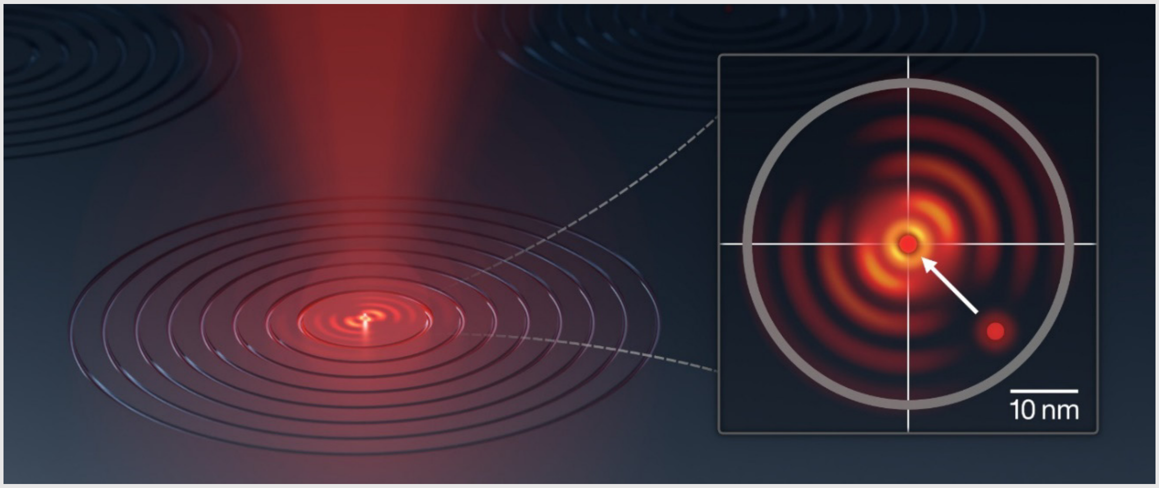

Figure 3.1: The integration of quantum emitters with photonic structures is critical to control light in chip-scale devices. In this illustration, a quantum dot is precisely aligned within a circular grating (center dot in the inset), emitting much more efficiently than a misaligned dot would (off-center dot in the inset). [35] [36]

Scaling quantum systems is a central theme of the NIST QIS research program, as it is necessary for most high-impact applications of quantum technologies. Using light to connect qubits that store and process quantum information is a powerful approach to building large-scale quantum computers, networks, and sensors, but the connections must perform well at the extraordinarily faint, single-photon level. Integrated photonics, which involves fabricating microscopic structures on chip-scale devices using the same kinds of tools and facilities used to make semiconductor chips, can perform well at the single-photon level because of the exquisite control over shapes and materials that chip fabrication entails. This then leads to the challenge of aligning qubits with the photonic structures, and this alignment must be extremely good.

To meet this challenge, researchers at NIST have developed traceable standards and calibrations for cryogenic optical microscopes enabling the alignment of quantum dots (a type of qubit) and photonic structures to within an error of just 10 to 20 nanometers (about one-thousandth the thickness of a sheet of paper).[37] This calibration overcame a long-standing difficulty in a popular integration process and paves the way to high-yield integration of quantum dots and photonic structures for quantum computing, networking, and sensing.

[35] https://www.nist.gov/news-events/news/2024/03/bullseye-nist-devises-method-accurately-center-quantum-dots-within-photonic
[36] Image courtesy of S. Kelley/NIST
[37] 'Traceable localization enables accurate integration of quantum emitters and photonic structures with high yield,' doi.org/10.1364/OPTICAQ.502464

3.2 The National Science Foundation (NSF)

NSF promotes the progress of science by funding research at over 2,000 academic institutions throughout the United States in a broad range of disciplines, including QIS. For several decades, NSF has invested in the foundational R&D driving the quantum revolution. Whether it is GPS systems, magnetic resonance imaging (MRI) technology, or lasers that enable today's internet, many technologies that leverage quantum effects have their roots in NSF investments. The future of QIS and engineering promises to be even more impactful, enabling computers with unprecedented power, new materials, sophisticated sensors and imaging tools, interconnects for quantum state transduction, and networks for entanglement distribution. NSF investments are enabling seminal steps in all of these areas, with end-user applications in all fields of science and engineering and the development of the quantum-literate workforce necessary to implement this new technology.

The NQI Act calls on NSF to support QIS centers and coordinate core programs to accelerate QIS research and education. Implementation is underway with several efforts highlighted on an NSF QIS webpage and factsheet.[38] [39] In aggregate, over 9,000 people (faculty, students, and postdoctoral fellows) are engaged in QIS research funded by NSF. Over 260 colleges and universities have NSF grants for QIS projects. NSF's budget request to Congress articulates three goals for NSF investments in QIS:[40]

(1) Answer key science and engineering questions to expand the fundamental understanding of quantum phenomena and systems.
(2) Deliver proof-of-concept devices, applications, tools, and systems with demonstrable quantum advantages as compared to their classical counterparts.
(3) Empower the full spectrum of talent to which NSF has access to build capacity and generate the quantum-literate workforce that will implement the results of these breakthroughs.

QIS R&D Programs at NSF:

- Quantum Leap Challenge Institutes (QLCIs) are large, ambitious institutes for QIS research and education. Five QLCI sites currently foster collaborations with 117 academic institutions and 67 industry partners. They engage over 160 faculty, 140 postdoctoral researchers, and 550 students, and have produced over 570 peer-reviewed research publications since their inception in 2020.[41]
- The NSF National Quantum Virtual Laboratory (NQVL) pilot, design, and implementation phases (see Solicitations NSF 23-604 and NSF 24-586) will support community infrastructure and testbeds to facilitate the translation from basic science and engineering to the resultant technology, while at the same time emphasizing and advancing its scientific and technical value. The NQVL aims to develop use-inspired and application-oriented quantum technologies in academic settings. In the process, NQVL researchers will explore quantum frontiers, foster QIS workforce education and training, engage in outreach activities at all levels, and promote input and participation from the full spectrum of talent in QIS.[42]
- Core NSF Programs are a substantial and sustained source of support for QIS and quantum engineering research. NSF programs in areas such as computer science, engineering, biology, and mathematical and physical sciences currently fund approximately 1,600 QIS projects at

[38] https://new.nsf.gov/focus-areas/quantum
[39] https://www.nsf.gov/news/factsheets/Expanding_the_Frontiers_of_Quantum_Science_508.pdf
[40] https://new.nsf.gov/about/budget/fy2025
[41] https://new.nsf.gov/funding/opportunities/quantum-leap-challenge-institutes-qlci
[42] https://new.nsf.gov/news/nsf-national-quantum-virtual-laboratory-advances

more than 260 institutions in 47 states led by over 2,000 investigators, training over 2,500 graduate students. A "Connections in QIS" webpage lists several core programs underpinning QIS research.[43] These programs are recognized as an important source of new ideas and opportunities all across the United States.

- Expanding capacity through efforts such as the ExpandQISE Solicitations NSF 24-523, NSF 23-551, and NSF 22-561 increase research capacity and broaden participation by providing support to build and maintain close connections between new efforts and already-impactful QIS centers or research institutions. Establishing and nurturing a critical mass of QIS talent at more institutions is an intentional goal. The program now funds a total of 56 projects with a budget of $99M, including thirteen awards to Historically Black Colleges and Universities (HBCUs), nineteen awards to institutions in the Established Program to Stimulate Competitive Research (EPSCoR) jurisdictions, 23 awards to Minority Serving Institutions, and 51 awards to non-R1 institutions.[44]
- Other large QIS R&D efforts throughout the country include two NSF Quantum Foundries, several NSF Physics Frontiers Centers, the Center for Quantum Information and Control, an Engineering Research Center, several Materials Research Science and Engineering Centers, a National Quantum Nanofab project, and several Centers for Chemical Innovation.

NSF QIS R&D activities highlights:

- (December 22, 2023) NSF issued a Dear Colleague Letter (NSF 24-042) on "Funding Opportunities for Engineering Research in Quantum Information Science and Engineering," describing opportunities for quantum engineering research funding through several programs in the NSF Directorate for Engineering.
- (January 10, 2024) The NSF Future Manufacturing solicitation (NSF 24-525) includes thrust areas to invite research in the manufacturing of quantum devices, circuits, and systems.
- (April 2024) NSF awarded an NSF Regional Innovation Engines (NSF-Engines) development grant for "Quantum Crossroads" to strengthen QIS and technology translation partnerships in the Illinois and Wisconsin region, including the Chicago Quantum Exchange.[45]
- (April 2024) the NSF Quantum Research Showcase in Washington, D.C. highlighted the breadth of NSF investments in QIS. The Showcase brought together 40 researchers, educators, and students from across the country to discuss research, education, and workforce development initiatives with stakeholders through demonstrations, prototypes, and interactive materials.
- (May 6, 2024) NSF issued Dear Colleague Letter (NSF 24-086) "NSF-NIH Pathfinder Supplements on Quantum Sensors for Biomedical Science" to announce an opportunity for researchers currently supported by NSF to request supplemental funding to extend their research on quantum sensing toward biomedical and clinical applications.[46]
- (May 2024) NSF published a *Science Matters* essay on "concepts in quantum materials and computing: from dreams toward use."[47] Other *Science Matters* essays on QIS topics include: "Curious about Quantum?"[48] "Bringing you the quantum future—faster,"[49] and "Bringing quantum entanglement to the people."[50] NSF *Discovery Files* videos include podcast interviews

[43] https://beta.nsf.gov/funding/opportunities/connections-quantum-information-science-cqis
[44] https://new.nsf.gov/news/quantum-science-engineering-expands-across-nation-39m-nsf
[45] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2315739
[46] https://www.nsf.gov/pubs/2024/nsf24086/nsf24086.jsp
[47] https://new.nsf.gov/science-matters/concepts-quantum-materials-computing-dreams-toward
[48] https://new.nsf.gov/science-matters/curious-about-quantum
[49] https://new.nsf.gov/science-matters/bringing-you-quantum-future-faster
[50] https://new.nsf.gov/science-matters/bringing-quantum-entanglement-people

on "Understanding the Universe with Quantum,"[51] and "Understanding Quantum Computing."[52]

- (June 20, 2024) NSF announced a $20M award for a National Quantum Nanofab (NQN) facility to accelerate co-design and development of atomic and photonic quantum devices. The NQN will enable quantum device fabrication, characterization, and packaging capabilities for applications ranging from quantum computers and networks to atomic clocks, and new quantum sensors. NQN will be an open-access national facility for academic, Government, and industrial users.[53] [54]
- NSF Workshops bring together a broad range of scientific communities to identify research opportunities, catalyze partnerships, and share results. A sampling of NSF workshops that pertain to QIS include:
    - In 2024, the NSF Division of Chemistry supported the "NSF/UKRI Bilateral Workshop on Quantum Information Science in Chemistry," held in Alexandria, VA.[55] The workshop brought together scientists from the United States and United Kingdom to discuss research opportunities at the intersection of QIS and chemistry. Based on the workshop outcomes, NSF and UKRI/EPSRC issued a joint funding opportunity aimed at fostering international collaborations that advance our fundamental understanding of QIS concepts in the context of chemical systems, or that leverage QIS concepts to advance chemistry research.[56] [57]
    - In 2024, the NSF Division of Mathematical Sciences (DMS) Analysis Program supported the "C*-Algebraic Quantum Mechanics and Topological Phases of Matter" workshop (DMS-2406319). The Applied Math Program supported "Beyond IID in Information Theory 12" (DMS-2409823). The Topology Program funded "Quantum Topology, Quantum Information and connections to Mathematical Physics" (DMS-2350250). The Society for Industrial and Applied Mathematics "Quantum Intersections Convening" (DMS-2425995) was funded by Applied Mathematics, Topology, Foundations, and Statistics. In 2023, "ICMS: Topological Quantum Computing" (DMS-2327208) was funded by the Applied Math Program.
    - In 2024, the NSF Engineering Directorate supported the "ERVA Visioning Event on Quantum-Enabled Technologies,"[58] and the second "NNCI Workshop on Quantum Engineering Infrastructure."[59] The latter was organized by the National Nanotechnology Coordinated Infrastructure (NNCI) consortium subgroup on Transforming Quantum Research in collaboration with NSF AccelNet Global Quantum Leap. The 2023 NNCI annual meeting and "Workshop on Nanotechnology Infrastructure of the Future" both included QIS topics.[60] [61]
    - In 2024, the NSF Technology, Innovation and Partnerships (TIP) Directorate continued its investment in a set of projects that collectively constituted a Quantum Technologies Track within the NSF Convergence Accelerator. Earlier, TIP supported a workshop to explore the nexus of climate science and quantum computing in 2023.[62]

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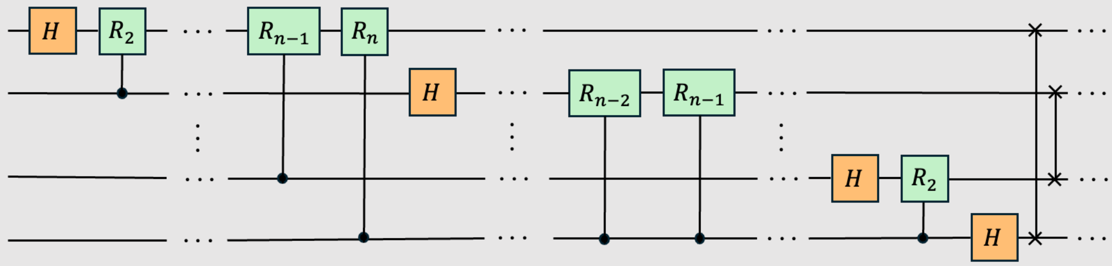
[51] 'Understanding the Universe with Quantum | NSF Discovery Files Podcast' https://www.youtube.com/watch?v=LDcJSvaSOYg
[52] 'Understanding Quantum Computing | NSF Discovery Files Podcast' https://www.youtube.com/watch?v=ohHW4EOPmw4
[53] https://www.quantum.gov/nsf-investing-20m-in-quantum-nanofabrication-infrastructure
[54] https://new.nsf.gov/news/nsf-announces-20-million-investment-quantum
[55] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2403812
[56] Workshop report: https://arxiv.org/abs/2409.04264
[57] MPS Dear Colleague Letter: https://www.nsf.gov/pubs/2024/nsf24134/nsf24134.jsp;
UKRI funding call: https://www.ukri.org/opportunity/epsrc-nsf-exploiting-quantum-information-science-in-chemistry/
[58] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2048419
[59] For a report from the first workshop see: https://nnci.net/sites/default/files/inline-files/WQEI_final_report_final.pdf
[60] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2331369
[61] https://nanoinfrastructureworkshop.sites.stanford.edu/
[62] https://www.quantumforclimateworkshop.com/

Box 3.3

Highlight: Article surveys the current status of quantum computing algorithms



$$R_k = \begin{pmatrix} 1 & 0 \\ 0 & \exp(2\pi i\, 2^{-k}) \end{pmatrix}$$

Figure.3.3: Circuit diagram of the quantum Fourier transform (QFT). The QFT is used in several important quantum algorithms including Shor's algorithm for factoring integers and computing discrete logarithms, phase estimation, and more. The gates shown are the Hadamard (H) and the phase gate (R_k).[63]

The impact of quantum computing on society will depend to a large degree on algorithms that harness quantum degrees of freedom to perform some tasks more efficiently than ordinary, classical computers. For researchers and the public alike, a resource that elucidates such algorithms is quite valuable. A recent article titled "Quantum Algorithms: A survey of applications and end-to-end complexities" does just that, with a tabulation of quantum algorithms and the problems they could solve.[64] These outstanding problems include computational challenges in materials science, quantum chemistry and pharmaceuticals, nuclear and particle physics, many-body physics, optimization (including finance), differential equations, machine learning, and cryptanalysis. The article not only surveys application areas for quantum algorithms, but also their underlying algorithmic primitives. In addition, it examines technical caveats, subtleties, and oracle instantiations to enable an evaluation of the total resources required, thus providing an honest assessment of the potential computational advantage. The article is written using a modular construction that mirrors that of complex quantum algorithms and enables rapid evaluation of how end-to-end complexities are impacted when subroutines are altered. Several authors of the paper received funding from U.S. Government agencies including NSF. A related resource is known as the Quantum Algorithm Zoo.[65]

[63] Image courtesy of NSF, adapted from doi.org/10.48550/arXiv.2310.03011
[64] 'Quantum algorithms: A survey of applications and end-to-end complexities,' doi.org/10.48550/arXiv.2310.03011
[65] https://quantumalgorithmzoo.org/

3.3 The Department of Energy (DOE)

DOE promotes America's prosperity and security through multiple efforts including basic and applied scientific research, discovery and development of new technologies, and isotope production. The DOE National Laboratories are a network of outstanding intellectual assets, unique among world scientific institutions, that also serve as engines of economic growth regionally and across the country.[66] As authorized by the NQI Act, DOE established five National Quantum Information Science Research Centers (NQISRCs).[67] DOE also continues to strengthen and coordinate QIS research throughout its core programs. The DOE Office of Science's (SC's) QIS website provides detailed information about SC QIS programs and access to SC-sponsored workshop reports.[68]

QIS R&D Programs at DOE:

QIS activities span the technical breadth of DOE SC, with investments from all of its research programs—Advanced Scientific Computing Research (ASCR), Basic Energy Sciences (BES), Biological and Environmental Research (BER), Fusion Energy Sciences (FES), High Energy Physics (HEP), the Isotope Program (IP), and Nuclear Physics (NP). DOE SC supports a diverse portfolio of QIS research to advance quantum sensing, computing, and networking, as well as to develop supporting infrastructure and supporting technology. In addition, the DOE National Nuclear Security Administration conducts research on quantum computing hardware and algorithm development in support of stockpile stewardship. Activities are expanding to incorporate QIS in application-based R&D in DOE technology offices as appropriate.

The DOE SC Program Office's QIS web pages,[69] previous years' annual reports on the NQI Program, and the DOE FY 2025 Budget Request contain a broad discussion of how QIS connects to the mission of each DOE component. In brief:

- Quantum sensing efforts in DOE SC core research programs include biosensors and bioimaging, the creation of next-generation detectors and characterization tools, enhancing diagnostic capabilities for plasma and fusion science, using QIS-enabled sensors and experiments to explore new physics and the nature of dark matter and energy, and the use of sensors, radiation-resilient quantum circuits, and nuclear clocks for nuclear science.
- Quantum computing topics span basic research in algorithms, computer science, computing models, complexity theory, software, hardware, quantum simulators, and quantum computing applications in several domains relevant to DOE's mission space and the broader community.
- Quantum networking research and quantum communication projects focus on entanglement generation and distribution, quantum state teleportation, classical-quantum communication coexistence, networking of quantum sensors, and the development of quantum networking architectures, protocols, components, and applications.
- Supporting technology and infrastructure for QIS includes DOE user facilities, such as the Nanoscale Science Research Centers, X-ray light sources, quantum computing and networking testbeds, foundries for spin and superconducting qubits, and the development and stewardship of technologies for producing isotopes needed for quantum systems.

[66] https://science.osti.gov/Laboratories
[67] https://nqisrc.org/
[68] https://science.osti.gov/Initiatives/QIS
[69] https://science.osti.gov/Initiatives/QIS/Program-Offices-QIS-Pages

- Community Resources include a well-established merit-review-based access policy, whereby DOE user facilities continue to support QIS research by offering a suite of enabling resources.[70] User facilities that have strong engagement with the QIS research community include the Leadership Computing facility, the X-ray and Neutron sources, the Nanoscale Science Research Centers, and Fermilab's Cryogenic Facilities. Additionally, Oak Ridge National Laboratory's (ORNL's) Quantum Computing User Program provides access to industrial quantum computing resources for a broad user base,[71] while DOE SC's Quantum Computing Testbeds for Science program provides the research community with fully transparent access to novel quantum computing hardware at Sandia and Lawrence Berkeley National Laboratories.[72] [73]
- Interdisciplinary Centers: The five DOE NQISRCs leverage investments in research and facilities and bring unique approaches to community building through shared research and workforce development efforts. The NQISRCs also create partnerships with efforts developed by other agencies (*e.g.*, NSF QLCIs and the QED-C), the private sector, and academia. In addition, smaller research teams are supported as part of the Energy Frontier Research Centers, focusing on quantum chemistry and materials and related QIS R&D.

DOE QIS R&D activity highlights:

Funding announcements:

- Since FY 2023, the DOE SC has accepted proposals for QIS through the Annual Open Solicitation that is available continuously throughout the FY, as well as the annual solicitation for the SC Early Career Research Program.[74] [75] In addition, proposals for QIS research are accepted through the DOE EPSCoR program.[76]
- (October 30, 2023) DOE FES announced $11.4M in awards for Research on QIS for Fusion Energy Sciences to advance quantum algorithms relevant to fusion and plasma physics on existing and near-term quantum computers, develop novel high-sensitivity measurement techniques for plasmas, and explore the use of high energy density physics methods for novel QIS materials discovery and synthesis.[77]
- (January 19, 2024) DOE ASCR released the Funding Opportunity Announcement (FOA) "EXPRESS: EXPloratory Research for Extreme-Scale Science" which includes "Quantum Hardware Emulation."[78]
- (January 22, 2024) DOE BES released an Energy Frontier Research Centers FOA, which called for renewal proposals for supporting transduction and new quantum methods for advanced sensing and process control, as well as new proposals focused on co-design of materials and processes to revolutionize QIS fabrication.[79]
- (February 7, 2024) DOE ASCR released the FOA for "Accelerated Research in Quantum Computing," which will provide $45M towards the development of a modular software stack and toward quantum utility demonstration.[80]

[70] https://science.osti.gov/User-Facilities
[71] https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/
[72] https://qscout.sandia.gov
[73] https://aqt.lbl.gov
[74] DE-FOA-0003432
[75] DE-FOA-0003176-000001
[76] DE-FOA-0003444
[77] https://science.osti.gov/-/media/funding/pdf/Awards-Lists/2891-FES-QIS-Awards-List.pdf
[78] SC_FOA_0002950
[79] DE-FOA-0003258
[80] DE-FOA-0003265

- (February 10, 2024) As part of the DOE SC Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) program, ASCR announced $1.15M for increased reliability for near-term quantum computers.
- (February 12, 2024) BER announced $250k for Accelerating Quantum Imaging with an Ultra High Speed Imaging Platform with End User Programmable FPGA and GPU.
- (April 1, 2024) DOE BER announced $1.65M in awards for Extended SWIR Single Photon Avalanche Photo Detector Technology for Bioimaging and for quantum-enhanced coherent Raman microscopy and optical and NMR detection of nanodiamond quantum sensors.
- (May 7, 2024) DOE HEP released a funding announcement titled QIS Enabled Discovery for High Energy Physics, which will provide up to $70M in the next five years for using QIS to support the HEP mission of understanding how the universe works at its most fundamental level.[81]
- (July 8, 2024) DOE BER announced interest in receiving applications for Quantum Enabled Bioimaging and Sensing Approaches for Bioenergy as part of the SBIR/STTR program.
- (July 10, 2024) DOE's BES & Advanced Materials and Manufacturing Technologies Office announced support for two innovators working on technology transfer for quantum sensors and scalable quantum computers though the Lab-Embedded Entrepreneurship Program.
- (September 4, 2024) DOE BES announced support for 10 new and renewing multi-disciplinary, multi-institutional research centers under the Energy Frontier Research Centers Program, including three awards for QIS R&D – the Quantum Photonic Integrated Design Center, the Center for Molecular Quantum Transduction, and the Center for Quantum Sensing and Quantum Materials.[82]
- (September 9, 2024) DOE ASCR announced $65M in funding in quantum computing for ten projects, comprising a total of 38 separate awards. These investments target software, control systems, and algorithmic advancements toward utility for scientific research problems in DOE's mission space by improving all levels of the quantum computing software stack.[83]

R&D for Supporting Technology:

- DOE IP has developed new methods for producing stable isotopes of ytterbium-171, -172, and silicon-28, which are relevant to quantum memory and quantum computation, respectively. New production methods for semiconductor grade gas are being investigated. DOE IP is investigating a production pathway to replenish rubidium-87 inventories used in atomic clocks.
- DOE IP manages the helium-3 inventory for the nation, which is critical for the operation of cryogenics necessary for many QIS technologies, and is working to develop new sources of it. Other investments in helium-3 include capture from additional storage beds of tritium to increase the nation's stockpile.

Community Engagement, Workshops, and Reports:

- (2023) DOE BES & NSF sponsored an assessment on Advancing Chemistry and Quantum Information Science: An Assessment of Research Opportunities at the Interface of Chemistry and QIS.[84]

[81] DE-FOA-0003354-000001
[82] https://www.energy.gov/science/articles/department-energy-announces-118-million-energy-frontier-research-centers
[83] https://www.energy.gov/science/articles/department-energy-announces-65-million-quantum-computing-research
[84] 'Advancing Chemistry and Quantum Information Science: An Assessment of Research Opportunities at the Interface of Chemistry and Quantum Information Science in the United States', doi:10.17226/26850

- (December 20, 2023) DOE and NIH hosted a roundtable on "Quantum Computing for Biomedical Computational and Data Sciences.[85]
- (January 2024) DOE BER released the Biomolecular Characterization and Imaging Principal Investigator (PI) meeting proceedings on bioimaging and quantum imaging and sensing.
- (April 2-4, 2024) DOE BER held the expanded Enabling Capabilities and Resources PI meeting, in conjunction with the Genomic Sciences meeting, featuring a session on quantum imaging and sensing in biology.
- (May 20-22, 2024) Led by the DOE NQISRCs, the Joint Algorithms & Applications Workshop discussed the latest developments in quantum algorithms and applications in QIS.
- (May 30-31, 2024) The first iteration of a new workshop series on the subject of Radiation Impact on Superconducting Qubits brought together the broader QIS, particle, and nuclear physics communities to assess the effects of radiation and cosmic rays on superconducting solid-state qubits and development of the tools needed to address the problem.
- (August 17, 2024) DOE ASCR published a report from the Workshop on Basic Research Needs in Quantum Computing and Networking, where major opportunities and challenges were discussed and identified.[86]
- (September 17-19, 2024) The DOE NQISRCs met to showcase the scientific achievements at each center and coordinate activities. Topics of discussion included the impact of the Centers on the QIS landscape, facilities and instrumentation developments, partnerships with industry and academia to accelerate innovation, QIS ecosystem stewardship, and workforce development.

<u>QIS R&D Advances:</u>

- (September 26, 2023) DOE SC-funded research identified the stability and molecular pathways to create the desired vacancies for qubits and determine their electronic properties. These advances will help the design and fabrication of spin-based qubits with atomic precision in semiconductor materials, having implications in quantum computing and sensing.[87]
- (November 16, 2023) DOE BES funded researchers at Pacific Northwest National Laboratory developed a hybrid quantum flow approach, QFlow, to integrate features of both classical and quantum computing to solve chemical problems. Current quantum computing applications are significantly limited by the size of available quantum devices. QFlow combines variational problems defined by effective Hamiltonians, which capture the energy of a system using a subset of orbitals, and drastically reduces the dimensionality of the problem.[88]
- (November 20, 2023) An international team that included ORNL and academia was awarded the 2023 Gordon Bell Prize for the development of a method for achieving quantum accuracy in materials simulations.[89]
- (May 20, 2024) DOE BER-funded work demonstrated unique spectroscopic properties of quantum spectroscopy and a dramatic increase in the sensitivity of fluorescence imaging.[90]
- (April 3, 2024) Scientists at QSA worked with academia to demonstrate quantum state control of individual polyatomic molecules, CaOH, in a one-dimensional array of optical tweezers. Polyatomic molecules have rich internal structures including rotations, vibrations, and nuclear

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[85] 'Quantum Computing for Biomedical Computational and Data Sciences: A Joint DOE-NIH Roundtable,' doi:10.2172/2228574
[86] https://www.osti.gov/servlets/purl/2001045
[87] 'Engineering the formation of spin-defects from first principles,' doi:10.1038/s41467-023-41632-9
[88] 'Quantum flow algorithms for simulating many-body systems on quantum computers,' doi:10.1103/PhysRevLett.131.200601
[89] 'Large-Scale Materials Modeling at Quantum Accuracy: Ab Initio Simulations of Quasicrystals and Interacting Extended Defects in Metallic Alloys.' doi:10.1145/3581784.362703
[90] https://www.energy.gov/science/ber/articles/seeing-color-entangled-photons-molecular-systems

spins that could be harnessed for next-generation quantum technologies, and the realization of an optical tweezer array demonstrates the ability to control this structure at the level necessary to build a novel quantum platform.[91]

- (April 24, 2024) DOE NP-supported research on spectroscopic measurements and models of energy deposition in the substrate of quantum circuits by natural ionizing radiation suggest several paths to reducing the impact of background radiation on quantum circuits.[92]
- (June 27, 2024) DOE ASCR supported research at Sandia National Laboratories and academia that discovered that quantum computers are usually not faster than regular computers; instead, they use far less memory. This revelation shifts the conventional focus of the benefits of quantum computing from speed to memory efficiency. The finding could also help researchers to address real-world uses that impose large memory demands.[93]
- (July 8, 2024) The first mechanical detection of nuclear decays using quantum control of an optically-levitated nanoparticle has been observed by DOE NP-supported researchers. This technique could enable detection capabilities for noninteracting particles, such as sterile neutrinos or dark matter.[94]

[91] 'An optical tweezer array of ultracold polyatomic molecules,' doi:10.1038/s41586-024-07199-1

[92] 'Spectroscopic measurements and models of energy deposition in the substrate of quantum circuits by natural ionizing radiation.' doi.org/10.48550/2404.10866 [accepted to PRX Quantum]

[93] https://www.sandia.gov/labnews/2024/06/27/quantum-computers-unexpected-advantage/

[94] 'Mechanical Detection of Nuclear Decays.' doi.org/10.1103/PhysRevLett.133.023602

Box 3.4

Highlight: Advances for "Programmable" Optical Qubits

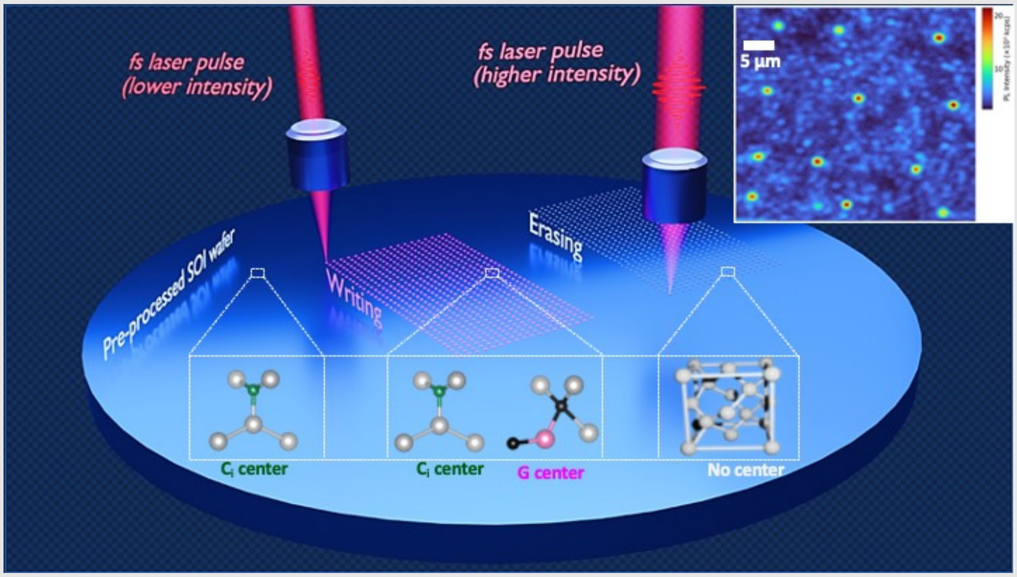

Figure 3.2: An artistic depiction of a new method to create high-quality color-centers (qubits) in silicon at specific locations using ultrafast laser pulses (fs: femtosecond, or one quadrillionth of a second). The inset at the top-right shows an experimentally observed optical signal (photoluminescence) from the qubits, with their structures displayed at the bottom.[95]

Connecting large arrays of solid-state qubits to build a quantum computer is a challenging task. As quantum emitters, silicon-based qubits offer benefits in scalability, ease of integration, long coherence times, and bright telecom-band single photon emission. Current manufacturing approaches include creating qubits by annealing an entire silicon wafer at high temperatures. With these methods, defect-based qubits such as color centers and quantum emitters form randomly in the silicon's crystal lattice. However, without knowing exactly where qubits are located in a material, realizing a quantum computer with connected qubits will be difficult. A research team supported by the DOE FES and led by Lawrence Berkeley National Laboratory has developed a method that programs the formation of qubits in silicon for large-scale manufacturing using a femtosecond laser. Their experiments explored the role of hydrogen in qubit formation, using hydrogen-based defect activation and passivation at the single quantum emitter level.[96] This advancement could lead to more controlled manufacturing of qubit arrays.

[95] Image courtesy of K. Jhuria/Berkeley Lab
[96] 'Programmable quantum emitter formation in silicon,' doi.org/10.1038/s41467-024-48714-2

3.4 The Department of Defense (DOD)

The DOD Research & Engineering mission supports the national defense strategy via basic and applied research, advanced technology development, and operational tests and evaluations of new technologies. Quantum science is one of DOD's 14 critical technology areas and has been a focus of sustained DOD funding for over 30 years.[97] DOD continues substantial investments in basic QIS R&D activities via several offices, agencies, and laboratories including: the Office of the Under Secretary of Defense for Research and Engineering (OUSD(R&E)), the Defense Advanced Research Projects Agency (DARPA), the Air Force Research Laboratory (AFRL), the Air Force Office of Scientific Research (AFOSR), the Army Research Laboratory (ARL), the Army Research Office (ARO), the Naval Research Laboratory (NRL), and the Office of Naval Research (ONR). The DOD FY 2025 Budget Request highlighted that "The DOD's R&D of quantum technologies is critical to maintaining the Nation's technological superiority," with the intent to mature, accelerate, demonstrate, and transition existing and emerging quantum technologies, along with their supporting supply chains, and cultivate the technical talent needed to develop and maintain such advanced technology.[98]

DOD QIS R&D Programs:

The DOD quantum R&D programs span atomic clocks, quantum sensing, quantum computing, and quantum networking from fundamental to applied R&D:

- Atomic clock programs across DOD are advancing the technology readiness level (TRL) of precision timekeeping technologies that support DOD missions such as synchronized timing and precision targeting, positioning, and navigation in denied environments. These efforts include: OUSD(R&E)'s Next Generation Atomic Clock (NGAC) program, executed by ONR,[99] OUSD(R&E)'s and ARL's Low-Cost Chip-Scale Atomic Clock (LCCSAC) program,[100] the new OUSD(R&E) Rack Mounted Optical Clock (RMOC) procurement program which is through the Accelerate the Procurement and Fielding of Innovative Technologies Pilot Program,[101] the United States Naval Observatory (USNO) timekeeping research for the USNO Master Clock,[102] AFRL's Quantum Sensing and Timing Program,[103] DARPA's H6 program,[104] and DARPA's Robust Optical Clock Network (ROCkN) program.[105]
- Quantum Sensors will address long-term military challenges for obtaining military advantage in intelligence, surveillance, and reconnaissance (ISR), as well as PNT. The Transition of Quantum Sensors program is a first of its kind 6.3 budget activity that has been established at the Defense Innovation Unit (DIU) with OUSD(R&E) support to mature certain quantum sensors toward TRL 6.[106] Additional R&D programs to develop gyroscopes, accelerometers, magnetometers, gravimeters, and electrometers include the OUSD(R&E)/ARL Center for Excellence in Advanced Quantum Sensing,[107] DARPA's Science of Atomic Vapors for New

[97] https://www.cto.mil/usdre-strat-vision-critical-tech-areas/
[98] comptroller.defense.gov/Portals/45/Documents/defbudget/FY2025/budget_justification/pdfs/03_RDT_and_E/RDTE_OSD_PB_2025.pdf
[99] https://www.onr.navy.mil/-/media/Files/Funding-Announcements/Special-Notice/2020/N00014-20-S-SN17.ashx
[100] https://www.arl.army.mil/lccsac/
[101] https://www.defense.gov/News/Releases/Release/Article/3745188/dod-announces-next-round-of-projects-to-receive-funding-from-pilot-program-to-a/#:~:text=The%20purpose%20of%20the%20APFIT,businesses%20and%20nontraditional%20defense%20contractors.
[102] https://www.cnmoc.usff.navy.mil/Our-Commands/United-States-Naval-Observatory/Precise-Time-Department/
[103] https://www.afrl.af.mil/RVQST/
[104] https://www.darpa.mil/program/h6
[105] https://www.darpa.mil/program/robust-optical-clock-network
[106] https://www.diu.mil/latest/defense-innovation-unit-launches-first-cso-under-new-emerging-technology
[107] https://www.cto.mil/news/dod-launches-center-of-excellence-in-advanced-quantum-sensing/

Technologies (SAVaNT),[108] Quantum Apertures,[109] Macaroni,[110] and Quantum Imaging of Vector Electromagnetic Radiation (QuIVER) programs,[111] ARL's Electromagnetic Field Sensing with Rydberg Atoms program,[112] ARO's Quantum State Engineering for Enhanced Metrology and Multi-qubit Enhanced Sensing and Metrology Multidisciplinary University Research Initiatives (MURIs),[113] ONR's atom interferometry efforts for inertial and gravity sensors, AFRL's Quantum Sensing and Timing (QST),[114] DIU's Quantum IMU Experiment (QuIX), DIU's Quantum Transitioning Inertials Program (Q-TIP) programs, and the AFOSR MURI on Cold Molecules.

- Quantum Computing will address long-term military challenges in areas such as access to high-performance computing. Ongoing basic research efforts include DARPA-led efforts on alternative computing,[115] Underexplored Systems for Utility-Scale Quantum Computing (US2QC),[116] and the Quantum Benchmarking Initiative (QBI).[117] MURI awards support QIS research across the DOD. This includes AFOSR MURIs on Dissipation Engineering, Quantum Random Access Memory, Synthetic Quantum Matter, and N-qubit Gates, the AFOSR/ONR Quantum Photonics MURI, the AFOSR National Science Portal topic on Leveraging Quantum Computing to Explore Computational Challenges, the ARO MURIs on Enhanced Quantum Control via Spectator Qubits and Quantum Error Correction Under Control, the ARO/AFOSR MURI on Modular Quantum Computing, and the ONR MURIs on Molecular Qubits for Synthetic Electronics and Novel Routes to Majorana Qubits for Topologically-Protected Quantum Information.
- Materials Research for QIS focuses on materials science approaches to solving scientific challenges in solid-state-based quantum systems. Current programs include the AFOSR Create the Future Independent Research Effort program to study the next generation of point defects in wide band gap materials and in group II-oxide hosts for quantum sensing and quantum networking applications, the AFOSR/LPS program on Materials Characterization and Quantum Performance: Correlation and Causation to investigate the ways in which materials properties affect gate-defined quantum dots and superconducting qubit performance, the AFOSR MURIs on Non-Hermitian Programmable Materials at Exceptional Points, Dislocations as One-Dimensional Quantum Matters, Piezoelectric Materials Interfaced with Semiconductors for Integrated Quantum Systems, Principles of Non-reciprocal Quantum Materials and Tunable Superconducting Diodes, Hot Solid-State Qubits, and the ARO MURI on Ab-Initio Solid-State Quantum Materials: Design, Production, and Characterization at the Atomic Scale.
- Quantum Networks are expected to be a resource for fundamental R&D and impact the internal architectures for large-scale quantum systems such as quantum computers. The DOD service labs (AFRL, ARL, and NRL) have efforts in heterogenous quantum networking R&D including photonic, atomic/ionic, and superconducting technologies, as well as efforts in algorithms, transduction, and joint designs of integrated ionic and photonic components. Beyond internal data routing for a quantum computer, there may yet be broader external opportunities for quantum networks, such as those being explored by DARPA's Quantum Augmented Network

108 https://www.darpa.mil/program/science-of-atomic-vapors-for-new-technologies
109 https://www.darpa.mil/program/quantum-apertures
110 https://www.darpa.mil/program/macaroni
111 https://www.darpa.mil/program/quantum-imaging-of-vector-electromagnetic-radiation
112 https://www.army.mil/article/242980/army_researchers_detect_broadest_frequencies_ever_with_novel_quantum_receiver
113 https://www.cto.mil/wp-content/uploads/2020/02/fy2020-muri-press-release.pdf
114 https://afresearchlab.com/technology/quantum/
115 https://www.darpa.mil/news-events/2020-05-11a
116 https://www.darpa.mil/news-events/2021-04-02
117 https://www.darpa.mil/news-events/2024-07-16

(QuANET) program.[118] In addition, DOD quantum networking testbeds include the Starfire Optical Range 1-Mile site, AFRL Distributed Quantum Networking Test Bed, and service-lab participation in the Washington Metropolitan Quantum Network Research Consortium (DC-QNet). Other programs include ARO MURIs on Quantum Network Science and Entanglement, AFOSR MURIs on Quantum Many-Body Physics with Photons, Free-space Atmospheric Link for Quantum Optical Networks (FALQON), and Quantum Information Concepts from Tensor Networks, and an ONR MURI on Fundamental Limits of Distributed Entangled Quantum Sensing.

DOD QIS R&D activity highlights:

Funding QIS R&D:

- (2024) DARPA issued several special notices for Disruption Opportunities in 2024 related to QIS,[119] including Measurement-based Quantum Information and Transduction (MeasQuIT),[120] Synthetic Quantum Nanostructures (SynQuaNon),[121] Photon-Efficient Nanoscale Optical Metrology (PhENOM),[122] and Automated Prediction Aided by Quantized Simulators (APAQuS).[123]
- (September 20, 2023) The DOD announced nearly $240M to eight regional innovation hubs that will be a part of the Microelectronics (ME) Commons, with four of these hubs supporting quantum technology.[124]
- (October 2024) DARPA ran QIS-related Advanced Research Concepts during 2024, which included Imagining Practical Applications for a Quantum Tomorrow (IMPAQT), intended to explore the capabilities of hybrid quantum-classical computational systems.[125]
- (February 23, 2024) AFOSR, ARO, and ONR released a FY 25 MURI funding announcement that include topics on multi-qubit gates, hot solid-state qubits, principles of non-reciprocal quantum materials and tunable superconducting diodes, quantum machine learning foundations for quantum data processing, quantum simulators for materials design, and fundamental limits of distributed entangled quantum sensing.[126]
- (May 3, 2024) AFOSR released the FY 2024 National Science Portal. One topic, Leveraging Quantum Computing to Explore Computational Challenges, seeks to explore the viability of novel quantum algorithms relevant for the DOD and Air Force to expand research capabilities.[127]
- (May 31, 2024) DARPA published a solicitation, Enhancing Quantum Sensor Technologies with Rydberg Atoms (EQSTRA), seeking atomic vapor sensing research proposals.[128]
- (September 17, 2024) DOD announced $269M in awards for 33 new technical projects under the Microelectronic Commons initiative. AFRL, in collaboration with academia and industry, received a four-year $15M award that focuses on developing and transitioning the building

[118] https://sam.gov/opp/4587b8304a0b4ad3828cb1bed1ee7482/view
[119] https://www.darpa.mil/work-with-us/disruptioneering
[120] https://www.darpa.mil/program/measurement-based-quantum-information-and-transduction
[121] https://www.darpa.mil/program/synthetic-quantum-nanostructures
[122] https://www.darpa.mil/program/photon-efficient-nanoscale-optical-metrology
[123] https://sam.gov/opp/d50c14eb2b184bb5bd69a51b8669a070/view
[124] https://www.defense.gov/News/News-Stories/Article/Article/3532338/
[125] https://www.darpa.mil/arc
[126] https://grants.gov/search-results-detail/352609
[127] https://grants.gov/search-results-detail/353974
[128] https://sam.gov/opp/c56228ff6cca422290356fdb404cdc8e/view

blocks of a quantum network to foundries and combining these components into systems on chip.[129]

QIS R&D in the News:

- (September 27, 2023) As part its QuIX program, DIU received an industry developed, fully integrated, high-performance atomic gyroscope and accelerometer for space flight.[130] This atomic inertial sensor is the first of its kind to undergo space qualification and is expected to be the first to operate in space.
- (October 11, 2023) DOD-funded researchers demonstrated a new neutral atom qubit using the nuclear spin of a metastable state in Ytterbium-171. The work achieved the execution of high-fidelity one and two qubit gates on Yt-171 and determined that a large fraction of gate errors can be converted into “erasure errors,” which greatly simplifies error correction processes.[131]
- (November 29, 2023) AFOSR-sponsored research, jointly funded by NSF and DOE Q-NEXT, demonstrated an innovative approach that makes qubits easier to control at higher temperatures by strain engineering a diamond membrane, leading to reduced coupling of the qubit to lattice vibrations and prolonged coherence times. The work also showed that the quantum system could be controlled via microwaves for less resource-intensive operations.[132]
- (April 5, 2024) NRL researchers demonstrated the optimal suppression of time-varying errors in matter-wave-interferometer inertial sensors through synchronous control of sensor parameters. This patent-pending Continuous 3D-Cooled Atom Beam Interferometer is derived from a cold and continuous beam of atoms to explore atom-interferometry-based inertial measurement systems as a path to reduce drift in Naval navigation systems.
- (June 20, 2024) Six months into the second phase of DARPA’s Quantum Benchmarking Program, five teams have highlighted research findings focused on specific applications where quantum computing might make an outsized impact over digital supercomputers, along with size estimates for what quantum computer is needed to achieve the desired performance.[133]
- (June 11, 2024) ONR-funded researchers demonstrated a novel atom-interferometer gravimeter that holds the atoms in an optical lattice and is capable of minute-level interrogation times. The system demonstrated 6 nm/s^2 accuracy, a factor of four better than atomic fountain counterparts.

[129] https://www.defense.gov/News/Releases/Release/Article/3908176/administration-awards-269m-for-microelectronics-manufacturing-and/
[130] https://www.diu.mil/latest/quantum-sensing-enters-the-dod-landscape-in-first-of-a-kind-high-performance
[131] ‘High-fidelity gates and mid-circuit erasure conversion in an atomic qubit,’ doi:10.1038/s41586-023-06438-1.
[132] ‘Microwave-Based Quantum Control and Coherence Protection of Tin-Vacancy Spin Qubits in a Strain-Tuned Diamond-Membrane Heterostructure,’ doi:10.1103/PhysRevX.13.041037.
[133] https://www.darpa.mil/news-events/2024-06-20

Box 3.5

Highlight: Air Force demonstrate quantum magnetometers as navigation aids

Figure 3.5: (Top Left) MagNav equipment loaded onto a DOD Aircraft prior to its first real-time demonstration.[134] (Top Right) MagNav sensors loaded in AgilePod on a DoD Aircraft prior to real-time flight test. (Bottom) Close up of the AgilePod.[135]

The Global Positioning System (GPS) provides the world with position, navigation, and timing (PNT) information. However, GPS is subject to denial and disruption, opening vulnerabilities affecting access to critical PNT. Certain quantum sensing technologies can offer alternatives to GPS, for example through gravimetry or magnetometry.

In partnership with industry, academia, and an FFRDC, AFRL and the Air Force Institute of Technology (AFIT) led the development of a new navigation system called Magnetic Anomaly Navigation (MagNav). MagNav uses the low-drift nature of quantum magnetometers to measure the Earth's magnetic field. A proof-of-concept was conducted in 2016 by AFIT using data from a geosurvey aircraft,[136] and follow-on efforts resulted in real-time flight testing on manned operational platforms in early 2024, completing the first continuous multi-hour, over-water demonstration.

In a different demonstration under an SBIR contract, a MagNav system produced a measurement of the Earth's crustal field despite the magnetic interference from the metal and equipment on the plane. The demonstration showed the viability of quantum magnetic sensors to assist in long range, over water airborne navigation.[137]

MagNav is advancing through a joint effort between the Defense Innovation Unit's (DIU) Transitions for Quantum Sensor (TQS) program and OUSD(R&E) with strong engagement and transition partners across the services. The TQS program focuses on demonstrating the military utility of quantum sensors to address strategic competencies like PNT and anomaly detection.

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[134] https://www.af.mil/News/Article-Display/Article/3408951/magnav-project-successfully-demonstrates-real-time-magnetic-navigation/

[135] Images courtesy of OUSD(R&E)

[136] "Absolute Positioning Using the Earth's Magnetic Anomaly Field," doi:10.1002/navi.138.

[137] https://www.jbcharleston.jb.mil/News/Commentaries/Display/Article/3869993/jb-charleston-demos-real-time-quantum-magnetic-navigation-technology/

3.5 The National Aeronautics and Space Administration (NASA)

NASA continues to drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth. NASA's QIS research portfolio includes several activities led by various directorates and programs at NASA Headquarters, supported by the Jet Propulsion Laboratory (JPL), Glenn Research Center (GRC), Ames Research Center (ARC), and Goddard Space Flight Center (GSFC), along with national and international partners in FFRDCs, academia, and industry. These activities in basic and applied science and engineering span QIS areas in quantum computing and software, quantum sensing, quantum communications and networking, as well as space-based fundamental science and exploration.

NASA QIS R&D activity highlights:

- The Biological and Physical Sciences Division at NASA Headquarters funds a number of space- and ground-based QIS projects. These include the Cold Atom Lab (CAL) on the International Space Station and its follow-on, the Bose Einstein Condensate CAL, which enables quantum research and tests of fundamental physics in a microgravity environment. The Space Entanglement and Quantum Annealing Experiment (SEAQUE) will test how exposure to space radiation affects a quantum entanglement source. These R&D projects, many based at JPL, involve a number of academic and international partners including the European and German space agencies.
- NASA flew a quantum-based x-ray microcalorimeter on JAXA's XRISM mission, launched in 2023, to study the hot universe including exploding stars and clusters of galaxies.
- NASA installed a quantum-based single nanowire single-photon detector at the Mount Palomar observatory to detect faint signals from the Deep Space Optical Communications technology demonstration on Psyche, now transmitting to Earth from beyond Mars.
- NASA GSFC is engaged in cross-Government quantum networking research and experiments with seven agencies as a member of the DC-QNet Consortium. NASA-supported research topics span quantum augmented network model adaptations, free-space quantum networking studies, link-modeling, and fiber stabilization.
- GSFC recently established the Quantum Engineering and Sensing Technology (QuEST) Laboratory, focused on promoting and accelerating quantum-sensing technologies for space-based science and exploration. GSFC is collaborating with a number of universities on research projects including quantum networking and quantum computing.
- NASA's Quantum Artificial Intelligence Laboratory (QuAIL) at ARC conducts R&D in quantum computing and communications in collaboration with other Government agencies, academia, international institutions, and industry. The QuAIL team published a recent article describing NASA's work in assessing and advancing the potential of quantum computing.[138]
- GRC has worked with multiple organizations to develop low size, weight, and power (SWaP) quantum technologies and has also established metrology capability to fully characterize entanglement sources for both terrestrial and aerospace applications.

[138] 'Assessing and advancing the potential of quantum computing: A NASA case study,' doi.org/10.1016/j.future.2024.06.012

Box 3.6

Highlight: NASA-DLR CAL and BECCAL Experiments on the International Space Station

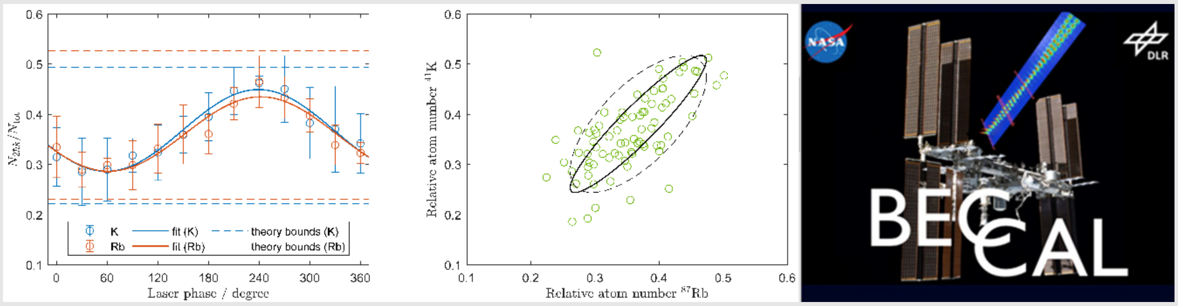

Figure 3.6: (Left) Simultaneous interferometry of 87Rb and 41K BECs showing the expected fringes and phase-correlations in CAL.[139] *(Right) Graphic for the future BECCAL mission.*

Bose-Einstein Condensate Cold Atom Lab, or BECCAL, is a joint German Aerospace Center (DLR) and NASA mission. BECCAL is a follow-on to the Cold Atom Lab (CAL) on the International Space Station (ISS). CAL was launched to the ISS in 2018 and demonstrated the first Bose-Einstein condensate in orbit reaching temperatures below 100 pK with ^{87}Rb, ^{41}K and ^{39}K. CAL research over the last year resulted in a number of scientific results, including the first dual-species atom interferometry in space which serves as a pathfinder for important applications in fundamental physics, geodesy, and PNT.[140] More recently, a CAL demonstration used an atom interferometer to measure the vibrations aboard the ISS, becoming the first atom interferometry-based quantum sensor in space. Such quantum sensors are some of the most precise instruments in the world on the ground, and promise to be orders of magnitude more sensitive in the microgravity of space.

CAL has collected quantum data from tens of thousands of experimental runs, supporting five principal investigation teams. For BECCAL, JPL is developing a narrow-scope ground testbed to provide support and training prior to a fully DLR-provided ground testbed system delivered to JPL. Selection of U.S. BECCAL PI-led projects is planned for 2025, with launch to the ISS planned for 2027.

[139] 'Quantum gas mixtures and dual-species atom interferometry in space,' doi.org/10.1038/s41586-023-06645-w

[140] 'Pathfinder experiments with atom interferometry in the Cold Atom Lab onboard the International Space Station,' doi.org/10.1038/s41467-024-50585-6

3.6 The National Security Agency (NSA)

The NSA sponsors and performs QIS R&D via the Laboratory for Physical Sciences (LPS), including quantum computing and sensing, along with several enabling technologies. Based on the importance of QIS to national security, LPS has spearheaded efforts to support the NQI and contribute to the goals of the National Strategy for QIS. LPS sponsors extramural research projects that target fundamental questions needed to understand the potential of quantum computing and grow robust, interconnected research communities at universities, laboratories, and commercial enterprises, both directly and in partnership with ARO, AFOSR, and other agencies.[141] LPS also conducts internal research related to quantum computing and sensing at its College Park, MD facility. In 2020, the LPS Qubit Collaboratory (LQC) was created to support the NQI Act as a QIS Research Center, enabling strong interactions with agencies, industry, and academic institutions across the Nation. As part of the LQC, the Qubits for Computing Foundry (QCF) was initiated to fabricate state-of-the-art qubits for the broader research community. In addition, NSA, in its cybersecurity capacity, is charged with several key roles in defending National Security Systems from the risks posed by the adversarial acquisition of a cryptanalytically-relevant quantum computing capability.

NSA QIS R&D activity highlights:

- LPS's extramural quantum computing research programs include: Quantum Computing in the Solid State with Spin and Superconducting Systems (QCS^5), Trapped Ions and Neutral Atoms (TINA), Quantum Characterization of Intermediate-Scale Systems (QCISS), and New & Emerging Qubit Science & Technology (NEQST).
- LPS and ARO launched the TINA program in August 2024. This program focuses on three sub-topic areas: (1) performing two-qubit gates between two spatially separated modules; (2) increasing the speed of high-fidelity qubit operations; and (3) increasing the versatility of atomic qubits through innovative concepts in a multi-qubit setting.
- LPS is collaborating with AFOSR to start the Materials Characterization and Quantum Performance program, which takes a "materials-first" approach to improving stability and reproducibility of state-of-the-art qubits and focuses on solid-state qubits built from semiconductor and superconductor material systems. The goal is to use materials characterization to identify correlations between material properties and qubit performance.
- The QCF, in partnership with MIT Lincoln Laboratory and Industry, provided state-of-the-art superconducting and spin qubits to research groups that would not otherwise have access. The Lincoln Laboratory QCF foundry has advanced beyond a pilot phase and has the capacity to support over twenty research projects per year.[142] As of April 2024, this foundry has supported efforts at AFOSR, AFRL, ARO, DARPA, DOE, NSA, NSF, and ONR, totaling 145 qubit devices shipped to date.
- LQC hosted a community workshop to identify research opportunities that could be pursued if one had access to a small-scale fully-open quantum processor. Three opportunities were identified: (1) A robust 3-qubit device that supports 95% of hands-on workforce development needs; (2) A device with less than 7-qubits with various connectivity and coupling to support research of open quantum systems and provide hardware to enable quantum characterization, verification, and validation; (3) A 17-qubit device to make elementary quantum error correction processors accessible to the U.S. research community.

[141] http://www.lps.umd.edu/solid-state-quantum-physics/index.html
[142] https://www.qubitcollaboratory.org/qubits-for-computing-foundry-qcf-announcement/

- The quantum sensing research program at LPS focuses on defect centers in solid state materials and their use as sensitive, near-field magnetometers. The emphasis is on microscopic imaging of important materials and circuits, both quantum and classical, and identifying potential applications to a range of national security problems.

Box 3.7

Highlight: Pushing the limits of superconducting qubit gate errors

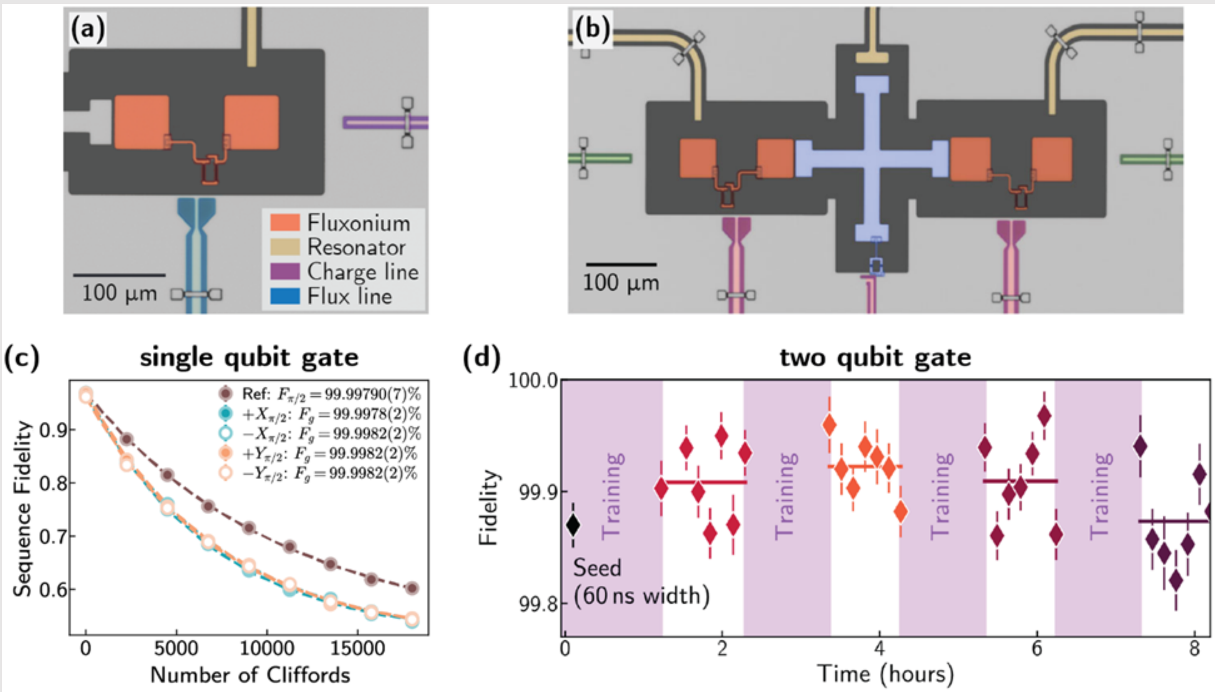

Figure 3.7: (a) Device image for leading 1 qubit error on fluxonium.[143] (b) Device image for a high fidelity two-qubit gate with fluxonium.[144] (c) Example data from (b), illustrating the achieved 1-qubit gate fidelity exceeding 99.9978% and (d) 2-qubit gate fidelity exceeding 99.9% (Error % = 100 % – fidelity %).

The LPS/ARO portfolio is focused on uncovering and overcoming fundamental limits on qubit performance. A basic measure of performance is qubit gate error. As an example, performers in the LPS QCS[5] program have reached record-low qubit gate errors in both superconducting and semiconducting qubits. Figure 3.7 shows recent examples for a novel superconducting qubit type: The Fluxonium Qubit, which has reached record fidelities for both 1 and 2 qubit gates.

[143] 'Suppressing Counter-Rotating Errors for Fast Single-Qubit Gates with Fluxonium,' doi.org/10.48550/arXiv.2406.08295
[144] 'High-Fidelity, Frequency-Flexible Two-Qubit Fluxonium Gates with a Transmon Coupler,' doi.org/10.1103/PhysRevX.13.031035

3.7 The Intelligence Advanced Research Projects Activity (IARPA)

IARPA sponsors high-risk, high-payoff R&D to deliver innovative technologies to the intelligence community and the Federal Government. Since its inception in 2008, IARPA has invested in quantum-computing research, represented currently by the four-year Entangled Logical Qubits (ELQ) program.[145] The ELQ program seeks to demonstrate a high-fidelity logical entangled state and utilize it to teleport a logical state from one error-corrected logical qubit to another. ELQ has four performers, each pursuing different technical expressions of qubits drawn from superconducting, neutral-atom, and trapped-ion technologies.

Box 3.8

Highlight: Different architectures for logical qubit entanglement

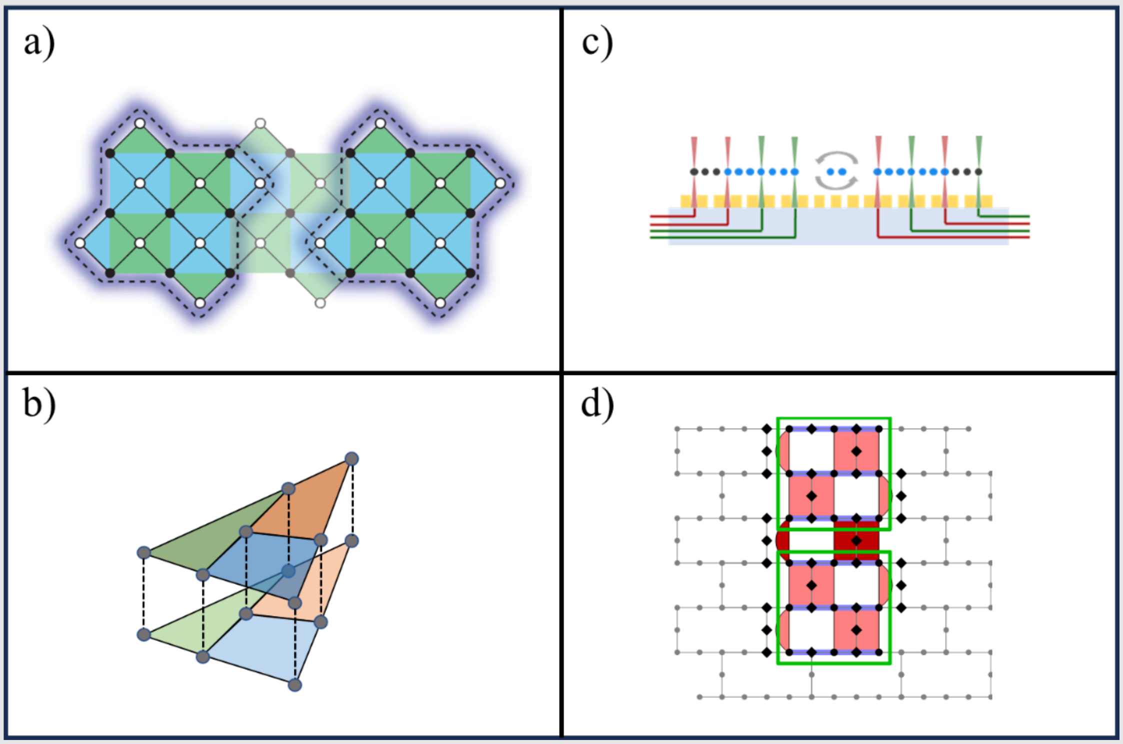

Figure 3.8: ELQ's logical-qubit entanglement concepts. (a) Logical entanglement concept based on the surface code and the lattice surgery approach, to be realized separately using fluxonium and transmon qubits. (b) Applying transversal gates between copies of the Steane (color) code, made with neutral-atom qubits. (c) Logical qubit entanglement using the lattice surgery approach between color codes in trapped-ion systems incorporating integrated optics. (d) Lattice surgery concept based on the so-called heavy-hex code, to be implemented on a transmon-based quantum computer.[146]

Logical qubits and operations involving their entanglement will be integral to future quantum computers used for solving sophisticated problems beyond the reach of classical computers. Logical qubits undergoing logical operations, including entanglement, must be accompanied by quantum error correction, a process that counters inevitable mechanisms of noise by identifying errors and correcting them while the quantum computation is taking place. Logical entanglement itself is a resource for quantum computing, being essential for logical qubit teleportation and related logical gates.

[145] https://www.iarpa.gov/research-programs/elq
[146] Images courtesy of IARPA

For quantum-computing architectures to be effective, the complexities associated with logical operations and quantum error correction must be specially designed and implemented to prevent instances of error from dispersing and multiplying uncontrollably, providing a property called fault-tolerance. IARPA's ELQ program looks ahead to these future challenges in quantum computing by having its teams (a) incorporate quantum error correction in all logical qubit protocols, (b) implement logical qubit operations fault tolerantly, and (c) demonstrate entanglement and teleportation through systems comprising independently operable logical qubits. The final goal of ELQ is to teleport cardinal logical states with an average success rate of 95% or higher in a modular, fault-tolerant architecture. ELQ is in its initial phase, where the four teams are investigating and optimizing architectural concepts while building initial, high-performance stages for single logical qubit operation (see Box 3.8). The program is expected to make profound advances toward realizing the full potential of quantum computing.

3.8 Concluding remarks for QIS R&D Overview

It should be emphasized that the selected QIS R&D highlights featured in the boxes and points throughout this Section provide only a representative sampling of the recent breakthroughs and capabilities that have been accelerated by NQI activities across Federal agencies.

4 QIS Policy Areas

The *National Strategic Overview for QIS* provides recommendations to strengthen the U.S. approach to QIS R&D, focusing on six areas: science, workforce, industry, infrastructure, security, and international cooperation, as shown in Figure 4.1. This section presents a brief overview of the policy goals for each of these topics, along with highlighted activities that have been undertaken across the Federal Government to fulfill these policy objectives.

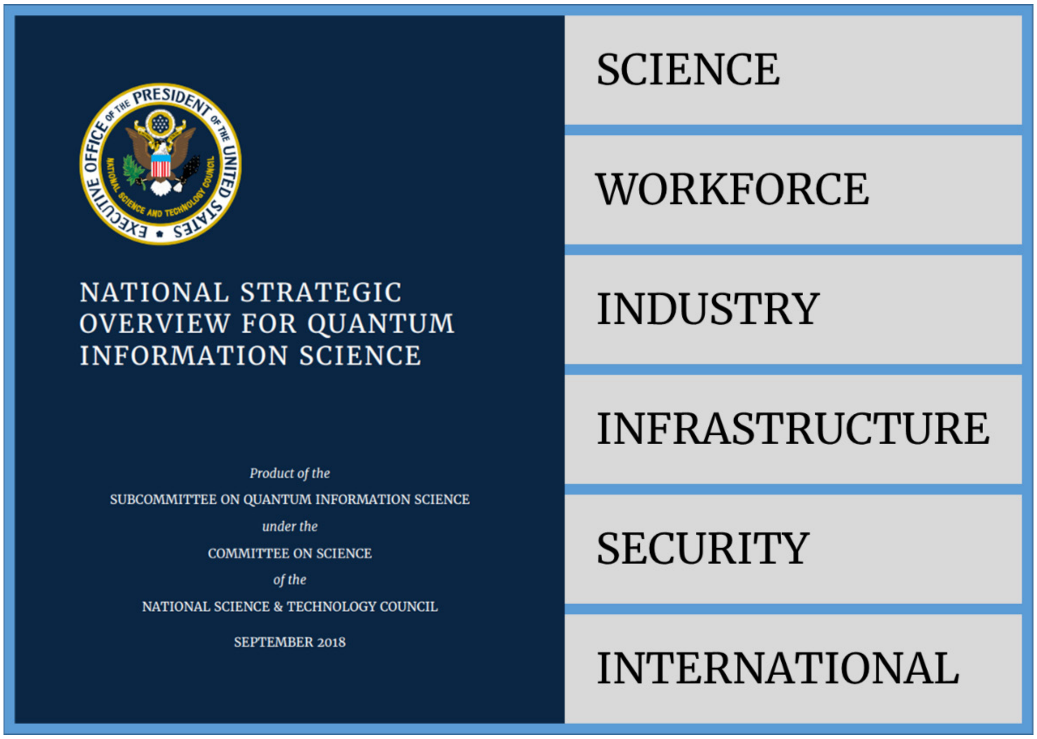

Figure 4.1: Policy topics discussed in the National Strategic Overview for QIS

4.1 Choosing a Science-First Approach to QIS

Investment in fundamental science provides a foundation for the Nation's prosperity and security.[147] The initial exploration of quantum mechanics led to transformative technologies such as atomic clocks, GPS, lasers, transistors, and magnetic resonance imaging. Meanwhile, the exploration of information theory brought about key advances in communication, computation, and data science. The confluence of these two fields creates new scientific vistas to explore with the compelling potential for new QIS applications and use cases. One of the ongoing challenges is to balance efforts between developing particular technologies or applications and supporting fundamental science.

Many in the scientific, business, and academic communities have asserted that QIS holds tremendous opportunities for revolutionary technologies, but investments in basic research are needed to establish the critical technical foundations.[148] Therefore, it is the policy of the United States to establish and lead the scientific development of QIS. Exploring fundamental problems in the field and its enabling technologies is prioritized as a means to produce new understanding, develop new capabilities, and

[147] 'Science the Endless Frontier' www.nsf.gov/about/history/nsf50/vbush1945_summary

[148] See the Quantum Frontiers Report (2020); Federally funded QIS workshop reports; the 2019 White House Academic Roundtable on QIS; the 2018 White House Summit on QIS Summary: https://www.quantum.gov/wp-content/uploads/2021/01/2018_WH_Summit_on_QIS.pdf

nurture a culture of discovery. Implementing this science-first approach entails strengthening core QIS R&D programs, launching new QIS centers, and exploring quantum frontiers. The following actions support this approach:

- The SCQIS coordinates QIS R&D across relevant agencies by sharing information and developing policy recommendations. The SCQIS has routine discussions, convenes events, and forms Interagency Working Groups (IWG) for various topics as needed. The SCQIS, with support from the NQCO, utilizes quantum.gov to help coordinate and showcase NQI activities.
- The SCQIS Science IWG and NQCO convened the sixth Federal QIS Program Day, hosted by DOE, bringing together QIS program managers, researchers, and stakeholders from across the Government to discuss projects and directions for QIS R&D.
- Over 5,000 scholarly publications per year in the field of QIS acknowledge funding from U.S. Government agencies. This statistic shows that agencies engaged in the NQI are supporting the generation of new knowledge and the pursuit of basic research with a vigorous pace. The rate of publications has nearly doubled since the NQI Act.[149]
    - Broken down by agency, over 3,500 QIS publications per year acknowledge NSF funding, over 2,500 acknowledge DOE funding, and over 1,500 acknowledge DOD funding. Individual publications often acknowledge multiple sources of funding, emphasizing the benefit of leveraging synergies across different programs.
- DOE has released multiple calls for proposals and made multiple awards that have quantum computing thrusts, including ASCR Accelerated Research in Quantum Computing, ASCR EXPRESS, BES EFRC, and the SBIR/STTR programs. DOE also provides community resources, such as its quantum computing and networking testbeds, and DOE SC user facilities are fully engaged in providing capabilities and expertise to serve users from the broader QIS research community.
- DOE announced awards and solicitations in quantum sensing: BER announced $250k for Accelerating Quantum Imaging with an Ultra High Speed Imaging Platform with End User Programmable FPGA and GPU and three $1.65M awards for quantum-enhanced coherent Raman microscopy, Extended SWIR Single Photon Avalanche Photo Detector Technology for Bioimaging, and optical and NMR detection of nanodiamond quantum sensors.
- IARPA explores and values a scientific approach toward universal fault-tolerant quantum computing by investing in the underlying fundamentals of quantum error correction and fault-tolerance, through programs emphasizing their co-development by theory and experiment.
- NIST has many foundational QIS research programs on both campuses (Gaithersburg, MD and Boulder, CO), as well as at universities participating with its joint institutes JILA, JQI, and QuICS. NIST has strengthened and expanded these programs, which include theoretical and experimental scientific studies on complex physical systems and qubit types, quantum states of light, physics beyond the Standard Model, exploring the boundaries of classical and quantum physics, the new physics and mathematics necessary for quantum information processing and characterization, technologies that underpin the deployment of QIS applications, material design, and QIS for biology and chemistry.

[149] Based on bibliometric analysis using Dimensions for NSF, with the search string: (“quantum information science” OR “quantum information” OR “quantum engineering” OR “quantum device” OR “quantum technology” OR "quantum computing" OR "quantum computer" OR "quantum algorithm" OR "quantum compiler" OR "quantum networking" OR "quantum network" OR “entanglement distribution” OR “quantum sensing” OR “atom interferometer” OR “photonic chip” OR “atomic clock” OR “quantum materials” OR “quantum material” OR “quantum chemistry” OR "bell's inequality" OR "bell inequality" OR "bell state" OR “quantum entanglement” OR “quantum superposition”) AND published article

- NIH hosted seminars and workshops to build a community of biomedical and quantum experts through the QIS and Quantum Sensing in Biology Interest Group and the Quantum Computing: New Frontiers in Biomedical Research Innovation Lab to build teams to explore opportunities for R&D of quantum technologies that address biomedical problems.[150] [151]
- NIH launched two Quantum Technology Prize Challenges for the NIH Quantum Biomedical Innovations and Technologies (Qu-BIT) Program: (1) NIH Quantum Sensing Technology Challenge and (2) NIH Quantum Computing Challenge to spur innovative biomedical quantum technology applications by inviting multi-disciplinary teams to propose new biomedical use cases for quantum technologies and to adapt them to biomedical research and clinical settings.[152] [153] [154]
- NIH launched an Innovation Lab aimed at leveraging quantum computing to tackle complex biomedical challenges, such as those found in cancer research.[155] This lab will gather experts from various disciplines to collaborate on new quantum algorithms that can provide advantages over classical methods. The Innovation Lab aims to make advancements in areas like biomedical imaging, genomic sequence analysis and drug discovery.
- The SCQIS Quantum Networking IWG (QN-IWG) facilitates the implementation of the *National Strategy for A Coordinated Approach to Quantum Networking Research*.[156] This strategy includes four technical recommendations—(1) continue research on use cases, (2) prioritize cross-beneficial core components, (3) improve classical support capabilities, and (4) leverage "right-sized" testbeds—and three programmatic recommendations—(1) increase interagency coordination in quantum networking, (2) establish timetables for R&D infrastructure, and (3) facilitate international cooperation. A small sampling of the efforts include:
  - The NQCO published the *Summary of the 2023 QN-IWG Workshop*.[157] This workshop was held in 2023 and brought together fifteen agencies to discuss progress and challenges in implementing the Quantum Networking Strategy.
  - The AFRL Starfire Optical Range utilizes adaptive optics expertise at the site to enable its daytime quantum networking capabilities. The site is also home to the 1-Mile testbed, which can simulate satellite-ground links for relevant atmospheric conditions/effects. The program rapidly matures technology at the testbed for future deployment in the quantum ground terminal, currently under development.
  - DC-QNet is a fiber-based network that connects six metropolitan agencies via a dark-fiber network to perform entanglement distribution at kilometer distances. Participants include NRL, ARL, USNO, NIST, NSA, NASA, and affiliate members NIWC and AFRL.
  - NASA Goddard Space Flight Center (GSFC) established the Goddard Quantum Network Initiative. The primary node provides an interface for orchestrating quantum networking resources between the Goddard Local Quantum Network and member nodes of DC-QNet.
  - DOE added to ongoing programs in quantum networking and funded three multi-institutional research projects under the solicitation for "Scientific Enablers of Scalable Quantum Communication,"[158] as well as releasing a new FOA on "Advanced Research in Quantum

[150] https://oir.nih.gov/sigs/qis-quantum-sensing-biology-interest-group
[151] https://datascience.nih.gov/news/quantum-computing-new-frontiers-biomedical-research-innovation-lab
[152] https://ncats.nih.gov/research/research-activities/quantum
[153] https://www.challenge.gov/?challenge=nih-quantum-sensing-technology-challenge
[154] https://www.challenge.gov/?challenge=nih-quantum-computing-challenge
[155] https://apply.knowinnovation.com/quantum-biomed/
[156] https://www.quantum.gov/wp-content/uploads/2021/01/A-Coordinated-Approach-to-Quantum-Networking.pdf
[157] https://www.quantum.gov/wp-content/uploads/2024/01/2023-QN-IWG-Workshop-Event-Summary.pdf
[158] https://science.osti.gov/grants/Lab-Announcements/-/media/grants/pdf/lab-announcements/2023/LAB_23-3040.pdf

Computing," that included parallel and distributed models in its scope.[159] DOE released its "Report for the ASCR Workshop on Basic Research Needs in Quantum Computing and Networking," where grand challenges were identified.[160]

- The NSF Engineering Research Center for Quantum Networks is working to develop long-distance quantum communications networks enabled by fault-tolerant quantum repeaters.[161]

- The national strategy for quantum sensing *Bringing Quantum Sensors to Fruition* was released in February 2022.[162] The strategy made four recommendations: (1) Agencies leading QIST R&D should prioritize partnerships with end users to elevate the technology readiness of quantum sensors, (2) Agencies that use sensors should conduct feasibility studies and jointly test prototypes with QIST R&D leaders, (3) Agencies that support engineering R&D should develop broadly applicable components and subsystems, and (4) Agencies should streamline technology transfer and acquisition practices. Efforts to implement this strategy include:
  - The DHS Science and Technology Directorate (S&T) sponsors the R&D of emerging quantum sensor technologies to strengthen national security and is assessing the utility of quantum sensors to support the supply chain security of microelectronics and magnetometers to confirm the integrity of integrated circuits.
  - The Photonic and Atomic Navigation and Timing via Optical Metrology (PHANTOM) Seedling for Disruptive Capabilities Program (SDCP) focuses on coupling atomic and photonic systems to produce small SWaP PNT and time synchronization systems that can be produced at large scales to assist navigation and time synchronization in GPS-denied environments. This effort is a collaboration between multiple AFRL Technical Directorates, academia, NIST, and FFRDCs.
  - The DIU Q-TIP program is underway. This joint program was created as part of OUSD(R&E)'s Transitioning Quantum Sensors initiative and is led by DIU and Principal Investigators at AFRL and Naval Information Warfare Center (NIWC). The program seeks to transition quantum inertial sensing and magnetic navigation technology to enable high-accuracy PNT in air and sea environments in which GPS is unavailable. The program will conclude with operational tests of quantum inertial measurement units (IMUs) and magnetic navigation systems that would be transitioned to air and sea platforms across the Army, Navy, and Air Force.
  - NASA funded the Quantum Engineering and Sensor Technology Laboratory (QuEST) for R&D into Earth Science, Planetary Science, and Space Navigation and Timing applications.
  - The QED-C produced a report, "Quantum Sensing Use Cases," that provides an industry perspective to complement the national strategy for quantum sensors.
  - NSF created the Quantum Sensing Challenges for Transformational Advances in Quantum Systems (QuSeC-TAQS) program in alignment with the NSTC strategy on quantum sensors. NSF allocated $30M to fund 18 projects under Solicitation NSF 22-630 from this program.[163]

[159] https://science.osti.gov/grants/FOAs/-/media/grants/pdf/foas/2024/DE-FOA-0003265.pdf
[160] https://www.osti.gov/servlets/purl/2430035
[161] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1941583
[162] https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf
[163] https://new.nsf.gov/news/quantum-scale-sensors-yield-human-scale-benefits

    - Two NSF QLCIs focus on quantum sensing research: Quantum Systems through Entangled Science and Engineering (Q-SEnSE) and Quantum sensing for Biophysics and Bioengineering (QuBBE).[164] [165]
    - NIH announced a Notice of Special Interest: Quantum Sensing Technologies in Biomedical Applications, to support innovative and potentially transformative research projects in quantum technology applications in biomedical disciplines.[166]
    - DOE SC's Biological and Environmental Research (BER) program announced multiple awards and solicitations relevant to quantum sensing. BER announced its interest in receiving applications for quantum enabled bioimaging and sensing approaches for bioenergy, awarded $18M for research in Bioimaging and Sensing Approaches for Bioenergy, and released a Transitioning Quantum Imaging and Sensing Technologies to Bioimaging Markets Research Study on QIST's potential to disrupt bioimaging.
    - DARPA supports multiple programs pioneering R&D in quantum sensing such as AMBIIENT, A-Phl, SAVaNT, and QuIVER.
- The DOD Basic Research Office and its Military Service counterparts, AFOSR, ARO, and ONR have led foundational research in QIS for over three decades with both internal and external funding programs such as the Single Investigator programs, the Vannevar Bush Faculty Fellowship program, and MURIs. Single investigator programs and Young Investigator Programs run by AFOSR, ARO, and ONR in related fields such as materials science, condensed matter, and atomic and optical physics provide a scientific backbone underpinning many QIS efforts.
- DHS S&T follows a science-first approach to quantum in a number of ways and approaches QIS technologies with a critical and open mind. DHS S&T is engaged with the scientific community through conferences and workshops, as well as organizations such as the QED-C. DHS S&T actively funds research in support of quantum science such as exploring methodologies and tools for synthetic data generation that can be applied to Homeland Security environments.
- The DARPA Quantum Benchmarking (QB) program is applying scientific rigor to understand progress in quantum computing research.[167] Performers are documenting analyses of applications and supporting software projects in publications and preprints.[168]
- NASA has many ongoing external scientific collaborations, including developing a space deployable quantum computer and investigating quantum computing-enabled high-performance computing for flow-based multi-physics modeling.
- NASA JPL is building a strontium clock to serve as a test of a compact flight optical lattice clock. JPL is collaborating with academia on the Space Entangled Annealing QUantum Experiment (SEAQUE) which launched to the International Space Station on November 4, 2024.
- In 2023, NSF funded over 1,600 active projects in QIS, led by over 2,000 unique Principal Investigators and co-Principal Investigators in over 260 Universities and Colleges in the U.S. These projects leverage support from over 20 NSF core programs in 9 Directorates with the overarching goals of advancing science and engineering in quantum frontiers, enabling multidisciplinary collaboration, developing workforce talent in the context of cutting-edge research, and translating basic research into end-user capabilities.
- The NSF Transformative Advances in Quantum Systems (TAQS) crosscutting program supports small teams of three or more faculty to explore innovative multidisciplinary research in QIST.

[164] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2016244
[165] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2121044
[166] https://grants.nih.gov/grants/guide/notice-files/NOT-EB-23-022.html
[167] https://www.darpa.mil/news-events/2024-06-20
[168] https://www.darpa.mil/work-with-us/publications-highlighting-potential-impact-of-quantum-computing-in-specific-applications

Funded projects develop new ideas, concepts, and technologies in QIST, with a focus on quantum functionality and result in experimental demonstration or proof-of-concept. Since 2018, the NSF TAQS program has awarded over $100M for efforts in quantum sensors (QuSeC-TAQS, 2023),[169] quantum interconnects (QuIC-TAQS, 2021), and two idea incubator rounds (QII-TAQS, 2019 and RAISE-TAQS, 2018). The TAQS program supports a science-first approach to QIS R&D by funding efforts to develop transformative ideas across key areas of QIST including biosensing, simulation, networking, computation, and education.

[169] https://new.nsf.gov/news/quantum-scale-sensors-yield-human-scale-benefits

4.2 Creating a Quantum-Smart Workforce for Tomorrow

The United States has built a strong foundation for QIS R&D over the past decades, with a baseline of research infrastructure and a scientific and technical workforce comprising talented college graduates, Ph.D. students, postdoctoral researchers, staff scientists, and professors. The workforce has grown through the steady process of funding fundamental research and through job opportunities at universities, Federal laboratories, and quantum-related industries. Yet, in recent years, this workforce has come under strain as the need for technical talent outstrips supply with competing demands from industry, academia, and the Federal Government. Furthermore, the growth has not resulted in a workforce that is representative of all of America, with many groups still underrepresented.

To help ensure the United States creates a diverse, inclusive, and sustainable workforce that possesses the broad range of skills needed by industry, academia, National Laboratories, and the U.S. Government, the SCQIS released a *QIST Workforce Development National Strategic Plan* in 2022.[170] This plan outlined four actions to help meet this goal: (1) Develop and maintain an understanding of the workforce needs in the QIST ecosystem, with both short- and long-term perspectives; (2) Introduce broader audiences to QIST through public outreach and educational materials; (3) Address QIST-specific gaps in professional education and training opportunities; and (4) Make careers in QIST and related fields more accessible.

The actions are supported by a set of recommendations for Federal agencies and opportunities for the broader QIST ecosystem. In support of this plan, agencies have been carrying out a series of activities to help develop the QIST Workforce, some of which are described below. This list is not comprehensive and there are other actions being undertaken at National Labs, academia, and industry.

Action 1: Develop and maintain an understanding of the workforce needs in the QIST ecosystem, with both short-term and long-term perspectives

- NIST supports various QED-C workforce development activities, including ongoing analysis of quantum industry workforce needs, an intern training program, a mentoring program, hosting student e-poster sessions, and career events such as QED-C's 'Quantum Jobs' initiative that helps those considering a career in QIST make connections and identify jobs in industry, academia, and Government.
- Two NSF projects – "Education Landscape for Quantum Information Science and Engineering: Guiding Education Innovation to Support Quantum Career Paths" – are gathering data on QIST industry jobs, associated skills and knowledge needs, and QIST education pathways and curricula across the United States.[171] [172]
- Complimentary work is supported by the NSA LQC award "Analysis of occupations, expertise, and educational pathways within the quantum information science and technology workforce in industry and Government."
- The NQCO engages in bilateral and multilateral dialogues about international QIST workforce needs and potential ways for like-minded countries to collaboratively address talent shortages, including the launch of EntanglementExchange.org as a portal for international exchange opportunities in QIST.[173]

[170] https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf
[171] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2333073&HistoricalAwards=false
[172] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2333074&HistoricalAwards=false
[173] https://entanglementexchange.org/

Action 2. Introduce broader audiences to QIST through public outreach and educational materials

- Through the Q2Work Award, NSF helped established a national program focused on education in quantum science at the K-12 level.[174] The program, called the National "Q-12" Education Partnership, was launched by OSTP and NSF in 2020.[175] Q-12 is a consortium that expands access to K-12 quantum learning tools and inspires the next generation of quantum leaders. Support for this activity continued in FY 2025. NSA's LQC joined NSF to co-sponsor the Q-12 partnership.
- In March 2024, an NSF Workshop was held to develop implementation ideas for a national center or hub for quantum education and workforce development at the K-12 level and beyond.
- In June 2024, the DOE NQISRCs coordinated a 4-week-long "QCamp Students." The camp was aimed at the high school student level to jumpstart a pathway to a career in QIST. The centers also facilitated a 3-day "QCamp Teachers" for high school teachers to facilitate QIS workforce training.
- In August 2024, the DOE-funded C2QA offered a four-day virtual workshop to introduce high school students to the exciting world of QIS and quantum engineering. Students explored the basic principles that underlie quantum technologies and gained an appreciation for their novel capabilities.
- NSF QLCIs sponsor experiences for the public such as museum exhibits and quantum-themed escape rooms, quantum lab tours for summer camps, and summer research opportunities for students.
- NASA Space Communications and Navigation collaborated with a subject matter expert industry partner team to produce Quantum Communication 101, a pedagogical, STEM-oriented introduction to the subject of QIS.[176]

Action 3: Address QIST-specific gaps in professional education and training opportunities

To address gaps in coursework, agencies funded short courses, workshops, and summer programs:

- The C2QA QIS 102 Applied Quantum Computing Summer School, hosted at Brookhaven National Laboratory, offered a three-week virtual workshop to introduce rising college juniors, seniors, and recent college graduates to QIS. Through a series of demonstrations and hands-on programming labs, students learned how to apply quantum algorithms to specific problem domains where they may have an advantage over classical methods.
- The 2024 U.S. Quantum Information Science Summer School was the second joint summer school facilitated by the DOE NQISRCs; this year hosted at ORNL. Attendees, including junior and senior undergraduate, graduate students, postdoctoral researchers, and early-career researchers, participated in hands-on quantum science and technology activities in a laboratory setting that is home to multiple world-leading facilities.
- The C2QA QIS 303 Quantum Error Mitigation Virtual Workshop introduced advanced undergraduate students, beginning graduate students, postdoctoral researchers, and other practitioners to QIS. During the program, QIS experts discussed quantum error mitigation through a series of lectures, seminars, and office-hour discussions.

[174] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2039745&HistoricalAwards=false
[175] https://q12education.org/
[176] https://www.nasa.gov/directorates/somd/space-communications-navigation-program/world-quantum-day/#hds-sidebar-nav-5

- NSA's LQC hosted its fourth annual Summer of Quantum short course in July 2024. This virtual two-week course introduces quantum computing to first- and second-year graduate students and qualified undergraduates in QIS-related fields.
- In 2024, the NSF Directorate for STEM Education supported a workshop on "Quantum Horizons: Empowering Faculty for the Future of Quantum Information."
- In 2024, NSF helped fund, "Quantum Noir: A conference series focused on Faculty, Researchers, and Students of Color (+) in the Quantum Sciences."
- NSF QLCI activities include developing new curricula, classes, and degrees, such as Master's Degrees in Quantum Science and Technology, an undergraduate minor in QIST, internship and summer programs for students, certificate programs for professional education and cross-training, opportunities for high school teachers to join QIS research teams each summer, multi-institutional partnerships on curriculum development, and liaisons with community colleges.

To increase QIST awareness in the existing workforce:

- DHS S&T supported a DHS-wide Quantum Community of Interest. This community makes the existing DHS workforce more quantum aware by raising the general level of awareness of QIS throughout DHS and providing regular educational opportunities to understand these emerging technologies and how they impact the DHS mission.

To support learning about QIST through internships:

- NASA QuAIL hosts over a dozen graduate-student-level interns and research assistants each year to work on a research project together with a QuAIL team mentor for several months.
- The NIST SURF program inspires undergraduate students to pursue careers in STEM through summer research experiences at NIST, with many projects focused on QIS.
- The NASA-funded Quantum Engineering and Sensing Technology (QuEST) Laboratory brings together quantum physicists, space systems engineers, and space scientists to enable the rapid infusion of quantum technologies into space remote sensors. QuEST has hosted undergraduate and graduate interns sponsored by NASA, the Air Force, and NRO.

To provide research opportunities:

- IARPA funds research teams from academia, industry, and Government laboratories. These teams educate graduate students and postdoctoral researchers in areas critical to the future of quantum technologies, including in physics, engineering, mathematics, and computer science.
- NASA JPL has established the Space Quantum Innovation Center incorporating its spaceborne and ground leadership in quantum technologies for NASA. It is an organization comprised of the laboratory's quantum device fabrication capabilities, system testbed facilities, and key workforce to implement future quantum systems. The center is also working to establish a quantum hub with several universities that would share facilities, support future opportunities, and grow the workforce by developing curricula, internships, and partnerships.
- NIST supports students and postdoctoral researchers working in QIS through a range of programs. The NIST NRC Postdoctoral Research Associateships Program has attracted top talent into NIST QIS programs; many NIST NRC postdoctoral researchers have gone on to become leaders in industry, academia, and Government. NIST activities at joint institutes JILA, JQI, and QuICS involve direct engagement with universities and broader STEM outreach activities.
- NSF-funded projects in QIS R&D currently engage approximately 1,100 postdoctoral researchers, 4,700 graduate student researchers (including approximately 100 NSF Graduate Research Fellowship Program Fellows), and 1,400 undergraduate student researchers.

- The AFRL is helping shape the quantum workforce across the service through its workforce development initiatives which span high school week-long STEM events through multi-year postdoctoral research positions. At each level, the facilities and expertise of AFRL are shared to lower the financial entry point for gaining experience in quantum and adjacent technologies.
- The SQMS Quantum Undergraduate Internship, sponsored by DOE SC, places sophomore and junior undergraduate physics and engineering majors in a paid 10-week summer internship program. Students gain hands-on experience through access to state-of-the-art facilities under the mentorship of SQMS experts across 24 partner institutions.
- AFOSR and LPS continue to collaborate on a Young Investigator Program and awarded three outstanding quantum-computing proposals in FY 2024. This collaboration aims to advance the state-of-the-art in quantum computing systems by understanding and mitigating challenges, developing revolutionary new approaches, characterizing and reducing noise, and developing supporting technology. These awards increase the size and expertise of the quantum workforce by supporting early career academic and industry researchers.

Action 4: Make careers in QIST and related fields more accessible

Through targeted funding opportunities:

- NASA GSFC has collaborations with multiple academic institutions to develop new STEM research and educational infrastructure, including enabling students to study quantum science and engineering in GSFC's labs and facilities and enhancing institutional capabilities in quantum sciences and space technologies.
- The AFOSR National Science Portal is designed to capitalize on the demonstrated excellence at Historically Black Colleges and Universities / Minority Serving Institutions / Tribal Colleges (HBCU/MSI/TCs) and build their research capacity while stimulating and accelerating scientific projects addressing critical areas, including QIS. The FY 2024 topic on Quantum Computing aims to probe a broader research community – beyond the traditional quantum physics field – as to what computational challenges could be advanced by quantum computers.
- ARL manages a Center for Excellence in Advanced Quantum Sensing supported by OUSD(R&E) housed at a HBCU. This program provides a foundation to enhance participation among HBCUs and MSIs in DOD R&D.
- DOE SC's Reaching a New Energy Sciences Workforce (RENEW) program aims to build foundations for research at institutions historically underrepresented in the SC research portfolio. A portion of this program includes awards supporting quantum computing and networking workforce development and increasing participation of underrepresented institutions in quantum computing and networking workforce training.

Through career fairs and networking events:

- In 2024, QSA, in collaboration with other DOE NQISRCs, launched the "You Belong in Quantum Series!" to showcase distinguished leaders in QIS and their perspectives on improving representation, diversity, equity, and inclusion.
- In April 2024, the "QLCI Leap Forward Career Conference" brought together students from a network of NSF-funded QLCIs to engage with company representatives and potential employers in QIST industries, and to discuss salient issues in career development for early professionals in QIST.
- In September 2024, DOE hosted the QIS Career Fair: An annual career fair with participation by five DOE NQISRCs to recruit students, postdoctoral researchers, and early-career researchers to jobs in QIS. Participants heard from experts in Government, academia, and industry about the

QIS market, got their questions answered, built their professional networks, and met directly with potential employers. The event showcased jobs available at national laboratories, academic institutions, and industry.

- In 2024, NSF helped fund a "Quantum Leap Career Nexus Workshop" that brought together undergraduates, graduate students, postdoctoral scholars, and early-career professionals to build career skills, establish mentorships, widen networks, learn about emerging career pathways, create new connections between talent and employers in quantum science and engineering, and showcase research and work experience to secure promising placements.

Box 4.1

Highlight: Expanding Capacity in QIS Across the Nation – The NSF ExpandQISE Program

Figure 4.1: Map of Awardee institutions (blue stars) and Subawardee institutions (gold circles) from ExpandQISE.[177]

NSF has invested over $99M to help grow quantum research activities at more institutions across America through the NSF Expanding Capacity in Quantum Information Science and Engineering (ExpandQISE) program. The ExpandQISE Solicitations NSF 22-561, NSF 23-551, and NSF 24-523 were designed to increase research capacity and broaden participation by providing support to build and maintain close connections between new efforts and already-impactful QIS centers or research institutions.[178] Through this mechanism, NSF funds up-and-coming programs at a diverse range of institutions seeking to build their own quantum research and development infrastructure. Over the three years since its inception, the ExpandQISE program has funded 56 research projects aiming to break new ground in fields such as quantum computing, sensors, and materials.[179] [180]

> *"Maintaining our country's global leadership in quantum information science demands that we engage the full spectrum of talent that's waiting to be unleashed from each and every U.S. community,"* says NSF Director Sethuraman Panchanathan. *"The NSF ExpandQISE program is simultaneously strengthening the quantum workforce and investing in the scientific and technological advances that will be the foundation for a quantum-enabled future."*

Awards support faculty and staff across a broad range of U.S. institutions, including:

- 19 projects in U.S. States participating in the NSF EPSCoR program, which focuses on areas that have historically received less Federal funding for research than others.
- 43 awards to colleges or universities classified as emerging research institutions, i.e., institutions with established undergraduate or graduate programs but less than $50M in Federally-supported research expenditures annually.
- 23 awards to minority-serving institutions, including thirteen at historically Black colleges and universities (HBCU), and ten at Hispanic-serving institutions.

[177] Image courtesy of NSF
[178] https://new.nsf.gov/funding/opportunities/expanding-capacity-quantum-information-science
[179] https://www.quantum.gov/nsf-invests-an-additional-38m-to-expand-participation-in-qise/
[180] https://new.nsf.gov/news/quantum-science-engineering-expands-across-nation-39m-nsf

4.3 Deepening Engagement with Quantum Industry

The Nation's economic growth and prosperity rely on strong established industries and a vibrant ecosystem for innovation. Basic research fuels this ecosystem by creating new scientific understanding, new materials, new processes, new technologies, and specialized training for the technical workforce that keeps the United States at the forefront of industry capabilities. At the same time, the growth of new industries enables scientific discoveries and empowers the whole Nation.

Successful translation of scientific discoveries into deployed technologies is challenging. It often requires careful handoffs between scientists, engineers, developers, venture capitalists, entrepreneurs, manufacturers, and customers, all working together in an innovation ecosystem. Therefore, it behooves the United States to carefully support pathways and connections throughout the innovation community. The Government plays a key role both in identifying promising quantum technologies and kick-starting them where appropriate. Early-stage support to transition emerging technologies out of the lab is often warranted when a substantial market has not yet developed or when the Federal Government has a need for a particular application or capability. Government support is especially important if investors are reluctant to take on the full cost and potential risk associated with translating the research into products and services. To this end, agencies organized around the NQI have undertaken the following efforts to support and engage with the quantum industry.

- Agencies leverage SBIR and STTR programs to provide seed funding for early-stage R&D at startups and small businesses, including those seeking to market quantum technologies.[181] [182] In addition, CRADAs enable many agencies to partner with U.S. companies to accelerate the development of quantum technologies.[183]
- The innovation chain is one of five essential elements of the DOE NQISRC programs. Each of the centers have industry partners and include industry representatives on their advisory boards to ensure that the R&D conducted addresses challenges faced by the QIS commercial sector.
- In 2019, NIST established the Quantum Economic Development Consortium (QED-C) using its NQI Other Transaction Authority to enable and grow a robust commercial quantum-based industry and associated supply chain in the United States. NIST has an active seat on the QED-C Steering Committee. The QED-C is industry-led and now has activities addressing use cases for quantum, enabling technologies, standards and performance metrics, workforce development, legal aspects of quantum, and quantum for national security.
- Participation in the QED-C has grown to include more than 250 members, ranging from large, multinational corporations to small startups, academic institutions and professional societies, and many U.S. agencies seeking quantum industry engagement. Scientists from NIST and other U.S. agencies work within QED-C Technical Advisory Committees and as part of R&D teams helping address technical challenges faced by industry. The QED-C includes international engagement with members from 39 like-minded countries, helping establish and build the relationships needed to secure trusted global supply chains and access to top talent.[184]
- In FY24, DOC bureaus provided an informational panel session during a QED-C plenary meeting to educate members on services available to companies of all sizes. Participants included panelists from the International Trade Administration (ITA) and the Bureau of Industry & Security (BIS) and was moderated by NIST. The ITA continues to engage with, and support, the

[181] https://seedfund.nsf.gov/topics/quantum-information-technologies/
[182] https://grants.nih.gov/grants/guide/notice-files/NOT-EY-24-014.html
[183] https://www.nist.gov/tpo/partnerships/cooperative-research-and-development-agreement-crada
[184] https://quantumconsortium.org/membership/

QED-C and its members to understand supply chain chokepoints and international trade challenges.

- In June 2024, NIH co-organized a workshop with QED-C to bring industry, academic, and Government stakeholders to discuss gaps and opportunities for commercializing quantum sensing technologies for various biomedical applications.[185]
- NASA QuAIL collaborated with industry partners on research to improve the performance of superconducting quantum computing hardware.[186] [187]
- DHS S&T engages with the ATARC Global Quantum Working Group and attends quantum conferences and workshops. DHS S&T leverages these engagements as a means of connecting operational components with potential industry partners advancing solutions that may meet their current and future needs.
- IARPA engages academia and industry through its open calls for proposals. The ELQ program involves and funds several members of the quantum industry across a variety of technological sectors.
- The NASA-funded Atom Interferometer Gravity Gradiometer—built and operated by a small business focused on quantum sensing—is testing and modeling gravity sensors using atom interferometry.
- The LQC Qubits for Computing Foundry is partnering with industry to provide standardized semiconductor qubit devices to U.S. academic research groups.
- The NSF Industry-University Cooperative Research Centers program is designed to enable breakthrough research by enabling close and sustained engagement between industry innovators, world-class academic teams, and Government agencies.[188] Engagement with industry is also a priority for the NSF Convergence Accelerator program the NSF Innovation-CORPS (I-CORPS) program, and the NSF National Quantum Virtual Laboratory testbeds.
- The NSF QLCIs and the NSF Quantum Foundries engage over 100 industry partners.
- DOC ITA launched a quantum computing supply chain analysis to better understand and anticipate supply chain chokepoints and vulnerabilities for quantum that could hinder the future success and competitiveness of the U.S. quantum industry. This analysis includes assessment of trade and industry data as well as extensive engagements with industry stakeholders at workshops, policy roundtables, and other engagements.

[185] https://quantumconsortium.org/quantum-sensing-for-biomedical-applications/
[186] 'Quantum-enhanced greedy combinatorial optimization solver,' doi/10.1126/sciadv.adi0487
[187] 'Learning noise via dynamical decoupling of entangled qubits,' doi.org/10.1103/PhysRevA.107.052610
[188] https://iucrc.nsf.gov/

4.4 Providing Critical Infrastructure

Scientific infrastructure accelerates the cycle of progress from discovery and exploration to technology development by providing key shared technical and scientific capabilities to a larger community. QIS requires increasingly complex experimental and technical systems as researchers carry out more sophisticated efforts. New applications and new lines of inquiry with extraordinarily fragile quantum states require platforms with specialized materials, exacting tolerances, new quantum control systems, and in some cases ultracold temperatures. Building upon investments made in other contexts such as nanotechnology and semiconductor development, additional investments in infrastructure can catalyze progress and enable scientific and technical breakthroughs that would not otherwise occur.

Infrastructure draws together collaborations and teams that require certain equipment or facilities to carry out their R&D enterprises. Hence, the research community, as well as the operational systems for quantum information processing, can be profoundly influenced by early planning and investment in infrastructure, transforming the realm of the possible by distributing costs and maintaining key knowledge, staff, and abilities in centralized facilities.

Activities to support the identification and development of infrastructure include:

- The NIST Gaithersburg Center for Nanoscale Science and Technology and Boulder Microfabrication Facility, both of which provide researchers with access to state-of-the-art nanoscale measurement and fabrication tools and methods, along with associated technical expertise. NIST also utilizes laboratory facilities for quantum networking projects at both campuses, most notably to support DC-QNet.
- NASA GSFC conducted tests with a Superconducting Nanowire Single Photon Detector enabling detection and coincidence measurement of entangled photons between GSFC and NIST using fiber optics. The detector enables approximately two orders of magnitude increase in photon rates due to enhanced detection efficiency compared to existing technology.
- NSA hosts the LQC Quantum Research Center which leverages collaborations between LPS personnel and extramural researchers to launch novel projects of a scope that neither group could pursue independently.
- NSA initiated the Qubit Foundry program to supply state-of-the-art qubits to U.S. researchers, removing the barrier to progress associated with the need for individual laboratories to invest in sophisticated fabrication equipment.
- DHS S&T aims to provide and secure critical infrastructure by investigating quantum technologies to complement the DHS components' mission spaces. These include use cases within DHS components such as the Cybersecurity and Infrastructure Agency (CISA), as well as the U.S. Coast Guard (USCG), where quantum technologies could help secure critical infrastructure. One of the use cases identified is the need to maintain communications within critical infrastructure after an electromagnetic pulse event, which could be solved by the Rydberg atom electric field sensor's potential resilience to such an event. For the USCG, use cases have been identified for PNT needs in the case of GPS denial, which is also a large threat to critical infrastructure needs.
- Some advancements in critical quantum computing infrastructure – hardware and software – funded by IARPA are made available to other U.S. Government-funded programs, for their benefit in various quantum-technology pursuits.
- Several of NSF's major research facilities and other research infrastructure investments enable research across QIS. Notable examples are NSF's National High Magnetic Field Laboratory and

NSF's Center for High-Energy X-Ray Sciences, both of which will continue to provide critical tools for frontier research in quantum materials.[189] [190]

- DARPA's Quantum Benchmarking Initiative has partnered with the State of Illinois to create the Quantum Proving Ground, where quantum prototypes will be tested and evaluated. The facility includes shared equipment and facilities, including research and collaboration space for academia and industry. [191]
- The Low Background Cryogenic Facility at Pacific Northwest National Laboratory is designed to study superconducting quantum devices in a low ionizing radiation environment.[192]
- The SQMS Quantum Garage at Fermi National Accelerator Laboratory opened in November 2023 as one of the largest quantum research laboratories in the country. The 6,000 sq ft lab space is home to six extra-large dilution refrigerators and devices capable of reaching millikelvin temperatures and extremely high and low magnetic field environments.
- The DOE-funded Quantum Science Center's QUIET and LOUD are twin underground and above-ground facilities hosted at the Fermi National Accelerator Laboratory. These brand-new quantum sensor and computing research infrastructure facilities are among the first of their kind to be operational in the Nation. Together, QUIET and LOUD will allow for controlled experiments with quantum sensors and qubits to make direct comparisons between an environment with significantly reduced cosmic ray interference and the ambient environment on Earth's surface. Cosmic radiation may affect the quality of quantum sensing and computation.
- The DOE ASCR Quantum Computing Testbeds for Science program provides the research community with fully transparent access to quantum computing hardware based on superconducting and trapped-ion qubits. These facilities allow the research community to exploit architectural details and co-design software tools of unprecedented quality. DOE ASCR supports two projects to develop and demonstrate regional scale — intra-city or inter-city — quantum networking testbeds.
- The DOE ASCR-funded Quantum Computing User Program provides access to cloud platforms for commercial quantum computing platforms through a merit-reviewed process, ensuring the research community has access to hardware for running the largest possible applications. NSF is promoting the availability of cloud-based access to quantum-computing platforms to advance R&D and build capacity in the academic setting.[193]
- The DOE BES Nanoscience Research Centers user facilities have developed capabilities for QIS research, emphasizing synthesis and characterization of materials, structures and devices.
- The NSF NQVL is an overarching shared infrastructure that aims to develop use-inspired and application-oriented quantum technologies and will be a flagship quantum testbed activity for the NSF TIP Directorate. The NSF NQVL program is motivated by the grand challenge of demonstrating practical quantum advantages that can fulfill the promise of a new, marketable QIS technology. This program offers the connection between the NSF investments in basic science today into the promised technologies of the future. The first round of NQVL pilot projects were awarded in FY 2024.[194]

[189] https://nationalmaglab.org/
[190] https://www.chess.cornell.edu/partners/chexs
[191] https://sam.gov/opp/1153a9e09e5e4911899230bee76ffd33/view
[192] 'Abatement of Ionizing Radiation for Superconducting Quantum Devices,' doi.org/10.1088/1748-0221/19/09/P09001
[193] https://www.quantum.gov/nsf-funds-access-to-cloud-based-quantum-computing-platforms/
[194] https://new.nsf.gov/news/nsf-national-quantum-virtual-laboratory-advances

- The new NSF National Quantum Nanofab (NQN) will enable quantum device fabrication, characterization, and packaging capabilities that are essential to advancing applications ranging from quantum computers and networks, to atomic clocks and advanced quantum sensors. Funded as part of NSF's Mid-Scale Research Infrastructure 1 (Mid-scale RI-1) program, NQN will be an open-access national facility for academic, Government, and industrial users.[195]
- The CHIPS and Science Act authorized the Economic Development Administration (EDA) to establish the Regional Technology and Innovation Hubs (Tech Hubs) program.[196] This program aims to drive regional innovation and job creation while advancing national security. A Tech Hubs designation signifies the U.S. Government's recognition of a region's potential to become a global leader in the manufacturing, commercialization, and deployment of a specific critical emerging technology. In October 2023, the President announced 31 designated Tech Hubs, two of which focus on quantum technologies.[197]
- In July 2024, EDA announced an award of approximately $41M to the Elevate Quantum Tech Hub to support key projects in quantum infrastructure, workforce development, and consortium coordination.[198]

[195] https://new.nsf.gov/news/nsf-announces-20-million-investment-quantum
[196] https://www.congress.gov/bill/117th-congress/house-bill/4346/text
[197] https://www.eda.gov/news/press-release/2023/10/23/administration-designates-31-tech-hubs-across-america
[198] https://www.eda.gov/news/press-release/2024/07/02/Elevate-Quantum-Tech-Hub

4.5 Maintaining National Security and Economic Growth

The *National Strategic Overview for QIS* recommends a comprehensive approach to ensure that the economic and security benefits of QIS are realized by the United States as scientific discoveries and technological opportunities emerge. This strategy includes maintaining awareness and agility, developing the market for QIS technologies, using Government-wide coordination mechanisms, and maintaining appropriate approaches to intellectual property and regulation.

Box 4.2

Highlight: Securing our Nation with Post-Quantum Cryptography

"The National Cybersecurity Strategy recognizes the need to prepare for revolutionary changes brought on by quantum computing. This is one of the reasons we've made investing in a resilient future a core pillar of that strategy." –National Cyber Director Harry Coker [199]

This past year marked an important milestone for post-quantum cryptography (PQC) efforts: the design and release of new encryption algorithms that are able to withstand attacks from a quantum computer. This eight-year endeavor was led by NIST's PQC standardization project, which establishes standards that will enable encryption to be secure against attacks from both classical and quantum computers and work with existing communications protocols.

In August 2023, the NIST PQC team announced that three new standardized encryption algorithms resistant to attack by quantum computers would be ready for use in 2024, and that others will follow.[200] Two PQC roundtables were convened to discuss plans for migration to PQC and get input from stakeholders in industry, Government, and academia. In July 2024, OMB released its Report on Post Quantum Cryptography as required by the Quantum Computing Cybersecurity Preparedness Act.[201] This report outlines the Federal Government's PQC migration strategy, provides cost estimates for the migration, and details NIST efforts to develop PQC standards. In August 2024, NIST announced the release of three PQC algorithm-based Federal Information Process Standards for immediate use.[202] These new standards secure a wide range of electronic information, from confidential email messages to e-commerce transactions that propel the modern economy. NIST is encouraging computer system administrators to begin transitioning to the new standards as soon as possible.

Actions listed below support these policy goals:

- ESIX provides a forum for agencies to discuss the national security implications of QIS and its enabling technologies. Through interagency and working group activities, ESIX is addressing the charge of the NDAA for FY 2022: (1) review and asses the economic or security implications of QIS investments; (2) review and assess threats to the Nation's QIS portfolio; (3) assess the export of technologies associated to QIS; and (4) provide recommendations to mitigate risks resulting from the assessment of (1)-(3).
- NIST leads a broad effort to establish post-quantum cryptography (PQC) (See Box 4.2).
- NIST supports the QED-C Standards & Performance Metrics and Quantum for National Security Technical Advisory Committee activities. For example, NIST is helping the QED-C develop Standardization Readiness Levels to enable the consortium to evaluate the potential impact of

[199] https://www.whitehouse.gov/oncd/briefing-room/2024/08/13/remarks-national-cyber-director-coker-remarks-at-white-house-event-on-post-quantum-cryptography/
[200] https://www.nist.gov/news-events/news/2023/08/nist-standardize-encryption-algorithms-can-resist-attack-quantum-computers
[201] https://www.whitehouse.gov/wp-content/uploads/2024/07/REF_PQC-Report_FINAL_Send.pdf
[202] https://www.quantum.gov/nist-releases-post-quantum-encryption-standards/

proposed standards and provide industry perspectives to U.S. standards developers. In addition, NIST actively engages with U.S. and international standards development organizations on QIS.

- The NIST *Safeguarding Science Research Security Framework* establishes guidance to assist the U.S. science and research community across the broad spectrum of international science and technology activities as well as Federal funding initiatives.[203]
- In September 2024, in concert with international partners, DOC BIS released an interim final rule and request for comment on export controls for certain quantum technologies.[204] The interim final rule implements worldwide export controls on quantum computers, related equipment, and components, materials, software, and technology that can be used in the development and maintenance of quantum computers.
- In October 2024, the Department of the Treasury issued a Final Rule to implement Executive Order 14105 of August 9, 2023, Addressing United States Investments in Certain National Security Technologies and Products in Countries of Concern (the Outbound Order). Quantum information technologies are identified in the Outbound Order as one of the technologies and products relevant to the prohibition and notification requirement.[205]
- DOE IP invests in technology development for the enrichment and production of isotopes critical to QIS R&D, increasing the Nation's indigenization of resources for QIS applications of importance to national security.
- DHS S&T is sponsoring the R&D of emerging quantum sensor technologies to strengthen national security. In particular, with the transforming Arctic region becoming an increasingly active operational area for the USCG and DOD, it is crucial to develop technologies that can support assured communications and high-accuracy sensing while operating in the complex polar electromagnetic environment. DHS S&T is facilitating prototype development of quantum Rydberg atom electric field sensors for enabling wideband electromagnetic sensing for over-the-horizon ionospheric communications.
- OUSD(R&E) is funding a study on assessing the strength and resilience of the U.S. quantum technology supply chain.
- IARPA maintains a robust Research Technology Protection Program (TPP) that, among other considerations, evaluates the research objectives for possible implications to national security. The potential for economic growth that a program could or would represent does not enter into decisions for research protection.
- While IARPA's mission is to advance national security, the open nature of IARPA's quantum-technology programs have led to the establishment of U.S.-based startup companies in QIS-relevant fields.
- The NSF Office of the Chief of Research Security Strategy and Policy (OCRSSP) released a 2024 JASON report on Safeguarding the Research Enterprise.[206] [207]
- The NSF OCRSSP announced a framework for Trusted Research Using Safeguards and Transparency (TRUST) to help NSF assess grant proposals for potential national security risks.

[203] 'Safeguarding International Science,' doi:10.6028/NIST.IR.8484
[204] https://www.federalregister.gov/d/2024-19633
[205] https://www.federalregister.gov/d/2024-25422
[206] https://new.nsf.gov/research-security
[207] https://new.nsf.gov/news/nsf-announcement-jason-report-safeguarding

- The NSF OCRSSP published several online research security training modules for the research community.[208] NSF partnered with NIH, DOE, and DOD on a solicitation seeking proposals to develop the training modules for recipients of Federal research funding.

4.6 Advancing International Cooperation

Scientific knowledge transcends national boundaries. International collaboration accelerates discoveries and provides an avenue to deepen relationships between nations. These relationships provide a platform to establish trust, facilitate communication, and demonstrate shared principles through the conduct of research and education. QIS R&D is deeply international, with talent, infrastructure, and industrial capabilities globally diffused. More than three dozen countries around the world have significant Government funding for QIS research, and at least 17 have national strategies for quantum technology development.[209] Over half of the roughly 9,000 publications per year in QIS with authors in the United States also have international coauthors, illustrating the importance and extent of international cooperation on basic research in QIS. Accordingly, it is the policy of the United States to promote and support international cooperation on QIS research and skills development, especially in ways that affirm principles of scientific rigor and research integrity, freedom of inquiry, merit-based competition, openness, and transparency.[210] By enhancing cooperation with those who share these foundational principles and values, we can ensure that the QIS capabilities of the United States and our close allies and partners remain strong, fostering a vibrant and secure international QIS ecosystem.

International collaboration is facilitated through a number of mechanisms. For instance, bilateral agreements between U.S. agencies and their international counterparts enable benefits such as a coordinated review process, reciprocal or joint funding, and student and researcher exchange to the benefit of both parties. Some agencies, pursuant to their mission and authorities, can pursue unilateral support for international research collaborators. Informal engagements with universities and industry are also essential to connect Government, academic, and private sector stakeholders. Through these collective approaches, a large number of Federally-funded QIS research projects and initiatives continue to enjoy international collaborators, resulting in coordinated efforts with mutual benefits.

- The SCQIS and OSTP coordinate with the State Department on opportunities for enhanced international cooperation in QIS. These have included quantum cooperation statements that articulate shared visions for the promotion of collaborative research efforts, enhancement of training opportunities, and growth of a global quantum market:
  - The United States signed a Joint Cooperation Statement for QIS with Germany in May 2024,[211] joining those signed previously with Australia, Denmark, Finland, France, Japan, the Netherlands, Republic of Korea, Sweden, Switzerland, and the United Kingdom. Each of these bilateral statements highlight the United States' commitment to building a vibrant international quantum ecosystem, embarking on good-faith cooperation, that is underpinned by our shared guiding principles, including openness, transparency, honesty, equity, fair competition, objectivity, and democratic values.
  - The NQCO and State Department continued participation in the multinational roundtable on Pursuing Quantum Information Together: 2^Nvs. $2N$ at a meeting hosted by Denmark and the Netherlands in October 2023, and another co-hosted by Australia and the United States in

[208] https://new.nsf.gov/research-security/training
[209] https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf
[210] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[211] https://www.state.gov/joint-statement-on-cooperation-in-quantum-information-science-and-technology-of-the-united-states-of-america-and-the-federal-republic-of-germany/

September 2024. These roundtables facilitate conversations among Government and national-level stewards of QIS R&D efforts, build on the event first launched by NQCO and the State Department in May 2022, and identify future cooperative activities to the "Guiding Principles" launched in the October 2023 meeting.[212]

  - As an output of the joint cooperation statements and the multinational roundtables, Australia, Canada, Denmark, Finland, France, Germany, Japan, Netherlands, Sweden, Switzerland, the United Kingdom, and the United States launched the Entanglement Exchange in November 2022. The Entanglement Exchange is a portal for highlighting international exchange opportunities for students, postdoctoral researchers, and researchers in QIS.[213] Since its launch, the Republic of Korea and India have been added to the Exchange.
  - The National Security Council (NSC), NQCO, and State Department launched the Quantum Development Group in July 2024, convening high-level Government officials from Australia, Denmark, Finland, France, Germany, Japan, Republic of Korea, United Kingdom, and the United States to discuss approaches to QIS and opportunities and challenges for Governments and the private sector to enhance QIS sector resilience and deepen cooperation.
  - In 2024, the State Department co-hosted Joint Committee Meetings on Science and Technology Cooperation with Germany, the United Kingdom, Switzerland, and Japan, convening experts from DOE, NIST, and NSF to discuss S&T matters of mutual importance, including opportunities for collaboration in QIS to realize its potential across a broad spectrum of applications.
  - The NSC and State Department have ongoing bilateral dialogues with India, the Republic of Korea, and Singapore on critical and emerging technologies, including QIS. State participates in multilateral dialogues with QIS pillars with India and Korea, Japan and Korea, the Quad, and Australia and the United Kingdom (AUKUS).
  - In 2024 a U.S. Science Envoy traveled with State to Denmark, Finland, the Netherlands, and Sweden and with State and ONR to Czechia to visit universities, labs, industries, and QIS-relevant infrastructure to explore pathways for QIS cooperation.
  - BridgeUSA, State's largest and most diverse program, offers exchange opportunities for academics, students, and professionals, including those focused on QIS. BridgeUSA's privately funded exchanges are currently supporting nearly 240 visitors with elements of quantum in their exchanges that span university studies, collaborative research, and internships.
  - The United States was among the co-sponsors of the General Assembly of the United Nations resolution to designate 2025 as the "International Year of Quantum Science and Technology," an initiative to celebrate the impacts of quantum science on society and an opportunity for building international partnerships and broader public engagement.

- U.S. international QIS activities are distributed across several agencies, each pursuing QIS mission-specific collaborations, unilaterally or in partnership with additional agency partners.
  - International engagement in DOE's QIS programs continues to grow. The DOE NQISRCs include institutions in Canada and Italy as full partners, and they have an increasing number of international affiliates making in-kind contributions to collaborative research projects. Additionally, ASCR's quantum computing testbeds have attracted interest from the

[212] https://techamb.um.dk/impact/multilateral-dialogue-on-quantum
[213] https://www.entanglementexchange.org/

international research community. BES user facilities support research from the international QIS community.

- AFRL has a project agreement with an international partner to develop quantum networking capabilities. This work includes the development of a quantum ground terminal to be used to communicate with a quantum capable satellite slated to launch late 2025.
- NIST supports QED-C internationalization activities. The consortium now accepts participation applications from 39 like-minded countries—adding one country in 2024—and partners with similar international quantum industry consortia, such as QuIC (European Union), QIC (Canada), and Q-STAR (Japan).[214]
- NIST regularly engages the international community and hosts delegations from other countries to discuss collaboration on QIS, most recently from Australia, Denmark, the European Union, Italy, Israel, Japan, Singapore, South Korea, and the United Kingdom.
- NIST works collaboratively with its peer National Metrology Institutes (NMIs) around the world. NIST signed an amendment to an existing memorandum of understanding to include cooperation on research and development (R&D) related to Precision Metrology for Quantum Computing with the Korea Research Institute of Standards and Science (KRISS) and updated an existing MOU with Japan's National Institute of Advanced Industrial Science and Technology (AIST) to include quantum technology. NIST chairs the recently formed Technical Committee 25 – Quantum Measurement and Quantum Information of the International Measurement Confederation, providing a unique venue for NMIs to jointly advance quantum metrology.
- NIST co-organized an International Bureau of Weights and Measures Workshop on accelerating the adoption of quantum technologies through measurements and standards.[215] The workshop brought together NMIs from around the world to consider their role in advancing quantum technologies.
- NASA collaborates internationally through MOUs and other mechanisms. For example, NASA JPL is a supporting partner in the European Space Agency Atomic Clock Ensemble in Space mission to launch a cesium atomic clock to the International Space Station early next year. JPL is also partnering with the German Space Agency (DLR) on developing the follow-on flight mission to the Cold Atom Laboratory (CAL) on the International Space Station, called BECCAL (See Box 3.6). NASA Space Communications and Navigation recently signed a Study Agreement with a quantum computing center housed at an overseas university to explore collaborative projects in quantum STEM and research.
- In March 2024, NASA's QuAIL team briefed roughly 40 graduate students from two United Kingdom Universities. This event was planned in conjunction with the United Kingdom Science & Innovation Network, British Consulate-General San Francisco.
- IARPA's portfolio includes U.S. teams and their international colleagues working closely together to advance the theoretical and experimental science relevant to quantum computing and quantum error correction.
- NSF has announced several opportunities to facilitate international collaboration in QIS, with mechanisms for joint or supplemental funding. Several examples of NSF Dear Colleague Letters encourage international collaboration in QIS in alignment with principles articulated

[214] https://quantumconsortium.org/quantum-consortia-qic-qed-c-q-star-and-quic-form-international-council-to-enable-and-grow-the-global-quantum-industry/
[215] https://www.bipm.org/en/bipm-workshops/quantum-tech

in several bilateral quantum cooperation statements, and consistent with the NSF Proposal and Award Policies and Procedures Guide.

- To facilitate international cooperation in QIS research, NSF supports a project called the 'Global Quantum Leap.' [216]
- NIH is pursuing collaborative opportunities with like-minded international countries, such as the United Kingdom and Finland, for quantum technology applications in biosciences and human health.
- DHS S&T participates in international quantum activities that are relevant to Homeland Security missions. DHS S&T co-hosted an Advance Research Workshop held in December 2023 with the theme of "Pursuing Quantum Sensing for Reliable Roadmaps." This workshop, sponsored by the NATO Science for Peace and Security Program, brought together attendees from academia, industry, and multiple Government agencies to discuss the current state-of-the-art research, economic and market drivers, and to determine use cases quantum sensors in security applications.
- OUSD(R&E) is participating in the enhanced trilateral security partnership among AUKUS on advanced capability development. AUKUS intends to build upon longstanding bilateral ties to strengthen the ability to support the security and defense interests of each member.
- OUSD(R&E) hosted the International Workshop on Quantum Technology Collaboration from May 6-10, 2024 in Washington, D.C. with participation across the international quantum community including representatives from the Republic of Korea, Singapore, India, Japan, Sweden, the United Kingdom, and Italy to interact with DOD members of the technical community to focus on collaboration opportunities in quantum technology development and to align strategies and forge new collaborative networks between the United States and each partner nation.
- DOC established a Supply Chain Center, housed within ITA, which aims to serve as the analytic engine for supply chain resilience policy action within the U.S. Government. One area the Center intends to focus on is Critical and Emerging Technologies, including QIS.

[216] https://www.globalquantumleap.org

5 Summary and Outlook

The timeline in Figure 5.1 summarizes some key events for the establishment and implementation of the National Quantum Initiative.

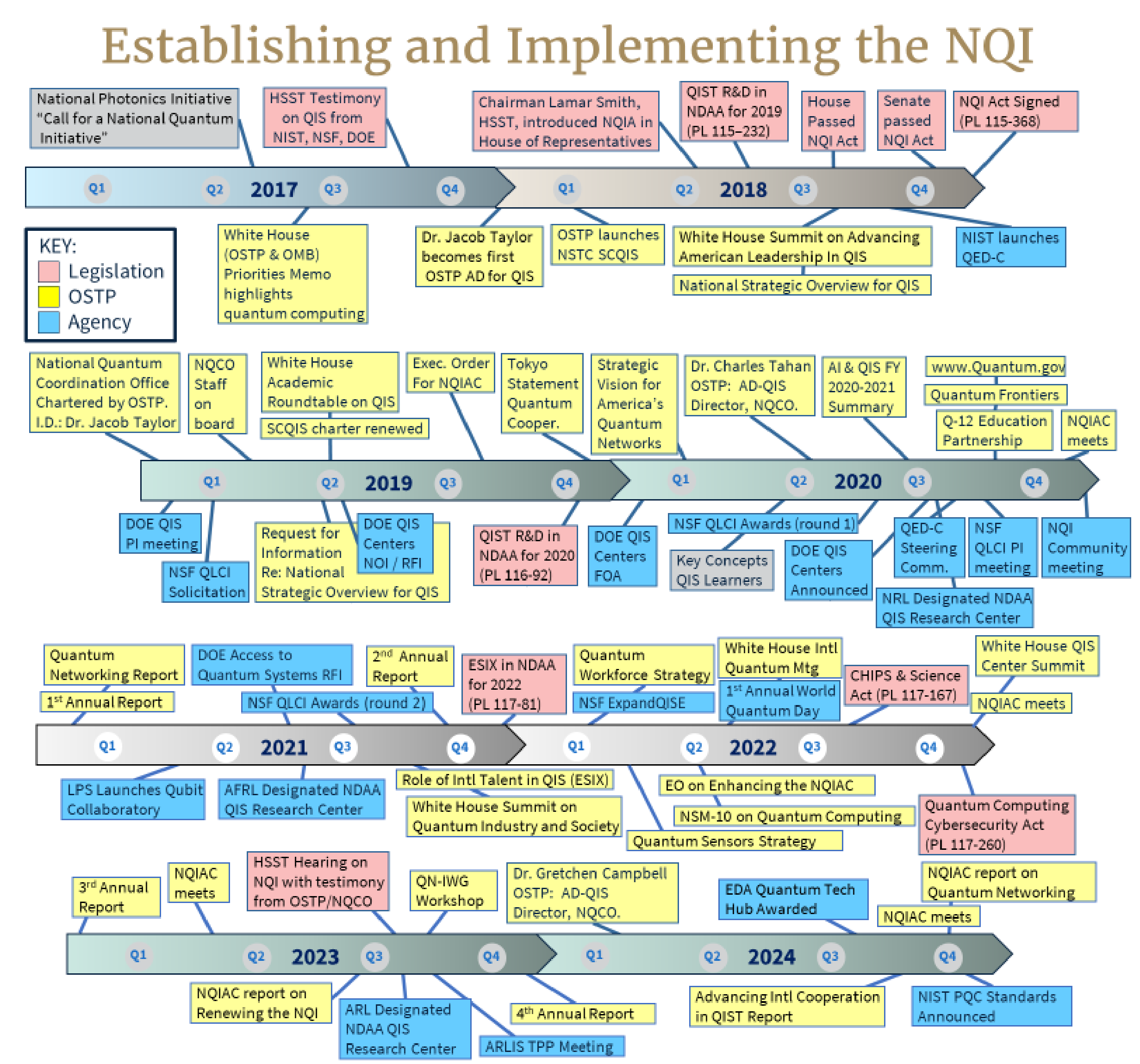

Figure 5.1: Timeline of actions establishing and implementing the NQI. Color-coding shows legislative process in red, OSTP and NSTC actions in yellow, and agency actions in blue. The NQI was introduced in Congress, passed in the House, passed in the Senate, and signed into law by the President, reflecting bipartisan support. The NDAA for FY 2019, FY 2020, and FY 2022 are shown on the timeline because they authorize QIS R&D supported by DOD and ESIX. Selected actions led by OSTP and the NSTC SCQIS and ESIX Subcommittees are highlighted in yellow. Agency actions on QIS R&D have been ongoing during this time, and select NQI-authorized agency activities are highlighted in blue.

The NQI Act calls for a 10-year NQI Program, with an assessment of United States leadership in QIS after five years and an updated strategic plan at that time. The National Strategy for QIS has been augmented by additional SCQIS and ESIX reports since the NQI was established. The budget data and programmatic overview provided in this annual NQI Supplement to the President's Budget is an important step to support the NQI Program development, implementation, and planning. Looking forward, the SCQIS and ESIX, with support from the NQCO and information from the NQI Advisory Committee, will work to identify the most important metrics to chart progress towards NQI Program goals and priorities. As the landscape of QIS R&D evolves, the Subcommittees will develop new policies and update current ones to ensure activities are in alignment with the current and future needs of the QIS ecosystem. By continuing to prioritize investment in fundamental QIS across agencies, the United States will be positioned to capitalize on scientific advancements in this emerging area for economic prosperity, national security, and the benefit of the American people.