NATIONAL QUANTUM INITIATIVE SUPPLEMENT TO THE PRESIDENT'S FY 2021 BUDGET

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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The National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS) was legislated by the National Quantum Initiative Act and coordinates Federal research and development (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 2021 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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Abbreviations and Acronyms

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
ARO	Army Research Office
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
ESIX	Subcommittee for Economic and Security Implications of Quantum Science
FBI	Federal Bureau of Investigation
HSST	House Committee on Science, Space, and Technology
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
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NQCO	National Quantum Coordination Office
NQI	National Quantum Initiative
NQIAC	National Quantum Initiative Advisory Committee
NRL	Naval Research Laboratory
NSA	National Security Agency
NSC	National Security Council
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
QED-C	Quantum Economic Development Consortium
QLCI	Quantum Leap Challenge Institutes
R&D	research and development
SCQIS	Subcommittee on Quantum Information Science
USPTO	United States Patent and Trade Office
USDA	United States Department of Agriculture

Executive Summary

Quantum information science (QIS) unifies concepts from quantum mechanics and information theory, two foundational theories underpinning modern technology. QIS research includes transformative new types of computers, sensors, and networks that can improve the Nation's prosperity and security. Investment in fundamental QIS research thus lays a foundation for industries of the future, and opens new frontiers in science.

> *Quantum Information Science represents a foundational shift in our understanding of physics and information science, with the potential for dramatic technology impact.*
> *-Dr. Charles Tahan, Assistant Director for QIS, Office of Science and Technology Policy*

The National Quantum Initiative (NQI) Act became Public Law 115-368 in December 2018 to accelerate American leadership in quantum information science and technology. The NQI Act authorizes U.S. Federal Departments and Agencies (hereafter, "agencies") to establish centers and consortia to foster QIS research and development (R&D). The NQI Act also calls for coordination of QIS R&D efforts across the Federal government, and with industry and the academic community.

This is the first Annual Report on the NQI Program budget, as required by the NQI Act. The release of this report follows the ramp-up of the NQI Program during 2019 and the establishment of several NQI centers and a consortium during 2020, with actual budget authority of $450 million for QIS R&D in 2019, over $580 million of enacted budget authority for QIS R&D in FY 2020, and a requested budget authority of $710 million for QIS R&D in FY 2021.

The United States has invested in fundamental QIS R&D, with core efforts underway in over a dozen agencies. Therefore, to highlight the entire Federal QIS R&D ecosystem, the substantial and sustained efforts funded by the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), the Department of Energy (DOE), the Department of Defense (DOD), the Intelligence Community (IC), and the National Aeronautics and Space Administration (NASA) are recognized. This report includes brief summaries of agency efforts in addition to progress on cross-cutting QIS policy topics.

The strategic plan guiding NQI Program investments is the *National Strategic Overview for Quantum Information Science*. Released by the National Science and Technology Council (NSTC) Subcommittee on QIS in 2018, the *Strategic Overview* identifies policy areas discussed here in Section 4, namely: investing in fundamental quantum information science and engineering, developing the workforce capacity, engaging with industry, investing in infrastructure, maintaining economic and national security, and encouraging international cooperation.

Looking towards the future, agency efforts in QIS R&D are growing because QIS can have profound and positive impacts on society. While the development of QIS technology is at an early stage, now is a critical time to develop infrastructure and fundamental scientific knowledge needed to grow the marketplace and foster QIS-inspired technology and applications.

1 Introduction

Quantum Information Science (QIS) builds on quantum mechanics and information theory to explore the fundamental limits for computation, communication, and measurement. The improved understanding of the quantum world provided by these explorations shows that in some cases, the performance of quantum information systems is vastly superior to that of traditional classical technologies. Building on key QIS discoveries since the 1980's, pioneering QIS experiments since the 1990's, quantum engineering from the 2000's, and commercial activity now, the world is on the cusp of a second quantum revolution. Prospects for innovation fueled by QIS, with implications for jobs and security, motivated the United States to enact the National Quantum Initiative.

The National Quantum Initiative Act (NQI Act) was signed into law on December 21, 2018, "to provide for a coordinated Federal program to accelerate quantum R&D for the economic and national security of the United States" [1]. The NQI Act authorizes NIST, NSF, and DOE to strengthen QIS Programs, Centers, and Consortia. The NQI Act also calls for a coordinated approach to QIS R&D efforts across the United States (U.S.) Government, including the civilian, defense, and intelligence sectors. To guide these actions, the NQI Act legislates some responsibilities for the NSTC Subcommittee on Quantum Information Science (SCQIS), the National Quantum Coordination Office (NQCO), and the National Quantum Initiative Advisory Committee (NQIAC). Recognizing that QIS technologies have commercial and defense applications, additional authorization for QIS R&D is legislated by the National Defense Authorization Act[2,3]. Civilian, defense, and intelligence agencies all have a long history of investments in QIS, and have a stake in future QIS discoveries and technology development. The NQI now provides an overarching framework to strengthen and coordinate QIS R&D activities across agencies, along with private sector industry and the academic community.

The *National Strategic Overview for QIS*[4] recommends strengthening the United States' approach to QIS R&D by focusing on six areas: science, workforce, industry, infrastructure, security, and international cooperation. Key activities on these topics supported with Federal budgets are reported here. For example, NIST formed the Quantum Economic Development Consortium (QED-C), NSF announced Quantum Leap Challenges Institutes (QLCI), and DOE established its National QIS Research Centers. Further examples, along with mechanisms to coordinate QIS R&D efforts across the Federal government are also provided in Sections 3 and 4.

Figure 1.1: U.S. CTO Michael Kratsios visits Fermi National Laboratory to learn more about the lab's quantum research efforts. Credit: OSTP

The SCQIS, NQIAC, and NQCO are legislated by the NQI Act. Their activities build on a history of Federal QIS R&D coordination via interagency activities such as the 2009 NSTC Report on *A Federal Vision for*

[1] https://www.congress.gov/115/plaws/publ368/PLAW-115publ368.pdf
[2] https://www.congress.gov/115/plaws/publ232/PLAW-115publ232.pdf
[3] https://www.congress.gov/116/plaws/publ92/PLAW-116publ92.pdf
[4] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

QIS[5], and the 2016 NSTC Report from the Interagency Working Group on QIS[6]. U.S. QIS R&D efforts are also informed by numerous Federally-funded workshops led by the QIS R&D community[7].

Box 1.1

COORDINATING BODIES OF THE NATIONAL QUANTUM INITIATIVE

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

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

The National Quantum Initiative Advisory Committee (NQIAC) is the Federal advisory committee called for in the NQI Act and established by Executive Order 13885[8] to council 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 to the President, the Secretary of Energy, and the SCQIS to consider when reviewing and revising the NQI Program. The NQIAC consists of leaders in the field from industry, academia and the Federal government. The membership of the NQIAC is listed on the DOE site[9].

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

[5] https://www.quantum.gov/wp-content/uploads/2020/10/2009_NSTC_Federal_Vision_QIS.pdf
[6] https://www.quantum.gov/wp-content/uploads/2020/10/2016_NSTC_Advancing_QIS.pdf
[7] See the Quantum Frontiers Report bibliography https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf
[8] https://www.federalregister.gov/executive-order/13885
[9] https://science.osti.gov/About/NQIAC/About/Members

2 Budget Data

This section presents the U.S. Federal budgets for QIS R&D based on Fiscal Year (FY) 2019 actual expenditures, FY 2020 estimated expenditures, and FY 2021 proposed budgets. During this period, the Administration R&D Budget Priorities Memos[10] have consistently highlighted how QIS R&D is important for industries of the future.

Figure 2.1 shows overall Federal budgets for U.S. QIS R&D efforts aggregated across several agencies (NIST, NSF, DOE, NASA, DOD, and DHS), and also aggregated across several QIS subtopics (e.g., computing, networking, sensing, fundamental science, and technologies). Much of the growth in QIS R&D budgets is for NQI activities such as the establishment of quantum consortia by NIST, Quantum Leap Challenge Institutes (QLCI) by NSF, QIS National QIS Research Centers by DOE, and coordination and strengthening of core QIS programs across many agencies. Sustained growth in U.S. QIS R&D will position American universities, industries, and government researchers to explore quantum frontiers, advance QIS technologies, and develop the required workforce to continue American leadership in this field and related industries of the future.

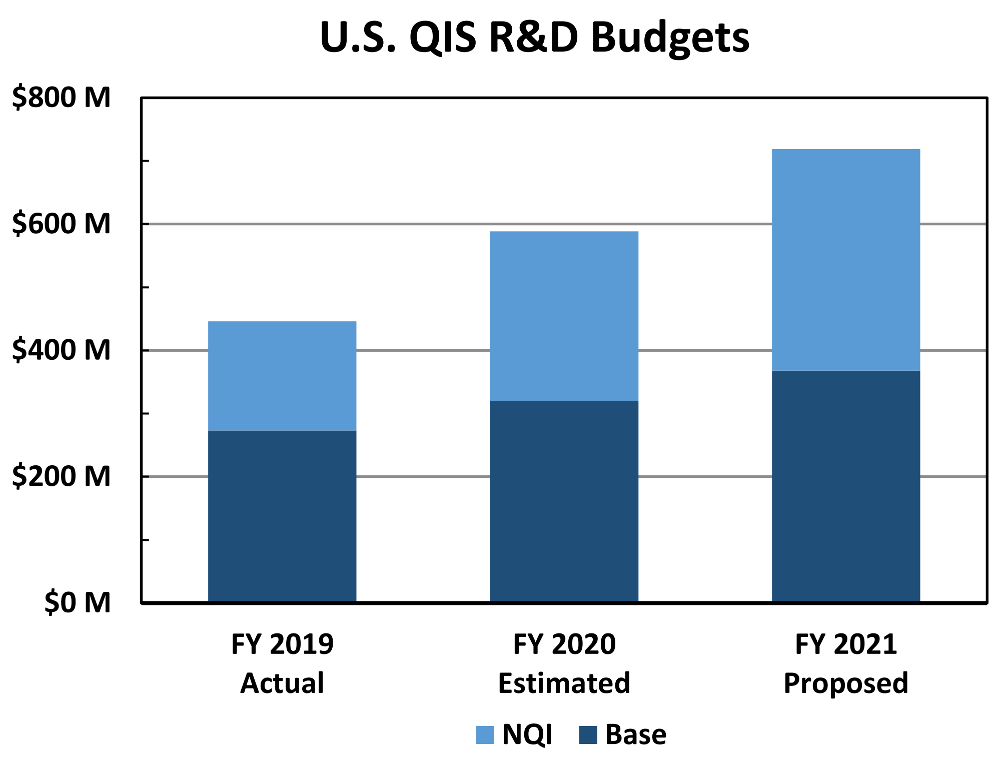

Figure 2.1: U.S. R&D budgets for QIS since the inception of the NQIA. The bar heights represent the total budget for each fiscal year (FY 2019 actual expenditures, FY 2020 estimated expenditures, and FY 2021 proposed budgets). The portion of each bar marked "NQI" identifies funding allocated for NQIA-authorized activities; this additional funding is on top of the budgets for baseline QIS R&D activities. Increases reflect the Administration's priority to grow QIS R&D.

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[10] For example, see R&D Priority Memos:

- FY 2019 (https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/memoranda/2017/m-17-30.pdf);
- FY 2020 (https://www.whitehouse.gov/wp-content/uploads/2018/07/M-18-22.pdf);
- FY 2021 (https://www.whitehouse.gov/wp-content/uploads/2019/08/FY-21-RD-Budget-Priorities.pdf); and
- FY 2022 (https://www.whitehouse.gov/wp-content/uploads/2020/08/M-20-29.pdf)

The President has made a commitment to double QIS R&D budgets[11] to accelerate American leadership in QIS and technology. This commitment refers to a doubling over a two year period (2020 – 2022), starting from a baseline of $435 million in 2020[12]. Agencies are well on the way to realizing this goal, with growth in QIS budgets catalyzed by NQI activities as shown in Figure 2.1, and discussed in a fact sheet[13] released by OSTP.

Budget allocations over five different NQI Program Component Areas or PCAs are discussed next. These PCAs are consistent with the classification used in the *National Strategic Overview for QIS*.

NQI Program Component Areas

- **Quantum Sensing and Metrology (QSENS)** refers to the use of quantum mechanics to enhance sensors and measurement science. This can include uses 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 development of quantum bits (qubits), algorithms and software for quantum computing, both with digital quantum computers and prototype devices, and with analog quantum simulation of quantum systems in the laboratory.
- **Quantum Networking (QNET)** efforts include exploring, creating, and using coherent or entangled multi-party quantum states, distributed at distance, for new information technology applications and fundamental science.
- **Quantum Advancements (QADV)** include fundamental research activities enabled by quantum devices and QIS theory, for example improved understanding of materials, biology, nuclear matter, engineering, chemistry, cosmology, classical computation techniques, and other aspects of fundamental science.
- **Quantum Technology (QT)** includes work with end-users to develop new use cases for quantum technologies, and as well as work on basic supporting technology for QIS, e.g., creating necessary infrastructure, equipment, testing, and manufacturing techniques. This category also includes R&D efforts to mitigate risks and challenges enabled by new quantum information developments, e.g., R&D on quantum-resistant cryptosystems and other post-quantum applications, and R&D to maintain an understanding of the impact of quantum technologies.

Figure 2.2 shows allocations by NQI Program Component Areas for FY 2019, FY 2020 and FY 2021. The bar chart uses a "layer-cake" for each year to show amounts budgeted for each PCA. The totals are the same as those in Figure 2.1. Figure 2.2 reports the total U.S. QIS R&D budgets by PCA, but does not distinguish between baseline core programs and NQI activities.

Figure 2.3 presents allocations by PCA using a radar plot. Using separate directions for each PCA, and the distance from the center (zero dollars) to show PCA budgets, one can see the "footprint" of U.S. QIS R&D budgets change from 2019 to 2021. Figure 2.3 shows how increases occurred for each PCA during this period, and in line with a new coordinated Federal vision[14] for quantum networking, the PCA with the largest increase was for QNET.

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[11] https://www.whitehouse.gov/briefings-statements/president-trumps-fy-2021-budget-commits-double-investments-key-industries-future/
[12] https://www.whitehouse.gov/wp-content/uploads/2017/12/Artificial-Intelligence-Quantum-Information-Science-R-D-Summary-August-2020.pdf
[13] https://www.whitehouse.gov/wp-content/uploads/2020/02/FY21-Fact-Sheet-IOTF.pdf
[14] https://www.quantum.gov/wp-content/uploads/2021/01/2020_NQCO_Vision_QN.pdf

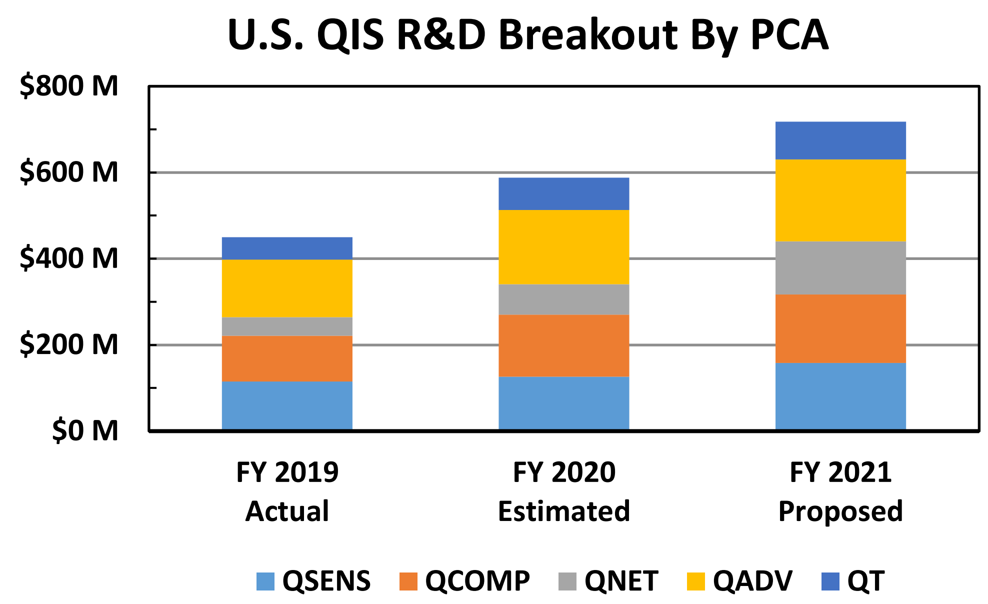

Figure 2.2: U.S. QIS R&D Budget allocations by NQI Program Component Area (PCA) topic for FY 2019 actual expenditures, FY 2020 estimated expenditures, and FY 2021 proposed budgets.

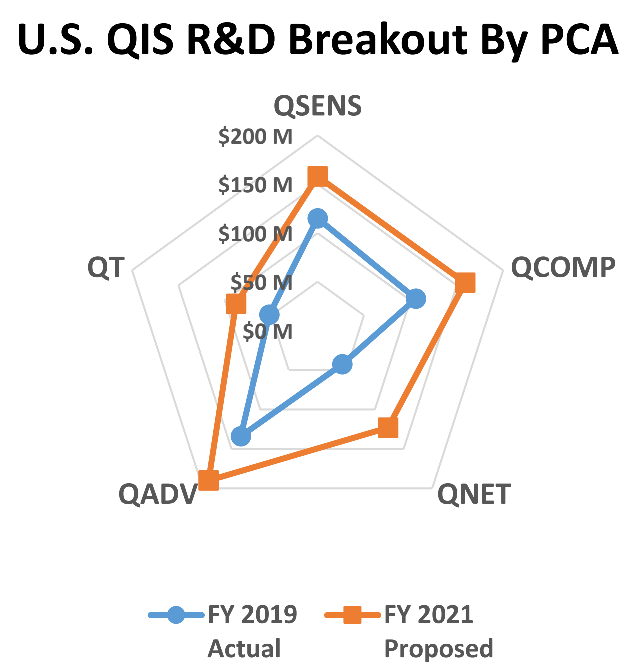

Figure 2.3: Radar plot of U.S. QIS R&D budgets by PCA for FY 2019 actual expenditures and FY 2021 proposed budgets, using different directions for each PCA (topic), and distance from the origin (|r|) to represent budgets. The change in "footprint" shows an increase in each PCA, and illustrates the largest increase for QNET.

A final breakdown for the budget data presented here shows QIS R&D budgets by agency. Figure 2.4 shows the total QIS R&D budgets for the three agencies prominently identified in the NQI Act: NIST, NSF, and DOE.

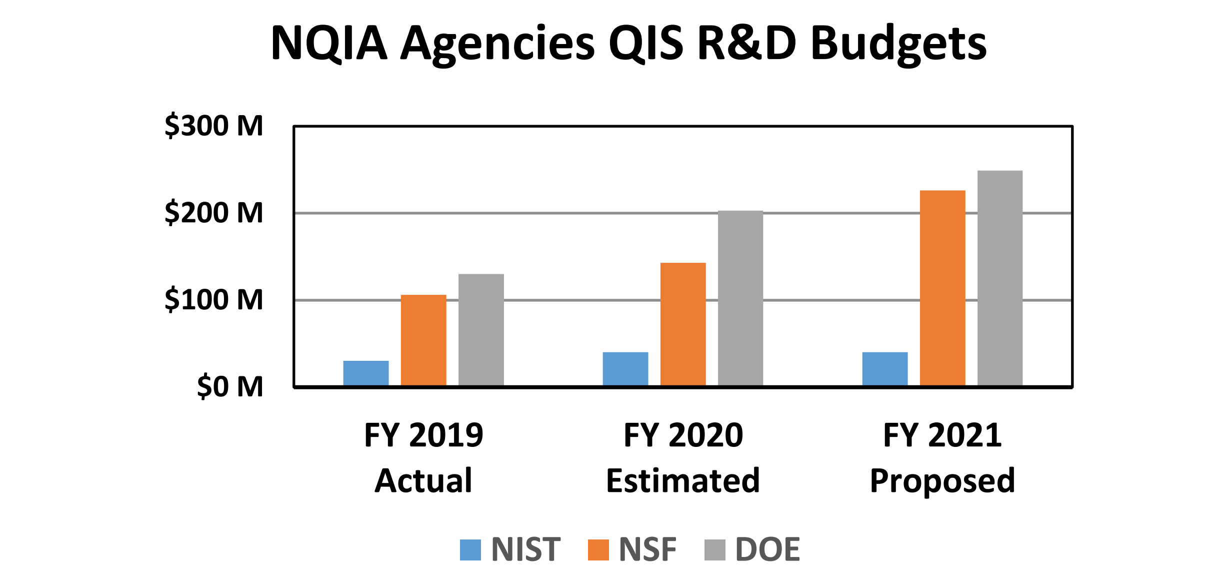

Figure 2.4: QIS R&D Budgets for three Agencies identified in the NQI Act, showing FY 2019 actual expenditures, FY 2020 estimated expenditures, and FY 2021 proposed budgets.

In summary, the budget data shows U.S. Government investments in QIS R&D, including activities authorized by the NQI Act. Figures 2.1-2.4 present the budget portions for NQI activities, portions for different NQI Program Component Areas, and portions for different agencies identified in the NQI. The NQI Act has led to increased investment in QIS R&D across the Federal government and across each PCA. Budget data in this report reflect information provided by agencies to the Office of Management and Budget (OMB) regarding their QIS R&D efforts. The budget data collection process for the QIS crosscut is now established, so it can be routinely accomplished to support monitoring, implementing, and revising the NQI Program.

The next sections describe how agencies are using these budgets to advance quantum information science and engineering (QISE). Adding emphasis on engineering, as called for by the NQI Act, is in recognition of the increasingly important role engineering will play as basic QIS discoveries are translated to technology that can be applied to address agency missions and needs in industry and society. Section 3 starts with QIS R&D program highlights from NIST, NSF, and DOE, the three agencies prominently identified in the NQI Act, and highlighted in Figure 2.4. Then Section 4 highlights activities supported by several agencies that move the Nation forward in the key QIS policy areas identified in the *Nation Strategic Overview for QIS*.

3 QIS R&D Program Highlights

This section describes QIS R&D activities supported by agencies, emphasizing the role of NIST, NSF and DOE because they have particular responsibilities authorized by the NQI Act. In an effort to survey more of the QIS R&D ecosystem supported by the Federal government, highlights are also provided from DOD, NASA, LPS, and IARPA. It is valuable to understand how each agency has a different mission but works together as part of the Federal QIS Ecosystem to advance basic science and explore use-cases for QIS-inspired technologies. Figure 3.1 illustrates the "three pillars model" of the Federal QIS ecosystem to provide this perspective.

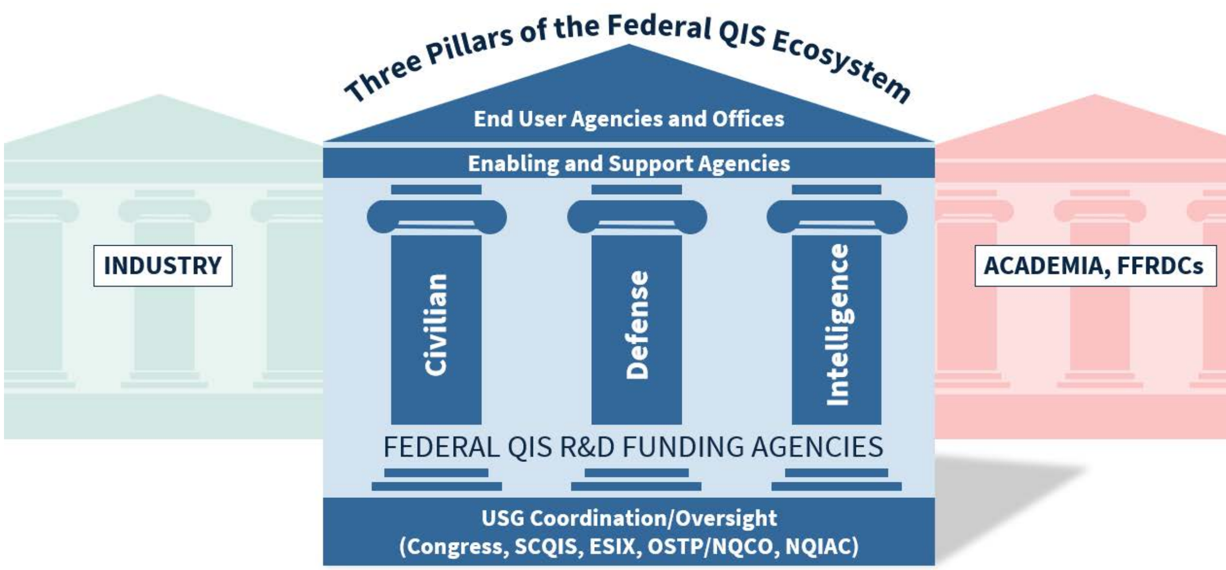

Figure 3.1: Federal QIS R&D funding agencies can be seen as three pillars that support the Federal QIS ecosystem. Civilian science agencies (DOE, NASA, NIST, NSF) stand alongside the Department of Defense science agencies [DARPA, ARO, AFOSR, ONR, ARL, NRL, AFRL, OUSD(R&E)] and the Intelligence Community science agencies (IARPA, LPS) to collectively support QIS R&D efforts. Within Federal government, administrative support enabling the QIS ecosystem also comes from FBI, USPTO and DOS, and potential end users include NIH, DHS, USDA, DOI, DOD, and ODNI. Authorization, coordination and oversight are provided by Congress, SCQIS, ESIX, OSTP, NQCO, and NQIAC. Industry, Academia, and Federally Funded Research and Development Centers (FFRDC's) are also critically important to the broader QIS R&D ecosystem.

Section 3 continues with QIS R&D program highlights in subsections 3.1 from NIST, 3.2 from NSF, 3.3 from DOE, 3.4 from DOD, 3.5 from NASA, 3.6 from LPS, and 3.7 from IARPA.

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 prosperity. With emphasis on precision metrology and cybersecurity, NIST conducts open, world-class research touching all elements of the National QIS agenda. As authorized by the NQI Act, NIST is coordinating consortia focusing on quantum technologies and the prerequisite supply chains, while maintaining its fundamental QIS R&D programs. NIST has been a leader in QIS R&D for over three decades, including a seminal workshop on QIS at its Gaithersburg campus in 1994. Ongoing quantum activities at NIST can be found at https://www.nist.gov/topics/quantum-information-science.

QIS R&D activities supported by NIST relevant to the NQI include:

- NIST initiated the formation of the Quantum Economic Development Consortium (QED-C; https://quantumconsortium.org/), which aims to extend U.S. leadership in quantum research by building the future supply chain needed for the quantum economy. NIST is using its new Other Transaction Authority to support and establish the QED-C in coordination with SRI International.
- NIST engages with industry through Cooperative Research and Development Agreements (CRADA) that facilitate access to NIST laboratories and the transfer of technology.
- NIST's Center for Nanoscale Science and Technology (CNST) is a national user facility in which many types of QIS devices may be prototyped. NIST's Boulder microfabrication facility is a leading facility for superconducting devices and integrated photonics.
- NIST works collaboratively with its peer National Metrology Institutes around the world on quantum metrology, including methods for dissemination of the International System of Units or SI.
- NIST's joint institutes—JILA (with the University of Colorado/Boulder) and the Joint Quantum Institute or JQI and the Joint Center for Quantum Information and Computer Science or QUICS (with the University of Maryland at College Park)—provide QIS instruction and research opportunities to undergraduate and graduate students. The NRC Postdoctoral and JILA Visiting Fellows programs provide additional opportunities for transformative post-graduate and early-career experiences.
- NIST initiated an effort to design a prototype compact optical atomic clock that would have a sufficient holdover time to provide a backup to GPS for up to two weeks. The focus is to have a power requirement on the order of 100 watts and a size of a few liters. Such a clock, if made and appropriately priced, could be placed on cell phone towers and internet switching stations.
- NIST established a program on building a scalable quantum repeater using ion trap technology to support the numerous efforts to build a general-purpose quantum network. Two missing technologies for such a network are quantum memory and a quantum repeater.

NIST QIS R&D activities highlighted in the news:

- NIST Post-Quantum Cryptography Standards has entered the final selection round. This is crucial to secure our public key infrastructure once a general-purpose quantum computer becomes available[15].

[15] https://www.nist.gov/news-events/news/2020/07/nists-post-quantum-cryptography-program-enters-selection-round

- NIST demonstrated a new path for building single atom transistors that can form the basis for solid-state quantum computing[16].
- NIST developed methods to perform custom calibrations for the handful of companies that make single photon devices. The techniques have become sufficiently routine that NIST is moving forward to create a calibration service[17].
- NIST demonstrated a next generation time scale that exploits the most reliable optical clocks and creates improved time-transfer capabilities[18].
- NIST formally established a participation agreement for membership with the QED-C, with the formal approval by the QED-C Steering Committee[19].

Box 3.1

The Quantum Economic Development Consortium or QED-C is an industry-led consortium that aims to extend U.S. leadership in quantum research by building the future supply chain needed for the quantum economy. The QED-C membership is composed of companies, non-profits, and academic institutions that span the quantum ecosystem. The QED-C steering committee consists of representatives from both large companies and small/start-up companies, together with two government agencies (NIST, DOE). Beyond this, a range of companies, non-profits and academic institutes have signed letters of intent and will be converting to full membership during the fall of 2020.

The QED-C brings together members to identify cross-cutting issues technology and workforce gaps, and to work in a pre-competitive space to move the entire industry forward. Federal agencies, including NIST, DOE, and AFRL engage with the QED-C by participating in meetings and providing technical expertise at workshops and for technical advisory committees (TACS).

[16] https://www.nist.gov/news-events/news/2020/05/nist-scientists-create-new-recipe-single-atom-transistors
[17] https://www.nist.gov/news-events/news/2019/12/counting-photons-now-routine-enough-need-standards
[18] https://www.nist.gov/news-events/news/2019/10/jila-team-demonstrates-model-system-distribution-more-accurate-time-signals
[19] https://www.nist.gov/news-events/news/2020/09/quantum-economic-development-consortium-confirms-steering-committee

3.2 The National Science Foundation (NSF)

NSF promotes the progress of science by funding basic research at approximately 2000 academic institutions throughout the United States. As authorized by the NQI Act, NSF is strengthening core programs related to QISE and establishing new institutes focusing on multidisciplinary QIS research challenges and training. NSF has supported QIS research since the field's inception in the early 1980's. Ongoing QISE research at NSF are described here: http://nsf.gov/quantum.

QIS R&D Programs at NSF relevant to the NQI:

- The Quantum Leap Challenge Institutes (QLCI) program (Solicitation NSF 19-559) supports large-scale interdisciplinary research projects that advance the frontiers of QIS and engineering. QLCI institutes foster multidisciplinary approaches to scientific, technological, educational, and workforce development goals for quantum computation, quantum communication, quantum simulation, and quantum sensing. See Box 3.2 and Figure 3.2. Three institutes have been funded in FY 2020, and NSF expects to fund additional institutes in FY 2021.
- To grow the QIS R&D community, NSF created the Quantum Idea Incubator for Transformational Advances in Quantum Systems (QII-TAQS) Program (Solicitation NSF 19-532). This supports interdisciplinary teams that explore highly innovative, original, and potentially transformative ideas for developing and applying quantum science, quantum computing, and quantum engineering. NSF funded 19 QII-TAQS projects with grants totaling over $32 million in 2019 and 2020. An earlier Dear Colleague Letter (NSF 18-035) for "Transformational Advances in Quantum Systems" resulted in 25 Awards, totaling $25 million, in 2018.
- A quantum foundry solicitation (NSF 18-578) was issued to accelerate quantum materials design, synthesis, and characterization. The resulting NSF Award 1906325 supports infrastructure for prototyping and developing quantum materials and devices.
- The Quantum Computing and Information Science Faculty Fellows (QCIS-FF) program (NSF 19-507) aims to grow academic research capacity and support advances in quantum computing and communication over the long term, with support to help universities hire faculty in Computer Science departments to work on quantum computing and communication. Thus far, 13 faculty fellow positions have been funded around the country through this program.
- The NSF Connections in QIS (CQIS) meta-program lists several ongoing NSF programs that support fundamental QISE-related research and training[20].

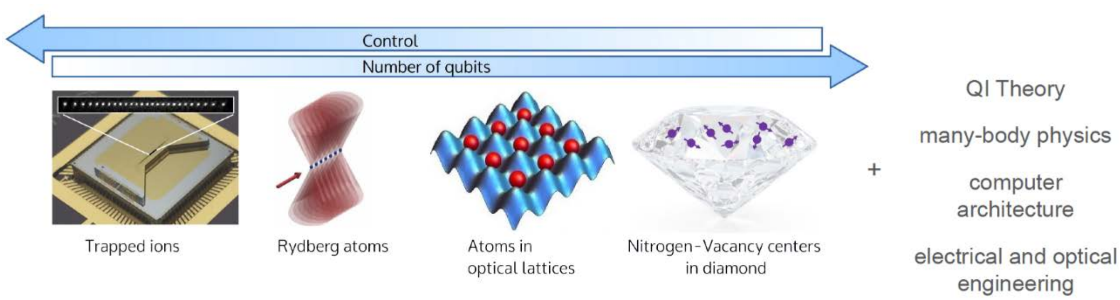

Figure 3.2: The challenge of scaling quantum information processing systems will be investigated with a diverse portfolio of platforms and approaches. Image credit: CIQC at the University of California, Berkeley.

[20] Connections in QIS meta-program: https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505283

- The Quantum Leap, unveiled in 2016 as one of NSF's 10 Big Ideas[21], involves all parts of NSF to support cutting-edge research and training in QISE, laying important groundwork for the NQI. Quantum Leap activities include the Quantum Science Summer School (NSF Award 1743059) jointly supported with AFOSR and DOE; and the "QISE-Net Workshop Series: Cross-Sector Connections" (NSF Award 1747426). Recent Quantum Leap activities include: DCL NSF 20-073 "Enabling Quantum Computing Platform Access"; DCL NSF 20-056 "Quantum Algorithm Challenge"; DCL NSF 20-063 for supplements supporting international QISE activities, and the Convergence Accelerator Solicitation (NSF 20-565) Quantum Technologies track.
- Along with Quantum Leap activities and core programs, NSF supports several centers and hubs that focus on QIS. These include four Physics Frontiers Centers: the Institute for Quantum Information and Matter (IQIM) at Caltech, the Center for Ultracold Atoms (CUA) at Harvard and MIT, the JQI at the University of Maryland, and JILA at the University of Colorado. NSF also supports the Center for Quantum Information and Computing (CQUIC) at the University of New Mexico, the Institute for Theoretical Atomic and Molecular Physics (ITAMP) at the Harvard Smithsonian Center for Astrophysics, the Science and Technology Center for Integrated Quantum Materials (CIQM) at Harvard, the Engineering Research Center for Quantum Networks (CQN) at the U. of Arizona, the multi-institutional Software-Tailored Architecture for Quantum co-design (STAQ) project, and the multi-institutional Enabling Practical-Scale Quantum Computing (EPiQC) project.

NSF QIS R&D activity highlights in the news:

- NSF announced $9.75 million for Quantum Computing Faculty Fellows to stimulate universities across the country to create more QIS faculty jobs in computer science departments and foster interdisciplinary research and curricula[22].
- NSF announced[23] $1 million for QIS education, establishing the Q2Work Program[24] aimed at supporting learners and educators in QIS and technology[25].

Box 3.2
Quantum Leap Challenge Institutes (July 21, 2020) NSF announced $75 million over five years for three Quantum Leap Challenges Institutes starting in 2020[26], in alignment with the NQI. NSF Director Sethuraman Panchanathan stated that "*QIS has the potential to change the world. But to realize that potential, we must first answer some fundamental research questions*." • NSF QLCI for Enhanced Sensing and Distribution Using Correlated Quantum States University of Colorado • NSF QLCI for Hybrid Quantum Architectures and Networks University of Illinois, Urbana-Champaign • NSF QLCI for Present and Future Quantum Computing University of California, Berkeley The institutes comprise an interconnected community of 16 core academic institutions, 8 national laboratories, and 22 industry partners.

[21] https://www.nsf.gov/news/special_reports/big_ideas/quantum.jsp
[22] https://www.nsf.gov/news/news_summ.jsp?cntn_id=301001&org=CISE
[23] https://www.nsf.gov\news\special_reports\announcements\080520.jsp
[24] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2039745&HistoricalAwards=false
[25] https://www.nsf.gov/news/special_reports/announcements/080520.jsp
[26] https://www.nsf.gov/news/special_reports/announcements/072120.jsp

3.3 The Department of Energy (DOE)

DOE ensures America's prosperity and security through several mechanisms including basic and applied scientific research, discovery and development of new technologies, and scientific innovation. The DOE National Laboratories are a system of intellectual assets unique among world scientific institutions and serve as regional engines of economic growth for States and communities across the country. As authorized by the NQI Act, DOE is strengthening core programs and establishing new Centers focusing on QIS research. Additional information about ongoing QIS activities at DOE is available at: https://science.osti.gov/Initiatives/QIS.

DOE's Office of Science (SC) involvement in QIS is driven by its mission needs and reflects its status as the Nation's leading supporter of basic research in physical sciences and the unique capabilities and expertise that are resident in the DOE National Laboratory complex[27]. DOE continues to invest in early stage QIS research in key DOE areas including computing, simulation, sensing, and communication through its various components:

- **Advanced Scientific Computing Research (ASCR)** QIS contributions include providing early access to new technology through quantum testbeds, exploring DOE-relevant applications, and ensuring that application needs inform next-generation device design and basic research programs in applied mathematics, networking, and computer science.
- **Biological and Environmental Research (BER)** can benefit from QIS imaging and sensing approaches to expand experimental observation capabilities for environmental parameters or biological and physical materials.
- **Basic Energy Sciences (BES)** supports research to advance the control of quantum coherence and entanglement in novel quantum materials and systems to enable applications encompassing information processing, secure communication, sensors, energy generation, and control of chemical reactions. BES research and infrastructure for advanced synthesis, fabrication, characterization, theory, modeling, testing, benchmarking, and development will advance QIS.
- **Fusion Energy Sciences (FES)** aims to identify and refine quantum simulation capabilities that can solve important fusion and plasma science problems, quantum sensing approaches that can enhance diagnostic capabilities for plasma and fusion science, and apply plasma science techniques to improve quantum control.
- **High Energy Physics (HEP)** QIS research includes: field theory techniques, gauge symmetries, and tensor networks invoking quantum information and entanglement concepts and quantum simulations of HEP quantum problems. QIS-enhanced sensing using superposition, entanglement, and/or squeezing can provide information for previously inaccessible regimes of the dark sector (dark matter and dark energy) and new interactions that cannot be probed by other detectors. HEP also promotes quantum simulation experiments and/or theoretical, computational, and/or experimental research at the intersection of quantum gravity, information theory, error correction, and teleportation.
- **Nuclear Physics (NP)** QIS research includes: cryogenics, hyperpolarized gases, nuclear and atomic spin manipulation, laser cooling, superconducting RF cavities, and atom trapping; solution of fundamental field theories that underlie nuclear physics, such as quantum chromodynamics;

[27] https://science.osti.gov/Initiatives/QIS/Program-Offices-QIS-Pages

and applications of quantum computing including many-nucleon problems of relevance to nuclei, nuclear structure and reactions, and bulk nuclear matter.

The DOE National Nuclear Security Administration QIS research includes: development of mission-relevant algorithms for simulation capabilities and deployment of test beds.

DOE QIS R&D activity highlights in the news:

- DOE announced up to $625 million for National QIS Research Centers[28] with Funding Opportunity Announcement DE-FOA-0002253, following responses to a public Request for Information (Federal Register Document 84 FR 22834). See the resulting Centers in Box 3.3.

Box 3.3

National QIS Research Centers. DOE announced five QIS Research Centers on August 26, 2020:

- Q-NEXT · Next Generation Quantum Science and Engineering
  Argonne National Laboratory
- C2QA · Co-design Center for Quantum Advantage
  Brookhaven National Laboratory
- SQMS · Superconducting Quantum Materials and Systems Center
  Fermi National Accelerator Laboratory
- QSA · Quantum Systems Accelerator
  Lawrence Berkeley National Laboratory
- QSC · The Quantum Science Center
  Oak Ridge National Laboratory

The DOE National QIS Research Centers involve research at 11 DOE Labs, 39 Academic institutions, and 14 Companies. Under Secretary for Science Paul Dabbar stated: "We are on the threshold of a new era in Quantum Information Science and quantum computing and networking, with potentially great promise for science and society."[29]

- In August 2019, DOE announced $60.7 million in funding to advance the development of quantum computing and networking[30] and $21.4 Million for QIS Research with projects linked to both Particle Physics and Fusion Energy[31].
- DOE's HEP program selected 21 new QIS projects in particle physics ranging from quantum sensors for detection of rare particles, to quantum computing efforts to analyze particle physics data, and quantum simulation experiments connecting the cosmos to quantum systems. Six Fusion Energy Science projects will examine the application of quantum computing for fusion and plasma science, uses of plasma science techniques for quantum sensing, and the quantum behavior of matter under high-energy-density conditions.
- In April 2020, DOE announced $12 million for additional research on QIS and fusion energy[32].
- DOE released its Quantum Internet Blueprint workshop report[33].
- DOE's Oak Ridge National Laboratory participated in the Quantum Supremacy research highlighted in Box 3.4.

[28] https://science.osti.gov/Initiatives/QIS/QIS-Centers
[29] Department of Energy Announces $60.7 Million to Advance Quantum Computing and Networking | Department of Energy
[30] https://www.energy.gov/articles/department-energy-announces-607-million-advance-quantum-computing-and-networking
[31] https://www.energy.gov/articles/department-energy-announces-214-million-quantum-information-science-research
[32] https://www.energy.gov/articles/department-energy-announces-12-million-research-quantum-information-science-fusion-energy
[33] https://www.osti.gov/biblio/1638794/

Box 3.4

Quantum Computational Supremacy

(October 23, 2019) A joint research team from Google Inc., NASA Ames Research Center, and the DOE's Oak Ridge National Laboratory published their results in Nature reporting that a quantum computer can outperform a classical computer at certain tasks, a feat known as quantum supremacy. The quantum computer, built by Google and dubbed Sycamore, consisted of 53 qubits. The classical computer was ORNL's Summit, housed at the Oak Ridge Leadership Computing Facility and at the time was ranked as the world's most powerful thanks to its more than 4,600 compute nodes, each running at 40 teraflops.

Both systems performed a task known as random circuit sampling, designed specifically to measure the performance of quantum devices such as Sycamore. The simulations took 200 seconds on the quantum computer, using quantum algorithms. After running the same simulations on Summit, the team extrapolated that the calculations would have taken the world's most powerful system more than 10,000 years to complete with the state-of-the-art classical algorithms that they implemented. Thus, they provided experimental evidence that quantum computing offers an advantage for a well-defined computational task, demonstrating quantum supremacy, and provided critical information for the design of future quantum computers. Importantly, the manner in which a quantum computer's algorithmic advantage scales with the number of qubits was demonstrated. Not only was Sycamore faster than its classical counterpart in this example, but it was also approximately 10 million times more energy efficient.

The quantum supremacy result was built upon over 30 years of fundamental R&D, with sustained and significant support from Federal agencies and augmented by the private sector. Federal funding that contributed to the foundational scientific and engineering knowledge underpinning this effort came from numerous agencies including projects supported early on by LPS, IARPA, NSF, NIST, and DOD.

Achieving quantum computational supremacy, even for an esoteric problem, was seen as a major milestone because it proves quantum computers offer a significant advantage over classical computing resources. The challenge ahead is to find ways to demonstrate a similar advantage for hard problems that are important for society.

See comments from NASA[34], NASA Ames Research Center, Oak Ridge National Laboratory[35], and the U.S. Chief Technology Officer[36] on this achievement.

[34] https://www.nasa.gov/feature/ames/quantum-supremacy/
[35] https://www.ornl.gov/news/quantum-supremacy-milestone-harnesses-ornl-summit-supercomputer
[36] https://www.whitehouse.gov/articles/america-achieved-quantum-supremacy/

3.4 The Department of Defense (DOD)

The DOD Research & Engineering mission supports the national defense strategy, from basic and applied research through operational test and evaluation. Quantum science is one of DOD's top 11 modernization priority areas, and has been a focus of sustained funding for almost thirty years. DOD continues substantial investments in basic QIS R&D activities via several DOD offices, agencies, and laboratories. As illustrated in Figure 3.1, these include: the Office of the Under Secretary of Defense for Research and Engineering (OUSDRE); the Defense Advanced Projects Agency (DARPA); the Army Research Laboratory (ARL), the Army Research Office (ARO); the Naval Research Laboratory (NRL); the Office of Naval Research (ONR), the Air Force Research Laboratory (AFRL); and the Air Force Office of Sponsored Research (AFOSR).

DOD QIS R&D activity highlights:

- The Office of the Under Secretary of Defense for Research and Engineering (OUSDRE) created the Principal Director for Quantum Science position in 2018 to lead DOD efforts at technology modernization in quantum science, one of DOD's top technology modernization priority areas.
- The Vannevar Bush Faculty Fellowship, the DOD's most prestigious single-investigator award, supports basic research with the potential for transformative impacts. Currently, several Vannevar Bush Fellows lead QIS research efforts.
- The DOD R&D programs span atomic clocks, quantum sensing, quantum computing, and quantum networking – from fundamental to applied.
- DARPA QIS programs include Optimization with Noisy Intermediate Scale Quantum devices (ONISQ). ARL and ARO support the Center for Distributed Quantum Information. Other highlights include several new Multidisciplinary University Research Initiatives (MURI) awards, extensions, and solicitations from AFOSR and ARO; new partnerships between ARL, NRL, and the UMD Quantum Technology Center; and an OUSD(R&E) Center of Excellence in Advanced Quantum Sensing. New workforce development and education activities included new quantum short courses from AFRL, and ARO grants to support high school and undergraduate student participation in a quantum summer camp.
- The AFRL Information Directorate partnered with the State University of New York (SUNY) and several other entities to create the Innovare Advancement Center,[37] an open campus for fundamental science and innovation. At the end of FY2020, this included holding a $1,000,000 International Quantum U Tech Accelerator event[38]. Additionally, during FY 2020, AFRL held quantum collider[39] events that included pitch days for Quantum Information Technologies wherein companies selected through submitted proposals pitch ideas for STTR PHASE I contracts.

[37] https://www.innovare.org/
[38] https://www.af.mil/News/Article-Display/Article/2344258/air-force-navy-accelerate-quantum-research-with-international-virtual-event/
[39] https://usafquantumcollider.com/

3.5 The National Aeronautics and Space Administration (NASA)

NASA drives advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality and stewardship of Earth. NASA's research portfolio includes some activities focusing on, and motivated by, QIS. NASA has begun exploring the design, development, and deployment of high-rate and high-fidelity space-to-ground quantum network links. In January 2020, NASA and NIST co-sponsored the *Workshop on Space Quantum Communications and Networks*[40] that focused on the critical quantum technologies for space communications and networking NASA would need to develop and mature for an efficiently-designed and executed quantum-technology demonstration space mission. For several years, NASA's Quantum Artificial Intelligence Lab[41] (QuAIL) at NASA Ames has been acting as the space agency's hub for assessing the potential of quantum computers to impact computational challenges faced by the agency. As noted in the Box 3.4, their efforts contributed to the Quantum Supremacy milestone published at the beginning for FY 2020.

3.6 The National Security Agency (NSA)

NSA's Laboratory for Physical Sciences (LPS) has been a sustained sponsor of quantum computing and enabling technologies since the mid-1990s. LPS currently houses four main divisions related to information science and technology, including Solid-State and Quantum Physics[42]. LPS quantum programs span multiple qubit technologies and fund researchers around the country and the world, as well as robust internal research groups at its facility at the University of Maryland, College Park. QIS R&D supported by LPS includes superconducting qubits, trapped ions, qubits in silicon, new and emerging qubit science and technology, quantum state transduction, and characterization of intermediate scale quantum systems. LPS funds graduate students with the Quantum Computing Graduate Research (QuACGR) fellowship program. LPS also worked with DOD to issue a public request for information regarding the R&D community needs and interest in a foundry for qubits for computing[43].

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[44]. Over the last decade, this has involved several applied research programs that explore quantum computing. Ongoing activities include Quantum Enhanced Optimization (QEO), which is focused on advancing quantum annealing through an improvement in scaling complexity over classical methods and the LogiQ program, which seeks solutions to encoding imperfect physical qubits into logical qubits.

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[40] https://www.nasa.gov/directorates/heo/scan/engineering/technology/quantum_communications_workshop
[41] https://ti.arc.nasa.gov/tech/dash/groups/quail/
[42] http://www.lps.umd.edu/solid-state-quantum-physics/index.html
[43] https://beta.sam.gov/opp/98673a00eabb4ffda553f133e5211d77/view
[44] https://www.iarpa.gov/index.php/research-programs/quantum-programs-at-iarpa

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. The following sections of this report (4.1 – 4.6) present a brief overview of policy goals for each of these topics, along with highlighted activities undertaken across the Federal government to fulfill these 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[45]. Historically, the exploration of quantum mechanics precipitated transformative technologies such as atomic clocks and the global positioning system, lasers, transistors, and magnetic resonance imaging. Meanwhile, the exploration of information theory precipitated transformative advances in communication, computation, and data science. The confluence of these fields opens up new scientific vistas to explore, with compelling potential for new QISE applications and use-cases. One of the ongoing challenges is to balance efforts between particular technologies and fundamental science.

The scientific, business, and academic communities have made it clear[46] that QIS holds tremendous opportunities for revolutionary technologies, but investments in basic research are needed to establish critical technical foundations. Therefore, it is the policy of the United States to lead with the science.

[45] V. Bush, *Science the Endless Frontier* (1945) https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm

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

Exploring fundamental problems in QIS and its enabling technologies is prioritized as a means to produce new understanding, develop new capabilities, and 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. The SCQIS, with support from the NQCO, launched the website www.quantum.gov[47] to help coordinate and showcase NQI activities.
- The White House Academic Roundtable on QIS, convened by SCQIS in May 2019, brought together Academic leadership including University and College deans and vice-presidents for research, along with SCIQS agency directors to discuss the landscape for growing academic QIS programs.[48]
- The SCQIS and NQCO produced the *Quantum Frontiers Report*[49] to highlight broad areas, Quantum Frontiers, where solutions to grand challenges are likely to produce transformative advances in QIS. This report collected and organized concepts put forward by the QIS R&D community through responses to an RFI,[50] QIS workshops, roundtables, and studies, and identified the following eight frontier areas as priorities for the government, private sector, and academia to explore:
    - Expanding Opportunities for Quantum Technologies to Benefit Society
    - Building the Discipline of Quantum Engineering
    - Targeting Materials Science for Quantum Technologies
    - Exploring Quantum Mechanics through Quantum Simulations
    - Harnessing Quantum Information Technology for Precision Measurements
    - Generating and Distributing Quantum Entanglement for New Applications
    - Characterizing and Mitigating Quantum Errors
    - Understanding the Universe through Quantum Information
- The SCQIS Science IWG and NQCO convene an annual QIS Program Day that brings together QIS program managers from across the government to discuss projects and directions for QIS R&D.
- *A Strategic Vision for America's Quantum Networks*[51] was released in coordination with the SCQIS. The SCQIS established a Quantum Networking WG to further develop coordinated approaches to quantum network R&D.
- Centers and institutes recently established by DOE and NSF will bring together thousands of scientists, engineers and technicians to investigate the basic scientific principles underlying QIS.
- Many of the QIS R&D efforts highlighted in Section 3 benefit from coordination among several Federal agencies.

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[47] https://www.quantum.gov/
[48] https://www.quantum.gov/wp-content/uploads/2021/01/2019_WH_Academic_RT_on_QIS.pdf
[49] https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf
[50] https://www.federalregister.gov/documents/2019/05/30/2019-11317/request-for-information-on-national-strategic-overview-for-quantum-information-science (Request for Information on National Strategic Overview for Quantum Information Science)
[51] https://www.quantum.gov/wp-content/uploads/2021/01/2020_NQCO_Vision_QN.pdf

4.2 Creating a Quantum-Smart Workforce for Tomorrow

The United States has built a strong foundation for QIS R&D over the past few decades, with a baseline level of research infrastructure and a scientific and technical workforce comprising talented college graduates, Ph.D. students, postdocs, 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-adjacent industry. This approach naturally depends year-by-year on the pace of scientific breakthroughs and the level of support from agencies. This organic, market-driven quantum workforce has seen a tremendous strain as the need for technical talent outstrips supply because of the tremendous increase in domestic QIS industry investment and worldwide efforts in QIS R&D. Additionally, the field is poised for more growth because of the projected applications for QIS technologies. Given the present and anticipated increases in QIS jobs, and the long time-horizon for training, the existing supply of crucial talent is well below the current demand. To support workforce development, the following actions have been undertaken:

- The SCQIS is coordinating workforce development across its member agencies through its IWG on Workforce. The IWG has been engaging with education and industrial communities, the QED-C, and other agencies to understand the supply and demand for a QIS workforce. As a major funder of workforce development and in recognition of the interdisciplinary nature of QIS, NSF has formed its own working group to ensure coordination across several of its directorates.
- In partnership with NSF, the NQCO at OSTP has spearheaded an initiative focused on early education and outreach for quantum education. This included facilitating the Core Concepts for Future learners of QIS workshop[52], and launching the National Q-12 Education Partnership[53], a public-private partnership with the goal of broadening quantum opportunities for high schools.
- Workforce development continues to result from the support of graduate students and post-doctoral researchers. The majority of R&D activities discussed in the previous section directly involve contributions from both the groups.
- NIST continues to support students and postdocs working in the QIS arena through a range of programs, including ongoing activities at their joint institutes (JILA, JQI, and QuICS). Likewise, DOE supports students and postdocs working in the QIS arena through a range of supported projects and at DOE National Laboratories. Additionally, the DOE's Computational Science Graduate Fellowship is actively expanding its support of QIS focused students.
- NSF places a primary focus on the development of a broad-based, diverse workforce for QIS. Activities include: their joint industry-academia graduate training program, known as QISE-NET[54] that establishes the "triplets" program; Quantum Science Summer Schools[55] for training of graduate students and postdoctoral researchers in key quantum science topics and their technological applications, hosted in collaboration with the DOE and the AFOR; NSF Quantum Computing & Information Science Faculty Fellows program[56] and support of their Graduate Research Fellowship Program[57], which continues to align awards with Administration priorities, including QISE.

[52] https://www.nsf.gov/news/special_reports/announcements/051820.jsp
[53] https://www.nsf.gov/news/special_reports/announcements/080520.jsp and https://www.q12education.org
[54] https://qisenet.uchicago.edu/
[55] http://qs3.mit.edu/
[56] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505535
[57] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=6201

4.3 Deepening Engagement with Quantum Industry

The Nation's economic growth and prosperity relies on strong established industries and a vibrant ecosystem for innovation. Basic research fuels this ecosystem by creating new understanding, new materials, new processes, new technologies, and 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 new scientific discoveries and empowers more of the Nation to benefit.

However, the successful translation of discoveries to deployed technologies is challenging. It involves careful handoffs between scientists, engineers, developers, venture capitalists, entrepreneurs, manufacturers, and customers, working together in an innovation ecosystem. Therefore, it behooves the United States to search for, and when appropriate, kick-start quantum technologies by careful support of pathways and connections throughout the innovation community. To this end, agencies organized around the NQI have undertaken the following efforts to support and engage with the quantum industry.

- The SCQIS established an End-User IWG to connect developers with potential early-adopters of QIS technologies. One of the goals of this working group is to help other government agencies understand QIS opportunities and to develop potential applications.
- The *National Strategic Overview for QIS* and the NQI Act identified consortia as mechanisms to foster emerging technologies by growing the market, prioritizing pre-competitive research needs, and establishing norms and standards. NIST establish the QED-C[58], as legislated in the NQI Act and in FY 2020, NIST used 70% of the new funds provided by Congress to support this engagement. NIST and DOE continue to provide oversite via active seats on the QED-C board.
- The QIS Centers and Institutes supported by DOE and NSF each have industry partners as connecting universities and National Laboratories with industry partners is expected to foster technology transfer. As part of the response to the funding opportunity announcement, DOE Quantum Center applicants were to propose industrial partnerships and engagement with the NIST QED-C.
- SBIR/STTR programs operated by several SCQIS Agencies (including NASA, NSF, DOE, and DOD) provide direct seed funding to startups and small businesses in the quantum technology economic sector to support critical R&D activities.
- I-Corps programs help university researchers explore entrepreneurial opportunities and understand the potential economic impacts of new scientific capabilities.
- The NSF Convergence Accelerator program added a Quantum Technology track in FY 2020 to explore near term use-cases for QIS in society; this builds upon three workshops hosted by NSF in FY 2019. The Convergence Accelerator requires teams to leverage public-private and other types of partnerships to rapidly transition research outputs into practical quantum technologies.
- In FY 2020, NSF began offering supplements to research teams to support graduate-student work on industry-based quantum computing cloud platforms, at no financial cost to academic researchers.

[58] https://quantumconsortium.org/

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 investigations. New applications and new lines of inquiry with extraordinarily fragile quantum states require platforms with specialized materials, exacting tolerances, ultralow temperatures, and new quantum control systems. 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 also 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 DOE centers and NSF institutes highlighted previously represent a major investment in infrastructure for the NQI.
- NASA AMES has augmented infrastructure to allow test of a Quantum Annealer, while the Space Technology Mission Directorate has made investments that will enable or enhance future NASA missions and applications to other government agencies and the commercial sector.
- NSF is providing scientists with access to research infrastructure and instrumentation across several scales to enable R&D in QIS and quantum materials, through targeted NSF investments and industry and interagency partnerships including coordinating with industry partners in FY 2020 and beyond to provide academic researchers with access to industry-based quantum computing cloud platforms. Moreover, NSF is continuing to support its investment in the Software-Tailored Architecture for Quantum co-design project (PHY-1818914), which aims to construct a practical quantum computer with demonstrable advantage over current computer technologies. Finally, the NSF Q-AMASE-i program established a Foundry in FY 2019 with mid-scale infrastructure for rapid prototyping and development of quantum materials and devices.
- DOE continues to expand support for its Nanoscale Science Research Centers to support development of new QIS tools and materials and to provide access to early quantum technologies through its quantum testbed programs. In addition, DOE's Oak Ridge National Laboratory is providing access to current quantum computers through its Quantum Computing User Program.
- NIST helped launch the Boulder Cryogenic Quantum Testbed[59] where researchers can probe and compare the performance of a type of material called dielectrics using standardized tools and experimental protocols.
- LPS, along with ARO, released a Qubits for Computing Foundry RFI[60] to better understand upcoming community needs.

[59] https://www.colorado.edu/today/2019/10/03/new-boulder-facility-help-pave-way-quantum-computers
[60] https://beta.sam.gov/opp/98673a00eabb4ffda553f133e5211d77/view

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 and technology 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. Actions listed below support these policy goals.

- The ESIX Subcommittee provides a forum to address economic and national security issues.
- Industry consortia such as the QED-C, with leadership from NIST, DOE and DOD, provide a forum to address concerns regarding the market for emerging technologies.
- NIST, as part of the Department of Commerce, engages directly with industries via CRADA arrangements that focus on technology transfer.
- Post-quantum cryptography, also known as quantum-resistant cryptography, includes ongoing key measures such as updating standards and cryptographic solutions. Research in this area is supported by several SCQIS agencies, with different approaches at NIST, NSF, and DOD.
- Through its Office of Technology Transitions, DOE is organizing several Quantum Innovation Xlab events to promote exchange of information and ideas between industry, universities, investors, and end-use customers with Lab innovators and experts.
- The NSF Q-AMASE-i program requires the foundries to intertwine industry partners closely with foundry operations and technological development activities in order to accelerate the development of the Nation's quantum technologies economic sector.
- Atomic clocks have historically been a large market for quantum technology. Atomic clocks with enhanced stability and deployment capabilities are expected to have significant economic impacts.

4.6 Advancing International Cooperation

Scientific knowledge transcends national boundaries. International collaboration not only accelerates discoveries, it also provides an avenue to deepen relationships between nations. These relationships provide a platform to establish trust, to facilitate communication, and to share and demonstrate American values through the conduct of research and education. The international flow of capital, knowledge, and talent enables even greater cooperation. Accordingly, international relations and cooperation are an essential component of any strategy that addresses scientific capabilities, economic competitiveness, and security.

Bilateral agreements to support joint projects exist for several U.S. agencies and their international counterparts. Managing collaborative QIS projects with these mechanisms confers benefits such as a coordinated review process and reciprocal or joint funding. Unilateral support for international research collaborators is available from some U.S. agencies as well, in alignment with the agency mission. Through these mechanisms, and also through more informal academic avenues, a large number of federally-funded QIS research projects continue to enjoy international collaborators, resulting in coordinated efforts with mutual benefits.

Actions to encourage and enhance international cooperation on QIS are highlighted here. Specifically, these actions support the policy goals to expand the discovery space, increase the global talent pool, and grow the marketplace for QIS concepts and technologies.

- The United States and Japan jointly developed and signed the Tokyo Statement on Quantum Cooperation[61]. This seminal statement outlines principles for international cooperation around QIS, like “embarking on good-faith cooperation, that is underpinned by our shared values such as freedom of inquiry, merit-based competition, openness and transparency, accountability, and reciprocity, and promotes protection of intellectual property, safe and inclusive research environments, rigor and integrity in research, research security, and reducing administrative burdens.” See Figure 4.2.
- The United States and Australia Joint Commission Meeting on Science and Frontier Technologies Dialogue highlighted QIS: “To accelerate discovery in quantum information science, the United States and Australia are identifying opportunities to share resources and expertise, including between industry and government stakeholders, for strengthened bilateral cooperation. Further, both countries are exploring ways to leverage existing programs and opportunities to deepen cooperation, realize the transformative potential of QIS, and advance its positive impact on the national security and economic prosperity of both countries.”[62]
- The SCQIS and OSTP coordinate with DOS to facilitate opportunities for enhanced international cooperation in QIS. These have included:
    - The United States-Australia Quantum Industry Dialogue, which convened industry, academic, and government stakeholders to share perspectives on securing domestic quantum industry competitiveness and creating pathways to enhance bilateral private sector and public-private collaboration.
    - The United States-United Kingdom quantum working group dialogue, which brought together interagency stakeholders to identify areas for cooperation across basic research, marketplace growth, and workforce development.
- NIST participates in the development of international standards for QIS technologies.

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[61] https://www.state.gov/tokyo-statement-on-quantum-cooperation/
[62] https://www.state.gov/u-s-australia-joint-commission-meeting-on-science-and-frontier-technologies-dialogue/

- NSF announced an opportunity (NSF 20-063) for QISE research awardees to apply for supplemental funding to support international collaboration.
- DOE Office of Science is exploring QIS partnership with several countries.
- The AFRL and NRL partnered on an International Quantum U Tech Accelerator event with Innovare Advancement Center.
- NIST, in coordination with the SCQIS and DOS is helping to develop an option for international companies to participate in the QED-C.
- Through these mechanisms, and also through more informal academic avenues, a large number of federally-funded QIS research projects continue to enjoy international collaborators, resulting in coordinated efforts with mutual benefits.

Figure 4.2: December 2019, Tokyo: Nicholas Hill, Acting Deputy Chief of Mission for the U.S. Embassy, Tokyo and MATSUO Hiroki, Director-General for Science, Technology and Innovation Policy in Japan's Cabinet Office signed the Tokyo Statement on Quantum Cooperation. From left to right: Melinda Pavek, Director of Science, Innovation and Development, U.S. Embassy Tokyo; Jacob Taylor, Assistant Director for Quantum Information Sciences, White House Office of Science and Technology Policy; Nicholas Hill, Acting Deputy Chief of Mission, U.S. Embassy Tokyo; MATSUO Hiroki, Director-General for Science, Technology and Innovation Policy, Japan Cabinet Office; OKU Atsushi, Director for Quantum Technology Team, Japan Cabinet Office; KAJIWAKA Kenichi, Director of Council For Science, Technology and Innovation, Japan Cabinet Office.

5 Summary and Outlook

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

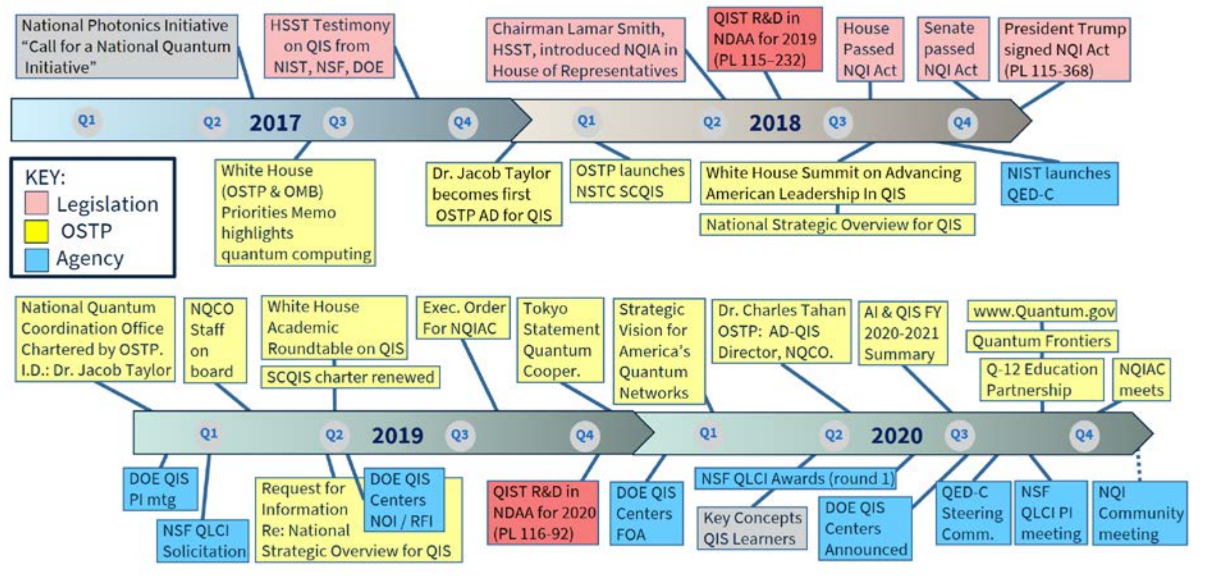

Figure 5.1: Timeline of actions establishing and implementing the NQI. Color-coding shows legislative process in red; OSTP and NSTC actions in yellow; Agency actions in blue. The NQI was introduced in Congress, passed in the House, passed in the Senate, and signed into law by the President, reflecting bipartisan support. The National Defense Authorization Act (NDAA) for FY 2019 and FY 2020 are shown on the timeline because they authorize QIST R&D supported by DOD. Selected actions led by the White House OSTP and the NSTC Subcommittee on QIS are highlighted in yellow. Agency actions on QIS R&D have been ongoing during this whole time. Selected NQI-authorized activities are highlighted here in blue, notably to establish consortia and centers called for by the NQI Act.

Looking to the future, the NQI Act calls for a 10-year duration for the NQI Program. The NQI Act also calls for a reassessment after 5 years, and an updated strategic plan at that time. To support the Program development, assessment, and planning, the budget data and programmatic overview provided in this first-ever NQI Supplement to the President's Budget is a first and important step. Looking forward, the NSTC Subcommittee on QIS, with support from the NQCO (see Figure 5.2) and information from the NQI Advisory Committee, will work to identify the most important metrics to chart progress towards the Program goals and priorities. By continuing to support investment in 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 betterment of the American people.

Figure 5.2: Explanation of the seal for the National Quantum Coordination Office. For more information see www.quantum.gov.