Acronyms

USDA	Department of Agriculture
DOD	Department of Defense
DOE	Department of Energy
NIH	National Institutes of Health
DOI	Department of the Interior
DHS	Department of Homeland Security
State	Department of State
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
NSA	National Security Agency
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
QIS	Quantum Information Science
NSTC	National Science and Technology Council
SCQIS	NSTC Subcommittee on Quantum Information Science

1 Quantum information science: the next technological revolution

Quantum information science (QIS) applies the best understanding of the sub-atomic world—quantum theory—to generate new knowledge and technologies. Through developments in QIS, the United States can improve its industrial base, create jobs, and provide economic and national security benefits. Prior examples of QIS-related technologies include semiconductor microelectronics, photonics, the global positioning system (GPS), and magnetic resonance imaging (MRI). These underpin significant parts of the national economic and defense infrastructure. Future scientific and technological discoveries from QIS may be even more impactful. Long-running U.S. Government investments in QIS and more recent industry involvement have transformed this scientific field into a nascent pillar of the American research and development enterprise. The Trump administration is committed to maintaining and expanding American leadership in QIS to enable future long-term benefits from, and protection of, the science and technology created through this research. Based on the collective input of all the Government agencies invested or interested in QIS, this document presents a national strategic approach to achieving this goal.

Specifically, the United States will create a visible, systematic, national approach to quantum information research and development, organized under a single brand and coordinated by the National Science and Technology Council's (NSTC) Subcommittee on Quantum Information Science (SCQIS). These efforts will leverage existing programs and approaches, adapt to the changing and improving scientific and technical knowledge, reflect the best understanding of opportunities and challenges in QIS for the Nation, and take new steps where appropriate. The national effort will:

- Focus on a science-first approach that aims to identify and solve Grand Challenges: problems whose solutions enable transformative scientific and industrial progress;
- Build a quantum-smart and diverse workforce to meet the needs of a growing field;
- Encourage industry engagement, providing appropriate mechanisms for public-private partnerships;
- Provide the key infrastructure and support needed to realize the scientific and technological opportunities;
- Drive economic growth;
- Maintain national security; and
- Continue to develop international collaboration and cooperation.

The key next step will be to develop agency-level plans that address the identified approaches and policy opportunities in the next section, which will be integrated into an overall strategic plan. This will enable new opportunities on a ten-year horizon, possibly including: the development of quantum processors which may enable limited computing applications; new sensors for biotechnology and defense; next-generation positioning, navigation, and timing systems for military and commercial applications; new approaches to understanding materials, chemistry, and even gravity through quantum information theory; novel algorithms for machine learning and optimization; and transformative cyber security systems including quantum-resistant cryptography in response to developments in QIS.

2 Summary of key policy opportunities

The policy opportunities identified in this strategic overview are summarized below. Following these recommendations, along with detailed planning and coordination made possible by the SCQIS as well as engagement with stakeholders, is crucial for the United States' future success.

Choosing a science-first approach to QIS

- Strengthen Federally-funded core research programs and use approaches ranging from distributed small grants to centers and consortia where appropriate, to support long-term QIS research
- Foster dialogue and collaboration between quantum-focused researchers across disciplines, and engage the broader scientific community to highlight and share relevant scientific advances, and grow and coordinate the quantum research community
- Establish and utilize a formal coordination body, such as the National Science and Technology Council Subcommittee on Quantum Information Science (SCQIS)
- Focus on Grand Challenges as a mechanism for driving advancements in the science and technology of QIS, and encourage Federal agencies to identify, prioritize, and coordinate investment in both fundamental and applied challenges

Creating a quantum-smart workforce for tomorrow

- Encourage industry and academia to create convergent, trans-sector approaches for diverse workforce development to meet the Nation's QIS needs
- Use and enhance existing programs to increase the size of the QIS-ready workforce
- Encourage academia to consider quantum science and engineering as its own discipline, with needs for new faculty, programs, and initiatives at all levels
- Address education in the area of quantum science at an early stage, including elementary, middle and high school levels
- Reach out to broader audiences by working with involved agencies and industry to highlight their investments, along with novel or unconventional approaches like utilizing art, media, and engagement with cultural institutions
- Encourage the QIS community to track and estimate the future workforce needs of quantum industry

Deepening engagement with quantum industry

- Foster the formation of a U.S. Quantum Consortium with participants from industry, academia, and Government to forecast and establish consensus on needs and roadblocks, coordinate efforts in pre-competitive research, address intellectual property concerns, and streamline technology-transfer mechanisms
- Increase investment in joint quantum technology research centers by partnerships between industry, academia, and Government to accelerate pre-competitive quantum research and development
- Maintain awareness of how the quantum revolution may effect agency mission spaces and how agencies can nurture the adoption of quantum technologies within the Federal Government by cultivating potential end-user application spaces

Providing critical infrastructure

- Identify critically needed infrastructure and encourage necessary investments by working with Government experts and stakeholders, as well as industry and academia.
- Encourage agencies to provide the QIS research community with increased access to existing and future facilities and supporting technologies
- Establish end-user testbed facilities along with training and engagement, thereby allowing Federal agencies and stakeholders to explore applications relevant to their respective missions
- Leverage existing infrastructure, including manufacturing facilities that can be repurposed and expanded, to rapidly advance quantum technology development

Maintaining national security and economic growth

- Maintain an understanding of the security implications of the changing science and technology landscape in QIS
- Promote mechanisms, such as the SCQIS, for all Government agencies to stay abreast of the defense and security implications of QIS technologies and help balance the benefits of economic growth with new risks created by the technology
- Ensure consistent application of existing classification and export control mechanisms to provide the largest amount of information possible to American universities and industry about actions related to QIS research to encourage economic opportunities, protect intellectual property, and defend national-security-relevant applications.

Advancing international cooperation

- Seek to increase international cooperation with like-minded industry and Government partners
- Ensure the United States continues to attract and retain the best talent, and has access to international technologies, research facilities, and expertise in QIS
- Identify strengths and focus areas, as well as gaps and opportunities, of international actors to better understand the evolving international QIS landscape from both technical and policy perspectives.

Next steps

Government agencies have been asked to create detailed execution plans in support of these policy goals and informed by these policy options. Specifically,

1. Agencies participating in the SCQIS shall provide written plans for addressing the policy goals outlined here by the first quarter of 2019, or a later date as arranged with OSTP and the SCQIS.

2. Consistent with law, agencies shall convene stakeholders in consultation with OSTP and the SCQIS to identify Grand Challenges in specific sub-fields, such as: quantum accurate sensors, quantum sensing technology, applications of quantum networks, development of quantum-resistant cryptographic standards and systems, commercial possibilities for NISQ quantum devices, approaching the high-fidelity limit of qubit operation, and foundational new science from QIS.

3 Challenges this strategic overview addresses

The rapid growth of QIS and the expectation that this trajectory will continue over the next decade create unique opportunities and challenges for the U.S. research and development enterprise. Underscoring the Trump Administration's commitment to advancing QIS, the NSTC elevated its work on the subject and established the SCQIS, which has identified four key challenges that need to be addressed with a whole-of-Government response.

First, improving and facilitating **coordination** both within the Government and between public and private institutions will create a robust domestic ecosystem and provide worldwide leadership in this international environment. The Nation already has strong and diverse programs in QIS at the Federal-agency level driven by individual mission spaces, as described in the Appendix. Similarly, companies have begun making major investments in the field, inspired by the promise of future applications. At the same time, foreign countries are making investments and seeking to build their own QIS base in competition with the United States. Coordinating U.S. efforts will take advantage of the Government and industry activities to maintain and accelerate U.S. leadership in QIS.

Second, growth within industry, academia, and Government requires maintaining and expanding a broad and viable **workforce**—a quantum-smart workforce—able to enact critical elements of the research and development enterprise. Such a workforce will attract and retain key jobs throughout the Nation, and enable new industrial and academic efforts that rely upon QIS as a base technology.

Third, future progress in QIS requires strong **cross-community connections** between disciplines, from physics to computer science to engineering. These interactions already occur through research collaborations, but would benefit further from formal interdisciplinary research and training programs at earlier levels of education. As growth continues, collaborations and cooperation—between disciplines and nations, between industry and academia—must be promoted, even as competitive pressures may make this more difficult.

Fourth, significant uncertainty remains regarding the overall economic and national security impact of QIS research and development. With strong industrial engagement now beginning, it is crucial to maintain a culture of **discovery**. The likely best-use commercial cases of quantum devices are *unknown at this time* and must be found through research. Maintaining this focus, despite significant countervailing pressures, is necessary. The technologies that are anticipated to result from this approach may also play a role in solutions to some of the Nation's most pressing national security concerns, but will require maintaining an understanding of national security implications of QIS.

In order to maintain and expand American leadership in this critical technology given these challenges, we must improve our capacity for cutting edge research and development, expand the QIS-literate workforce, and seamlessly coordinate between government, academic, and private sector players.

4 Choosing a science-first approach to QIS

Quantum information science—including concepts and technology that support revolutionary advances in computing, communications, and metrology—arises from a synthesis of quantum mechanics and information theory. It examines uniquely quantum phenomena that can be harnessed to advance information processing, transmission, measurement, and fundamental understanding in ways that classical approaches can only do much less efficiently, or not at all. Current and future QIS applications differ from prior applications of quantum mechanics, such as the laser, transistor and MRI, by using distinct quantum phenomena—superposition and entanglement—that do not have classical counterparts.

Even though its origins can be traced back to the 1960's, QIS remains a rapidly evolving scientific and engineering discipline with substantial further discovery opportunities awaiting. This reflects the Government's long support of basic research and development in this field. Even now, while prototype QIS applications, platforms and devices are becoming commercially available, new applications and platforms will likely come from protocols and approaches that are not yet invented. **Thus, the Government should maintain robust and diverse platforms and research thrusts that continue to stimulate transformative and fundamental scientific discoveries by taking an approach that puts the science first.** This will require strengthening core research programs and finding new methods to broaden collaboration and participation.

To capitalize on QIS-inspired technologies and advance the science necessary to realize the associated gains, the development and pursuit of scientific and applied Grand Challenges will be the unifying strategy. Grand Challenges are those fundamental scientific or technology problems with answers that will be transformative for Nation and have broad economic and scientific impact. Potential solutions will take sustained investments for at least ten years and require multidisciplinary teams of researchers and technologists. Agencies, academia, and industry must work together to identify and prioritize Grand Challenges, as well as track their progress and reevaluate these scientific and technological opportunities as the research and development progress.

Solving Grand Challenges and realizing the potential of QIS will depend on employing effective models of coordination and collaboration to tap the unique skills and perspectives from Federal agencies, industry, and academia, and to create and maintain a dialogue between quantum-focused researchers across disciplines. Towards this end, centers and consortia can be a powerful means of gathering and maintaining research communities that can sustain such long-term, curiosity-driven research. In addition, the SCQIS's coordination role as well as mechanisms such as professional science and engineering society participation, coordinated Principal Investigator meetings, and dissemination of information through scientific journals, will help to highlight and share quantum scientific advances and to grow the quantum research community.

Grand Challenge opportunities

Quantum approaches motivated by Grand Challenges show promise for providing new capabilities and tools for sensing and metrology, communication, simulation, and computation. This is vital for fundamental research and promotes security, health, and the economy. For example, quantum sensing holds the promise to provide advanced sensors for military mission impact, to develop new measurement science and quantum-based standards, to improve navigation and timing technologies, and to environmental sensing in novel settings. Single-photon detectors may become possible at far infrared and microwave wavelengths to expand the range of discovery of the dark universe, while non-classical emitters could be integrated for sensing, communication, and computing systems at room temperature.

Today's noisy intermediate scale quantum (NISQ) technology will offer insight into the scientific and technological advances that can address QIS Grand Challenges in areas such as machine learning, simulation of many-body systems for materials discovery, chemical processes, quantum field theory, and dynamics of biological processes. Early exploratory efforts in NISQ systems are already yielding new understanding of these problems. This can help overcome scientific and technological barriers for developing resilient and reliable devices, including networking and storage devices, as well as algorithms and error correction techniques.

5 Creating a quantum-smart workforce for tomorrow

Growing an American quantum-smart workforce with expertise in a broad range of physical, information, and engineering sciences is crucial for assuring sustained progress in QIS. However, America's current educational system typically focuses on discrete disciplinary tracks, rarely emphasizing cross-disciplinary study that equips graduates for complex modern questions and challenges, prominently including QIS. While the responsibility of training students traditionally resides within the academic community, Government agencies and industry can partner with academia to meet the nation's future needs.

Fundamental research is the main mechanism for generating a qualified workforce in QIS. Within the context of the need for individuals with a broad mix of skills, support for the trans-sector and trans-disciplinary approach to research is essential. Students trained in such an environment will be exposed to a diverse yet convergent set of disciplines, along with the associated tools and infrastructure. This will allow students to obtain qualifications and skills required by U.S. industry, national laboratories, and academia. Existing approaches of this nature include special research tracks in academic programs, early career awards from Government agencies, support for focused research groups, and coordinated training with industry. Using and enhancing these programs can increase the size of the QIS workforce. Furthermore, approaches that synthesize these programs, such as industrial collaborations that engaging with a central, fundamental research program, can prepare students with additional skills crucial to entering the workforce in the private sector to further U.S. leadership in quantum science and technology.

Agencies will be encouraged to expand or develop specific programs that foster workforce development and build off each other's strengths and mission. A number of agencies already have existing programs, such as the National Science Foundation's (NSF) Graduate Research Fellowship Program and the Accelerating Discovery Program; the National Defense Science and Engineering Graduate Fellowship Program and the Quantum Science and Engineering Program at the Department of Defense (DOD); Science Undergraduate Laboratory internships, the Graduate Student Research Program, and the Computational Science Graduate Fellowship Program at the Department of Energy (DOE); and the National Institute of Standards and Technology's (NIST) joint research centers that combine Government researchers with university students, postdoctoral scholars, and faculty. These programs can be enriched, modified, and expanded when driven by agency need. Further improvements may include joining existing efforts of different agencies to increase impact, such as by creating joint early-career programs.

Looking to the longer-term horizon, academic faculty provide the bedrock of training programs. Universities should be encouraged to address the workforce development needs by adding tenured or tenure-track faculty within the interdisciplinary themes associated with QIS and consider Quantum Science and Engineering as a discipline for future concentration, exemplified in steps such as creating new departments or thesis tracks. Other avenues include new undergraduate programs, engagement with industry and Government for internships and externships—predominantly for U.S. persons—and new professional development programs, including encouragement for creation of specialized technical programs. These students become ambassadors of their discipline while following a wide range of different paths in their careers, increasing the societal impact of quantum-science education.

Beyond the university, outreach to a broader audience will be essential. A strong comprehensive program in K-12 computational and scientific thinking featuring computer science and physics must start with developing interest at an early stage. A critical role can be played by industry, professional societies, and agencies with vested interest in appropriate outreach, which can help provide access to novel technologies (for example via cloud-based approaches) as well as developing classroom-based learning opportunities and broader connections to the public over various media platforms. At the same time, informal education tools, such as those found in many museums across the Nation, are effective and complementary to the classroom. These overall efforts work best in coordination with the NSTC Committee on STEM and its subcommittees that address STEM and related education.

> **Improving academic-industrial pathways**
>
> One program that is expanding connections across sectors is the recently developed NSF-funded Quantum Information Science and Engineering Network, https://qisenet.uchicago.edu/, also known as "TRIPLETS." This effort promotes small research projects executed by American graduate students over a course of 3 years in close collaboration with an academic principal investigator and an industrial partner, including extended stays at an industrial laboratory or utilizing infrastructure. This enables a direct and smooth transition to an industrial environment upon the TRIPLETS project completion.

Workforce generation efforts and future U.S. workforce needs of the nascent quantum industry should be periodically assessed, through industrial engagement (described in the following section) and work with established STEM efforts. This information can help guide future programs to produce the diverse workforce needed to support the quantum ecosystem. In order to improve the workforce development program over time, an assessment plan of quantum workforce development activities should be encouraged to allow participants to select and expand the most successful strategies and adapt, change, or terminate what does not work. Collaboration with professional societies and organizations, industrial consortia, and local governments are other means of assessing workforce needs.

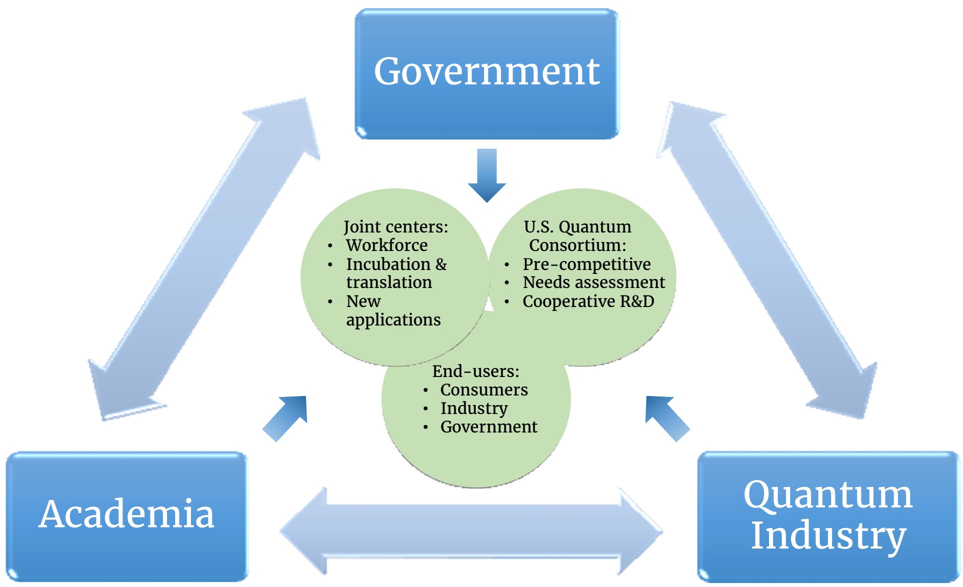
6 Deepening engagement with quantum industry

The revolutionary advances expected to come from QIS have already led to substantial industry attention on QIS research and development. Both large companies and a variety of startups and small businesses are investing heavily in quantum sensing, networking, computing, and supporting technologies. Several have already realized or will soon unveil next-generation quantum sensors, entanglement distribution over small networks, and quantum processors in the 50-qubit range, with plans to continue on a rapid-growth trajectory. In view of the economic and national security importance of QIS the Government will develop means to coordinate with U.S. industry.

A critical element in a robust quantum ecosystem is a strong base of quantum-essential supporting technologies that are not intrinsically quantum in themselves. Current examples include cryogenics, photonics, low-noise microwave amplifiers, and nanofabrication. Thus the consortium should work to identify and stay abreast of these evolving needs, as well as work in partnership with Government agencies and industry to nurture and grow these technologies in cases where they are weak or do not yet exist. Existing approaches such as SBIR and STTR programs that promote innovation for small businesses can be integrated with or combined with other approaches such as joint research centers.

In addition, as a key mechanism for industry engagement, the Government should foster the formation of a U.S. Quantum Consortium with participants from industry, academia, and Government. Like prior consortia such as the Semiconductor Research Corporation, a consortium provides a forum for technical exchanges and discussions to establish a mutual understanding of QIS industry's trajectory, opportunities, and critical technical gaps and projected needs (e.g., for workforce, infrastructure, standards, and road-mapping). Furthermore, the consortium can also provide a venue for joint public-private funding to address infrastructure and technology gaps, and key pre-competitive research and development. Additional input can be provided by advisory bodies as appropriate, such as the President's Council of Advisors on Science and Technology, as well as coordination with other NSTC subcommittees.

Finally, joint research centers— partnerships between industry, academia, and Government—can



accelerate pre-competitive QIS research and development, and in the process help address both the looming need for a greatly expanded and diverse quantum workforce and scientific and applied Grand Challenges. These centers can also facilitate and improve technology transfer from Government research labs. More generally, mechanisms such as incubators for translation from the lab to small companies should be expanded, and roadblocks removed where possible. For a meaningful collaboration environment to exist, intellectual property concerns will also need to be addressed and methods for realizing the development technology emphasized where possible.

7 Providing critical infrastructure

The successful development of technologies based on QIS will enable increasingly more advanced quantum research, but hinges on the availability of suitable tools, facilities, and other infrastructure items. The QIS research and development enterprise is not yet large enough to sustain an industry focused on developing and supplying all the necessary infrastructure. A targeted expansion of the relevant Federal and industrial infrastructure and support activities is needed to accelerate progress and prepare Federal agencies and industry to adopt the ensuing quantum technologies.

The U.S. Government can play a critical role in fostering this field by encouraging programs that target the development and fielding of supporting technologies, ranging from component technologies all the way to sophisticated fabrication and characterization technologies. Agencies will be encouraged to explore mechanisms to provide the QIS research community with increased access to existing and future Federal facilities, including manufacturing facilities that can be repurposed and expanded as well as systems and testbeds for post-quantum applications. As some of these infrastructure capabilities include large user facilities, the Government will consider enhancements to existing Federal facilities and whether Federally-funded QIS research centers should play a role in providing infrastructure or testbeds. Together, these actions will accelerate progress in QIS research and help solidify U.S. leadership in this field.

Current needs include: classical hardware components, materials characterization and fabrication facilities, critical minerals and materials, and a variety of end-user tools, platforms, and testbeds. The Government will engage with experts and stakeholders, as well as industry and academia, to identify critical infrastructure and map the current infrastructure landscape. For example, the U.S. Quantum Consortium can help determine which of the component technologies will have a sufficient economic base to encourage industrial development, can help develop industry engagement with post-quantum applications, and can also periodically track progress and tap external expertise to evaluate the effectiveness of investments being made. In accordance with evolving needs, these efforts should be on-going.

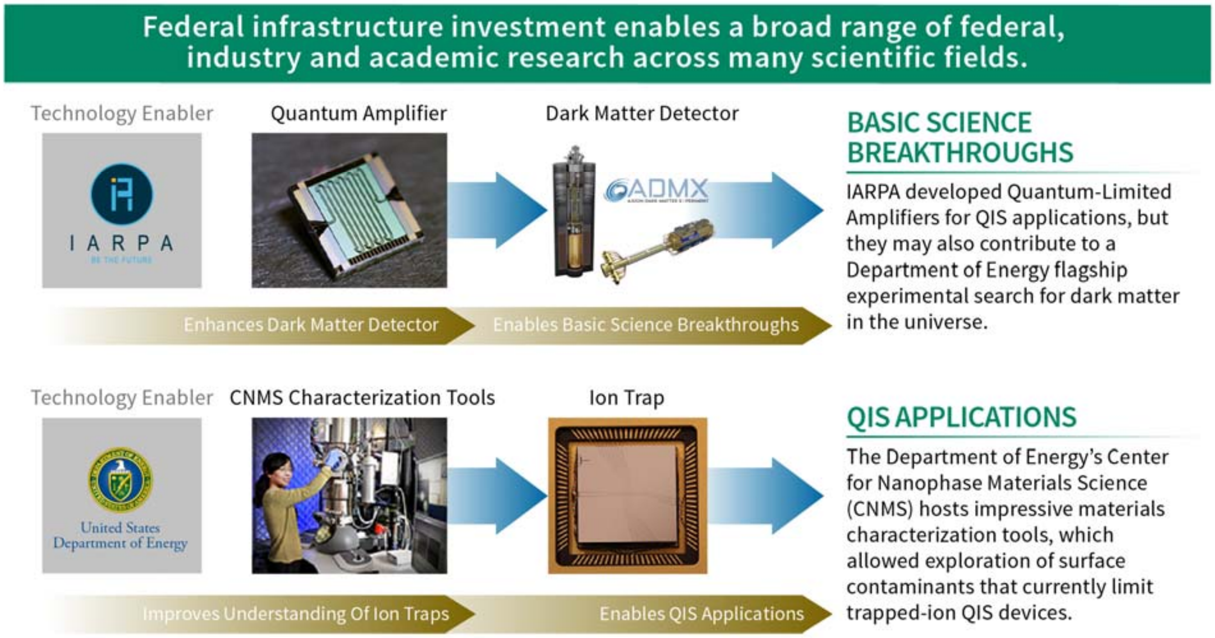
Enabling the next generation of quantum science

Quantum states are extraordinarily fragile, and successfully using them for applications will require an unprecedented level of control and sophistication. For this reason, QIS will require new classes of high-performance classical components and instrumentation capable of realizing these exacting requirements. These components will cover a broad range of technologies and systems, from ultra-cold cooling systems, to precision electronic and optical systems, and even rather basic components like cables appropriate for carrying quantum signals. The lack of suitable and reliable classical components and equipment is one of the biggest hurdles to surmount in attempting to realize useful QIS devices.

In addition, progress in certain areas of QIS is already limited by the unavailability of specialized materials and advanced technologies for materials characterization. For example, unknown dynamics on the metal surfaces of ion traps limit the performance of ion-based qubits. Recently, U.S. researchers made use of a Rapid Access Proposal to Oak Ridge's Center for Nanophase Materials Science to access a series of sophisticated tools for surface characterization to better understand these defects.

Quantum devices also require sophisticated fabrication capabilities. For instance, over the past decade, access to the Microsystems and Engineering Sciences Application (MESA) fabrication facility has allowed Sandia National Laboratories to develop and mature ion trap devices to a level where they now serve as the base component across numerous academic and industry labs, and enable exploration of quantum computing, quantum sensing, and other related technologies.

In addition to bolstering infrastructure, it is important to nurture the adoption of quantum technologies within the Federal Government by cultivating potential end-user agencies. A culture of information sharing has sprung up organically among the personnel at the Federal agencies funding QIS and those looking to leverage future applications. The Government will encourage this culture, and the inter-agency process will provide a sounding board for promulgating such shared interest and promoting the leveraging of Federal investments in advancing each agency's mission. Furthermore, it will explore methods to spur engagement from those end-user agencies that have not yet played a role in developing the technology, but could benefit from the output of this research. Indeed, the impact of QIS will be felt broadly, and it will be important for each agency to be aware of how the quantum revolution may augment its mission space. The establishment of end-user testbed facilities along with training and engagement will allow Federal agencies and stakeholders to explore relevant applications.



Quantum Amplifier: Image courtesy of UC Berkeley / Dark Matter Detector : Image courtesy of Lawrence Livermore National Lab
CNMS : Image courtesy of Oak Ridge National Lab / Ion Trap: Image courtesy of MIT Lincoln Lab

8 Maintaining national security and economic growth

National security needs often drive the advancement of new science and technology and enable economic development through enhanced Government investments, dedicated initiatives, and cross-agency collaborations. At the same time, creating new markets and industries enhance our ability to address national security needs, but the scientific and economic advances can lead to new risks. An appropriate balance between growth and risk can provide long-term benefits.

The technologies that are anticipated to result from intensified research and development in QIS may provide solutions to some of the nation's most pressing national security concerns. For example, advancements in quantum computing may allow for improvements in effective drug discovery, modeling of chemical reactions to enhance corrosion-resistant materials, and optimizing logistics solutions. These and other opportunities in networking and sensing can play a positive role in ensuring national security and defense.

However, there may be challenges to public safety and security that arise from these same technologies. For example, one key quantum algorithm will be able to break public-key cryptography, which secures transactions over the internet. While employing this algorithm is far beyond the current level of technology, the need to protect sensitive data and provide a reliable infrastructure over the long-term requires moving to "post-quantum" or "quantum-resistant" forms of cryptography.

QIS technologies being developed for military and defense applications can also accelerate advancements in the field, leading to substantial economic growth potential through the creation of new industries and products and their transition to consumer markets. The defense and intelligence communities have been strong investors in QIS research and development over the last twenty years, and continue to work across the basic science and applied technology areas to improve the understanding of what is possible with QIS and support the necessary technological base. Enhanced industrial engagement and infrastructure improvements described in the previous sections will also enhance national security and provide economic growth by fostering QIS within the United States rather than leaving innovators to seek support elsewhere.

As the technology evolves, its potential impact on military applications will mean that continual monitoring of export and trade regulations, including the Wassenaar Arrangement control lists and their domestic implementation in the Export Administration Regulations (EAR) and International Traffic in Arms Regulation (ITAR), will be necessary. Furthermore, the defense community has special needs for diverse workforce development; pathways should be added from programs that build a quantum-smart workforce into defense-related research and development. Finally, it is imperative that while developing the QIS enterprise in the United States, the Government also protects intellectual property and economic interests, seeks to understand dual-use capabilities, and supports national-security-relevant applications that emerge from QIS research at every level from basic research to commercialization of QIS technologies. Thus the SCQIS will, in conjunction with other NSTC subcommittees, Federal agencies, and the defense and intelligence communities, ensure consistent application of existing classification and export control mechanisms to provide the largest amount of information possible to American universities and industry about actions related to QIS research.

Improving defense through quantum technologies

Advanced computing capabilities have long been used to enhance both military capability and economic productivity. As such, general purpose quantum algorithms for optimization, machine learning, materials development, and chemical calculations should continue to be explored; although their quantum speed-up is still unknown, any improvements in direct computational ability or in resulting materials and systems could greatly impact military effectiveness.

Beyond computation, new or quantum-enhanced systems could enable the next-generation of sensors and detectors for defense applications. As an example, precision relies on the deep understanding of the quantum properties of atoms; further development can impact both next-generation Global Positioning Systems (GPS) and scenarios where GPS is unavailable. There are further synergies in defense requirements for low size, weight, and power devices via new modalities of sensing.

Exploration of quantum networking also has potential defense value, and could offer added functionality to quantum computation and quantum sensing. Robust solutions to distributing entanglement over multiple length scales—from across a chip to across the world—could enable distributed quantum computers and distributed sensors, with the potential for long-term impact in secure communication. Understanding how quantum effects impact communication, from bandwidth and latency, to security, to novel networking technologies and algorithms, will help realize the best networking systems.

9 Advancing international cooperation

Science, technology, and innovation are cornerstones of U.S. prosperity and economic development and also dominant forces internationally, particularly given the highly interconnected world of the 21st century, where businesses operate globally and scientists and engineers collaborate across borders. Considering the global nature of scientific and industrial enterprises, the United States, including the private sector, has cooperated with foreign partners in QIS research for more than twenty years. These partnerships have accelerated scientific discovery and technological applications while promoting U.S. economic growth and national security.

In order to maintain U.S. leadership and competitiveness in QIS, the United States must work with international partners, even while advancing domestic investments and research strategies. As discoveries accelerate in all sectors, the United States should seek to increase international cooperation with like-minded governments and industrial partners to ensure that technologies resulting from today's investments in basic research and technological development continue to benefit Americans. Sustained domestic investments and strategic international collaboration and cooperation will be vital to this goal.

The Government will focus on three strategic international efforts for QIS. The first effort will be regular reviews of international collaboration activities and partnerships, to identify and track worldwide QIS science and technology trends and identify gaps and opportunities, understand the evolving international QIS landscape, and inform existing programs. Second, the Government will identify and prioritize strategic bilateral partnerships to ensure that the United States continues to attract and retain the best international and has access to international technologies, research facilities, and experts in QIS. Third, the Government should encourage merit-based and transparent fundamental research and innovation systems, and open access to public data arising from QIS research, as appropriate, as well as to advance the development of international standards that enable adoption of new QIS-inspired technologies.

Appendix: Current U.S. leadership in QIS research areas

The United States sustains a vibrant community in QIS. World-leading research groups in the Nation's universities, companies, and national labs have driven progress in many of the critical areas of quantum computing and quantum systems for time-keeping, sensing, networking, and other applications. This status as a leader in quantum research and development is a direct result of the U.S. Government funding agencies and institutions sustained investment in basic and applied research. Both broad and focused programs, built atop a foundation of well-staffed and well-equipped research institutions, have created a talented workforce, encouraged broad innovation and exploration, and dedicated the necessary hard work in physics, materials science, and associated areas necessary to make progress in the development of working, controllable quantum systems. Throughout this effort, the United States has benefited from a many-headed funding model where, for example, one Agency continues to fund critical topics as another changes focus. Furthermore, combining funding driven by mission needs to ensure long-term development with science-driven funding to create the new ideas that seed further innovation provides additional resiliency.

Progress in QIS has recently begun a significant expansion from increases in private sector research and development. Over the last five years, particularly in quantum computing, large IT companies and the venture capital and start-up community have engaged with new QIS opportunities and formed groups and companies to pursue commercialization. It should be noted that all this is possible because of the wealth and know-how that these companies and communities gained from the previous computing and internet revolutions they helped create. The national strategic approach should continue to leverage these strengths of both the U.S. Government funding system and the U.S. innovation ecosystem.

Finally, significant contributions to QIS research have been made in other countries. The field has advanced in the United States in some part by recruiting, collaborating, and competing with science around the world. As a case in point, the first two-qubit gate proposal came from researchers in Europe, but was demonstrated in the Nobel-prize winning group of David Wineland at NIST. This reflects the increasingly global character of the science and technology enterprise. In a field where scientists are still very much fighting nature itself to make progress, humanity's combined effort may be necessary to tackle the challenge. U.S. leadership at this juncture will provide the key ingredients for this success.

QIS comprises fundamental science and technology across many platforms and topics, and touches upon many agencies. This includes the Department of Agriculture (USDA), Department of Defense (DOD), Department of Energy (DOE), National Institutes of Health (NIH), Department of the Interior (DOI), Department of Homeland Security (DHS), Department of State (State), National Aeronautics and Space Administration (NASA), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), National Security Agency (NSA), Office of the Director of National Intelligence (ODNI), Office of Management and Budget (OMB), and Office of Science and Technology Policy (OSTP).

The SCQIS assesses the national portfolio using seven broad categories: four in fundamental science (S1-S4) and three in technological development (T1-T3).

S1. Quantum sensing: leveraging quantum mechanics to enhance the fundamental accuracy of measurements and/or enabling new regimes or modalities for sensors and measurement science [**DOD, DOE, DHS, DOI, NIST, NSF, ODNI**]

S2. Quantum computing: from devices and algorithms for analog simulation of quantum systems in the laboratory to controlled digital quantum computers [**DOD, DOE, NASA, NIST, NSF, NSA, ODNI**]
S3. Quantum networking: exploring and using coherent or entangled multi-party quantum states, distributed at distances, for new information technology applications and fundamental science [**DOD, NASA, NIST, NSF**]
S4. Scientific advances enabled by quantum devices and theory advances: improved understanding of materials, chemistry, cosmology, classical computation techniques, and other aspects of fundamental science [**DOE, NIST, NSF**]
T1. Supporting technology: necessary analog, digital, electrical, mechanical, optical, computational, and cryogenic systems and techniques that underpin the fundamental science areas [**DOD**, **NASA, NIST, NSF, NSA, ODNI**]
T2. Future applications: opportunities for improvements in operations research, optimization, machine learning, drug discovery, etc. [**all SCQIS agencies engaged**]
T3. Risk mitigation: necessary infrastructure and support for quantum technologies and their impact, such as quantum-resistant cryptosystems and other post-quantum applications [**DHS, NIST, NSA**]

The Nation's efforts in these areas include a number of agencies that have over the years driven research and development in these seven categories. Current Federal agencies conducting or funding these topic areas are identified above. These seven areas represent the broad foundation necessary to support a full industrial and Governmental effort in quantum information science and technology. The SCQIS also has examined current funding, and finds at the present time that it is primarily focused on S1-S4, as shown in the graph below.