QUANTUM INFORMATION SCIENCE AND TECHNOLOGY WORKFORCE DEVELOPMENT NATIONAL STRATEGIC PLAN

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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Abbreviations and Acronyms

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
ARL	Army Research Laboratory
ARO	Army Research Office
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
ESIX	Subcommittee on Economic and Security Implications of Quantum Science
IARPA	Intelligence Advanced Research Projects Activity
IWG	Interagency Working Group
LPS	National Security Agency Laboratory for Physical Sciences
NASA	National Aeronautics and Space Administration
NDAA	National Defense Authorization Act
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NQCO	National Quantum Coordination Office
NQI	National Quantum Initiative
NSA	National Security Agency
NSF	National Science Foundation
NSTC	National Science and Technology Council
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
OUSD(R&E)	Office of the Undersecretary of Defense for Research and Engineering
QIST	Quantum Information Science and Technology
QED-C	Quantum Economic Development Consortium
QLCI	Quantum Leap Challenge Institutes
R&D	Research and Development
SCQIS	Subcommittee on Quantum Information Science
STEM	Science Technology Engineering and Mathematics.
USPTO	United States Patent and Trade Office

Executive Summary

Workforce development in Quantum Information Science and Technology (QIST) is a priority for the United States as part of the National Quantum Initiative.[1] To ensure economic and national security, several actions are recommended here to evaluate the QIST workforce landscape, prepare more people for jobs with quantum technology, enhance STEM education at all levels, accelerate exploration of quantum frontiers,[2] and expand the talent pool for industries of the future.

Beyond the significant technical challenges facing QIST research and development (R&D), the shortage of talent constrains progress. The field is currently creating more job openings than can be filled, with the variety of jobs related to QIST expanding in academia, industry, national labs, and government. New and sustained workforce training efforts are critical for maintaining American leadership in QIST. Fortunately, the requisite skills are widely applicable and in high demand. Therefore, investments that grow the professional expertise needed for QIST R&D will pay dividends in many sectors of the economy.

Building the Nation's QIST workforce will require coordination among U.S. Government agencies, academic institutions, professional societies, non-profit organizations, industry, and international partners. There are also important roles for STEM educators and institutional experts on diversity, equity and inclusion, to ensure that training in QIST will position more individuals for rewarding careers, and expand America's capacity for high-tech innovation.

Presidential Science Advisor Dr. Eric Lander spoke about the importance of growing the American high-tech workforce by, "not just cloning the people who are in it but expanding to include everybody in this country who wants to be part of it."[3] He said, "Focusing on the hardest, most important problems; making and investing in the right technical bets; and building and growing the scientists, engineers, and entrepreneurs of tomorrow – all in our unique American model of fair and free-market competition and cooperation is how we will continue to lead."

To ensure the United States creates a diverse, inclusive, and sustainable workforce that possesses the broad range of skills needed by industry, academia, national laboratories, and the U.S. Government, this document expands upon the workforce policies outlined in the *National Strategic Overview of Quantum Information Science*. It provides updates on current activities, additional recommendations, and criteria for success. Four critical actions are identified:

1. **Develop and maintain an understanding of the workforce needs in the QIST ecosystem, with both short-term and long-term perspectives;**
2. **Introduce broader audiences to QIST through public outreach and educational materials;**
3. **Address QIST-specific gaps in professional education and training opportunities; and**
4. **Make careers in QIST and related fields more accessible and equitable.**

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[1] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[2] https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf
[3] https://www.whitehouse.gov/ostp/news-updates/2021/10/07/readout-of-white-house-summit-on-quantum-industry-and-society/

Introduction

Quantum Information Science and Technology (QIST)[4] is a research and development (R&D) priority for the United States because it pushes the frontiers of science and engineering.[5] It lays a foundation for industries of the future, and can impact national security. To accelerate QIST R&D and grow the Nation's capacity to develop quantum technologies, the United States needs a talented, diverse, and adaptable workforce. However, the supply of such talent currently does not meet demand from the rapidly expanding industrial, national laboratory, government, and academic efforts. This is evident both in the United States and internationally.[6,7] Therefore, enhanced pathways are needed for near-term career pivots into the field, and also for longer-term approaches that develop talent through education, training, and outreach. To address these needs, a national strategy for QIST workforce development is presented here.

Historically, talent and creative ideas in QIST have come from experts in quantum physics and information theory. These fields have already produced transformative technologies for society. Quantum physics led to transistors, lasers, magnetic resonance imaging (MRI) scanners, and atomic clocks (e.g., for GPS navigation). Information theory catalyzed the development of computers, digital communication, and the internet. Collectively these fields – quantum physics and information theory – ushered in the modern digital age. Their confluence in the late 20th century, manifested as QIST, is now yielding more discoveries and new technologies based on new ways to acquire, encode, manipulate, process, and distribute information.

QIST now involves practitioners trained in a wide variety of disciplines such as computer science, engineering, chemistry, and materials science, who are working together often in multidisciplinary teams to pioneer revolutionary approaches to computing, simulation, sensing, timing, and networking. Furthermore, QIST advances are providing foundational knowledge and leading to applications in a growing number of fields. Quantum computing algorithms and hardware may facilitate developments in medicine, energy science, and agriculture, for example, with simulations of molecules involved in pharmaceutical compounds, artificial photosynthesis, or fertilizer technology.[8,9] Quantum sensing offers new modalities and enhanced measurement sensitivity relevant for domains as diverse as ocean navigation and neuroscience. Quantum networks can support disruptive applications in sensing, computing, and communication. But the pace of these developments ultimately depends on the people – the workforce – in QIST.

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[4] As described in the National Quantum Initiative Act, the term ''quantum information science'' means the use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information.

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

[6] https://www.zdnet.com/article/quantum-computings-next-challenge-finding-quantum-developers-and-fast/

[7] https://www.nytimes.com/2018/10/21/technology/quantum-computing-jobs-immigration-visas.html

[8] Commercial applications of quantum computing, doi:10.1140/epjqt/s40507-021-00091-1

[9] Quantum computing: progress and prospects, doi:10.17226/25196

Given the potential impacts of QIST,[10,11] the United States – along with many other nations – has embarked on a journey to further understand and harness the capabilities inherent in QIST. Building on decades of sustained Federal investments, the Unites States launched its National Quantum Initiative to accelerate the pace of QIST R&D.[12,13] Concurrently, there has been a global increase in investment by academia, industry, and national-level programs.[14]

The National Quantum Initiative Act (NQI Act) and the FY 2019-2022 National Defense Authorization Acts (NDAA) highlight the need for a QIST workforce.[15,16] Indeed, the development of a QIST-ready workforce with a broad range of skills is vital to ensure that the United States can contribute to and benefit from the quantum technology innovations of the 21st century. For it is the workforce that will accomplish the basic and applied R&D in a broad range of technologies, supply chains, and applications that are crucial for a healthy QIST portfolio across sensing, communication, and computation.

Challenges: Investments in QIST by new and existing companies have accelerated over the last decade, and the supply of talent is not keeping up with demand. Furthermore, while government funding for new quantum research centers established pursuant to the NQI Act and NDAAs (see Figure 4) will train more researchers, these new centers are creating even more staffing demands for QIST experts in the near term. The resulting growth in QIST-related careers now necessitates a commensurate increase in the number of scientists and engineers who are appropriately trained or positioned to easily transition into work on QIST-oriented technologies.[17] Workforce development has been a leading topic at numerous quantum-related workshops and conferences,[18– 23] and several new academic programs in QIST have been launched. To comprehensively understand the long-term and short-term scope of the QIST workforce shortage, there remains a need for additional information, including but not limited to data on the technical demands, training, awareness, retention, etc. Several challenges are listed here, and addressed in the following Sections.

A primary challenge for growing the QIST workforce is understanding the technical needs of the ecosystem. This is compounded by issues such as: the breadth of technologies involved (e.g., software and hardware that span sensing, computing, and networking and communication); the need for subject matter experts (at both the basic research, systems development, and engineering levels); and the wide

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[10] https://www.ida.org/research-and-publications/publications/all/a/as/assessment-of-the-future-economic-impact-of-quantum-information-science
[11] https://crsreports.congress.gov/product/details?prodcode=R45409
[12] https://science.osti.gov/-/media/nqiac/pdf/NQI_Program-coordination_NQIAC_20201027.pdf
[13] https://www.congress.gov/bill/115th-congress/house-bill/6227/
[14] https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf
[15] https://www.congress.gov/115/plaws/publ232/PLAW-115publ232.pdf (Sec. 234)
[16] https://www.congress.gov/116/plaws/publ92/PLAW-116publ92.pdf (Sec. 220
[17] https://www.aps.org/publications/apsnews/202106/qis.cfm
[18] https://www.afrl.af.mil/News/Article/2426785/afrl-set-to-co-host-two-day-virtual-quantum-collider-20/
[19] https://quantum-workforce.kavlimeetings.org/
[20] QED-C | TAC - QED-C (quantumconsortium.org)
[21] Preparing for the quantum revolution: What is the role of higher education, doi:10.1103/PhysRevPhysEducRes.16.020131
[22] https://quantum.mines.edu/nsf-qe-ed/;
[23] https://www.bnl.gov/c2qaquantumcareerevent

variety of required skills that comprise and support QIST. More data on all of these issues would better inform and track workforce development efforts.

A second challenge is that exposure to QIST at the high school or undergraduate level in the United States is limited, and rarely available prior to advanced coursework or research.[24] The ensuing lack of awareness can leave talented high school and undergraduate students to pursue other directions. A hypothesis is that more students might stay in STEM fields if they get excited about quantum and other cutting-edge technologies earlier in their education.[25,26] Moreover, because many QIST- and STEM-related jobs require some familiarity with quantum mechanics, the nation's capacity for several high-tech industries will be enhanced if sound approaches are implemented to further raise awareness of QIST.[22]

A third challenge is attracting and retaining professional talent as QIST becomes more of a global enterprise, requiring both domestic training and international cooperation. The United States has benefited tremendously from experts coming from all around the world to participate in R&D efforts in academia, national laboratories, and industry to advance their careers. As opportunities in QIST grow outside the United States, efforts to provide a welcoming cooperative environment should be sustained and adapted to create, attract, and retain talent by leveraging the strengths of institutions spanning all Carnegie Classification levels including 2-year-, minority-serving-, high research activity (R2), and Predominantly Undergraduate institutions (PUI).[27] Furthermore, recruitment and retention of expert talent into jobs that support federal needs often comes with additional challenges including requirements of citizenship, that are exacerbated by a tight and competitive labor market. This recruitment is critical as QIST activities undertaken by Federal Departments and Agencies (hereafter referred to as 'Agencies'), federal laboratories, Federally-Funded R&D Centers (FFRDC's), University-Affiliated Research Center Laboratories (UARCs), and the defense industrial base support basic research, infrastructure, and standards development, and provide hands-on training for junior scientists and technologists in QIST.

A fourth and overarching challenge is to develop a more diverse QIST workforce that is inclusive of all Americans who wish to participate in this area. This requires a systemic culture shift to create inclusive, supportive, and equitable work and learning environments, policies, and structures for people from every race, ethnicity, and gender.[26,28] Factors ranging from negative individual interactions to broad institutional practices result in a loss of diverse talent in many of the STEM fields that feed QIST (e.g., computer information science engineering, electrical engineering, materials science and engineering,

[24] Building a Quantum Engineering Undergraduate Program, arXiv:2108.01311
[25] https://www.aip.org/sites/default/files/aipcorp/files/teamup-full-report.pdf
[26] Women are underrepresented in fields where success is believed to require brilliance, doi:10.3389/fpsyg.2015.00235
[27] https://carnegieclassifications.iu.edu/classification_descriptions/basic.php
[28] https://www.aip.org/sites/default/files/aipcorp/files/teamup-full-report.pdf

and physics).[29,30,31,32,33,34] Integrating problem solvers from different backgrounds into a team enhances the likelihood of scientific success and promotes continuous innovation and economic growth,[35] and it is the right thing to do based on principles of equity and inclusion. Expanding the workforce in this way will take intentional actions, examples of which are discussed this document. The resulting benefits should enhance the impact of QIST research, stimulate innovation, and foster the development of technologies that benefit all of America, as new approaches and points of view are represented from the lab to the boardroom.

Approach: Given the varying lead times for outreach, education, and professional training to realize substantial impacts, it is necessary to have a strategy that helps address both the short- and long-term challenges outlined above. Furthermore, recognizing the critical nature of this need for several Agencies, coordination of federal efforts in workforce development should be done in such a way that enables more rapid progress in QIST R&D for all involved entities.

This Plan builds on lessons learned since the release of the *National Strategic Overview for Quantum Information Science (NSO)*[36] in 2018, and reflects the evolving QIST landscape. The next Sections update and expand upon policies and recommendations highlighted in the NSO, and support the following vision:

Vision

The United States should develop a diverse, inclusive, and sustainable workforce that possesses the broad range of skills needed by industry, academia, and the U.S. Government, while being able to scale and adapt as the QIST landscape evolves.

The strategic approach to realizing this vision is organized around four broad actions that are collectively, and individually, designed to confront the challenges outlined above:

- **Action 1:** Develop and maintain an understanding of the workforce needs in the QIST ecosystem, with both short-term and long-term perspectives;
- **Action 2:** Introduce broader audiences to QIST through public outreach and education materials;
- **Action 3:** Address QIST-specific gaps in professional education and training opportunities; and
- **Action 4:** Make careers in QIST and related fields more accessible and equitable.

The remainder of this report is organized as follows: each section focuses on an action, discusses the current landscape, provides specific recommendations for continued or expanded federal activities,

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29 https://www.quantum.gov/wp-content/uploads/2021/10/2021_NSTC_ESIX_INTL_TALENT_QIS.pdf
30 Preparing for the quantum revolution: What is the role of higher education, doi:10.1103/PhysRevPhysEducRes.16.020131
31 https://ira.asee.org/wp-content/uploads/2019/07/2018-Engineering-by-Numbers-Engineering-Statistics-UPDATED-15-July-2019.pdf
32 https://www.aps.org/programs/women/resources/statistics.cfm
33 https://www.aps.org/programs/minorities/resources/statistics.cfm
34 Systemic inequalities for LGBTQ professionals in STEM, https://doi.org/10.1126/sciadv.abe0933
35 Groups of diverse problem solvers can outperform groups of high-ability problem solvers, doi:10.1073/pnas.0403723101
36 https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

and suggests opportunities for industry academia, and other members of the community. Attention is given to growing diversity, fostering inclusion, and ensuring equity with regard to educational, research, and work opportunities. Each action will require partnerships with STEM education and institutional diversity and equity experts to inform and guide QIST R&D entities to effect genuine and long-lasting change. Finally, the Appendix outlines many of the ongoing federal activities that support QIST workforce generation. As shown in Figure 1, progress and long-term success will be measured in careers. Progress can be monitored by assessing how well programs inspire individuals, educate learners, and provide experiences to train the future workforce.

Inspire	Educate	Experiences	Careers
Motivate students and broaden public understanding via foundational education and outreach. Examples include: • **Q-12 Partnership** • **World Quantum Day**	**Develop and deploy formal and informal approaches. Examples include:** • **Quantum 101** • **QIST Minors** • **QIST Masters**	**Grow confidence through unique opportunities. Examples include:** • **Internships** • **Externships** • **Hands-On Research** • **After School Programs**	**Make people aware of the impactful and diverse options in QIST and encourage them to pursue careers in:** • **Industry** • **Academia** • **Government**

Figure 1: The success of this report will largely be measured by the QIST community's ability to inspire people to engage in QIST. This engagement will be met via accessible education of people at various education and career levels, the development of training experiences at various education and career levels, and pathways that efficiently connect workers to jobs and career opportunities.

Action 1. Develop and Maintain an Understanding 0f Workforce Needs in the QIST Ecosystem, with both Short-Term and Long-Term Perspectives

Goal: Understand the supply of and demand for QIST workers; assess the state of educational and training opportunities; and track the overall demographic make-up of the field.

To ensure that the United States remains a global leader in the rapidly evolving and competitive field of QIST, a more complete understanding of the workforce, education, and training landscape is required. The focus and size of education and outreach programs should be tuned to meet the workforce needs of industry, academia, and Agencies. Unfortunately, the QIST workforce landscape is difficult to assess due to the complex and interdisciplinary nature of the work, the globally interconnected circulation of talent and ideas, the sometimes-rapid evolution from basic research to industry developments, and the fact that tracking of workforce data specifically for QIST is just beginning. Furthermore, at the same time as new fundamental science sub-areas are still emerging, other areas of QIST are shifting from fundamental scientific research towards engineering and technology development, and from prototypes to product.

The breadth of this change is reflected in the range of core fields (e.g., computer science, electrical engineering, materials science, mathematics, chemistry, and physics), as well as in emerging and supporting fields (e.g., marketing and sales, manufacturing, systems engineering, and product development and design). Though there is breadth in the core and emerging fields, there is an understanding that technical skills including analytical problem solving and data analysis, along with organizational skills such as being able to work in teams, are important for QIST professionals to acquire. Current data suggests that deep, focused *QIST expertise* is still in demand, often at the PhD level or higher. However, there is growing demand for individuals who are *QIST-proficient* (having an undergraduate QIST-related major, minor, or track), *QIST-aware* (e.g., having just a single undergraduate course connecting with QIST), or *STEM professionals* (individuals who possess complementary skillsets needed by QIST industry) (see Figure 2).[37,38] As a result, companies, educators, and researchers are still grappling to understand exactly what skills are needed for both today's and tomorrow's workforce.

1.1 Current Landscape

At this time, there is no singular, comprehensive source of data that provides definitive, quantitative information regarding the QIST workforce landscape. Based on the information that is available, there appears to be a talent shortage at all levels. This assessment is based on:

- information from the Quantum Economic Development Consortium (QED-C), which administers a periodic survey to its members, as well as separate data collected and analyzed by researchers;[39]

[37] Building a Quantum Engineering Undergraduate Program, arXiv:2108.01311

[38] The exact definition of quantum-aware can vary. Here it is used to imply familiarity with the common language and general specifications associated with certain quantum technologies.

[39] Preparing for the quantum revolution: What is the role of higher education, doi:10.1103/PhysRevPhysEducRes.16.020131

- anecdotal input from a series of conferences, meetings and conversations with representatives from industry, academia, national labs, and the Federal government; and
- data available through online job boards.[40]

The QED-C surveys and job boards provide a useful, if incomplete, picture of the skillsets and educational training levels that the QIST ecosystem currently needs. Workers who possess skills in QIST software and hardware development, along with some business acumen are in particularly high demand.[41] Beyond jobs specifically requiring deep QIST expertise, there is a broad range of positions drawing on various science and engineering fields with needed skills including coding, data analysis, and digital and radio-frequency circuit design, as well as laboratory experience and knowledge of optical, materials, and mechanical engineering.[42]

Only about half of the roles sought by industry require QIST proficiency. The remainder rely on workers with, at most, a basic awareness of QIST. The desired education levels span bachelor's, master's, and doctoral degree recipients. Because this snapshot captures a field that largely exists in the R&D stage, continued monitoring of the needed skills and educational depths will be required as QIST matures and evolves.

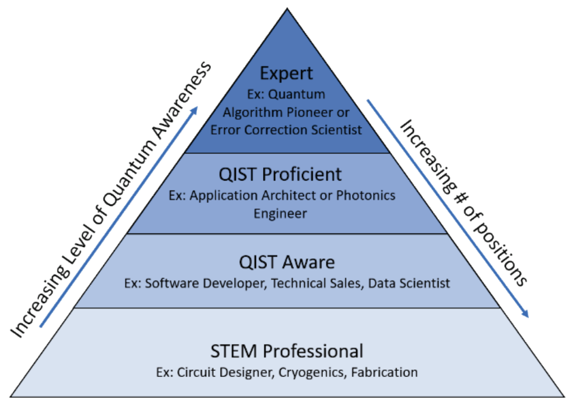

Figure 2: Borrowing from the quantum engineer pyramid,[47] the figure highlights the different levels of awareness that are referenced throughout this report. The levels do not indicate overall education, as a STEM professional could have an advanced degree in their area, with no quantum background. Likewise, a quantum-expert need not obtain a PhD in the field. Additional examples of job types and degree levels are available.[41]

The Federal government and many external professional societies track relevant metrics around STEM degree production.[43,44] Several Agencies and universities also support workshops that discuss academic STEM and QIST-specific programs. As a result, a more complete picture of the number of students graduating with the required skills is beginning to develop.

Programs to develop QIST-specific and related talent are being implemented at several levels, ranging from short courses to undergraduate minors to master's degree programs, and more are in development.[45,46,47,48] Yet, there is still a significant challenge because in many, if not most, U.S. academic institutions, traditional undergraduate quantum physics education focuses on treatments of quantum mechanics with very little content addressing quantum information science, or QIST per se.

[40] https://quantuqumconsortium.org/quantum-jobs/
[41] Assessing the needs of the quantum industry, arXiv:2109.03601
[42] Preparing for the quantum revolution: What is the role of higher education, doi:10.1103/PhysRevPhysEducRes.16.020131
[43] https://www.nsf.gov/statistics/
[44] https://www.aps.org/programs/education/statistics/index.cfm
[45] https://www.per-central.org/items/detail.cfm?ID=15731
[46] Achieving a quantum smart workforce, doi:10.1088/2058-9565/abfa64
[47] Building a Quantum Engineering Undergraduate Program, arXiv:2108.01311
[48] https://www.csusm.edu/quest/index.html

One possible metric of success in building the workforce is the growth of these programs nationwide, in terms of development and student participation.[49] A second metric is in building a diverse quantum workforce, in terms of the diversity of students who are identified as QIST-aware, -proficient, and -experts. Whether these newly developed programs will meet workforce needs is still an open question, which is partially complicated by continued uncertainty as to what constitutes a QIST qualified worker. For example, while an analysis of PhD dissertation titles provides some insight,[50] discerning between QIST-related and more general quantum physics and materials research is subjective. This poses an ongoing challenge for program development and data collection alike.

Finally, broadening participation in QIST is critical and will require a better understanding of current demographics within the QIST ecosystem. Currently, the best available demographics data are drawn from QIST-relevant fields, such as computer science, electrical engineering, and physics.[51,52] Unfortunately, these fields have among the lowest participation rates for people from backgrounds historically underrepresented in STEM, including Hispanics or Latinos, Blacks or African Americans, American Indians or Alaska Natives, persons with disabilities, and women from all backgrounds. In absolute numbers, women make up the largest of the underrepresented groups.[53,54,55] While low participation from these underrepresented backgrounds in QIST can be inferred from this data, limited demographic data on QIST-specific degree production means that the full extent of participation is difficult to ascertain. Instead, it must be drawn from the larger, coarser data previously mentioned. While demographic data from relevant fields provides a starting point, better tracking of QIST-specific progress towards creating opportunities, and attracting and retaining a diverse cadre of talent is needed.

Summary: Ensuring that a diverse, properly sized, and skilled workforce is developed to meet the evolving needs of the QIST ecosystem will require more training opportunities and more data. A full picture of the workforce landscape should be informed by metrics that elucidate the size and makeup of the growing QIST R&D community and assesses trends, forecasts and contingencies for both the supply (of) and demand for talent. While new programs to educate and train workers are being developed, the impact of these programs on workforce and skills-adoption should be assessed in the broader context of STEM education and high-tech employment. Based on the limited available data, the QIST R&D community must work deliberately to increase participation of people from underrepresented backgrounds in STEM, and to gain a deeper understanding of the QIST workforce landscape. Roles and responsibilities for these efforts are described next, in Sections 1.2 and 1.3.

[49] https://www.per-central.org/items/detail.cfm?ID=15731

[50] https://www.quantum.gov/wp-content/uploads/2021/10/2021_NSTC_ESIX_INTL_TALENT_QIS.pdf

[51] Women, Minorities, and Persons with Disabilities in Science and Engineering

[52] Preparing for the quantum revolution: What is the role of higher education, doi:10.1103/PhysRevPhysEducRes.16.020131

[53] https://ira.asee.org/wp-content/uploads/2019/07/2018-Engineering-by-Numbers-Engineering-Statistics-UPDATED-15-July-2019.pdf

[54] https://www.aps.org/programs/women/resources/statistics.cfm

[55] https://www.aps.org/programs/minorities/resources/statistics.cfm

1.2 Recommendations for U.S. Government

- The National Science and Technology Council (NSTC) Subcommittee on QIS (SCQIS), through its Interagency Working Group on QIST Workforce, should coordinate with the NSTC Committee on STEM Education (CO-STEM) to align data collection efforts and on-going STEM activities across the Federal government, including implementation of the STEM Education Strategic Plan.
- Agencies should support studies of U.S. and international QIST workforce supply and demand, and gather data on the demographics of populations in the QIST workforce and educational pipelines. For example, the NSF National Center for Science and Engineering Statistics survey of graduates could add specific tags for QIST in its data collection process.[56]
- The National Quantum Coordination Office (NQCO), SCQIS, and the Subcommittee on the Economic and Security Implications of Quantum Science (ESIX) should encourage the National Quantum Initiative Advisory Committee to develop and implement protocols to assess industry workforce needs and projections, with instruments that respect proprietary information.
- The SCQIS and ESIX should continue engaging with industry through consortia and other venues to better understand future workforce needs and supply.
- Surveys and workshops sponsored by Agencies should be designed to better understand what motivates workers to pursue careers in QIST and related STEM fields, as well as what factors draw talent into Federal government jobs.
- The SCQIS and ESIX should carry out biennial assessments of QIST workforce needs in the Federal government, including the civilian, intelligence, and defense sectors.

1.3 Opportunities for Academia, Industry and the Broader QIST Ecosystem

- Researchers can contribute by working with consortia such as the QED-C, professional societies, and other multi-institutional bodies to help assess the overall market for QIST talent, and understand what skills are most in demand. Quantitative results forecasting the demand for various skill sets in the QIST workforce can help to guide the development of appropriate training opportunities and programs.
- Consortia and professional societies can improve data collection by including questions about QIST jobs in their surveys. When carefully done, this can include studies of job roles that are adjacent to, but critical for, QIST, studies of end users and early adopters of QIST, and analyses of key positions in facilities and supply chain industries that enable QIST R&D.
- Thoughtfully collecting and using demographics data, including information needed to track the inclusion, participation, retention, and career outcomes of people from historically underrepresented backgrounds in STEM fields can help ensure that programs are structured to achieve a diverse QIST talent pool.
- Employers can engage with educators to provide guidance that may be used to align curricula and training experiences with the current and anticipated needs of the QIST economy.

[56] https://www.nsf.gov/statistics/srvygrads/

Action 2. Introduce Broader Audiences to QIST Through Public Outreach and Educational Materials

Goal: Increase awareness and knowledge of the implications and opportunities of QIST within the public and with students of all backgrounds.

Early and continued engagement in STEM fields is a key factor in retaining and mitigating attrition among people from backgrounds historically underrepresented in STEM fields.[57,58] Furthermore, parental and mentor knowledge of opportunities plays an important role in career choices.[59] While QIST falls within the general realm of STEM,[60] it has its own challenges and opportunities regarding outreach, education, and workforce development. For instance, QIST is still largely unknown and thus its benefits are likely not yet clear to most students, teachers, parents, or the general public.

To encourage growth in this base of domestic talent, it is aspirational that all learners should be empowered to see a place for themselves in the quantum-related careers roster.[61] This requires that learners are provided exposure to QIST via accessible outreach and educational opportunities. These can be during regular school and business activities, and also in informal learning venues such as museums, movies, games, and other media. The goal is that they understand what QIST careers exist and what skills are needed to contribute. In this way, K-12 education and outreach can play a pivotal role in building a diverse future QIST workforce.

2.1 Current Landscape

There is much work to be done to link students and teachers with resources at the right levels to nurture their excitement about QIST, while avoiding unrealistic hype. While global availability of open cloud-connected quantum computing prototypes offers profound outreach possibilities, continued effort around creating educational opportunities that connect to QIST concepts is needed. Mass media, pop culture, or press releases from Agencies, universities, and industry are common ways that students and families first hear about the field.[62] Adding “hooks” to QIST in such public venues can be powerful, but care must be taken to ensure that messaging is realistic, accurate, and points towards opportunities for further learning. The science education and communication communities have experience to draw from, so the quantum community should work with other science outreach experts, and experts in diversity, equity, and inclusion to project a message that encourages a broad range of participants in a wide range of venues to support access by a broader audience. Finally, while there have been some QIST-focused science exhibitions at museums,[63] there is a clear opportunity to expand offerings to increase in-person and virtual informal exposure to QIST.

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[57] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast-engage-to-excel-final_2-25-12.pdf
[58] https://www.usnews.com/news/articles/2011/08/29/stem-education--its-elementary
[59] Utility-value intervention with parents increases students’ STEM preparation and career pursuit, doi:10.1073/pnas.1607386114
[60] Developing a National STEM Workforce Strategy, doi:10.17226/21900
[61] Influencing participation of underrepresented students in STEM fields: matched mentors and mindsets, doi:10.1186/s40594-020-00219-2
[62] What the public thinks it knows about science, doi:10.1038/sj.embor.7400040
[63] https://www.mos.org/press/press-releases/QMC2019Winner

Box 1: Key Concepts for QIS Learners
An NSF sponsored workshop identified several Key Concepts for QIS Learners,[64] and produced a list with supporting fundamentals that can be curated, expanded, and adapted for students across computer science, mathematics, physics, and chemistry, as well as broader public audiences. Community input is welcomed, and related curricula are sought.[65] Key Concepts for QIS Learners include: ● Mathematics of probability, vectors, algebra, trigonometry, complex numbers, and linear transformations to describe the physical world via quantum mechanics ● The description of a quantum state ● Quantum measurement outcomes and applications ● The quantum bit, or qubit ● Entanglement and superposition ● Coherence and decoherence ● Quantum computers that solve certain complex computational problems more efficiently than classical computers ● Quantum communication using entanglement or a transmission channel, such as optical fiber, to transfer quantum information between different locations ● Quantum sensing using quantum states to detect and measure physical properties with the highest precision allowed by quantum mechanics To read more about Key Concepts for QIS Learners see https://qis-learners.research.illinois.edu/

At the American high school level, some schools still do not offer physics courses, and a majority of students will not have taken a physics course during their K-12 education;[66] even fewer students have the option to take computer science courses.[67] Based on available data, it appears that only a small minority of these available classes include quantum physics or QIST concepts.[68] Furthermore, those schools that do offer these opportunities tend to have lower enrollment of people from backgrounds historically underrepresented in STEM fields.[69] Another major challenge is that only about 1/3 of high school physics teachers majored in physics.[70] Efforts, partially supported by NSF, are underway to provide critically needed teacher development opportunities, but they are still small and will need to grow.[71,72]

To start addressing teacher preparation, student access, and community awareness, NSF, in coordination with the NQCO, facilitated a workshop where a group of various stakeholders outlined nine key QIST concepts across computer science, mathematics, physics, and chemistry that could be further expanded and adapted for students as well as broader public audiences.[73] These Key Concepts

[64] https://qis-learners.research.illinois.edu/
[65] https://q12education.org/learning-materials
[66] High School Physics Overview | American Institute of Physics (aip.org); hs-courses-enroll-13.pdf (aip.org)
[67] A Minuscule Percentage of Students Take High School Computer Science in the United States: Access Isn't Enough
[68] Based on discussions with the American Association of Physics Teachers
[69] https://www.future-ed.org/work/closing-the-excellence-gap/
[70] A Review of High School Physics Education in the United States of America
[71] https://quantumforall.org/
[72] NSF Award # 2015205 - Cross-Discipline Approach to Quantum Computing in High Schools: Building towards a Quantum Computing Workforce
[73] https://qis-learners.research.illinois.edu/

for QIS Learners are highlighted in Box 1. Expansion of these concepts and related teaching tools, with engagement of high school teachers, is underway as part of a project with an NSF grant.[74] Connecting these efforts with a broader audience requires the efforts of the larger QIST community.

To this end, OSTP and NSF spearheaded the National Q-12 Education Partnership (Q-12 Partnership) to begin fostering and grow such a community. This partnership, between the Federal government, industry, professional societies, and the educational community, is working to expand access to K-12 quantum learning tools, and inspire the next generation of quantum leaders (See Figure 3).[75] The Q-12 Partnership is growing a curated list of resources for QIST education, with materials contributed from a growing variety of teachers, professors, and R&D leaders.

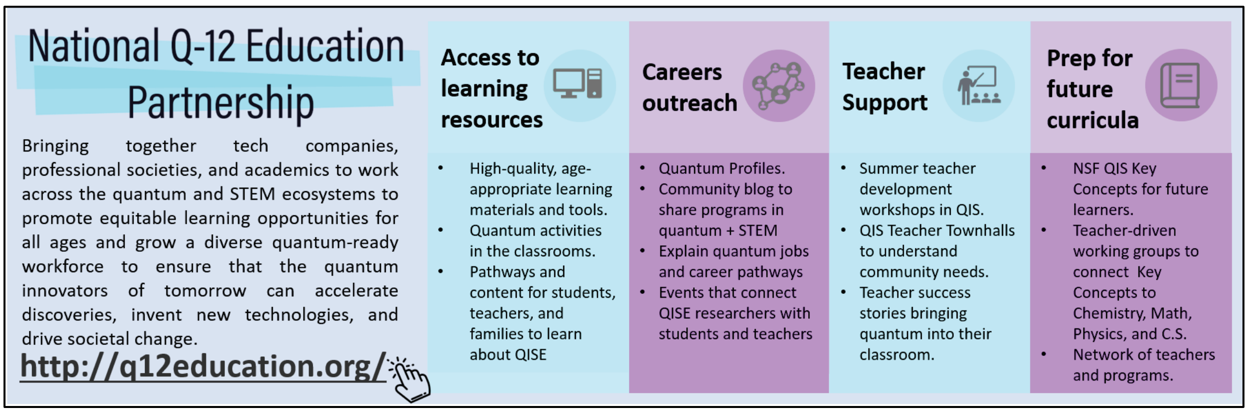

Figure 3: The National Q-12 Education Partnership is a collective effort to connect young students to QIST.

At the postsecondary level, a few colleges and universities have begun to offer introductory quantum courses that target non-STEM students.[76] These Quantum 101, or 'quantum for all,' courses provide a great opportunity to raise awareness and potentially draw students into the field. They can also be useful for adults or professionals in adjacent fields who want more background. Such courses can be offered in community colleges, military schools, as well as at a four-year college or university, including widely accessible teaching-focused state universities found throughout the nation. The latter have a higher proportion of first-generation college students as well as students from backgrounds historically underrepresented in STEM fields, providing a path for creating a diverse and inclusive QIST workforce. Some populations that take short courses or standalone classes for continuing professional education may also have opportunities to engage in QIST-related work in the near-term.

In conjunction with the above activities, building a bridge from educational pathways to training and work opportunities is an important step. Agencies, through existing and targeted programs, have begun to tackle this challenge. In 2020, the NSF issued two Dear Colleague Letters encouraging the submission of proposals for quantum-related activities at the K-12 level.[77,78] NSF's Education and Human Resources

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[74] NSF Award # 2039745 - Q2Work: Supporting learners and educators to develop a competitive workforce in quantum information science and technology

[75] https://www.quantum.gov/wp-content/uploads/2020/12/SummaryQ12KickOffEvent.pdf

[76] https://www.edx.org/course/quantum-mechanics-for-everyone

[77] NSF Dear Colleague Letter: Advancing Quantum Education and Workforce Development (NSF 21-033)

[78] NSF Dear Colleague Letter: Advancing Educational Innovations that Motivate and Prepare PreK-12 Learners for Computationally-Intensive Industries of the Future (NSF 20-101)

(EHR) directorate has also been funding teacher development opportunities,[79,80] and convergence activities for early quantum education.[81] NIST, for its part, leverages its Student High School Internship Program (SHIP) and Pathways program to give students hands-on opportunities to work in a lab, as the Army Research Office, Office of Naval Research, and Air Force Research Lab have done with intern and co-op programs. NASA's internship program includes a broad array of hands-on opportunities with NASA mentors, including in the areas of quantum computing and communication. See the Appendix for more examples of engagements by Agencies.

Summary: To develop the QIST workforce over the long term, more broadly available outreach, engagement, and early educational opportunities should be created and sustained. These opportunities should be designed to illustrate core principles, demystify QIST, highlight positive impacts on society, and explain QIST career options, while minimizing hype. Such activities should benefit the public, including educators, mentors, students, and families from all backgrounds. While QIST-based teacher development opportunities exist, they are still small in scale and too few students have the opportunity to engage with QIST core concepts. Enhanced education and outreach should be widely accessible and leverage promising practices in matters of diversity, equity, and inclusion.[82]

2.2 Recommendations for U.S. Government

- The NQCO should work with Agencies and the broader QIST ecosystem to amplify public outreach activities and incorporate clear and realistic descriptions of QIST advances, challenges, and opportunities.
- Government sponsored efforts that include workforce development activities, such as DOE's National Quantum Information Science Research Centers and NSF's Quantum Leap Challenge Institutes, should strive to create a positive and accurate branding of QIST. They should focus attention on realistic possibilities, and highlight ongoing efforts to create an environment that encourages, welcomes, and inspires involvement by everyone who might wish to participate.
- Agencies such as NSF and NASA should support efforts that promote the development of QIST awareness, starting with K-12 age groups. Such activities can add QIST concepts to existing education and outreach programs, invoke cultural and media institutions, leverage games, people profiles, experiences, and curricula to highlight QIST ideas, and build upon public-private partnerships such as the National Q-12 Education Partnership for QIS Education.
- Funding Agencies are encouraged to solicit and prioritize proposals for activities that widely disseminate key QIST concepts. Additional opportunities should be made available for grants and funding for QIST outreach and early education efforts. Opportunities to connect QIST-related activities with other K-12 initiatives should also be considered.
- Agencies should coordinate with each other and with professional societies and educational institutions to assess the level of engagement of various demographic groups in STEM, and QIST

[79] NSF Award # 2048691 - Preparing Secondary Teachers and Students for Quantum Information Science
[80] NSF Award # 2015205 - Cross-Discipline Approach to Quantum Computing in High Schools: Building towards a Quantum Computing Workforce
[81] NSF Award # 2040614 - Convergence Accelerator: National Quantum Literacy Workforce Curriculum and Training Network
[82] https://www.whitehouse.gov/wp-content/uploads/2021/09/091621-Best-Practices-for-Diversity-Inclusion-in-STEM.pdf

in particular, by tracking participation rates and studying potential barriers faced by individual groups, to determine how to improve, scale, and sustain participation in STEM fields.

- Stronger partnerships between museums/science centers and Agencies are recommended, to expand the intellectual breadth, geographic distribution, and accessibility of QIST exhibits, for example, by developing more digital exhibits and leveraging innovative approaches for hands-on, interactive engagement with broader audiences.

2.3 Opportunities for Academia, Industry and the Broader QIST Ecosystem

- QIST education research is needed. In addition to curriculum development, research on QIST education can inform workforce development approaches and programs. Assessing modules and lesson plans for K-12 courses and college-level Quantum 101 courses, and studying the educational impacts of such courses for both non-STEM and STEM majors can improve the way these concepts are taught, and broaden awareness of QIST concepts and career opportunities.
- To provide awareness of QIST concepts and career options, community colleges and other institutions that might not have formal QIST programs or courses can connect with local industries and universities to hold seminars, host speakers, and host outreach activities to highlight the need for vocational skills related to QIST, and showcase opportunities to pursue further studies through bridge programs, transfers, and higher education.
- To ensure broad access, the QIST community is encouraged to develop vetted and open-access repositories of learning resources that help students and educators find QIST lessons, games, simulations, laboratory demonstrations, or other media relevant for their knowledge, interest, and needs. Because the quality of a student's first contact with a subject is often a critical factor for their continued engagement, the formal assessment of early educational materials is paramount.
- Educators should stress the importance of mathematics and digital literacy, which are core competencies and indicators for future STEM engagement. Unfortunately, these are areas where U.S. students on the whole have room for improvement.[83,84] The overall benefits of STEM training should be emphasized, along with connections to other fields such as electrical and optical engineering, data science, computing and computer science, cyber-security, and artificial intelligence.
- The QIST education community is encouraged to continue working with secondary education teachers on the key concepts for QIST learners, so that the curated list and associated curricula connect to current science standards and learning objectives.[85] Materials and hands-on opportunities should be framed and written to promote both formal and informal engagement to target different audiences (e.g., math, computer science, or physics learners), while highlighting the field's transdisciplinary nature.

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[83] A study of the correlation between STEM career knowledge, mathematics self-efficacy, career interests, and career activities on the likelihood of pursuing a STEM career among middle school students, doi:10.1186/s40594-018-0118-3

[84] https://nces.ed.gov/timss/results19/index.asp#/math/intlcompare

[85] For example: https://q12education.org/learning-materials/framework

Action 3. Address QIST-Specific Gaps in Professional Education and Training Opportunities

Goal: Optimize graduate education and training opportunities for jobs in QIST.

Post-secondary education (post-high school education including professional certification, associate's, bachelor's, master's and doctoral degrees, and professional retraining programs) serves a crucial role in providing the education, training, and skills needed to enter the QIST workforce. As mentioned previously, industry, government, and academia are seeking a workforce which possesses varied depths of QIST knowledge and skills, with a critical need for non-QIST-specific skills.[86,87,88]

Short-term workforce needs will likely be filled by a combination of recent graduates and mid-career workers that transition into QIST employment. The role of engineers cannot be overemphasized. Much of the workforce moving into QIST employment is likely to come from computer science and engineering, electrical engineering, materials engineering, and other closely related fields. The overlap of engineering skills required for the development of a host of quantum technologies has led to the catch all term of 'quantum engineering'.[86] These new roles offer a strong contrast to previous QIST educational strategies which focused mainly on physics departments. Support for the development of a range of part-time or evening professional certificate and degree programs with an engineering focus is important. Given the prevalence of master's degree programs in many QIST-relevant fields (engineering, computer science, etc.) the opportunity to retool for QIST via a QIST-focused master's degree will be important, and such curricula should be assessed with respect to the impact on workforce development and broadening participation. Also important is support for students who are fully employed or non-traditional workers looking to make a career shift or change. Finally, steps must be taken to ensure that prospective entrants to the QIST workforce are connected with the employers who need their skills.

Looking toward a future in which mature QIST technologies are available, opportunities for training end users to leverage QIST cannot be overlooked. The end-user group is currently undefined but expected to be broad and cross multiple domains. For example, doctors may be able to obtain improved brain images from QIST-enhanced MRI, and military commanders may use QIST systems to optimize problems that tackle complicated logistics challenges. Training of QIST end users is a longer-term objective that will most likely be modeled after other training approaches; however, they will be distinctly different due to the expectation that these professionals will stay in their traditional career role, utilizing the advantages of QIST with the addition of QIST expertise. Inspiration for curricula can be gleaned from computer science (CS), and CS+X education programs to train and develop workforces for the industry.[89] Here, the X stands in for other fields that would leverage CS. Similarly, Quantum+X education could catalyze interdisciplinary training for the emerging quantum industry.

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[86] Building a Quantum Engineering Undergraduate Program, arXiv:2108.01311
[87] Achieving a quantum smart workforce, doi:10.1088/2058-9565/abfa64
[88] Preparing for the quantum revolution: What is the role of higher education, doi:10.1103/PhysRevPhysEducRes.16.020131
[89] https://cs.illinois.edu/about/history-timeline

Figure 4: The NQI and the FY20 NDAA authorized the creation of quantum institutes and centers to accelerate R&D in the United States. These networks of universities, companies, national laboratories, and Federal facilities play an outsized role in training the workforce, developing education materials and pathways, and performing public awareness campaigns at all levels.[90-100] *Examples of some of the ongoing efforts include: (1) job fairs that highlight different career pathways and opportunities for professional networking, (2) science outreach talks aimed at introducing a diverse group of students to QIST, (3) short schools and workshops focusing on both fundamental and applied QIST, (4) postdoctoral fellowships, (5) a portfolio of internships and apprenticeships for both undergraduate and graduate students, and (6) quantum education research. Learn more at* www.quantum.gov.

Finally, improving participation will require removing barriers and improving the culture, at both the individual level and at institutions. For students, training for a QIST career can be demanding, with time and financial costs being contributing factors in the decision to start or continue training and education programs.[101] Similarly, some institutions[102] also face challenges entering the QIST community because providing cutting-edge learning experiences to students often requires capital intensive infrastructure and a stable base of in-house QIST talent.[103,104,105] To meet the demand of training a diverse QIST

[90] https://www.quantum.gov/wp-content/uploads/2021/12/NQI-Annual-Report-FY2022.pdf
[91] https://quantumsystemsaccelerator.org/our-ecosystem/
[92] https://sqms.fnal.gov/workforce-development-opportunities/
[93] https://www.bnl.gov/quantumcenter/student-opportunities.php
[94] https://www.q-next.org/opportunities/
[95] https://qscience.org/opportunities/
[96] https://rqs.umd.edu/education/
[97] https://qubbe.uchicago.edu/research/workforce.html
[98] https://ciqc.berkeley.edu/educ-overview
[99] https://hqan.illinois.edu/education-and-workforce
[100] https://www.colorado.edu/research/qsense/workforce
[101] Source: uncertainties in the job market, loss of employment benefits, caregiver responsibilities
[102] Institutions may include, but are not limited to, 2- and 4-years colleges, non-R-1 institutions, MSIs, and HBCUs.
[103] Minority serving institutions, doi:10.17226/25257
[104] Community colleges in the evolving STEM education landscape doi:10.17226/13399
[105] http://www.tandfonline.com/doi/abs/10.1111/ecge.12016

workforce, there should be sustained investments to build education infrastructure and capacity at R2 and Minority Serving Institutions (MSIs), Historical Black Colleges and Universities (HBCUs), Tribal Colleges and Universities (TCUs), and Hispanics-Serving Institutions (HSIs), in order to enable their students to become QIST-aware, QIST-proficient, and QIST-experts. Efforts at each level must be undertaken to create an environment that not only welcomes participants of all backgrounds, but also removes barriers of entry into the QIST ecosystem, and strives to lower attrition of those who are engaged in the QIST workforce.

3.1 Current Landscape

The core concepts underpinning QIST are often taught in specialized, advanced undergraduate physics, chemistry, engineering, or computer science courses. However, much of the material in these courses still focuses on breakthroughs prior to the current era of QIST prototypes. This is also true of graduate coursework at most U.S. institutions, where the majority of educational engagement with QIST concepts and hands-on training has been available. Even at institutions with strong QIST programs, there are only a few examples where QIST concepts are deliberately included in the core curricula of fields such as engineering or computer science. However, curricula are beginning to change as schools start to offer thematic minor programs and introductory QIST courses.[106] QIST-focused certificate programs are also starting to be deployed.[107,108] In contrast, many international allies and competitors are already integrating QIST concepts at a much earlier stage, whether in physics departments or related areas.[109] The establishment of the U.S. NQI Centers and Institutes, Figure 4, is helping to provide additional training and educational opportunities.

Industry currently provides teaching materials, online access to quantum hardware, and certificate programs that are available to the public and educators. However, these efforts are mostly company-specific and do not focus on developing core concepts. As a result, these opportunities are most helpful to users who are already familiar with QIST concepts and want to build proficiency in the available tools.

Summary: Post-secondary education and training programs may have the greatest impact on the quality and adaptability of the U.S. QIST workforce. From undergraduate courses and internships to graduate research positions and cross-training opportunities, programs in higher education should include several on-ramps to facilitate pathways for students at all levels. A broad spectrum of training opportunities can meet the varied depth and disciplinary needs of QIST careers. Opportunities to up-skill or retrain researchers and professionals at various career stages are needed. Furthermore, recognizing that investments in education, training, and retraining can foster multiple points of entry and exit to/from QIST careers, it is valuable to develop programs that enable more workers to acquire skills that complement and support QIST R&D, even if they do not become subject matter experts. Industry has a crucial role, and is making important contributions to the QIST education landscape. There is, however, a need for broad engagement with professional educators to ensure that QIST

[106] https://www.compadre.org/per/items/5465.pdf
[107] https://professional.uchicago.edu/find-your-fit/professional-education/certificate-programs-quantum-engineering-and-technology
[108] https://learn-xpro.mit.edu/quantum-computing
[109] Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic, doi:10.1103/PhysRevPhysEducRes.15.010130

training opportunities create lasting, platform agnostic, value in the form of a broadly-skilled, agile, talent pool.

3.2 Recommendations for U.S. Government

- Agencies should look for ways to leverage graduate fellowships and undergraduate stipends to incentivize students to include QIST-related courses and research experiences in their educational pathway. For example, one could create a QuantumCorps scholarship program patterned after the successful NSF CyberCorps Scholarships for Service program.
- Agencies should support the creation of QIST career pivot programs that can retrain or up-skill professionals in adjacent fields. These programs can directly address QIST workforce needs by augmenting targeted skill sets for professionals in related specialties, or complementing partially-relevant skill sets with key additional knowledge, possibly through short courses, practice with new instrumentation, or certification with specific facilities, tools, or software. Such programs can also train QIST end users in various disciplines.
- Agencies should take advantage of existing programs, and develop new ones as need, that expand the range of institutions that can offer on-ramps to QIST jobs. Options include (but are not limited to) adding QIST to existing undergraduate and graduate curricula, giving students greater access to research infrastructure, and supporting faculty at a broader range of institutions to expand their own QIST knowledge and research programs.
- Agencies should encourage QIST curriculum development and curriculum research at several levels, including introductory courses, thematic minors, and master's programs. Assessment of these curricula should study how they support transitions among STEM fields and prepare participants for careers in QIST, and STEM more generally.
- Agencies should leverage public-private partnerships to support development of platform-independent resources for interested parties to engage with quantum computing hardware and software.
- Agencies should consider devoting additional resources for the development of QIST training courses that have significant hardware components, recognizing the pedagogical value of hands-on laboratory activities.

3.3 Opportunities for Academia, Industry and the Broader QIST Ecosystem

- Institutions of higher education can expand QIST courses and programs to increase opportunities for future workers and to build proficiencies that connect various specializations with QIST expertise. Opportunities include:
    - Formal (concentrations, minors, majors, and master's degrees) and informal (internships and externships) QIST programs that highlight QIST-specific challenges and techniques, with pathways to employment upon graduation.
    - QIST specific courses, which focus on the underlying science and theory, in addition to technologies and engineering aspects of QIST, with hands-on learning opportunities in software and hardware development and uses.
    - Short-term workforce needs can be addressed by QIST career pivot programs, including the development of relevant professional certificates, developed in conjunction with industry and non-profit associations, that target workers in QIS-adjacent/relevant fields.

- Institutions are recommended to develop and deploy a wide variety of resources for educators such as lesson plans, modules, courses, specializations, minors, and other potential courses of study at all education levels, and to encourage assessment and dissemination of such materials.
- Institutions are recommended to increase the adoption of skills training that crosses multiple technology areas in support of QIST. These include, but are not limited to, circuit testing and design, cryogenic engineering, microelectronics programming, nanofabrication techniques, and significant exposure to modern photonics and laser science.
- Employers from all sectors should continue to engage with educators and academic programs to provide guidance on how to align curricula and other educational experiences with changes occurring in the QIST economy.

Action 4. Make Careers in QIST and Related Fields More Accessible and Equitable

Goal: Reduce barriers to participation in QIST-related careers for everyone who may wish to work in this field. Increase the pool of talent available for QIST-related jobs throughout the Nation and in Federal Government, by strengthening and diversifying programs that have shaped and developed the QIST ecosystem thus far. Grow the QIST ecosystem further by including entities, institutions, and organizations that have not yet been engaged in QIST activities.

As the need for QIST expertise grows, we must ensure that considerations of diversity, equity, and inclusion play a key role in all developments. We must continue – and augment – the approaches that have led to U.S. leadership in QIST by developing multiple on-ramps for individuals from all areas of science and all backgrounds to ensure that the United States remains a world-leader. We also must maintain a welcoming environment for talent entering from outside the United States. Finally, we must ensure that the specific needs of the Federal government are addressed. Here, "we" refers to the entire QIST R&D and education community, including Agencies, industry, academic institutions at all levels, non-profits, and professional societies.

Maintaining and growing a robust pool of experts begins by supplementing and expanding the approaches that have made QIST a success in the United States over the past 25 years. To this end, the NSO highlighted the ongoing role and need for continued support and expansion of fundamental research, and encouraged the creation of more interdisciplinary and cross-disciplinary opportunities. The former can be met through continued support and appropriate strengthening of existing research training programs offered by Agencies. The latter can be accomplished with special programs that bring together subject matter experts from different disciplines in a coherent fashion, for example, to work on aspects of a project or a grand challenge through joint efforts, or with supplemental funding of graduate students advised by QIST faculty from multiple university departments. The National QIS Centers and Institutes highlighted in Figure 4 serve as good examples, but more efforts and additional on-ramps into the field are required.

Programs should be developed that increase the research capacity of institutions not yet deeply involved in QIST and provide new opportunities for students to participate in QIST research at a greater number of institutions. A prime example of such a program is the recent NSF solicitation "Expanding Capacity in Quantum Information Science and Engineering (ExpandQISE)." The ExpandQISE program is designed to engage the full spectrum of research talent by helping build and maintain a close connection between new efforts and the existing impactful work done at the QISE Centers (shown in Fig. 4) and other leading QISE research Institutions, while creating and nurturing the necessary critical mass at institutions not yet fully involved in QISE.[110]

As in the ExpandQISE program, considerations of diversity, equity, and inclusion must lie at the core of how the community moves forward. A diverse, equitable, and inclusive workforce leads to a more innovative environment, helping ensure that the technologies developed and the problems to which they are applied benefit the most people. As previously mentioned, QIST is currently composed of

[110] https://www.nsf.gov/pubs/2022/nsf22561/nsf22561.htm

several fields that have traditionally struggled to achieve diverse and equitable environments. This must be changed. Much work has been done over the last decade with varying degrees of success, and many lessons can be learned from current efforts in these and other fields.[111–115] However, taking these lessons, applying them, and generating change in QIST and beyond must be the focus of deliberate actions that begin immediately. For example, the TEAM-UP report recommends efforts be undertaken to create an inclusive environment, where all participants see a positive role for themselves in the community. Showcasing a diverse set of individuals through QIST profiles is a pillar of the Q-12 Partnership, and provides an opportunity for further engagement in this effort across the QIST community. Another example of such a deliberate action is requiring that the makeup of QIST panels and workshop attendees reflect the broad community of participants, ensuring that all gatherings encourage participation by people from backgrounds historically underrepresented in STEM.[116]

The QIST community needs to undertake a careful analysis of its efforts and ensure policies are being translated into practices and action, with their effectiveness monitored.[117] This report recognizes the outstanding challenges that still remain to be addressed, and recommends a focused effort over the next year to develop a QIST-specific understanding of these challenges at all levels and on-ramps, along specific actions beyond those noted in this report. This effort should start with listening sessions on how diversity, equity, and inclusion impact each level of QIST education and training, and their respective on-ramps to the field.

As we work to grow the QIST talent pool, it is also important to recognize the vital role that international participants have in the U.S. QIST ecosystem.[118] They participate in and contribute to almost all facets of the ecosystem. They study and carry out research as undergraduate and graduate students, perform independent research as post-docs, and lead research programs in industry and academia. Many immigrate to the United States, where they continue to contribute in a variety of ways, including in federal service. Others move back to their home countries or establish programs in new locations, which strengthens the global network of collaborators. The success of the U.S. enterprise has relied, and will continue to rely upon, this integral component of the QIST workforce.

The Federal government requires QIST subject matter experts to conduct cutting-edge research, inform policy decisions made by senior leaders, and oversee the strategic portfolio of government investments in QIST. The careful and dedicated work of civil servants over the last three decades has contributed significantly to shepherding the field to its current state, and will continue to play a vital role in future. The field's continued maturation will benefit from a steady stream of talented individuals working in government, who can develop and manage the next generation of programs that advance the science and develop QIST-related technologies. In contrast to jobs in academia and industry, most Federal government jobs have additional requirements, such as U.S. citizenship. The fact that more than half of

[111] https://www.aip.org/sites/default/files/aipcorp/files/teamup-full-report.pdf
[112] https://www.whitehouse.gov/wp-content/uploads/2021/09/091621-Best-Practices-for-Diversity-Inclusion-in-STEM.pdf
[113] Engineering societies' activities in promoting diversity and inclusion, doi:10.17226/25323
[114] Promising practices for addressing the underrepresentation of women in science, engineering, and medicine, doi:10.17226/25585
[115] Transforming trajectories for women of color in tech, doi:10.17226/26345
[116] https://www.nih.gov/about-nih/who-we-are/nih-director/statements/time-end-manel-tradition
[117] https://chicagoquantum.org/events/open-quantum-initiative-workshop-building-a-diverse-quantum-ecosystem

the conferred QIST-related graduate degrees are awarded to foreign national students emphasizes the need for promotion of available pathways to U.S. citizenship for those STEM-educated foreign nationals who are interested, as part of a balanced workforce development strategy. This strategy should incorporate the requirements specific to the Federal government by investing in the development of a domestic workforce across the QIST-aware, -proficient, and -expert levels.[118] Reaching out to the vast pool of domestic talent currently not part of the STEM workforce and ensuring that these individuals can identify a role to play has tremendous potential to addressing this need.

Finally, in planning the development of talent, one must heed the necessary timelines for education and training. For example, prioritizing increases for basic research staffing in QIST can increase the expert workforce within two years (by funding postdocs and engaging MS students) or over five to ten years (by engaging PhD, or undergraduates who may continue in the field). To fill immediate needs (6 months – 1 year), the existing talent pool of professional academic, industrial, national lab, and government science and technology experts are well-positioned to make lateral moves into QIST. This transition can be facilitated if assistance and incentives are provided, either through government- or privately-sponsored programs. For example, sabbaticals, fellowships, and professional exchange programs offer avenues for experts to stay at the forefront of the field, while also providing opportunities for attaining skills in QIST.

4.1 Current Landscape

QIST workforce development is often achieved through hands-on training opportunities supported by Agencies that conduct and fund basic research in QIST and adjacent fields. Funding helps to support research assistantships, internships, fellowships, and summer programs for students and postdocs. In some cases, this can serve as a bridge to federal employment. For example, the NIST-NRC Postdoctoral Research Associateship program brings in researchers as temporary federal employees, making the transition to a federal career easier.[119] While support for basic research in QIST has mostly increased across the QIST-relevant S&T Agencies over the past five years, Agencies are still struggling to hire and retain QIST experts. Hiring challenges are largely fueled by pay disparity between competing industry and government offers, lengthy on-boarding times, and requirements for extensive background checks that can prolong the hiring process.[120] Additionally, better public information campaigns are needed to highlight federal employment opportunities in QIST, for instance in the DOD labs and the Laboratory for Physical Science (LPS). Finally, working within the existing hiring framework is compressing pay scales, which carries the threat of motivating existing government experts to consider looking for more lucrative employment outside the government.

With respect to adapting talent, development programs and fellowships, such as the NSF Quantum Computing & Information Science (QCIS) Faculty Fellows program, the DOD Vannevar Bush Faculty Fellowship (VBFF) Program, the DoD Multidisciplinary University Research Initiative (MURI), the DoD Laboratory University Collaboration Initiative (LUCI) Fellowship, as well as the visiting scholar programs and senior technical leadership development programs are important in facilitating exchanges

[118] https://www.quantum.gov/wp-content/uploads/2021/10/2021_NSTC_ESIX_INTL_TALENT_QIS.pdf
[119] https://www.nist.gov/iaao/academic-affairs-office/nist-nrc-postdoctoral-research-associateships-program
[120] https://www.quantum.gov/wp-content/uploads/2022/01/Summary-QIS-Fed-Workforce-JAN2022.pdf

between industry, academia, and the government. Finally, all Agencies recognize that QIST has become an activity involving a cross section of disciplines, and have started to look at ways to assemble much-needed multi-disciplinary teams to address major challenges.[121]

Summary: As the field of QIST advances, we must ensure all available sources of talent can participate. The United States will need a strong domestic workforce, including a growing number of people with QIST expertise who can be cleared to work in Government jobs. Taking deliberative steps to address inequities and grow a diverse workforce is required to meet the coming challenges. While continued support and expansion of core QIST-related research programs and training opportunities is one crucial avenue for the development of such talent, additional opportunities for training through internships and fellowships at Federal facilities can expand the pipeline, offering an important pathway for attracting talent to the Federal government. Finally, while domestic talent is deeply needed, the U.S. must also continue to support and recognize the importance of international talent in the QIST ecosystem.

4.2 Recommendations for U.S. Government

- The SCQIS and its workforce IWG should undertake a series of listening sessions and community engagements to develop an increased understanding of diversity, equity, and inclusion in QIST. A key focus should be understanding how the different on-ramps to the QIST workforce can be made more equitable. Such efforts will require community engagement, and this report should serve as a starting point for expanding this conversation.
- The SCQIS and its workforce IWG should coordinate with the NSTC Committee on STEM Education (Co-STEM) as they implement the STEM Education Strategic Plan. Coordination should help identify best practices and lessons learned across STEM to support actions and activities that can be tailored to QIST, which will increase diversity and enable an equitable and inclusive environment.
- Agencies should continue to support and invest in core R&D programs that train experts in disciplines related to QIST. This includes research experiences and mentoring at a wide variety of colleges and universities, including investments in MSI, R2, and community colleges.
- Agencies represented on the SCQIS and ESIX should collaborate to create QIST learning and training opportunities for Federal government staff.
- Agencies should review and maximize hiring authorities that enable them to be competitive in attracting and retaining talent to work on QIST topics. Such reviews should look at policies that provide professional support and educational opportunities to retain and advance entry of mid-career employees.
- Internships and externships can assist prospective individuals in exploring job options in the QIST workforce by creating opportunities for people at various career stages, or at various stages of education, to spend time in industry, government facilities, and national laboratories. Agencies should encourage institutes, centers, and other large efforts to foster internships and externships, as well as interdisciplinary collaborations and hiring practices, and support research programs that expand QIST training opportunities such as sabbaticals, fellowships, and visiting scholar programs.

[121] Details of these programs can be found on individual agency websites and at quantum.gov

- The Government should strive to increase access to hands-on learning opportunities – especially for students and faculty at institutions that do not have extensive research infrastructure – by leveraging Research Experiences for Undergraduates (REU) and Research Experiences for Teachers (RET) activities at NSF–funded university sites, NSF Quantum Leap Challenge Institutes, NIST, and the DOE-supported National QIS Research Centers, and also in research facilities operated by DOD, including its designated DOD QIST Centers.
- Agencies should expand support for efforts that build communities such as the QED-C, NSF-industry partnerships, TRIPLETS, INTERN, Convergence Accelerator, DOD MURI programs, and other approaches. Such programs may be tailored to connect potential students to industry and other job opportunities. These activities should include outreach efforts to ensure that students are aware of, and have access to, opportunities in industry that have similar objectives and complement government-sponsored programs.
- Agencies should strive to expand opportunities for post-graduate QIST work within Federal laboratories through programs like the NIST-NRC Postdoctoral Research Associateship that provide a bridge to Federal government employment.
- Agencies should also contribute to, and support contributions to, the *quantum profiles* (see Figure 2 and Sec. 4.3) to illustrate impactful career paths.
- Agencies should work to ensure that QIST education and workforce activities connect with and leverage the larger list of STEM activities supported across the Federal government.
- Agencies should cooperate with international partners to enable circulation and growth of talent through exchange programs and other mechanisms.

4.3 Opportunities for Academia, Industry and the Broader QIST Ecosystem

- The QIST community is encouraged to develop a campaign that promotes careers in QIST through *QIST profiles*.[122] This effort should work to spotlight the breadth of roles, skills, and levels of knowledge needed throughout the QIST ecosystem. Marketing should highlight a broad range of participants and opportunities from diverse racial, ethnic, and gender backgrounds, as well as educational diversity (e.g., R2, community colleges, and MSI educational paths), serving as a means to connect with underrepresented groups. Resources should be Section 508 compliant to ensure universal accessibility.
    - Industry is encouraged to play a role in this effort, highlighting careers and continuing to contribute to the development of accessible QIST platforms and learning tools.
    - The QIST community should develop studies that seek to understand how language, images, and media inspire different target populations (students, general public, educators, etc.) to develop positive branding that resonates with, and is accessible to, a diverse audience.
- To recruit students and professionals with diverse backgrounds, the QIS R&D community can create unique experiences that give learners a chance to see QIST "in action" and demonstrate how individuals with widely different talents can make a meaningful contribution to the field.
- The academic community can encourage long-term mentorship of QIST students, alumni, and workers to guide these individuals throughout their educational and career paths, improving

[122] https://q12education.org/about/careers

retention of talent, especially of people from backgrounds that are historically underrepresented in STEM.

- Institutes, centers, and other large group efforts can nurture interdisciplinary collaborations and hiring practices, to expand QIST training opportunities and grow the impact of QIST R&D.
- The industrial and academic communities can work to strengthen recruitment and retention of domestic and international QIST talent into U.S. companies and universities.
- The industrial and academic communities can work with quantum consortia and professional societies to identify mechanisms (internships, externships, extended visits, training programs, and partnerships) to increase the quality, diversity, and flow of QIST workers across sectors, connecting them to employment opportunities, and identify levers to encourage more interaction across disciplines and recruit more talent into QIST.

Conclusion

The United States has invested in QIST through focused research programs, technology transfer, and national and global infrastructure for over 25 years. The establishment of the National Quantum Initiative is a bold acknowledgement that QIST R&D is important and that a substantial workforce in this area is needed. An appropriately educated and trained workforce is vital to ensure the United States and international allies reap the benefits that QIST can bring to national and economic security. Healthy development of QIST manufacturing and supply chains, infrastructure, discoveries, and innovations all depend upon a robust, talented, and agile workforce. Furthermore, advances in technologies often come from the confluence of outstanding talent and the emergence of unforeseen applications that naturally arise from foundational research. Due to the massive increase in investments that are helping spur technological development in QIST, workforce adaptability is crucial in hedging against the near-term hurdles that must be overcome to remain competitive in this global enterprise.

As QIST evolves, education and training at all levels, from K-12 to graduate education and beyond, will need to keep pace to fill the workforce gaps. To aptly inform QIST curriculum development, outreach, and education programs will require coordination and feedback mechanisms between industry, academia, national labs, and government to assess the evolving, highly varied, and interdisciplinary QIST workforce needs and skills. Developing the national workforce will require drawing on all available talent by broadening outreach, and by increasing learning and professional opportunities for people from all backgrounds and from a larger range of institutions. To improve engagement, special care must be taken with regards to the branding of QIST, to increase awareness of breakthroughs, and to improve public engagement. Additionally, policy actions relevant to QIST in the area of workforce, education, and broadening participation should be continuously assessed at all levels.

The health of the QIST ecosystem depends on the combined and highly interdependent work and workforce produced by academia, government, national labs, and industry. Sustained investment in this growing ecosystem will support continued discoveries and breakthroughs in QIST, the inception of future technologies, and the development of top talent.

Appendix: QIST Opportunities Supported by Federal Agencies

Below is a sample of the education and training opportunities offered by several of the Agencies engaged in QIST. The majority of the mentioned programs here have explicit connections to QIST. Learn more about QIST opportunities by going to www.quantum.gov and exploring individuals agencies websites.

DOD: The DOD's basic research agencies in the individual services – the Air Force Office of Scientific Research (AFOSR), the Army Research Office (ARO), and the Office of Naval Research (ONR) – as well as the Office of the Secretary of Defense (OSD) and the three service labs, support QIST workforce development through existing programs such as the Vannevar Bush Faculty Fellowship Program (VBFF), the Multidisciplinary University Research Initiative (MURI), the Laboratory University Collaboration Initiative (LUCI), Single Investigator grants, the Science Math and Research for Transformation (SMART) program, and the National Defense Science and Engineering Graduate (NDSEG) Fellowship program. These offer opportunities connecting extramural researchers to the service labs, through internships for students and educators, fellowships for students and postdocs, summer programs for students and faculty, and outreach activities for students and teachers ranging from K-12 through post-secondary education. Notably, many of these activities involve the international research community through grants and open-campus initiatives. Organizations within DOD have also sponsored a variety of QIST-specific summer schools, and the Quantum Computing Graduate Research (QuaCGR) Fellowship Program. QuaCGR is sponsored jointly by the ARO and the Laboratory for Physical Sciences (LPS) to stimulate U.S. graduate student participation in research related to quantum computing, and to assist in the training of graduate students to prepare them for careers in quantum information science.

Individual government organizations stood up a number of internal quantum-focused courses for their existing workforce, while also leveraging those provided by industry. Opportunities to aid the workforce in attaining QIST laboratory skills were set up with various government laboratories by offering off-site tours at their facilities. Engagement with the U.S. Naval War College (USNWC) brought insight into potential technologies for future operational vignettes. Summer internships of SMART, NREIP, Pathways Students, and NDSEG interns were specifically crafted to provide exposure to and experience with QIST.

DOE: The DOE's mission includes workforce development activities that either produce a workforce in areas of DOE need or make use of the unique resources at DOE's 17 National Laboratories. In addition to programs that provide visiting faculty, undergraduate, graduate, and community college students with opportunities to do research at DOE's labs, the five NQIA-authorized National QIS Research Centers will sponsor QIST-specific workforce development activities.

IARPA: IARPA's mandate is to conduct cross-community research, target new opportunities and innovations, and generate revolutionary capabilities. Workforce development is accomplished through numerous research programs, some of which are tailored towards QIST. IARPA also participates in the ODNI Intelligence Community postdoctoral program.

NASA: Through its internship and Pathways programs, NASA engages directly with STEM students to develop their understanding and build connections with NASA's subject matter experts. Within NASA's Space Communications and Navigation (SCaN) Program, NASA focuses on quantum communication in its SCaN Internship Project (SIP) at the high school junior through PhD candidate levels, as well as outreach with the general public and in K-12 schools. Through the Quantum Artificial Intelligence Lab (QuAIL) group, NASA mentors' students at all levels in quantum computing, quantum sensing, and quantum-enhanced machine learning, that includes seeking physics insights in order to co-design robust quantum hardware, developing high performance quantum circuit simulators, designing quantum software tools and algorithms, and implementing end-user applications on emerging quantum hardware.

NIST: The primary means by which NIST supports the QIST workforce development is via technical and scientific training of university graduate students, postdoctoral researchers and guest researchers who participate in the NIST mission and programs, its joint institutes (JILA, JQI, and QuICS), its Summer Undergraduate Research Fellowship (SURF) program, and its Summer High School Intern Program (SHIP).

NSA: NSA takes a holistic approach to workforce development and actively invests in national and local activities to broaden STEM participation. In addition to participating in most of DOD's workforce programs, NSA offers a range of STEM-focused opportunities that are regularly used for QIST workforce development. These include internships, scholarships, a co-op program, and more for students starting in high school and continuing beyond advanced degrees. LPS has also initiated both national and targeted quantum computing fellowships for graduate students, and participates in the ODNI IC Postdoctoral Research Fellowship Program. In addition, LPS has also created a national-level quantum information science research center supporting fundamental research, workshops, and QIST co-curricular activities for post-secondary education students.

NSF: At the NSF, all aspects of education, from K-12, undergraduate, and graduate levels are addressed together with teacher training and development, informal education, broadening participation and inclusion, diversity, and partnership. This is achieved by a suite of programs that are also open to QIST-specific needs.[123] NSF also has QIST-specific programs, such as the "TRIPLETS" program that funds a university PI, industrial partner, and graduate student to work together over a period of three years; the Quantum Computing and Information Science Faculty Fellows (QCIS-FF) program; and the Quantum Leap Challenge Institutes (QLCI) program that funds multidisciplinary teams. NSF is continuously assessing the effectiveness of their programs in addressing dynamically changing challenges, such as making sure the opportunities for growth in competitiveness are made available to all institutions.

[123] NSF Dear Colleague Letter: Advancing Quantum Education and Workforce Development (NSF 21-033)