THE ROLE OF INTERNATIONAL TALENT IN QUANTUM INFORMATION SCIENCE

A Report by the

SUBCOMMITTEE ON ECONOMIC AND SECURITY IMPLICATIONS OF QUANTUM SCIENCE

COMMITTEE ON HOMELAND AND NATIONAL SECURITY

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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Acronyms

AFRL	Air Force Research Laboratory
ARL	Army Research Laboratory
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOS	Department of State
ESIX	Subcommittee on Economic and Security Implications of Quantum Science
FBI	Federal Bureau of Investigation
IARPA	Intelligence Advanced Research Projects Activity
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NQCO	National Quantum Coordination Office
NQI	National Quantum Initiative
NRL	Naval Research Laboratory
NSA	National Security Agency
NSC	National Security Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
QED-C	Quantum Economic Development Consortium
QIST	Quantum Information Science and Technology
R&D	Research and Development
S&T	Science and Technology
SCQIS	Subcommittee on Quantum Information Science
STEM	Science, Technology, Engineering, and Mathematics
SWaP-C	Size, Weight, and Power - Cost
USD	United States Dollars

Executive Summary

Quantum Information Science and Technology (QIST) has substantial scientific, economic, and national security implications. Maintaining leadership in this critical emerging technology will depend on growing a diverse and expert workforce, especially as the global pace of QIST research and development (R&D) increases.

Talent required to develop QIST is currently in short supply, both nationally and internationally. Global investments in QIST are intensifying the workforce shortage as countries strive to produce, attract, and retain top talent. Increasing the capacity for QIST R&D in companies, universities, and national laboratories, and the Federal government will require a sustained commitment to grow a diverse and expert workforce. Welcoming international researchers and fostering international cooperation will remain important. Joint efforts on education, training, and workforce development are mutually beneficial for the United States and its partners and allies.

Concerns exist about the methods used by some strategic competitors to gain access to U.S. technology, both licitly and illicitly, to the detriment of academia, the private sector, governments, and international collaboration networks. With QIST growing in economic and national security importance, it increasingly becomes a target because U.S. technical expertise and intellectual property (IP), built through years of dedicated training and research, are extremely valuable.

The key objective is to carefully balance measures to promote an open innovation ecosystem with those to protect national security. The potential risk associated with accepting foreign visitors and immigrants into the United States must be balanced against the crucial and beneficial role they play in contributing to a dynamic U.S. and global research enterprise. A one-sided approach will only imperil our vibrant QIST research community, disadvantage our economic competitiveness, or impede the pace of R&D, as discovery, supply chains, and importantly talent, span many countries. A more nuanced approach is needed.

This report highlights the critical role that international talent plays in ensuring a vibrant and successful U.S. research enterprise in QIST, including the importance of close collaboration with foreign partners, while also stressing the importance of protecting the technology and expertise of the United States and our international partners. It finds that maintaining a strong flow of international students and researchers is an essential component to developing the expert QIST workforce required to achieve U.S. QIST goals as part of an advancing global research enterprise.

To ensure continued U.S. leadership in QIST, this report recommends the following:

1. The United States should continue to develop and support policies that welcome talented individuals from all over the world, while implementing appropriately balanced protections that mitigate potential research security concerns.
2. Federal organizations should engage in close collaboration with allies and partners to ensure a vibrant and secure international QIST ecosystem that is underpinned by shared values and principles including freedom of inquiry, merit-based competition, openness and transparency, accountability, and reciprocity.
3. The NSTC Subcommittee on Quantum Information Science (SCQIS) should develop a five-year strategic plan for QIST workforce development, to assess evolving workforce needs, grow the domestic pool of talent, and foster ways to attract and retain top QIST talent from around the world.

4. Federal organizations that fund research, development, and acquisition of QIST should develop coordinated, comprehensive technology protection plans to safeguard intellectual capital and property, while accounting for specific mission needs. These measures should address current and evolving methods used to target U.S. technology, while promoting U.S. ideals of open and transparent R&D.

Section 1: The Economic and Security Implications of Quantum Information Science and Technology

FINDINGS
1.1: QIST is a growing enterprise with important economic and national security implications, and a reliance on a complex, international ecosystem.
1.2: U.S. leadership in QIST faces increasing global competition. Fair and open competition is welcome as it advances the field and confers benefit to all participants.
1.3: Most QIST technologies remain somewhat nascent—to bring them to maturity will require extensive field testing, as well as prioritized and sustained R&D investments.
1.4: Maturing QIST technologies will require a broad, diverse, and expert workforce to undertake the necessary R&D.

Quantum Information Science and Technology (QIST)—a critical and emerging technology spanning the subfields of quantum computing, networking, sensing, and metrology—leverages the fundamental quantum properties of matter to generate new information technologies. While the full potential impact of these technologies is unknown and evolving, the underlying principles hold promise for the development of new tools for scientific discovery, new methods for sending or computing information, and a number of other applications with significant economic and national security implications.

The United States has been a leader in QIST since the field's inception. Early recognition of the importance of QIST by Federal agencies helped foster and support a robust research community in the United States and with close international partners. These early efforts established a strong foundation that enabled exciting discoveries.[2] A national effort to accelerate, advance, and harness this potential was codified by the launch of the National Quantum Initiative (NQI) Act in 2018 (P.L. 115-368) and the National Defense Authorization Acts (NDAAs) for Fiscal Years 2019 (P.L. 115-232; Sec. 234) and 2020 (P.L. 116-92; Sec. 220).

Major efforts around the globe and growing investments by multinational corporations have begun to alter the investment landscape in QIST. A number of countries have also established national-level programs, with cumulative global funding expected to exceed $20 billion USD over the next decade.[3] The majority of these countries uphold and adhere to the same core research principles and values practiced in the United States and are ideal for continued international collaboration and coordination in this technology space.[4] As the QIST landscape and implications evolve, the United States must remain engaged in a vibrant, international QIST research ecosystem that still safeguards domestic and global equities and interests.

The list of potential applications of QIST technologies with expected economic impact is extensive and growing. For example, quantum sensors allow improved sensitivity, opening up a broad spectrum of applications for fundamental science, natural resource exploration, and biotechnology. Quantum

[2] https://www.nist.gov/topics/physics/introduction-new-quantum-revolution/nist-jump-starts-quantum-information

[3] https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf

[4] These countries include those that, in good faith, uphold and adhere to core research principles and values — including freedom of inquiry, merit-based competition, openness and transparency, accountability, and reciprocity — and promote the protection of intellectual property, safe and inclusive research environments, and rigor and integrity in research.

computing may provide exponential speed-ups or more accurate solutions for certain sets of problems in cybersecurity, chemistry, materials science, machine learning, and finance. These potential applications have led to a growing investment by industry and venture capital (VC) in QIST, which underscores the expected economic potential of the technology.[5] In fact, over the last decade, VC funding has invested more than $2.5 billion USD in over 100 quantum-related startups,[6,7] and the U.S. Quantum Economic Development Consortium (QED-C) now has a membership of over 160 U.S. companies, universities, and non-profits.[8] Many QED-C members have international offices or employ foreign nationals, and their success is dependent on a competitive and fair global market.

QIST also has the potential to impact national security. For example, a large-scale quantum computer would threaten most of the public-key encryption infrastructure currently protecting economic and national security communications.[9] Similarly, efforts are underway to develop quantum sensors that could improve positioning, navigation, and timing. These sensors could enable navigation that is less susceptible to disruptions in global navigation satellite systems.[10] This is just a sampling, with other novel QIST applications still to be discovered and their implications yet to be understood.

Overall, QIST technologies are likely to provide economic and national security advantages to those countries that are successful in leading their development. Therefore, it is imperative the United States plays a leading role in this technology arena, while also working to strengthen collaborations with allies and partners who share similar research values. This effort requires interfacing with and leveraging an increasingly global and interconnected QIST research community, one that includes broad international academic collaborations, dispersed supply chains for advanced enabling technologies, and a global talent pool. All of these components are essential for expanding the research infrastructure now that would allow us to quickly adopt significant advances with economic or national security implications when they present themselves.

While QIST R&D investment continues to grow, it is important to note that many QIST-based technologies remain nascent. The *National Strategic Overview for Quantum Information Science,*[11] the national strategy for QIST R&D released by the NSTC Subcommittee on Quantum Information Science (SCQIS), recommends a science-first approach: research to understand and address issues surrounding the ultimate viability, utility, and application of quantum information science. Timelines for bringing commercially viable products to market depend on the specific technology and are, at present, often speculative.

While prototype quantum sensors exist and a limited number will likely be fielded for practical applications within the next five years, many remain in the laboratory with significant challenges to overcome to reduce size, weight, and power, as well as cost (SWaP-C).[12] Further R&D efforts can focus on enabling technology that could reduce SWaP-C and make the sensors more robust. Likewise, while

5 The Quantum Gold Rush, https://www.nature.com/articles/d41586-019-02935-4
6 https://medium.com/le-lab-quantique/new-record-looms-in-vc-funding-of-quantum-startups-484b82541004
7 https://www.zdnet.com/article/quantum-computing-is-at-an-early-stage-but-investors-are-already-getting-excited/
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research on quantum computing applications of commercial interest are still being investigated, thus far, no such algorithms that run on currently available hardware have demonstrated a clear quantum advantage in the commercial context.[13] Significant improvements in system scale and performance are needed before such devices can transcend the academic and national lab context and become viable for commercial applications.

The additional development effort needed to reach deployable QIST technologies will require a diverse workforce pulling from a wide variety of disciplines and skillsets.[14] Deep technical quantum expertise will be needed to advance the basic science; broad quantum-capable engineering skills will be required to develop and engineer the base and supporting technologies; and quantum-awareness across a range of end-users will be needed to define and execute on potential applications. With increased investments and opportunities, demand for suitable personnel has grown dramatically in the past decade, across academia, industry, and government. However, as highlighted in the next section, supply has not kept pace.

The importance of QIST — its intersection with economic and national security implications, combined with recent efforts in the area of research security[15] — has raised concerns that malign actors taking advantage of the field could overshadow the immense benefits of international collaboration and spur reactions that would be detrimental to our own competitiveness in the field. This report presents key findings that highlight the critical role foreign talent plays in the U.S. QIST ecosystem. The findings outline the importance of ensuring a stable supply of talent in QIST-related fields appropriate for strategically meeting national needs, and the need to work together to protect R&D. Policy recommendations are provided in an effort to ensure that an optimal balance can be struck between the two.

[13] NASEM 2019. Quantum Computing: Progress and Prospects. https://doi.org/10.17226/25196

[14] https://arxiv.org/pdf/2109.03601.pdf

[15] https://trumpwhitehouse.archives.gov/wp-content/uploads/2020/07/Enhancing-the-Security-and-Integrity-of-Americas-Research-Enterprise.pdf

Section 2: The QIST Workforce and the Importance of Foreign Talent

FINDINGS
2.1: Industry, academia, and the U.S. Government currently face a shortage of talent in QIST. While in the long term the National Quantum Initiative programs will generate new workforce talent, there is still an immediate need for talent across multiple sectors and an uncertainty if these programs can meet future needs of academia, national laboratories, industry, and the Federal Government.
2.2: Foreign talent constitutes approximately half of the U.S. graduates in QIST related fields, and flows into the United States from all over the world.
2.3: As of 2017, approximately 70% of foreign national Science, Technology, Engineering and Mathematics (STEM) PhD students who graduated from U.S. institutions of higher education stayed in the United States, where they contribute to the U.S. economy and support the global science and technology enterprise.
2.4: The development of new QIST expertise is slow, often taking 10 years of post-secondary education and training.
2.5: Addressing the growing demand for an expert QIST workforce will require both growing the domestic pipeline and promoting the flow of international talent into the United States.

Talent is the fuel for science and technology (S&T) advancements. Developing basic research into deployable, market-ready technologies requires a capable, skilled workforce. The workforce needs of QIST are quite expansive, cutting across multiple disciplines, the most relevant being physics, computer and information science, and electrical engineering.[16] Expertise in these fields is also in high demand in several other high-tech sectors, including semiconductors.[17]

Developing the Nation's QIST enterprise requires a sustained effort to grow the U.S. talent base at all levels of education and all career stages. This goal also requires careful alignment of QIST workforce supply with demand.

The demand for talent is expected to grow along with the rapid rise in global QIST investment –more than $20 billion USD projected over the next decade.[18] Major QIST-related investments from industry and VC-backed startups are driving a surge in job postings. Recent increases in funding for activities authorized in the NQI Act, supporting multiple research centers and institutes set up by the Department of Energy (DOE) and the National Science Foundation (NSF), require faculty, research scientists, post-doctoral associates, and graduate and undergraduate students, along with technical support. Similar investments have been made from national security and defense agencies. Combined, this growth also drives a need for supporting and enabling technologies, which increases demand for quantum-related scientists, engineers, and technicians. While no authoritative data source currently exists for accurately

[16] The most QIST-relevant degree fields are physics, electrical engineering, and computer science, according to (a) preliminary search of keywords for online job postings and (b) analysis of doctoral thesis titles, abstracts, and keywords.

[17] https://cset.georgetown.edu/publication/the-chipmakers-u-s-strengths-and-priorities-for-the-high-end-semiconductor-workforce/

[18] https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf

projecting future QIST workforce needs, indicators, including job-board analysis and conversations with representatives from the QED-C, industry, academia, national laboratories, and the Federal Government suggest a significant unmet demand for talent at all levels. Over time, the education and training opportunities coming from the NQI-related activities will generate new talent. Whether these efforts catch up with and meet the growing demand is an open question.

Historically, the United States has been a beacon for scientists and technologists, who have been attracted to U.S. scientific leadership, industrial opportunity, and guiding principles that support scientific integrity through an open and transparent R&D ecosystem. For decades, the United States has benefitted tremendously from foreign researchers' intent on studying or immigrating here, and bringing their bright ideas and hard work to advance the state of S&T. These workers have played an important role in achieving U.S. scientific and technology goals.

Foreign-born workers represent 44% of all U.S. science and engineering workers with PhDs,[19] and contribute immensely to U.S. innovation and entrepreneurship.[20] For example, in artificial intelligence (AI), another priority technology area, a recent analysis found that the majority of the "most promising" U.S.-based AI startups have foreign-born founders.[21]

Publicly available datasets can help better understand the current U.S. QIST workforce landscape and the role of foreign talent within it. While there is currently no comprehensive source of data on QIST students or workers, some insights can be gleaned from degree fields most often listed in QIST job advertisements (i.e., physics, computer science, and electrical engineering) and preliminary analysis of trends in QIST-focused doctoral dissertations. The data presented in this section provide context about the likely U.S.-based talent pool for the QIST workforce, including doctoral, master's, and bachelor's degree holders.

From 2014 to 2018, approximately 43% of physics, 56% of computer and information science,[22] and 64% of electrical engineering PhDs awarded in the United States were earned by foreign nationals.[23] An even higher share of postdoctoral associates in these fields in the United States were temporary residents (63%, 64%, and 74%, respectively) in 2016.[24] See Figure 1a for a summary. Over the past two decades, foreign students and postdoctoral associates in science and engineering fields have come to the United States from over 200 countries of origin.[25]

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[19] NSB, NSF. 2019. *Science and Engineering Indicators 2020*. https://ncses.nsf.gov/pubs/nsb20198/

[20] See, for example, Hunt, Jennifer. 2011. "Which Immigrants are Most Innovative and Entrepreneurial? Distinctions by Entry Visa" *Journal of Labor Economics*, vol. 29, no. 3 https://www.journals.uchicago.edu/doi/pdf/10.1086/659409; Azoulay, Pierre, et al. 2020. "Immigration and Entrepreneurship in the United States" NBER Working Paper No. 27778. https://www.nber.org/papers/w27778

[21] Center for Security and Emerging Technology. 2020. *Most of America's "Most Promising" AI Startups Have Immigrant Founders* https://cset.georgetown.edu/research/most-of-americas-most-promising-ai-startups-have-immigrant-founders/

[22] Due to differences in the taxonomies of the degree fields among different data sets, some reported data is for computer and information science, while other reported data is for computer science or computer and mathematical science.

[23] Calculated based on custom tabulations provided by the National Center for Science and Engineering Statistics (NCSES) from the Survey of Earned Doctorates in the academic years 2014–2018.

[24] NCSES. 2018. *Survey of Graduate Students and Postdoctorates in Science and Engineering Academic Year 2016*. https://ncsesdata.nsf.gov/gradpostdoc/2016/

[25] https://ncses.nsf.gov/pubs/nsb20197/international-s-e-higher-education

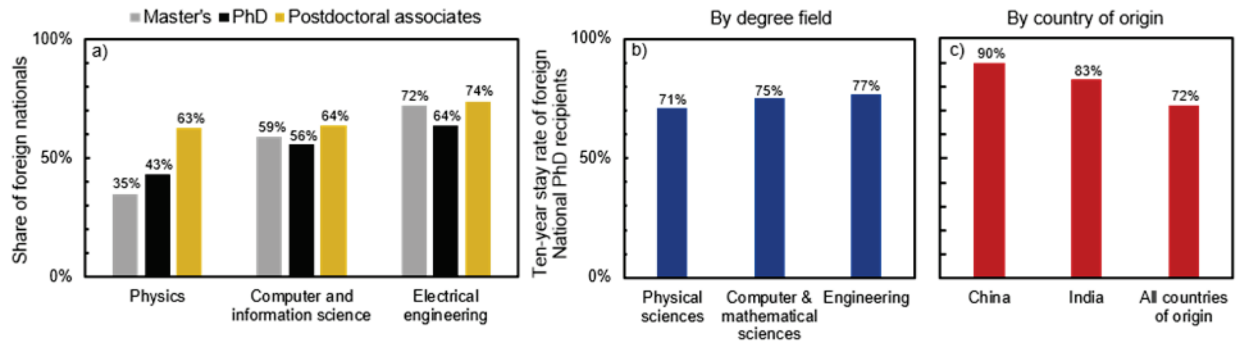

Figure 1: a) Share of master's (grey) and PhD (black) degrees awarded to foreign nationals from 2014-2018 in physics, computer and information science and electrical engineering at U.S. institutions of higher education, and share of postdoctoral associates (yellow) who are foreign nationals working at U.S. institutions of higher education in 2016. b) Average stay rate of foreign national PhD recipients in the physical sciences, computer and mathematical science and engineering 10 years following graduation. c) Average stay rate of science and engineering PhD recipients from China, India and all countries of origin 10 years following graduation. Data in panel a) based on National Center for Education Statistics (NCES) Integrated Postsecondary Education Data System-Completions (master's), National Center for Science and Engineering Statistics (NCSES) Survey of Earned Doctorates (PhDs), NCSES Survey of Graduate Students and Post-doctorates in Science and Engineering (postdoctoral associates). Data in panels b) and c) calculated from NSF's Science and Engineering Indicators 2020.

As shown in Figure 1b and 1c, the majority of foreign national PhD recipients in science and engineering typically work in the United States for at least 10 years following graduation (approximately 71% in physical sciences, 75% in computer and mathematical sciences, and 77% in engineering) where they continue to provide value and advance U.S. interests.[26] Notably, the rates are highest for science and engineering PhD recipients from China (90%) and India (83%).[27] However, these stay rates are several years out of date, and anecdotal evidence suggests that foreign nationals are increasingly being recruited by and moving to countries other than the United States. This shift appears to be at least partially driven by increased opportunities in other parts of the world, coupled with less certainty and predictability from the U.S. immigration system.

Current progress in QIST is largely based on years of basic scientific research carried out by the U.S. university community. Aside from the students themselves working in university labs, a number of the faculty members who generated this knowledge and are training these students are foreign-born themselves.[28] They too are a critical component of the QIST ecosystem.

Preliminary analysis of dissertation records suggests that fewer than 5% of PhDs in physics, electrical engineering, and computer information science and engineering awarded by U.S. institutions of higher education from academic years 2014 to 2018 focused directly on a QIST topic.[29] However, it is estimated

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[26] Partnership for a New American Economy, "The H1-B Employment Effect," 2015; http://research.newamericaneconomy.org/wp-content/uploads/2015/04/H1B_12.7.pdf

[27] National Science Board, National Science Foundation. 2019. *Science and Engineering Indicators 2020*. https://ncses.nsf.gov/pubs/nsb20198/

[28] https://ncses.nsf.gov/pubs/nsb20198/data#supplemental-tables Table S3-21

[29] These estimates are based on search queries of dissertation abstracts, titles, subjects, and keywords in the ProQuest Dissertations database, believed to be the most complete collection of U.S. dissertation records available. The number of QIST-focused dissertations was estimated using search terms that aimed to target QIST rather than quantum science and technology more generally. The results of this approach vary with the choice of search terms queried, and also as records are added or updated. Based on this method, we estimate that an average on the order of 100 to 200 QIST-focused dissertations were awarded per academic year at U.S. Institutions between 2014 and 2018. During this window, the

that approximately half of these degrees were awarded to foreign nationals.[30] However, QIST workforce needs are broad and cut across many disciplines; this characteristic suggests that a much larger share of PhD recipients — including those in chemistry, mathematics, and materials science — have skills applicable to QIST R&D and therefore are part of the QIST workforce pool.[31] Of course, not all students who graduate in a QIST relevant field will choose a career in that field, as the skills and knowledge obtained are applicable to many other fields.

The demand for QIST hires is not limited to PhD-holders; those with bachelor's or master's degrees are likely to play an increasing role in the QIST workforce over time, as basic research translates to the development and engineering of QIST-based technologies.[32] In U.S. institutions from 2014 to 2018, the majority of master's degree recipients in computer and information science (59%) and electrical engineering (72%) were foreign nationals; fewer master's degree recipients in physics (35%) were foreign nationals.[33] At the bachelor's degree level, foreign nationals numbered less than 10% of degree recipients in computer and information science and physics, and approximately 14% of degree recipients in electrical engineering.[34]

Developing new domestic STEM talent pools is a priority for the United States. It also takes time, particularly in the complex fields pertinent to QIST where the median time to complete a doctorate degree is approximately six years,[35] and a master's degree is two to three years; both follow four to five years for a bachelor's degree.[36] Therefore, new efforts to train a QIST workforce are unlikely to immediately bear fruit. Attracting domestic university students to QIST-related fields of study requires an increased flow of high school students who are aware of QIST and incentivized to pursue careers in the field. Efforts to grow the QIST workforce by promoting lateral workforce movement via retraining should be considered and may take less time. Even still, such efforts will draw talent from other critical areas, while still requiring support and training mechanisms.

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number of dissertations awarded increased at an average rate of 11 to 16 percent per year, depending on the breadth of QIST-focused search terms queried. It is important to note that the distinction between QIST and quantum S&T remains difficult to define; the numbers increase significantly if "quantum" is included with any term.

[30] This estimate is based on a weighted average of the statistics on the share of PhDs in physics, computer science, and electrical engineering awarded to foreign nationals that appears in Figure 1. The average is weighted according to the relative number of QIST-focused PhDs awarded from each of the three disciplines from 2014-2018. This approach assumes that the share of PhDs awarded to foreign nationals in a given field (e.g., physics) is the same for the subset of students in that field who focused on QIST topics.

[31] Assessing the Needs of the Quantum Industry, https://arxiv.org/abs/2109.03601

[32] See, for example, Fox, Michael FJ, Benjamin M. Zwickl, and H. J. Lewandowski. 2020. "Preparing for the quantum revolution: What is the role of higher education?" *Physical Review Physics Education Research* 16, no. 2: 020131. https://journals.aps.org/prper/abstract/10.1103/PhysRevPhysEducRes.16.020131

[33] Calculated based on National Center for Education Statistics (NCES) IPEDS-C data on master's degrees awarded over academic years 2014–2018.

[34] Calculated based on NCES IPEDS-C data on bachelor's degrees awarded in academic year 2018.

[35] NCSES. 2018. *Doctorate Recipients from U.S. Universities: 2017*. See table 31: https://ncses.nsf.gov/pubs/nsf19301/data

[36] National Student Clearinghouse Research Center. 2016. Time to Degree: A National View of the Time Enrolled and Elapsed for Associate and Bachelor's Degree Earners (Signature Report No. 11). Herndon, VA: National Student Clearinghouse Research Center. https://nscresearchcenter.org/signaturereport11/; American Institute of Physics. 2020. *Physics Bachelor's Degrees: 2018*. https://www.aip.org/statistics/reports/physics-bachelors-degrees-2018; American Institute of Physics. 2014. *Trends in Exiting Physics Master's*. https://www.aip.org/sites/default/files/statistics/graduate/trendsmasters-p-12.2.pdf

Alternatively, foreign researchers and students who come to the United States often have some or all of the requisite education and training to pursue careers in QIST. Retaining foreign talent provides a faster path to supplementing the U.S. workforce in critical QIST technical areas. As noted above, U.S. academic institutions already look to international students to help advance their ongoing basic R&D. Just as importantly, these foreign researchers and students bring with them a diversity of scientific ideas, experiences, and skillsets that add to a robust scientific discourse and faster technical advancement. These benefits are conferred to the U.S. research enterprise while the foreign national is working or studying, but can also persist even if the researcher does not stay.[37] Furthermore, in cases where a researcher eventually leaves the United States, the researcher is likely to maintain professional contacts in the United States, which may lead to future scientific collaborations that benefit the United States and the scientific enterprise as a whole.

Benefits from the appropriate international flow of talent are also exemplified by a survey of Nobel laureates. Of the 95 Nobel Prizes from 2000 to 2019 recognizing U.S. scientists, over 1/3 were awarded to immigrants to the United States.[38] Another example comes from the U.S National Institute of Standards and Technology (NIST) and three of its Nobel Laureates. They each shared the Prize with a colleague who either immigrated to,[39] spent time in,[40] or, from abroad, mentored students who carried out forefront research in[41] the United States. This flow of talent and knowledge into and out of the United States led to benefits not just for the United States, but also for the global scientific enterprise.

The U.S. demand for an expert QIST workforce can most effectively be addressed by increasing the domestic pipeline while also sustaining and promoting the influx of top international students and immigrants. Disruptions to the flow of international talent would slow R&D, lower supply, and increase domestic need, thereby significantly hampering efforts to meet the rising QIST workforce demands.

[37] https://www.aps.org/policy/analysis/upload/APS_Report_J1_OPT_Importance_2020.pdf
[38] https://nfap.com/wp-content/uploads/2019/10/Immigrants-and-Nobel-Prizes.NFAP-Policy-Brief.October-2019.pdf
[39] https://www.nobelprize.org/prizes/physics/2001/ketterle/facts/
[40] https://www.nobelprize.org/prizes/physics/2012/haroche/facts/
[41] https://www.nobelprize.org/prizes/physics/1997/cohen-tannoudji/biographical/

Section 3: QIST in a Global Enterprise

FINDINGS
3.1: QIST has become a global scientific enterprise and the United States benefits from the flow of ideas, talent, and technology, as do other participants.
3.2: Ensuring the United States retains its status as a destination of choice for QIST researchers, including workshops and conferences, and continues to welcome ideas from around the world, is critical to the United States remaining at the forefront of information exchange and innovation and to accelerating progress in the field.
3.3: U.S. and allied technology, data, and IP are targeted by some malign actors, through illegal or otherwise illicit means.
3.4: The U.S. Government uses a multi-layered approach to protect technology.
3.5: Avenues to access protected U.S. technology include programs that place international and domestic researchers in potentially compromising positions.
3.6: Coordinated efforts, between Federal agencies, between U.S. Government and academia/industry, and between the United States and international partners, will ensure QIST continues to advance while providing a fair, competitive ecosystem.

The QIST ecosystem is increasingly international. The rise of investment has created a landscape where expertise, resources, and infrastructure are globally diffused. Accordingly, international collaboration is a pillar of the U.S. QIST strategy, underscoring its importance to advance the field.[42] Truly fair, productive, and responsible collaboration requires participants to affirm and abide by the foundational principles of research integrity. These principles include freedom of inquiry, merit-based competition, accountability, reciprocity, and openness, all of which constitute a set of values held by the United States and its partners and allies.

Openness and a commitment to research integrity fuels American innovation, but it is not without risk. Malign actors, typically under the direction of a government or corporate entity, can deploy a variety of illicit or illegal methods to draw intellectual capital and advanced technology away from the United States and its partners and allies.[43] An example is the problematic deployment of state-sponsored talent recruitment programs, to exploit, influence, and undermine the research activities and investments of the United States and our allies.[44] Some of these efforts encourage or direct unethical or criminal behaviors, while others create conflicts of commitment and/or conflicts of interest for participating researchers. Ultimately, the programs can lead to the loss of intellectual capital, sensitive technology, and/or intellectual property (IP).[45–47] As a critical emerging technology worldwide, QIST is

[42] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_NSO_QIS.pdf
[43] https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf
[44] https://www.hsgac.senate.gov/imo/media/doc/2019-11-18%20PSI%20Staff%20Report%20-%20China's%20Talent%20Recruitment%20Plans.pdf
[45] https://trumpwhitehouse.archives.gov/wp-content/uploads/2020/07/Enhancing-the-Security-and-Integrity-of-Americas-Research-Enterprise.pdf
[46] https://www.nbr.org/wp-content/uploads/pdfs/publications/IP_Commission_Report_Update.pdf
[47] https://www.judiciary.senate.gov/imo/media/doc/05-13-14PassmanTestimony.pdf

a target for such malign activity, endangering fundamental research, technology development, and the global community of QIST researchers.

History provides some guidance on how to proceed with balancing these benefits and risks. For fundamental research, National Security Decision Directive 189 (NSDD 189), which was issued in 1985, enshrined U.S. commitment to openness and the free exchange of ideas for federally funded basic research.[48] While NSDD 189 still holds today, the global environment that engendered it has changed. The United States is now far more interconnected with its allies and competitors across many sectors. The ongoing digital age allows the rapid sharing of data and knowledge. The private sector now funds more S&T than before. The United States also proudly hosts more foreign S&T students than it did 30 years ago. These changes bring numerous benefits, such as a stronger push for mutual prosperity, rapid sharing of knowledge and ideas, and accelerated discovery. They also bring new risks, including novel pathways to siphon intellectual capital and property from a broader set of targeted stakeholders, not all of whom are equally resourced to address it.

In the face of such risks, the key objective is to carefully balance measures to promote an open innovation ecosystem with those to protect national security. It is paramount that the United States reaffirm NSDD 189 for basic QIST research and concomitantly look thoughtfully across the R&D pipeline to deploy measures that promote the research enterprise, while protecting it as appropriate. A number of existing protection measures are used for deployable technologies. For instance, the Department of Commerce's Export Administration Regulations and the Department of State's (DOS) International Traffic in Arms Regulations both help address national security-related controls at a commercial stage of technology development.[49] At earlier research stages, National Security Presidential Memorandum 33 directs Departments and Agencies to develop policies and procedures for researchers to disclose all potential conflicts of interest and conflicts of commitment when pursuing Federal grants.[50] In cases of misconduct, corrective action, including criminal investigations, can be initiated where appropriate.[51] Efforts like the NSTC Subcommittee on Research Security and this subcommittee intend to provide a forum for discussion, coordination, and achieving the appropriate balance of openness and protective measures.[50] Multi-layered approaches that leverage a diverse and flexible set of tools for technology protection would best reflect the dynamic, interconnected nature of the global ecosystem.

Balancing openness and protection cannot occur within the Federal government alone. The implementation of risk mitigation measures is most effective when coordinated across Federal agencies, academia, industry, and foreign partners. It requires awareness-building and sustained engagement with the academic and private sector members of the domestic QIST ecosystem.[52,53] Robust and secure supply chains are key components of this ecosystem as well, with companies worldwide supporting basic QIST R&D or bearing specific production competencies for critical QIST components. For example, the QED-C represents a useful forum for companies and universities to collaborate on pre-competitive research and supply-chain development, where those interactions are

[48] https://catalog.archives.gov/id/6879779
[49] https://fas.org/sgp/crs/natsec/R41916.pdf
[50] https://www.whitehouse.gov/ostp/news-updates/2021/08/12/readout-of-national-security-presidential-memorandum-33-community-forum/
[51] https://www.whitehouse.gov/ostp/news-updates/2021/08/10/clear-rules-for-research-security-and-researcher-responsibility/
[52] https://www.nature.com/articles/d41586-021-00901-7
[53] https://www.aps.org/publications/apsnews/updates/china-risk.cfm

protected by a membership agreement that enforces a set of core values. Involving a diverse set of stakeholders will yield precise technology-protection regimes, arranged and defined such that they do not inadvertently limit the technology gains and goals of the United States and our allies and partners.

International engagement is an essential part of balancing openness and protection. Over 60 bilateral S&T agreements and numerous additional arrangements provide the U.S. Government a mechanism to cooperate with trusted partners to facilitate mutually beneficial scientific collaboration and protect IP. Multilateral approaches including the Wassenaar Arrangement, continued security obligation annexes, and focused bilateral export control and nonproliferation dialogues provide avenues to coordinate commensurate steps to safeguard both U.S. and allied systems against malign actions. One important step that other countries should consider is foreign investment screening, like the U.S. Committee on Foreign Investment in the United States (CFIUS) process, that can help identify the risks to national security arising from the potential acquisition of domestic businesses, as well as their IP, by foreign actors looking to appropriate critical technologies.

Coordinated and sustained efforts with allies and partners can build a shared risk perception, help mitigate vulnerabilities in our interconnected systems, stem unwanted technology proliferation, and enhance overall S&T cooperation. Accordingly, working with international partners on our common interests is key to promoting and protecting QIST. For instance, the 2019 Tokyo Statement, signed by the United States and Japan, was the first instance of two governments declaring a mutual desire for enhanced QIST cooperation, explicitly grounded in shared values of research integrity, which served as a prelude to deeper cooperation.[54]

In summary, neither unfettered openness nor complete isolation is the solution to the risks that come from an interconnected innovation ecosystem. A one-sided approach will only imperil our vibrant QIST research community, disadvantage our economic competitiveness, or impede the pace of R&D, as discovery, supply chains, and importantly talent, span many countries. A more nuanced approach is needed. For talent specifically, potential risk mitigation must be mindful of the overwhelmingly beneficial role foreign talent plays in the QIST workforce. The free flow of ideas and talent, regardless of origin, benefits both the U.S. and global QIST ecosystem, especially because no single country is the undisputed leader in every subfield of QIST.[55–57] The movement of students, scholars, and researchers to and from the United States leads to the synergy of new ideas, builds new skills and expertise, and forges new connections among QIST stakeholders; these factors all drive better research outcomes and strengthen the global QIST ecosystem.[58,59] Therefore, a coordinated effort across Federal agencies, the private sector, and with international partners is needed to encourage information flow, champion scientific norms of open research, and advance the field while protecting this important technology.

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[54] https://www.state.gov/tokyo-statement-on-quantum-cooperation/

[55] https://nfap.com/wp-content/uploads/2019/01/2018-BILLION-DOLLAR-STARTUPS.NFAP-Policy-Brief.2018-1.pdf

[56] American Physical Society, "How International Students and Researchers Benefit the United States: Their Experiences, Their Stories," 2020; https://www.aps.org/policy/analysis/intl-benefits.cfm

[57] https://www.sciencemag.org/careers/2017/05/how-get-most-out-attending-conferences

[58] https://blogs.scientificamerican.com/guest-blog/how-international-cooperation-in-research-advances-both-science-and-diplomacy/

[59] https://royalsociety.org/topics-policy/projects/knowledge-networks-nations/report/

Policy Recommendations

QIST is a global endeavor. International researchers who come to work in the United States are critical to ensuring that the United States achieves its long-term R&D goals and to advancing QIST globally. Yet, there are risks posed by those who seek to disrupt and disregard the core values that underpin the Nation's scientific enterprise. To reduce this risk, the United States should: continue to welcome foreign talent, work with international partners to create a vibrant and secure global QIST ecosystem, grow its talent base, and develop sensible technology protection plans that balance economic and scientific opportunity with potential risks.

Recommendation 1: The United States should continue to develop and support policies that welcome talented individuals from all over the world, while implementing appropriately balanced protections that mitigate potential research security concerns.

- The United States should implement policies to diversify and expand the locations from which the United States attracts talent.
- The U.S. Government should cooperate and collaborate with partners and allies to increase the global pool of talent through international agreements.
- The United States — working across government, industry, academia, and other relevant stakeholders — should take steps to better understand how current policies support U.S. workforce demands and projected five-year needs to help inform future policymaking.

Recommendation 2: Federal organizations should engage in close collaboration with allies and partners to ensure a vibrant and secure international QIST ecosystem that is underpinned by shared values and principles, including freedom of inquiry, merit-based competition, openness and transparency, accountability, and reciprocity.

- The United States should implement policies to support cross-training and reciprocal research exchanges with QIST centers worldwide.
- As the United States conducts outreach on QIST protections, it should work with foreign allies and partners (both public and private) on commensurate steps to build and protect values/principles as part of an aligned network.
- The United States should work with international partners and allies to promote consistent technology protections and appropriate, targeted export control regulations across countries. Efforts should be sufficient to address concerns, while still being mindful of unintended hindrances to development.

Recommendation 3: The National Quantum Coordination Office (NQCO) and NSTC Subcommittee on Quantum Information Science (SCQIS) should augment the *National Strategic Overview for Quantum Information Science* with a strategic plan for QIST workforce development. A five-year plan should assess evolving and future workforce needs, grow the domestic pool of talent, and foster ways to attract and retain top QIST talent from around the world.

- The plan should identify and prioritize programs that grow and diversify domestic talent.
- Progress should be assessed after two-years.

- Special consideration should be given to training, recruiting, and retaining talent suitable for U.S. Government positions. This effort includes creating workforce development programs for U.S. citizens, making U.S. Government positions more competitive with private-sector positions, and reforming the clearance process to more easily accommodate the diverse and highly-technical talent base in emerging technologies such as QIST.
- The plan should include pathways, incentives, and goals for increasing, diversifying, and retaining international talent where advantageous.
- Special attention should be given to all aspects of the Federal QIST ecosystem, including civilian, intelligence, and defense entities in the full range of relevant fields.
- The NQCO should collect data from Federal agencies on the makeup of its QIST workforce and other critical data needed for understanding future workforce supply and demand.
- The NQCO should encourage development of additional sources of data to better understand and forecast workforce needs over time.

Recommendation 4: Federal organizations that fund research, development, and acquisition of QIST should develop coordinated, comprehensive technology protection plans to safeguard intellectual capital and property, while accounting for specific mission needs. These measures should address current and evolving methods used to target U.S. technology, while promoting U.S. ideals of open and transparent R&D.

- Each relevant Federal agency should establish a QIST protection plan. Individual agency plans should be coordinated with all U.S. Government stakeholders, with top-level coordination provided by the NSTC Subcommittee on Economic and Security Implications of Quantum Science (ESIX).
- ESIX and the NQCO should work to ensure the QIST community is aware of the present risks to the R&D enterprise, while working with international partners and allies to promote a fair and open R&D environment.
- The NQCO, working with QIST-relevant agencies, should coordinate robust outreach programs on QIST technology and protections, and assist the Department of State (DOS) in developing bilateral technology agreements.
- S&T agencies should work with the Federal Bureau of Investigation (FBI), Office of the Director of National Intelligence (ODNI), and other authorized agencies to develop and maintain a public awareness campaign to raise cognizance of risks pertaining to research practices in QIST. This campaign should include encouraging conversations on research security with international partners and working with researchers to help determine risks.