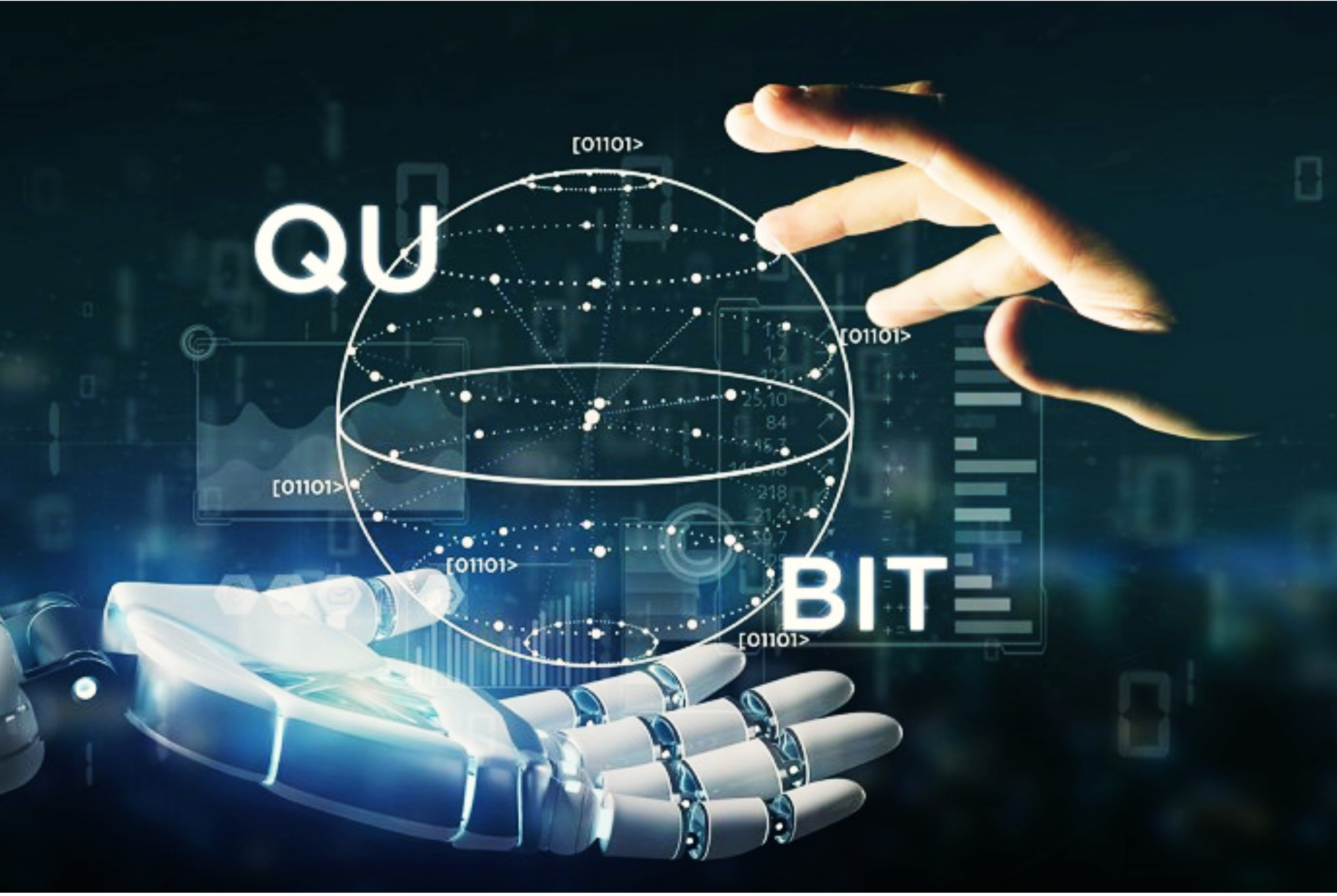
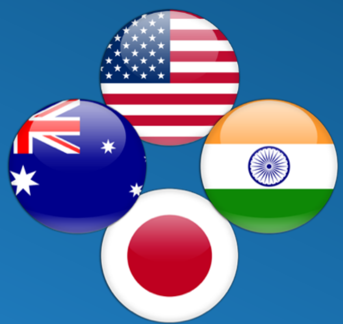


Quantum Science & Technology in the QUAD Nations

Landscape and Opportunities



Report
July 2024

QUAD INVESTORS NETWORK

QUIN Quantum Center of Excellence

TABLE OF CONTENTS

QUIN's Quantum Information Sciences Center of Excellence (QCoE) Task Force Reports

Summary of High-Level Outcomes

Key Members:
QCoE Co-Chairs: Dr. Cathy Foley (Australia)[1], Prof. Ajay Kumar Sood (India)[2], Prof. Hiroaki Aihara (Japan)[3], Dr. Celia Merzbacher (United States)[4]
QUIN Members: Karl Mehta[5], Dr. Ryoto Sekine[6], Mohammad Aamir Sohail[7]

Introduction:

The Quad Investors Network ("QUIN") was created to accelerate investment in critical and emerging technologies among the Quad nations: India, Japan, Australia, and the United States. The overarching goals of the QUIN are to bring together key stakeholders from startups through large corporations and from public and private technology investors to increase collaboration at all levels, increase investments and the flow of capital, and ultimately grow business and trade among the Quad nations.

On November 7, 2023, the QUIN launched the Quantum Center of Excellence (CoE)'s Task Forces covering quantum computing, communications, sensing, and ecosystem & workforce development. Since then, the Task Forces have made significant strides in mapping the current landscape and identifying challenges in these respective domains, as well as devising priority opportunities on actions that the QUIN can take or help facilitate to overcome these challenges. This report gathers insights from domain experts from all four Quad nations. This collaborative effort culminated in a comprehensive set of suggestions that are presented in this document.

The Path Forward:

- **Stakeholder Feedback**: The next step involves releasing the report into the public domain. This is intended to solicit further input from both private and public stakeholders. By inviting comments, we aim to gain broader perspectives on the prioritization of the suggestions and identify potential resources for organizing teams to take action. Upon receiving feedback from a wide range of stakeholders, the QUIN will carefully analyze the inputs. This process will involve refining and prioritizing the suggestions to ensure they align with the collective goals and capabilities of the involved parties.

---

[1] Chief Scientist of Australia
[2] Principal Scientific Adviser to the Government of India
[3] Executive Vice President of the University of Tokyo
[4] Executive Director Quantum Economic Development Consortium
[5] Chairman Emeritus of the Quad Investors Network
[6] QUAD Fellow. PhD from Caltech. Director of Technology Development at PINC Technologies Inc.
[7] QUAD Fellow. PhD candidate at the University of Michigan

- **Action Plan Development**: Once the suggestions have been refined and prioritized, QUIN will work to secure commitments from both private and public sectors. This step is crucial for identifying and mobilizing the necessary resources to support the implementation of the prioritized suggestions. With resources secured and priorities established, the next phase involves forming dedicated teams. These teams will be tasked with developing detailed action plans, ensuring that each prioritized suggestion is addressed systematically and effectively.
- **Implementation**: The final step is executing the action plans. With the support of the dedicated teams and the mobilized resources, these plans will be implemented to achieve the intended outcomes.

***Process Overview*:**

The Task Forces began by convening regular meetings and workshops, bringing together leading investors, executives, and technologists from Australia, India, Japan, and the United States. Through these sessions, they performed a situational assessment of their respective quantum verticals with special emphasis on the current context of the Quad nations and their strategic competitors. Top challenges facing the Quad nations were also identified and typically categorized in terms of the scientific/technical, market/business, resource/supply chain, and policy, although the specifics vary depending on the Task Force. Finally, the Task Forces determined areas for further exploration for how the QUIN could initiate actions to overcome these challenges. In the following section, we list the high-level suggestions from the Task Forces.

***Actionable Items for the QUIN*:**

- **Quantum Computing**

  The Computing Task Force identifies priority opportunities for the QUIN to

  1. Establish shared test-bed facilities operated collectively by the Quad nations, as well as leverage existing testbeds and share best practices to inform future testbeds in the Quad nations. [*Technical Collaboration*, *Requires large funding*]
  2. Encourage and reinforce mechanisms for collaboration and information sharing between quantum computing companies. [*Policy* & *Commercialization Related*]
  3. Advocate for a Quantum Hackathon supported by the Quad. Participant groups must consist of at least three of the four Quad countries. [*Technical Collaboration*, *Requires Small Funding*]

- **Quantum Communications**

  The Communications Task Force highlights priority opportunities for the QUIN to

  1. Establish guidelines for the transfer of technologies critical for quantum communication. [*Policy Related*]
  2. Establish a Public-Private business model for scaling and commercializing quantum communication technologies. [*Requires Large Funding*]

3. Build opportunities to increase the free flow of capital and encourage investment in quantum communication initiatives. [*Policy Related*]
4. Enhance industry support for comprehensive training and qualification programs in quantum communication. [*Technical Collaboration*, *Requires Small Funding*]

- **Quantum Sensing**

  The Sensing Task Force presents priority opportunities for the QUIN to

1. Urge the Quad governments to resolve policy decisions on quantum technologies resulting from any joint Quad effort. Without high-level intervention on items including intellectual property, export controls and regulations, and national security concerns, the current landscape of highly regionalized investment and development will not change. [*Policy Related*]
2. Instigate a thorough study of the quantum sensing capabilities of each of the Quad nations. [*Policy* & *Commercialization Related*]
3. Host Quad quantum sensing showcases where technology developers, end-users, and investors can interact to increase interactions in a highly fragmented market. [*Commercialization Related*, *May require small funding*]

On behalf of the QUIN, I am grateful and extend my sincere thanks to our four co-chairs, the Task Force leads and members, as well as all stakeholders for their dedication, expertise, and hard work in advancing their shared mission. Through their collective efforts, the QUIN has progressed and laid the foundation for continued success in the future.

Thank You,

Karl Mehta
Chairman Emeritus,
Quad Investors Network (QUIN)

QUAD INVESTORS NETWORK

Quantum Ecosystem & Workforce Development Task Force Report

Key Members: TF Lead: Cathy Foley[8]
TF Members: Apoorva Patel[9], Andrew Dzurak[10], Anirban Pathak[11], Charlie Burnard[12], Hiroaki Tezuka[13], Kate Weber[14], Lincoln Carr[15], Reena Dayal[16]
QUIN Members: Mohammad Aamir Sohail[17]

Executive Summary

The Quantum Ecosystem & Workforce Development Task Force has analyzed the need to build robust quantum ecosystems across Quad nations. To this end, the task force has identified several key themes, with this report focusing on Theme 1: Skills, Training, and Workforce as a foundational step. The findings reveal a substantial gap between the high demand for skilled quantum professionals and the current availability of industry-ready talent. Despite significant investments and initiatives by each Quad nation to advance quantum research and development, challenges remain in developing a diverse and proficient quantum workforce.

The key findings of the report highlight the complexity and multidisciplinary nature of the quantum ecosystem, which encompasses quantum computing, communication, and sensing. This, in turn, requires a wide range of technical and business skills for the development and commercialization of quantum technologies. A critical issue is the mismatch between academic training and industry demands, emphasizing the need to bridge the gap between theoretical knowledge and practical skills. The report identifies several challenges to workforce development, including a shortage of industry-ready talent, the need for business skills, cautious market adoption, export control restrictions, and funding limitations. Addressing these challenges requires a multifaceted approach, including enhanced collaboration between academia and industry, increasing quantum literacy in schools, promoting diversity and inclusion, and inspiring the next generation of quantum professionals.

---

[8] Chief Scientist of Australia
[9] Professor at the Centre for High Energy Physics, IISc., Bangalore
[10] CEO & Founder of Diraq, Scientia Professor in Quantum Engineering at UNSW
[11] Professor at the Jaypee Institute of Information Technology, Noida
[12] Head of Governance at Q-Ctrl
[13] Chair, Global Consortium Alliance Working Group Q-STAR
[14] Head of Governance, Google Quantum AI
[15] Professor of Physics at the Colorado School of Mines
[16] CEO of Quantum Ecosystems and Technology Council of India (QETCI), Hyderabad
[17] QUAD Fellow, Ph.D. candidate at the University of Michigan

Introduction

The Quantum Ecosystem & Workforce Development Task Force has analyzed the need to establish a robust quantum ecosystem across the Quad nations. The term "quantum ecosystem" refers to a network of interconnected public and private organizations, researchers, investors, policymakers, and other stakeholders involved in the development, commercialization, and utilization of quantum technologies [4,12]. This ecosystem encompasses various fields, such as quantum computing, quantum communication, and quantum sensing. As of January 2024, the amount of investment in these segments worldwide was 6.7 billion USD, 1.2 billion USD, and 0.7 billion USD [5], respectively, and the number of start-ups was correspondingly 261, 96, and 48 [5].

The Task Force has outlined several key themes pivotal for developing a thriving quantum ecosystem across Quad nations. These themes are summarized in Table 1. Although the Task Force acknowledges the importance of each theme, this report discusses **Theme 1: Skills, Training, and Workforce** as a first step. The report offers a concise overview of the current situation regarding quantum workforce development in Quad nations. It also highlights the challenges and gaps that need to be addressed in order to build a quantum workforce across Quad nations.

Table 1: Themes of Quantum Ecosystem

Themes	Description
Skills, Training, and Workforce	Fostering a skilled workforce through training initiatives to meet the evolving demands of the quantum industry.
Start-up Culture and Boosting Start-ups	Exploring ways to promote a robust start-up culture and strategies to boost quantum technology start-ups.
Standards, Regulation, and Export Controls	Addressing the intricacies of standards, regulations, and export controls to ensure ethical and secure advancement within the quantum ecosystem.
Support to scale-up Businesses	Recognizing the need for support structures to facilitate the scaling up of quantum businesses in the respective nations.
Creating Demand for Quantum Technologies in different Industry Sectors	Stimulating demand across diverse industry sectors by demonstrating the transformative potential of quantum technologies through R&D initiatives and collaborations.
Access to Supply Chain	Enhancing access to robust and reliable supply chains to facilitate the seamless integration of quantum technologies into existing infrastructures and facilities for local repair support.

Social License, Ethics, Safety, and Inclusion	Upholding ethical standards, ensuring safety protocols, and promoting inclusivity to gather societal acceptance and support for quantum technologies.
Outreach and Education	Engaging in comprehensive outreach and educational efforts to raise awareness, foster understanding, and inspire participation in the development of quantum technologies.
Mid-Technology Readiness Levels	Navigating the challenges associated with mid-TRL technologies to bridge the gap between research and commercialization effectively.
Investment	Catalyzing investment flows into the quantum ecosystem to fuel innovation, drive R&D, and accelerate market adoption.
Public-Private Business Model	Exploring synergistic public-private partnerships to leverage resources, expertise, and networks for mutual benefit and sustainable growth.
IP management and understanding across countries	Developing robust intellectual property management strategies and promoting cross-border cooperation to navigate complex international IP landscapes effectively.

Navigating through the Quantum Workforce Landscape

Quantum Technology is advancing rapidly. For example, in 2019, Google announced that Sycamore, a 53-qubit quantum processor, had achieved quantum supremacy [13]. Quantum supremacy is reached when quantum computers can solve problems exponentially faster than classical computers. In December 2023, IBM unveiled its latest 1,121 superconducting qubit quantum processor, IBM Condor, and a roadmap to develop multichip processors, named the Kookaburra processor, with 4,158 qubits [14,36]. These rapid advancements are enabling organizations across various industries to adopt quantum technology in their businesses and daily operations [1-3]. These include companies like Rolls-Royce, Deloitte, Fujitsu, JP Morgan Chase, BMW, Roche, and BASF. For instance, Rolls-Royce, a prominent giant in the aviation industry, is joining forces with a QT startup, Classiq, and GPU's leader, Nvidia, to use quantum circuits to enhance the design of jet engines. JP Morgan Chase, in collaboration with QC Ware, is harnessing the power of quantum machine learning to train models for *deep hedging*. BMW Group has partnered with Pasqal, a quantum processor manufacturer, to advance metal fabrication and optimize manufacturing operations [15].

A significant hurdle these organizations face is the scarcity of well-trained individuals in quantum technologies (QT) [4]. While there are numerous job opportunities in QT, there is a pressing need for more talent with essential skill sets and specialized training. For example, in 2022, there were approximately 717 active job openings per month across various quantum technology domains worldwide, while the number of graduates with master's degrees skilled in quantum technology was only 450 in the same year [5].

Furthermore, the global market size for quantum technologies is projected to exceed 173 billion USD by 2040 [5]. This growth translates to an exponential increase in jobs in QT over the next two decades, with over 600,000 new positions worldwide expected by 2040 [6]. Quantum stakeholders and companies have already emphasized the challenges in finding individuals with the requisite skills to fill the new roles emerging in the job market [7-8]. Equally crucial is ensuring an adequate supply of skilled professionals to meet the surge in job opportunities over the next twenty years. Therefore, there is a need to address the challenge of quantum workforce development.

Current Context/Situational Assessment

The Quad nations, comprising Australia, India, Japan, and the United States, are at the forefront of advancing quantum technologies. Each nation recognizes the transformative potential of QIST across various sectors and has initiated a national quantum strategy to build a robust regional quantum ecosystem. To boost the development of the quantum industry and unleash new business opportunities with quantum innovation, several academic and industrial consortiums have been established across the Quad nations, including Quantum Australia, the Quantum Ecosystems and Technology Council of India (QETCI), Quantum STrategic industry Alliance for Revolution (QSTAR) in Japan, and Quantum Economic Development Consortium (QED-C) in the US.

Australia:

Australia launched a National Quantum Strategy in 2023, which outlines a vision for the growth of the quantum sector to 2030 and includes the ambition to build the world's first error-corrected quantum computer. This follows over 20 years of public investment, which has provided the foundation for world-leading innovation in quantum computing, communication, and sensing. Over that time, the Australian Government has announced A$1.3 billion in funding for quantum technologies[18]. This Strategy aims to help create a domestic quantum industry valued at A$6 billion and 19,400 jobs by 2045 [20].

Australia's National Quantum Strategy commits to actions that engage with the unique opportunities and challenges that the Australian quantum industry faces. The Strategy focuses on creating a thriving environment for the development and use of quantum technologies; addressing infrastructure needs and supply chain challenges; growing the future quantum workforce; ensuring the development of quantum technologies aligns with national interests; and the growth of a trusted and inclusive quantum ecosystem.
The delivery of initiatives under the Strategy is underway. In April 2024, the Australian Government awarded funding to the University of Sydney to establish Quantum Australia, a national center to serve as a single front door for Australia's quantum industry. The center will represent a consortium connecting over 50 domestic and international partners in

[18] The figure A$1.3billion was calculated from grants.gov.au, tenders.gov.au, and public funding announcements.

research, technology, and industry. In May 2024, the Australian Government opened the first round of the Critical Technologies Challenge Program, providing up to A$36 million to help address challenges of national significance using quantum technologies. Additionally, the Next Generation Quantum Graduates Program funds up to 20 PhD scholarships to attract and train Australia's next generation of quantum technology specialists.

Australia is home to leading research institutions working closely with industry. Australia has four Australian Research Council Centers of Excellence focused solely on quantum technologies, enabling domestic and international collaboration across universities, research institutions, and industry. These Centers of Excellence have produced spinouts such as Diraq, Quintessence Labs, QuantX Labs, Q-CTRL, Quantum Brilliance and Silicon Quantum Computing (SQC). Additionally, the Australian Government and Queensland Government have recently announced a joint A$940 million investment in PsiQuantum to build and operate its world-first utility-scale fault-tolerant quantum computer (FTQC) in Australia. Australia's established research ecosystem and strong talent pipeline attract partnerships between Australia-based quantum hubs and global companies such as Microsoft, IBM, and Google.

India:

The nation launched the National Quantum Mission (NQM) in 2023, a flagship initiative with a public investment of 60 billion INR (~ 750 million USD) from 2023-24 to 2030-31 [9,16-18]. This mission aims to develop a 50-1000 physical qubit quantum processor and algorithms within eight years, establish secure quantum communication networks, and fabricate essential quantum communication components, including superconducting nanowire single-photon detectors, next-gen photonic memory, and atomic magnetometers. Infrastructure development is also a key focus, with significant investments in building quantum labs and research centers, such as DRDO Young Scientist's Laboratory for Quantum Technologies (DYSL-QT) in Pune.

India's academic and research institutions are at the forefront of quantum research and development. Many institutes of national importance have established dedicated quantum centers and labs focusing on various aspects of quantum technology. Notable centers include the Center for Excellence in Quantum Technology (CEQT) at the Indian Institute of Science (IISc) Bangalore and the Center for Quantum Information, Communication, and Computing (CQuICC) Lab at the Indian Institute of Technology (IIT)-Madras. Furthermore, in September 2022, IIT Madras joined the IBM Quantum Network to advance 'Quantum Computing Skill Development and Research' for Indian industries. In partnership with IBM Research India, IIT Madras offers a fundamental course - Introduction to Quantum Computing: Quantum Algorithms and Qiskit.

The active participation of companies has provided a valuable impetus to India's quantum ambitions. Leading Indian corporations, including HCL Technologies, Infosys, and Tata Consultancy Services, are involved in quantum research and collaboration. At the same time, global multinationals like IBM, Capgemini, and Fujitsu have set up quantum research facilities in

India. A thriving startup ecosystem further bolsters the quantum landscape, with 14 startups like QNu Labs, QPiAI, and Quanfluence driving innovation.

Despite the progress, India faces several challenges in developing a robust quantum workforce. There is a notable shortage of skilled personnel in critical areas like experimental optics and atomic physics, which hampers technology and product development. While IISc., IISER-Pune, IIST-Thiruvananthapuram, and IIT-Jodhpur have started master's degrees in QT, there is a need for more programs and also appropriate resources for K-12 education to give early exposure to and generate enthusiasm for quantum science [21].

Japan:

Japan has proactively pursued the development of quantum capabilities, and the total public investment in QIST is around 80 billion Yen (around 700 million USD) [9]. In 2019, Japan initiated the Moonshot Research and Development Program, which aims to address significant global challenges through ambitious goals set for 2050. The Moonshot program is expected to invest around 15-20 billion Yen to achieve its goals of creating a fault-tolerant universal quantum computer by 2050, developing a NISQ computer, and demonstrating quantum error correction by 2030 [23].

Furthermore, in April 2022, the Japanese government formulated a new strategy [24-25], the Vision of Quantum Future Society, to promote society's positive evolution by embedding quantum technology throughout social and economic systems, driving advancements in quantum computing, communication, and sensing. A key element of Japan's strategy includes establishing advanced research centers and fostering international collaboration; for instance, the Okinawa Institute of Science and Technology (OIST) has launched the Center for Quantum Technologies [26]. Additionally, partnerships with institutions like RIKEN and corporations like Fujitsu have led to significant milestones, including the installation of a 64-qubit superconducting quantum computer.

Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) launched the Q-LEAP (Quantum Leap) initiative in 2018 for a period of 10 years to invest in R&D projects in three fields of quantum technology [27]:

- Quantum simulation and computation,
- Quantum sensing,
- Ultrashort pulse lasers.

MEXT Q-LEAP has also set up the Human Resources Development Program [28], which addresses the critical need for skilled quantum professionals. This program is designed to create a robust talent pipeline by integrating quantum education into higher education and specialized training. The initiative includes developing common core programs to provide a systematic understanding of quantum technologies and unique subprograms tailored to the strengths of various educational institutions. These subprograms include:

- F*ostering quantum natives through practical research and development*,
- *Quantum education for future technologies*, and
- *A hands-on program for fostering quantum-based thinkers among emerging engineers in various disciplines*.

By offering these comprehensive educational opportunities, Q-LEAP aims to nurture expert researchers and engineers capable of driving quantum technology advancements in multiple fields, such as information science, materials science, and condensed matter physics.

United States:

The United States has shown a strong dedication to advancing quantum technologies through the National Quantum Initiative (NQI) Act, enacted in 2018. This Act authorizes a significant five-year budget of around 1.2 billion USD [9,16-17,29]. As a part of the NQI, the Government has established five national centers led by the Department of Energy (DoE) national laboratories [30,33]. These include:

- Co-design Center for Quantum Advantage (C^2QA), Brookhaven National Laboratory
- Q-NEXT, Argonne National Laboratory
- Quantum Science Center, Oak Ridge National Laboratory
- Quantum Systems Accelerator, Lawrence Berkeley National Laboratory
- Superconducting Quantum Materials and Systems Center, Fermi National Accelerator Laboratory.

In addition, the National Science Foundation (NSF) funded the following quantum centers:

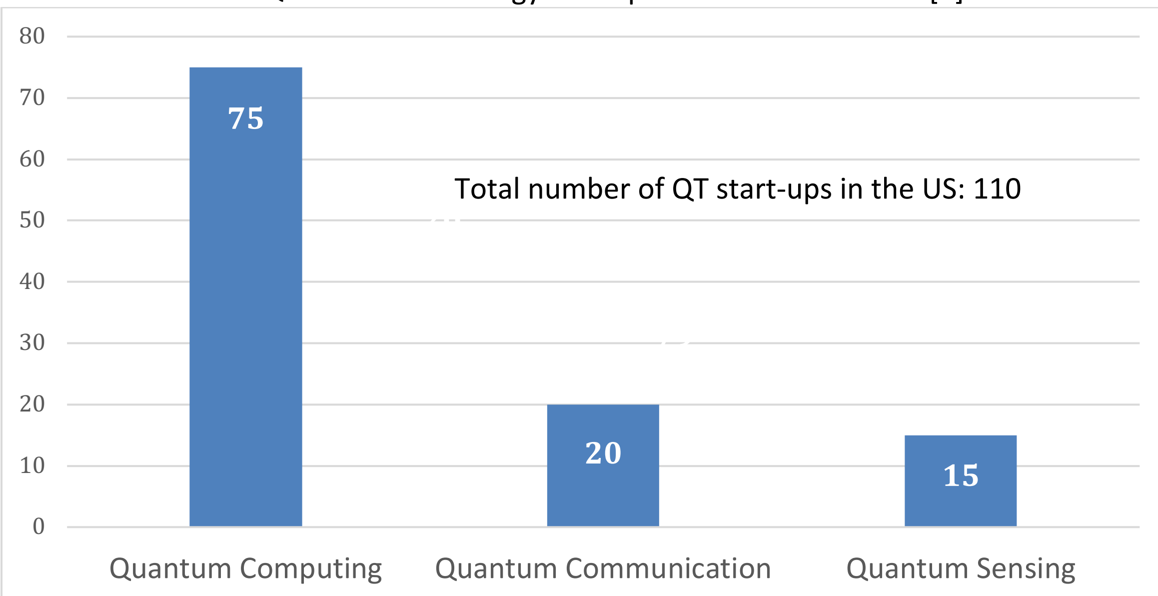
- Hybrid Quantum Architectures and Networks[19]
- Quantum Systems through Entangled Science and Engineering[20]
- Challenge Institute for Quantum Computation[21]
- Institute for Robust Quantum Simulation[22]
- Quantum Sensing for Biophysics and Bioengineering[23]
- Center for Quantum Networks[24]

The US is the leader in the global quantum industry with several prominent large tech companies that are making big bets on quantum computing. Notable examples include IBM, which is actively engaged in research and production of superconducting circuit-based commercial quantum computers. In 2019, Google AI reported, a 53-qubit superconducting quantum processor, while Microsoft has been exploring topological qubits and offers quantum software and access to quantum computers made by others through Azure. The US also claims

[19] https://hqan.illinois.edu/
[20] https://www.colorado.edu/research/qsense/
[21] https://www.ciqc.berkeley.edu/
[22] https://rqs.umd.edu/
[23] https://qubbe.uchicago.edu/
[24] https://cqn-erc.org/

a significant portion of the global QT startups and scaleups, which includes companies like IonQ, Quantum Computing Inc., Rigetti, PsiQuantum, Quantinuum, QuEra, Atom Computing, Infleqtion, Quantum Circuits, Zapata AI, and QC Ware (see Chart 1).

Chart 1: Number of Quantum Technology Startups in the United States [5].



The national strategic overview for QIST highlights the importance of building a quantum-smart workforce for the future. The plan for quantum workforce development emphasizes collaboration between industry and academia, utilizing existing programs while promoting quantum science and engineering as a distinct discipline. It advocates for early integration of quantum education in schools and innovative outreach methods to engage diverse audiences, alongside tracking and forecasting the future workforce needs of the quantum industry [31].

In February 2022, the National Science and Technology Council released the QIST workforce development national strategic plan [32]. The plan emphasizes the importance of understanding the current and future workforce needs within the QIST ecosystem, ensuring the consideration of both short-term and long-term perspectives. Addressing specific gaps in professional education and training opportunities related to QIST is another crucial aspect, ensuring individuals have the necessary skills and knowledge to contribute effectively. Finally, the plan aims to make careers in QIST and associated fields more accessible and equitable, fostering a diverse and inclusive workforce to drive innovation and advancement in this rapidly evolving domain.

Top Challenges Faced by Quad Nations

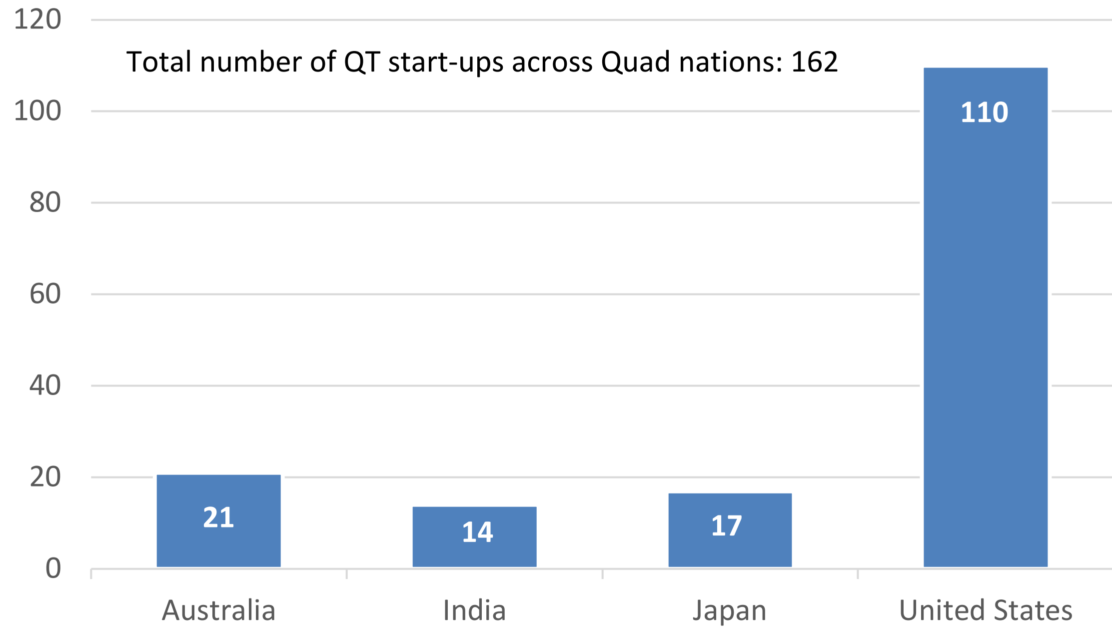
With the emergence of the QIST industry, a new workforce trained in QIST skills and knowledge is inevitable. The conventional approach to building a quantum workforce is introducing concept-focused graduate and undergraduate degree programs. However, this approach is inefficient because of the multidisciplinary nature of quantum technology. For example, the current global hiring is concentrated in quantum computing sectors (42%), followed by companies specialized in quantum hardware (32%) and quantum software (14%). In contrast, it is comparatively low for quantum communication (3%) and quantum sensing (2%) [4]. This non-uniform demand for QT requires universities and governments to gather information on market dynamics, what types of jobs are available in the QT industry, what skills and degrees are most relevant for these new jobs, and how students can tailor their degrees to best align with the current needs of the quantum industry. Navigating these intricacies of building a quantum workforce presents various challenges and opportunities, which are listed here.

1. The primary challenge for building a quantum workforce across Quad nations lies in comprehending the complex technical requirements of the Quad's quantum ecosystem. This encompasses several critical issues:
   - **Technological Breadth**: The ecosystem involves a wide range of technologies within quantum computing, quantum communication, and quantum sensing. This includes everything from the intricate design and manufacturing of quantum hardware, such as quantum processors and photon detectors, to developing sophisticated quantum software and algorithms necessary for practical applications.
   - **Need for Expertise**: Addressing technological challenges requires a substantial number of quantum experts. These specialists must possess deep knowledge of quantum mechanics, quantum information theory, and quantum cryptography, which enables them to push the boundaries of what is possible with quantum technologies.
   - **Skill Diversity**: In addition to quantum-specific knowledge, the ecosystem heavily relies on a variety of supporting skills. These include proficiency in classical computing, materials science, engineering, cybersecurity, data science, sales, marketing, and business development, which are crucial for integrating quantum technologies within existing systems and developing real-world applications.

   Acquiring more comprehensive data on these issues will significantly enhance efforts to develop a robust quantum workforce. These data can allow for the development of educational programs, training initiatives, and policy decisions aimed at fostering the next generation of quantum professionals and ensuring they are equipped to meet the technical demands of this rapidly evolving field.

2. **Training disparities across Quad nations**: There is a notable variation in training approach across the Quad nations, each showcasing distinct needs and priorities influenced by factors like existing infrastructure, educational systems, and industry focus areas [9]. For example, the US boasts a significant portion of quantum technology start-ups within the Quad nations (see Chart 2) and emphasizes training in specific quantum technologies as well as quantum applications. In contrast, India places considerable emphasis on foundational quantum theory and academic research. This creates critical challenges in crafting broadly applicable training programs that cater to the needs of all stakeholders across Quad nations.

Chart 2: Distribution of Quantum Technologies startups across Quad nations.



3. **Lack of industry-ready talent**: A notable gap exists between the theoretical emphasis of academic training and the practical skill sets demanded by industry, for instance, working with cryogenics systems, microwave electronics, and fiber optics [4,10-12,34]. This gap results in a pronounced mismatch in acquiring industry-ready talent and impedes the seamless transition of graduates into the workforce. Analyzing this gap helps align existing training programs or develop training methods with industry needs and address the challenges of transitioning from academia to industry.

4. **Need for softer business skills**: In addition to technical proficiency, the quantum industry emphasizes the need for softer business skills, such as strategic leadership, product development, market analysis, and project management, to navigate the intricate intersections between QT and business dynamics [4,10-12,34]. The lack of a workforce skilled in the depth of quantum information science, along with business skills, creates a gap between research advancements in QT and their commercial applications. As a result, this gap creates uncertainty among industries regarding the practical benefits and commercial viability of quantum technologies. This challenge underscores the imperative for closer collaboration between academia and industry to align training curricula with the applications of quantum technologies and address the challenges of transitioning from research to commercialization.

5. **Market Readiness:** Many industries, for instance, in India and Japan, approach the adoption of quantum technologies cautiously. This cautious approach poses significant challenges to workforce development, especially concerning hiring quantum experts. This caution is due to the need for more clearly defined commercial applications and uncertain market demand, leading companies to hesitate in investing in training and hiring quantum experts.

Consequently, there is a scarcity of opportunities for individuals seeking careers in quantum-specific domains, inhibiting the growth of a proficient workforce.

6. **Export control challenges:** One major concern revolves around general restrictions, particularly those pertaining to the transfer of technology and hardware components. The specialized nature of quantum technology and its dual-use applications subject it to heightened government scrutiny and export regulations. These restrictions present significant hurdles to collaboration in quantum technology and impede seamless knowledge exchange efforts. The impact of export control laws on training programs is particularly noteworthy. For example, students undergoing training in the US may encounter limitations in accessing essential hardware components for both research and commercialization purposes in other Quad nations due to export restrictions. These challenges highlight the imperative for the harmonization of export control regulations. Such harmonization efforts are essential to facilitate international collaboration and ensure equitable access to resources for quantum education and research.

7. **Funding and Resource Constraints:** Limited funding for education and training programs, coupled with a shortage of qualified instructors and infrastructure, makes it difficult to scale up training efforts and meet the growing demand for skilled quantum professionals. These constraints impede the expansion of quantum workforce development initiatives and hinder the ability to cultivate the necessary talent to drive advancements in quantum technology.

8. **Developing a diverse workforce**: Developing a diverse quantum workforce, inclusive of individuals from all backgrounds across Quad nations, is essential for driving the advancement of QT. Embracing diversity not only promotes equity but also harnesses a wide range of perspectives and talents, fostering innovation and creativity within the field. However, achieving this diversity requires efforts to address systemic barriers and biases that may hinder equal representation and cultivating an inclusive environment that respects the contributions of individuals from diverse backgrounds.

In conclusion, meeting the quantum skills needs of today and tomorrow demands a robust talent pipeline spanning schools, universities, vocational training, and industry. It is crucial to ensure that the current non-quantum workforce and students are aware of the diverse and engaging opportunities within the quantum industry. Looking forward, it is required to develop and promote quantum career paths. Moreover, early exposure to quantum education among high-school students motivates them to pursue a career in quantum technologies, which will be essential for long-term quantum workforce development.

References

[1] S. Mugel, C. Kuchkovsky, E. Sanchez, et al., "Dynamic portfolio optimization with real datasets using quantum processors and quantum-inspired tensor networks," Phys. Rev. Research 4, 013006 (2022). [https://link.aps.org/doi/10.1103/PhysRevResearch.4.013006].

[2] S. Yarkoni, F. Neukart, E. M. G. Tagle, et al., “Quantum shuttle: traffic navigation with quantum computing,” arXiv (2020). [https://doi.org/10.48550/arXiv.2006.14162].

[3] M. Mirhosseini, A. Sipahigil, and M. K. . O. Painter, “Superconducting qubit to optical photon transduction,” Nature 588, 599–603 (2020). [https://doi.org/10.1038/s41586-0203038-6].

[4] Kaur M, Venegas-Gomez A., “Defining the quantum workforce landscape: a review of global quantum education initiatives. Optical Engineering”- Aug 2022

[5] McKinsey & Company, Quantum Technology Monitor - April 2024

[6] Venegas-Gomez, Araceli. "The quantum ecosystem and its future workforce: A journey through the funding, the hype, the opportunities, and the risks related to the emerging field of quantum technologies." Photonics Views 17.6 (2020): 34-38.

[7] The New York Times: The Next Tech Talent Shortage: Quantum Computing Researchers’, Oct. 2018.

[8] The Guardian: How can we compete with Google?: the battle to train quantum coders, January 2019.

[9] QUREACA, Overview of Quantum Initiatives Worldwide 2023 https://www.qureca.com/overview-of-quantum-initiatives-worldwide-2023/

[10] Fox MF, Zwickl BM, Lewandowski HJ. Preparing for the quantum revolution: What is the role of higher education? Physical Review Physics Education Research. 2020 Oct 29.

[11] Rosenberg, J.L., Holincheck, N. and Colandene, M., 2024. Science, technology, engineering, and mathematics undergraduates’ knowledge and interest in quantum careers: Barriers and opportunities to building a diverse quantum workforce. Physical Review Physics Education Research, 20(1), p.010138.

[12] Hughes C, Finke D, German DA, Merzbacher C, Vora PM, Lewandowski HJ. Assessing the needs of the quantum industry. IEEE Transactions on Education. 2022 Mar 11;65(4):592-601.

[13] Arute, F., Arya, K., Babbush, R. *et al.* Quantum supremacy using a programmable superconducting processor. *Nature* **574**, 505–510 (2019). https://doi.org/10.1038/s41586-019-1666-5

[14] 10 Companies building Quantum Computers https://www.techtarget.com/searchdatacenter/feature/Companies-building-quantum-computers

[15] 7 Companies using Quantum Computing https://www.iotworldtoday.com/industry/7-companies-using-quantum-computing

[16] State of Quantum Computing: Building a Quantum Economy, Insight Report September 2022 - World Economic Forum

[17] Johnny Kung and Muriam Fancy, A quantum revolution: Report on global policies for quantum technology, CIFAR, April 2021; press search

[18] Department of Science and Technology (DST), India https://dst.zixwer/online/about

[19] National Quantum Strategy, Department of Industry, Science and Resources, Australia

[20] National Quantum Strategy, Department of Industry, Science and Resources, Australian Government, May 2023. https://www.industry.gov.au/publications/national-quantum-strategy

[21] Dr. Philip Nikolayev, Susmit Panda, India’s Quantum Technology Ecosystem: 2022-2023, Aspen Quantum Computing <A|Q|C>, December 2023.

[22] Yamamoto, Yoshihisa, Masahide Sasaki, and Hiroki Takesue. "Quantum information science and technology in Japan." Quantum Science and Technology 4.2 (2019): 020502.

[23] The Moonshot Research and Development Program, Japan. https://www8.cao.go.jp/cstp/english/moonshot/top.html

[24] Touching the Cutting Edge of Quantum Technology in the Homeland of the Superconducting Qubit https://www.japan.go.jp/kizuna/2022/05/cutting_edge_of_quantum_technology.html

[25] Strategy of Quantum Future Industry Development, Secretariat of Science, Technology and Innovation Policy, Cabinet Office Apr 2023. https://www8.cao.go.jp/cstp/english/strategy_r08.pdf

[26] US Quantum Computing Companies About To Win Contracts For Japan's Next Round Of Quantum Installations, The Quantum Insider. https://thequantuminsider.com/2023/10/11/us-quantum-computing-companies-about-to-win-contracts-for-japans-next-round-of-quantum-installations/

[27] MEXT - Quantum Leap Flagship Program (MEXT Q-LEAP) https://www.jst.go.jp/stpp/q-leap/en/index.html

[28] Q-LEAP, Human Resource Development Program https://www.jst.go.jp/stpp/q-leap/en/pdf/e_jinzai.pdf

[29] National Quantum Initiative, the U.S. Government. https://www.quantum.gov/

[30] A Brief Overview of Quantum Computing In The US, The Quantum Insider. https://thequantuminsider.com/2023/04/13/a-brief-overview-of-quantum-computing-in-the-us/

[31] National Quantum Strategic Overview for Quantum Information Science https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

[32] Quantum Information Science and Technology Workforce Development National Strategic Plan https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf

[33] How the Five National Quantum Information Science Research Centers harness the quantum revolution https://news.fnal.gov/2022/08/how-the-five-national-quantum-information-science-research-centers-harness-the-quantum-revolution/

[34] Quantum Industry and Workforce Review, Sydney Quantum Academy (SQA) https://sydneyquantum.org/quantum-industry-workforce-review/

[35] McKinsey & Company, Quantum Technology Monitor - April 2023

[36] Quantum Research, IBM Blog, "The hardware and software for the era of quantum utility is here". https://www.ibm.com/quantum/blog/quantum-roadmap-2033

[37] Quantum Computing Startups in Australia https://tracxn.com/d/explore/quantum-computing-startups-in-australia

Methodology

Chart 1: Quantum technology startups include quantum computing, quantum communication, and quantum sensing. The data for the number of QT startups in the United States is obtained from McKinsey & Company, Quantum Technology Monitor - April 2024.

Chart 2: To obtain the total number of quantum startups across Quad nations, we added the start-ups in quantum computing, quantum communication, and quantum sensing from McKinsey & Company, Quantum Technology Monitor - April 2024 [5] for Japan and the US. For India and Australia, we use references [21] and [37], respectively.

Quantum Computing Task Force Report

Key Members: TF Lead: Hiroaki Aihara[25]
TF Members: Akira Okada[26], Andre Saraiva[27], Avinash Palaniswamy[28], Hanhee Paik[29], Masao Kondo[30], Michelle Simmons[31], Rajamani Vijayaraghavan[32], Sridhar CV[33], Yuichi Nakamura[34]
QUIN Members: Ryoto Sekine[35], Asif Bhatti[36]

Executive Summary

Quantum computers have the potential to solve some of the computationally intractable problems of today, some of which may have a significant socio-economic impact. In recent years, much progress has been seen in their development, and many nations have incorporated quantum computing into their national strategies. While each of the Quad nations is a key player in the global quantum computing landscape, competition is fierce. While recognizing that collaboration between the Quad nations in the development of quantum computing is currently sparse, this Task Force identifies multilateral collaboration between the Quad nations as the key to a free and open Indo-Pacific. To this end, the Task Force identifies priority opportunities for the QUIN to

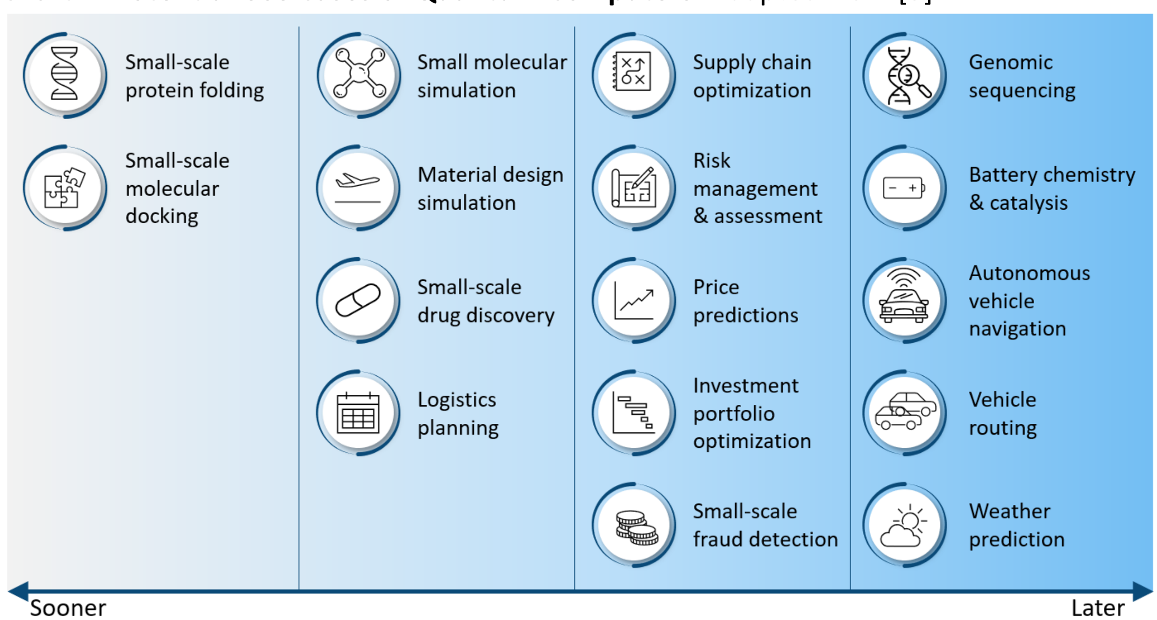
1. Establish shared test-bed facilities operated collectively by the Quad nations, as well as leverage existing testbeds and share best practices to inform future testbeds in the Quad nations. [*Technical Collaboration*, *Requires large funding*]
2. Organize venues for quantum computing companies and start-ups to discuss collective challenges and formalize proposals for addressing regulatory, policy, and business-related issues. [*Policy* & *Commercialization Related*]
3. Hold a Quad-sponsored Quantum Hackathon. Participant groups must consist of at least three of the four Quad countries. [*Technical Collaboration*, *Requires Small Funding*]

25 Executive Vice President of the University of Tokyo
26 Senior Vice President at NTT Science and Core Technology Laboratory Group
27 Head of Solid State Theory at Diraq
28 Chief Commercial Officer at Quantinuum
29 Senior Research Scientist, Quantum Growth and Ecosystem Development, IBM Quantum
30 Senior Director, Quantum Laboratory, Fujitsu Research, Fujitsu Limited
31 Founder and CEO, Silicon Quantum Computing and Director, Centre of Excellence of Quantum Computation and Communication Technology.
32 Associate Professor at the Tata Institute of Fundamental Research (TIFR), Mumbai
33 Head of Alliances, Incubation, Research and Innovation at Tata Consultancy Services, Delhi
34 PhD. Executive Professional, NEC Corp.
35 QUAD Fellow. PhD from Caltech. Director of Technology Development at PINC Technologies Inc.
36 Interim Executive Director, QUIN

Current Context / Situational Assessment

It has been 43 years since Feynman gave his seminal lecture on making a "simulation of Nature" by constructing a machine that leverages quantum mechanical properties [1]. Since then, our understanding of quantum computers has developed, with wide-spread interest skyrocketing upon discovery of quantum algorithms that can efficiently factor large numbers (Shor's algorithm), or search through unstructured databases (Grover's algorithm). This promise has led to an investment influx totaling $5.4 billion and a thriving ecosystem of 223 startups as of December 2022. In that year alone, seven out of ten quantum computing deals surpassed the $100 million threshold, underscoring substantial financial engagement in this field. Looking forward, the quantum computing landscape anticipates growth, with a projected market size ranging from $9 billion to $93 billion by 2040. With the potential use cases in Chart 1, industries ranging from chemicals, life sciences, finance, to automotives could potentially realize economic benefits ranging from $620 billion to $1,270 billion by 2035 [2].

Chart 1: Potential Use Cases of Quantum Computers. Adapted from [3].



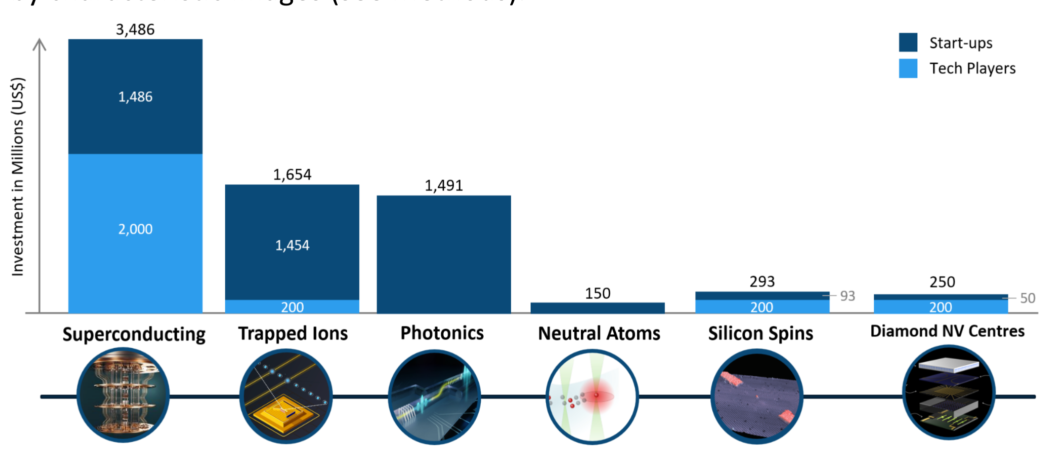
Despite these substantial developments, quantum computers exist in a strong developmental phase. A myriad of hardware platforms are still being explored with no clear long-term winner (see Table 1). While three groups have claimed "quantum computational supremacy" in tackling the problem of Gaussian Boson Sampling (GBS)[37], concrete demonstrations of quantum advantages, specifically those yielding significant economic value, remain absent on today's Noisy Intermediate-Scale Quantum (NISQ) hardware. Although the computational advantage of fault-tolerant QCs has been theoretically proven, technical challenges remain to practically scale and improve qubit quality to realize such machines.

[37] As of this report, Google (USA), the Chinese Academy of Sciences (China), and Xanadu (Canada).

Table 1: Landscape of different qubit platforms. Adapted from [4].

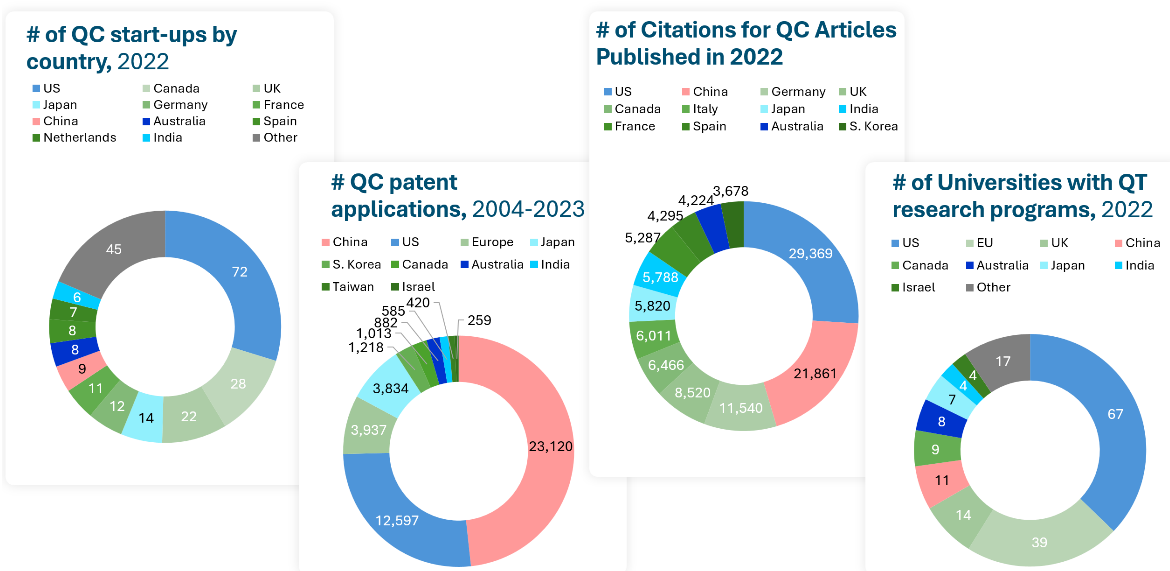
Qubit Type	Description	Companies/Start-ups
Superconducting	Transmon qubits are tiny chips of superconducting metals cooled to near absolute zero temperatures. They can leverage semiconductor fabrication techniques and offer high gate speeds and fidelities.	Google [USA], IBM [USA], Rigetti [USA], IQM [FIN], QuTech [NLD], Quantum Circuits [USA], Fujitsu [JAP], Riken [JAP], NEC [JAP]
Trapped Ions	Trapped ion qubits are atoms suspended in place by lasers in a strong vacuum. They boast long coherence times with high gate fidelities. Cryogenics are not required and the qubits are stable & reproducible.	IonQ [USA], Quantinuum [USA, UK], Oxford ionics [UK], AQT [AUT]
Photonics	Photonic qubits are encoded using optical properties such as the polarization and phase. Photonic QCs offer advantages including high-speed operation and low decoherence rates.	Psi Quantum [USA], Xanadu [CAN], OptQC [JAP]
Neutral Atoms	While similar to trapped ions, these qubits have neutral charge making them harder to isolate. They have the potential for all-to-all connectivity and display long coherence times. Cryogenics are not required and atoms are stable & reproducible	Infleqtion [USA], QuEra [USA], Atom Computing [USA], NanoQT [JAP]
Silicon Spins	Silicon spin qubits are made by confining electrons either by the precision placement of dopant atoms or by patterning nanoscale regions within a silicon wafer. These approaches directly leverage the highly developed silicon materials technology in the CMOS industry and display good gate fidelities and speeds.	Silicon Quantum Computing [AUS], Diraq [AUS], Intel [USA], Hitachi [JAP]
Diamond NV Centres	In this architecture, nuclear spins act as the qubits of the microprocessor, whilst the NV centres act as quantum buses. As they can operate at room temperature, they offer significant SWaP (size, weight, and power) and mobility advantages.	Quantum Brilliance [AUS], SaxonQ [DE], XeedQ [DE], Fujitsu [JAP]

Chart 2: Investment to date in Millions (US$) for different qubit platforms accompanied by characteristic images (see Methods).



While investing with such high risks may be daunting, perhaps some hope can be gleaned from the aforementioned case of GBS. While Google's 2019 feat of demonstrating "quantum supremacy" is often chalked off for having no real-life applications, it would be instructive to note that Google's machine only took a few minutes to solve the problem on a single chip nestled inside a dilution refrigerator. To solve the same problem on a classical computer would require a supercomputer the size of two tennis courts running at least a few days, consuming megawatts of power. As John Preskill, the Richard Feynman Professor of Theoretical Physics at the California Institute of Technology puts it, "Quantum David overpowers Classical Goliath" [4].

Chart 3: Situational Assessment of Quad Nations with respect to key metrics in Quantum Computing (QC) and Quantum Technology (QT). Where appropriate, the Quad nations are highlighted in shades of blue, allied nations in shades of green, and strategic competitors are indicated in shades of red. Countries grouped under "other" are shaded in gray. (see Methods).



A situational assessment of quantum development in the Quad nations shows that each country has its own strengths and different flavors of development toward quantum computing. For example, in the US, quantum development is driven primarily by private investors and corporations. It has a vibrant start-up culture with four out of the top five venture capital/private equity investments of all time in QC start-ups belonging to US companies[38]. Established tech companies such as Google, IBM, AWS, and Microsoft also invest heavily in developing their own quantum hardware. This development is sustained by the US' prominent role in cutting-edge research, ranked the global leader in terms of most impactful publications, as measured by the h-index in 2021 [2].

[38] Specifically, SandboxAQ ($500m in 2022), PsiQuantum ($450m in 2021), IonQ ($350m in 2021), and Rigetti ($345m in 2022) [2]

In Japan, on the other hand, quantum development primarily comes from the public sector ($1.8 billion [2]). Its quantum computing development is not funded by a national military. Boasting the second largest share of quantum patents by country between 2000-22, Japan has set a Moonshot Goal of realizing a fault-tolerant universal quantum computer by 2050. To this end, it is investing in multiple platforms, including optical, ion trap, superconducting, and silicon-based QCs. The fact that Japan has the underlying manufacturing/hardware capabilities to explore all of these directions is perhaps one of its greatest assets.

The funding for Australia's quantum computing programs dates back to 1999, when programs in silicon quantum computing were heavily supported by the Australian Research Council, with initial support from the US military. This strong investment has occurred through the past 25 years of Australian Centre of Excellence schemes, where leading experimental programs in silicon and more theoretical programs in optical quantum computing have now produced a vibrant ecosystem. Australia now ranks 6th in the world in terms of the universities with the most quantum technology programs and is home to eight quantum computing start-up companies.

In terms of quantum hardware, our assessment shows that India has recently started to invest relative to the other three Quad nations. In India, scientific development is primarily driven by the government, and some of the groundwork for quantum infrastructure development began with the Nano Mission (Mission on Nano Science and Technology), launched in May 2007. Hardware development, however, only really started gaining traction roughly ten years ago but is now clearly prioritized by the government, demonstrated, for example, by the recent launch of the *National Quantum Mission* with ~$750 million of funding. India's quantum computing start-ups, therefore, are unsurprisingly software-centric, and this, in fact, hints at India's greatest strength in terms of quantum computing. While all the Quad nations have access to IBM's quantum machines, India outstrips the other nations in terms of the number of Qiskit users. Indeed, India may potentially have the largest number of quantum literate scientists/engineers among the Quad nations.

Table 2: Number of QC Publications of individual or pairs of Quad nations as well as their main strategic competitor (see Methods).

	US	Japan	Australia	India	China
US	53,979	2,497	1,867	1,442	5,738
Japan	2,497	8,404	535	272	1,120
Australia	1,867	535	5,855	435	1,781
India	1,442	272	435	7,771	770
China	5,738	1,120	1,781	770	22,983

of QC publications
>5k
1k-5k
< 1k

In fact, it is clear from Chart 3 that the Quad nations are amongst the highest in the world in terms of quantum literacy and amount of quantum computing talent. However, from Table 2, it is painfully clear that there is very little sharing of this talent and a clear lack of exchange of people, sharing of technologies, resources, and materials. The key to a strong Indo-Pacific, especially in the face of a strong China (whose quantum funding is primarily military-driven), may lie in breaking down these barriers that currently exist between the quantum computing sector of the Quad nations.

Top Challenges Faced by Quad Nations

- **Scientific/Technical Challenges**: The glaring challenge for quantum computers today is that there are no clear winners, and no approaches have yet to reach level 4, as described in Table 3, which would allow for real-life applications of quantum computing. More detailed analyses of how many qubits with what level of connectivity and coherence times are required to tackle meaningful problems can be found elsewhere [6].

  Table 3: Quantum computing hardware platforms according to their level of development towards the universal quantum computer[39]. Adapted from [7]

Maturity	Level 1	Level 2	Level 3	Level 4
Milestone/ Threshold	Platforms demonstrating coherence properties (creating qubits)	Platforms demonstrating a universal gate set (controlling qubits)	Platforms demonstrating quantum error correction and/or error mitigation	Platforms demonstrating level 1-3 properties at scale
Hardware platforms (non-exhaustive)	Charge qubits	Photonics Spin Systems NV centers	Superconducting Qubits Trapped Ions Neutral Atoms	None (yet)

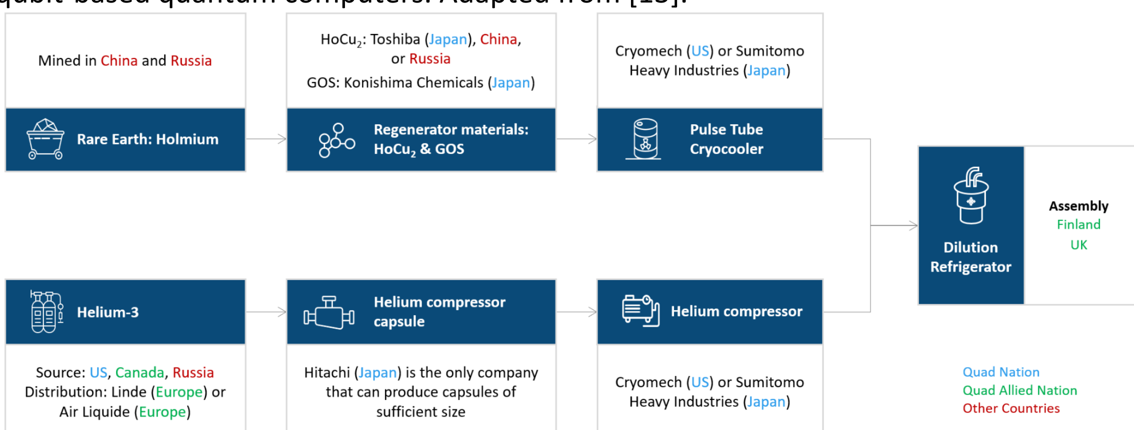
- **Market/Business Challenges:** While the advantage of fault-tolerant quantum computers compared to their classical counterparts has been established for multiple computational problems with significant socio-economic impact, the same cannot be said for the NISQ machines of today. Finding problems that can have sufficient quantum advantages to merit the cost of today's quantum machines is one of the top priorities for continued investment in this field. There are many case studies of companies attempting to answer this question. In 2021 for example, a study by GlaxoSmithKline found that for certain codon optimization tasks to develop recombinant protein therapies, D-wave quantum annealers can outperform classical computers [8]. Fujitsu has used its 8,192-bit digital annealer to partner with large automotive companies to

[39] Note Majorana qubits pursued for example by Microsoft have yet to even reach Level 1 on this chart.

address some of the myriad optimization problems challenging the industry, such as job shop scheduling and robot workflow [9,10]. Similarly, BMW is partnering with Honeywell and Entropica Labs to see if there are any near-term solutions to improving supply chains for automotive manufacturing [11]. Along with these case studies, it is also worth highlighting the myriad workshops and conferences that bring together quantum researchers and customers, academics, and industry researchers to try to address this question, such as the Quantum Annealing Workshop hosted by T. Kadowaki and H. Nishimori (the luminaries who formulated the concept of quantum annealing) at the Tokyo Institute of Technology in 2023[40].

- **Resource/Supply Chain Challenges:** QC supply chains today are still very ad hoc, reactive, and extremely underdeveloped. This reflects the research-oriented nature of the environments in which these systems are presently constructed. For photonic integrated circuit approaches for example, often specialized nonlinear photonic wafers can only be purchased from China, and certain resists used in lithography are only supplied by a single company. An in-depth risk assessment of dilution refrigerators and superconducting qubits has been conducted by the QED-C [13] and shown in Chart 4.

Chart 4: Supply Chain of Dilution Refrigerators, a key component of superconducting qubit-based quantum computers. Adapted from [13].



- **Policy Priorities:** through QUIN's interviews with private sector leaders, it has become clear that if governments truly want the private sector, especially in this area of long-term, high-risk, high-cost R&D, industries require clear government commitment and a clear target of deliverables. The former is also mirrored in the QED-C's independent report, where they surveyed its member companies to find that their first and second highest-ranked policy priorities were to "ensure continued government funding of QC-related R&D" and to "exploit government influence as an early QC customer" [14]. The second, i.e., to have clear goals connected to government priorities that are translated to specific objectives, is a requirement learned from analyzing ten

[40] A more exhaustive list of industry initiatives to find NISQ use cases can be found in [7], [12] and Appendix 1 of [13].

high-profile public-private partnership case studies such as Manufacturing USA and the DARPA Grand Challenge [12].

Priority Opportunities for the QUIN to Overcome Challenges

In this report, the Task Force would like to provide a shortlist of suggestions to overcome some of these challenges. As mentioned in the situational assessment, the Task Force realizes that there is a dearth of collaboration between the Quad nations for quantum computing, which is a direction that the QUIN is directly interested in fostering. In particular, is there a way to foster collaboration in a manner that will also address some of the scientific, market, supply chain, and policy challenges mentioned above? The initiative has the further requirement that it must be mutually beneficial to all the parties involved, be it public or private, or else it will not be sustainable.

With all this in mind, the Task Force suggests that the QUIN

1. *Establish a shared test-bed facility operated collectively by the Quad nations, as well as leverage existing testbeds and share best practices to inform future testbeds in the Quad nations.* [*Technical Collaboration*, *Requires large funding*]

   The idea is that the Quad nations can pool their resources to build this facility[41]. Naturally, most of the hardware and specialized equipment/cleanroom facility knowhow will come from the US, Japan, and Australia, but India has already demonstrated that it has a lot of software-centric researchers who can capitalize on these NISQ machines to attempt to find real-life applications, something that is sorely missing in today's quantum computing efforts. By sending students from their own countries to this facility, the Quad nations can further encourage multilateral collaborations between the new generation of quantum researchers. Furthermore, given the joint nature of this facility, perhaps it will be a good training ground for the Quad nations to pool resources and strengthen supply chain ties. A potential role model for this test-bed facility would be the National Quantum Computing Centre (NQCC). A list of existing or soon-to-be-developed quantum computing testbed facilities is shown in Table 4.

   It should also be noted that amongst the Quad nations, India and Australia do not have a quantum computing testbed facility. The Task Force strongly believes that all four Quad nations having their own test bed facility will not only be beneficial from a technological diversification standpoint, but even more importantly will allow all four countries to speak at the same table and shape global policies.

Table 4: Notable Quantum Testbed Facilities

[41] Noting that there may be limits due to export controls.

Facility	Mission
Advanced Quantum Testbed [Lawrence Berkeley National Lab, USA]	AQT explores and defines the future of superconduting quantum computers end-to-end with a full-stack platform for collaborative research and development. This platform comprises design and fabrication of novel qubits; architecture of quantum processors; cryopackaging and cryogenics; room temperature control chain, including hardware, firmware, and software; optimization tools for quantum circuits; and a suite of tools for quantum characterization, verification, and validation. These are available to users who participate in the platform's development, resulting in a virtuous cycle.
Argonne Quantum Foundry [Argonne National Lab, USA]	Led by Q-NEXT, a DOE National Quantum Information Science Research Center founded in 2020, this foundry will focus on developing scalable semiconductor quantum systems. The foundry will be home to the Intel Solid State Testbed, which supports full-stack integration and development, from quantum-dot qubit chips to systems architecture. Other instruments to be housed at the foundry are new CVD diamond growth tools, environment-controlled annealing furnaces, and tools to create localized quantum defects. It was officially opened in April 2023.
QSCOUT [Sandia National Lab, USA]	The Quantum Scientific Computing Open User Testbed (QSCOUT) is a DOE program funded by the Office of Science's Advanced Scientific Computing Research (ASCR) to build a quantum testbed based on trapped ions that is available to the research community. As an open platform, it will not only provide full specifications and control for the realization of all high- level quantum and classical processes, it will also enable researchers to investigate, alter, and optimize the internals of the testbed and test more advanced implementations of quantum operations.
National Quantum Computing Centre [UK]	The NQCC is the UK's national lab for quantum computing, whose vision is to solve some of the most complex and challenging problems facing society by harnessing the potential of quantum computing. It recently ran a competitive call for a quantum testbed facility which was won by QuEra Computing, the leader in neutral-atom quantum computers. The initial testbed in the UK will use neutral atoms to detect and correct errors inherent to quantum calculations. A key part of this process is qubit shuttling, which enables qubits to move while preserving their quantum state and allows for the entanglement of nearby qubits. Until now, this was a major barrier to achieving scalable, practical quantum computers and ultimately achieving quantum advantage. QuEra expects the facility to be operational in early 2025.
The University of Tokyo – IBM Quantum Hardware Test Center [JAP]	The superconducting testbed installed at the University of Tokyo is a testbed facility that creates a cryogenic environment of 10 milli-Kelvin. The dilution refrigerator system and the cryogenic microwave experimental electronics installed at the Cryogenic Research Center at the same time allow for verification experiments of ideas that will lead to quantum technological innovations in a broader sense. It hopes to become the "hardware dojo" of the University of Tokyo's Quantum Initiative, where new technologies whose principles can be verified can be put to practical use on the Quantum Systems Testbed.
The National Institute of Advanced Industrial Science and Technology (AIST), G-QuAT [JAP]	AIST has established a designated Global Research and Development Center for Business by Quantum-AI Technology (G-QuAT). G-QuAT plans to establish advanced convergence computational technology by utilizing quantum computing technology and classical computing technology, including AI. Furthermore, use case creation of quantum computers is addressed towards social implementation of advanced convergence computational technology. G-QuAT also plans to establish an evaluation method and lead toward its standardization to build resilience in the supply chain of high-performance materials/components. G-QuAT plans to introduce a quantum testbed facility with a myriad of quantum hardware platforms.

	The plan is to make these available worldwide, targeting a partial opening in 2024.

The Task Force recognizes that establishing a Quad centralized test-bed facility would be a lengthy process. Therefore, as a softer initial target it proposes establishing designated Quad quantum computing institutes from each nation and organizing joint research collaborations and student exchange programs between these. This is again motivated by the belief that strengthening ties between the up-coming generation of quantum computing researchers will help to navigate resource supply chains and break down scientific/technical barriers in the future. Sharing of knowhow and quantum curricula can also help in further standardizing and improving the level of quantum literacy for future generations.

2. *Encourage and reinforce mechanisms for collaboration and information sharing between quantum computing companies.* [*Policy* & *Commercialization Related*]

   Drawing parallels with other industries such as semiconductors, the Task Force recognizes that QC companies and start-ups have much to gain from openly discussing their challenges and forming a collective voice on matters pertaining to regulation, policy, business, supply chain, and standardization, amongst others. While there are a plethora of purely academic conferences as well as industry-oriented conferences that host companies, investors, and customers, the Task Force believes that there are still only a limited number of venues for companies to convene amongst themselves.
   Such discussions are taking place today at QED-C, Q-STAR, and perhaps also QETCI and AQA in India and AUS respectively. Perhaps a quad-based group could be formed under the auspices of these organizations.

3. *Advocate for a Quantum Hackathon supported by the Quad. Participant groups must consist of at least three of the four Quad countries.* [*Technical Collaboration*, *Requires Small Funding*]

   Recently, we have seen the emergence of quantum-related competitions, often with the aim of finding real-life applications of existing quantum hardware. Some examples include Fujitsu's quantum simulator challenge [16], the Tata Consultancy Services Quantum Challenge [17], as well as IBM's bi-annual global Quantum Challenge [18]. Especially in the case of Fujitsu's challenge, we think it is worth highlighting that the third place went to the Indian firms, Qkrishi and Bloq Quantum Private Limited. The Task Force wants to follow in the footsteps of these examples but further kick-start inter-Quad collaboration by requiring participant groups to be multinational.

Current News/Additional Resources

- **National Strategies**
  - USA: https://www.quantum.gov/strategy/
  - Japan: https://www8.cao.go.jp/cstp/english/strategy_r08.pdf
  - Australia: https://www.industry.gov.au/publications/national-quantum-strategy
  - India: https://tifac.org.in/images/nmqta/concept_note12.06.19.pdf
- **Topical Grants and Programs**
  - Australia: https://business.gov.au/grants-and-programs/australian-centre-for-quantum-growth
  - India: https://dst.gov.in/call-pre-proposals-setting-t-hubs-launched-under-national-quantum-mission
  - Patent Trends: https://quantumconsortium.org/blog/quantum-patent-trends-update-2022/

References

[1] "Simulating Physics with Computers." Richard Feynman, 1981.

[2] "Quantum Technology Monitor." McKinsey, 2023.

[3] "Unleashing The Business Potential of Quantum Computing." A. Meige, et al. Arthur D. Little, (2022).

[4] "Quantum computing 40 years later." John Preskill, 2021.

[5] "AFF Quantum Viewpoint." Asif Bhatti, Edlyn Levine, 2023.

[6] "Assessing requirements to scale to practical quantum advantage." M. E. Beverland, et al., (2022).

[7] "State of Quantum Computing: Building a Quantum Economy." World Economic Forum (2022).

[8] "mRNA codon optimization with quantum computers." D. Fox, et al., *PlusOne*, 2021.

[9] "Manufacturing gets ready for quantum computing." Fujitsu, 2019.

[10] "Digital Annealer - Quantum Computing Technology, Available Today." Fujitsu.

[11] "How BMW Can Maximize Its Supply Chain Efficiency With Quantum." Honeywell

[12] "Public-Private Partnerships in Quantum Computing." QED-C, 2022.

[13] "Toward a Resilient Quantum Computing Supply Chain." QED-C, 2022.

[14] "Quantum Computing Policy Priorities." QED-C, 2022.

[15] "Patent Landscape for Quantum Computing: A Survey of Patenting Activities for Different Physical Realization Methods."Fangzhou Qiu, 2024.

[16] "Fujitsu announces winners of the Fujitsu quantum simulator challenge." Jan. 25, 2024

[17] "TCS Quantum Challenge 2023."

[18] "IBM Quantum Challenges."

Methodology

Chart 2: Chart adapted from the McKinsey Monitor [2] and company interview. To approximate the tech player investments, their reporting assumed $500 million per major player (Google, IBM, Alibaba, AWS) and $200 million per medium player (Honeywell before the merger with CQC into Quantinuum, Intel, Fujitsu).

Chart 3: For the panel titled "# of Citations for QC Articles Published in 2022," the number of academic journal citations was taken from Web of Science on Feb. 20, 2024, using the Keyword "Quantum Computing" coupled with the appropriate country filters. The numbers for the panel "QC patent applications, 2004-2023" are from ref. [15], whereas the other panels were adapted from [2].

Table 2: Entries indicate the number of Quantum Computing Publications over all time, including the countries listed in the row and column of the table, as of Feb. 20, 2024. The data was collected by using the Keywords of "Quantum Computing" in Web of Science and then extracting the relevant numbers by applying country filters.

Quantum Communications Task Force Report

Key Members: TF Lead: Anil Prabhakar[42]
TF Members: Corey McClelland[43], Katsuyuki Hanai[44], Noel Goddard[45], R.P. Singh[46], Vikram Sharma[47],
QUIN Members: Mohammad Aamir Sohail[48], Aneesh Medhekar[49], Asif Bhatti[50]

Executive Summary

The report of the Quantum Communications Task Force highlights the important progress made and challenges faced in the development of quantum communication technologies across the Quad Nations. As quantum communication technology continues to evolve rapidly, the Task Force has identified cybersecurity vulnerabilities posed by quantum computers as a major concern. To address this issue, the report suggests focusing on Post-Quantum Cryptography (PQC) and Quantum Key Distribution (QKD) as key strategies. However, the landscape is complex and presents various challenges, including technological intricacies, workforce shortages, and regulatory ambiguities. Therefore, it is necessary to make concerted efforts to overcome these hurdles. Moving forward, the Task Force identifies priority for the QUIN to:

- Prioritize collaborative research and development efforts
- Establish standardized protocols for interoperability
- Advocate for policies supporting the unrestricted flow of capital
- Foster partnerships between academia and industry
- Invest in education and training programs
- Ensure sustained multilateral collaboration and strategic investment.

In conclusion, this report underscores the significance of quantum communication technologies in ensuring secure and resilient communication infrastructure. Through continued collaboration and strategic investments, the Quad Nations aim to establish themselves as leaders in quantum communication, safeguarding national security and driving innovation in the digital age.

Current Context / Situational Assessment

The development of quantum technologies is advancing rapidly, potentially revolutionizing fields such as drug discovery and material simulations. Quantum technology encompasses three subfields: quantum computing, quantum communication, and quantum sensing. In 2023, the

[42] Professor of Electrical Engineering at IIT-Madras, Co-founder of Quanfluence
[43] Chief Revenue Officer at Qubitekk
[44] Business Unit Manager - ICT Solutions Division Toshiba, Chair – Subcommittee Q-STAR
[45] CEO of Qunnect
[46] Professor at Physical Research Laboratory (PRL), Ahmedabad
[47] CEO and Founder of QuintessenceLabs
[48] QUAD Fellow, Ph.D. candidate at the University of Michigan
[49] Intern, America's Frontier's Fund
[50] Interim Executive Director QUIN

global quantum computing market was estimated to be worth 858 million USD [11], accompanied by projections of public funding exceeding $42 billion [6]. However, the immense computational power of quantum computers poses a significant cyber security threat to traditional cryptographic systems. A comparison of security levels shows that commonly used asymmetric algorithms, such as RSA, are not secure against quantum computing [2]. Using Shor's algorithm, quantum computers can crack existing classical cryptographic protocols such as RSA at an unprecedented speed, also putting authentication services at risk [25]. Previously, performing this task was impossible due to the slow speed of classical computers.

Within the next two or three decades, quantum computers are predicted to be able to break current public key encryption, which is useful for establishing secure communication over the internet [26]. This places the highest security concern on business organizations. For example, quantum threats would increase the number of data breaches of sensitive personal data, challenging the integrity of digital documents and breaking cryptocurrencies. According to research in 2021-22 by Deloitte, quantum computers could break the encryption of about 25% of bitcoins and 65% of ether coins, which could put more than 40 billion USD of value at risk [12]. As a result, there is an urgent need to find quantum-secure communication systems that can withstand these new quantum attacks.

Quantum communication enables the secure transfer of quantum information across distances, ensuring the security of communication even against the formidable computational power of quantum computers. There are multiple paths to quantum-secure communications that are being developed that offer complementary benefits, including post-quantum cryptography and quantum key distribution, which have gained more popularity and traction due to their advanced level of development and broader implementation.

1. *Post-Quantum Cryptography* (PQC): PQC involves developing cryptographic algorithms, like Lattice-based cryptography (such as CRYSTALS-Kyber and CRYSTALS-Dilithium), hash-based cryptography (such as SPHINCS+), and code-based cryptography (such as Classic McEliece). These PQC algorithms are based on advanced mathematical models that are difficult to solve even for quantum computers. These algorithms are purely mathematical model-based and do not require quantum physical systems [27].

2. *Quantum Key Distribution* (QKD): QKD is a hardware-based quantum encryption method complementary to PQC. It leverages the principles of quantum mechanics to establish a secret key between parties for secure communication. The secret key is later used to encrypt the messages using quantum-secure symmetric key algorithms such as AES256, which then enables secure encrypted communication using the classical internet. Notable protocols include BB84 and E91, and they have been deployed in several commercial and governmental projects globally [28].

Industries are actively developing solutions to resist quantum attacks, and some end-users are migrating to quantum-safe solutions. To sum it up, quantum communications technology is advancing in three key categories: pre-quantum networks, quantum networks, and the quantum internet. Pre-quantum networks are currently in use and enable the secure exchange of secret keys without direct physical contact between two parties using QKD. It also includes quantum random number generators (QRNGs), which are being developed separately by companies such as QuintessenceLabs, QNu Labs, Toshiba, and QRypt. Unlike classical random number generators, which rely on deterministic algorithms and can be predictable, QRNGs leverage the inherent randomness of quantum physics to produce unpredictable (true) secure random numbers and enable quantum-safe cryptographic operations [29].

The implementation of QKD marks a pivotal shift in security, with applications extending to national security, elections, finance, power grid security, and healthcare resilience (see Table 1). QKD is emerging as a leading commercial quantum solution with the support of companies such as BT Group, Northrop Grumman, and Sumitomo. Toshiba, a leading QKD technology Japanese company, anticipates the QKD market will reach a substantial value, estimating it to be worth 20 billion USD worldwide by 2035 [5].

Building upon the foundation of pre-quantum networks, the emergence of quantum networks represents a pivotal leap forward in communication technology, offering enhanced security and unprecedented capabilities. Quantum networks are in early development and allow direct communication between parties through entangled quantum states. The quantum networks not only offer heightened security but also an interconnected device landscape. This includes synchronized atomic clocks for precise timing and sensor networks propelling advances in astronomy, environmental monitoring, and healthcare. Furthermore, in order to scale up quantum computers, a quantum network will be necessary to exchange quantum information between them.

The quantum network market is anticipated to achieve a valuation of $5.5 billion by the year 2025 [3]. The future vision involves the quantum internet, a global network connecting various quantum devices; however, it demands significant hardware improvements, such as quantum repeaters, transducers, and quantum memories that can store quantum information for longer periods of time. It is a visionary infrastructure reshaping global connectivity, which will influence the digital economies, as well as instruments used in astronomical imaging and groundbreaking particle and gravitational physics experiments by enabling the establishment of entangled states over large distances.

Table 1: Emerging Application Areas for Quantum Communications.

	Energy and Gas •Secure Smart Grids •Quantum-secured data transmission
	Healthcare •Protected patient data •Secure telemedicine services
	Finance and Banking •Quantum-Safe Cryptography •Secure transactions
	Space •Resilient deep-space communications •Quantum-secured satellite networks
	Governement and Defense •Integrity verification •Verifiable digital signature

QKD Landscape in Quad Nations

Recently, significant progress has been made in QKD deployment and the building of quantum networks across the globe. Many countries are also working towards satellite-based QKD due to inherent losses over optical fiber, which limits QKD to just a few hundred kilometers. For instance, China's Micius Satellite facilitates communication between a fiber-based QKD backbone (connecting Beijing and Shanghai) and remote areas of China. Satellite-based QKD offers a promising solution for connecting local area quantum networks by leveraging the minimal loss and decoherence experienced in free space.

Quad nations have also demonstrated successful QKD-related missions/programs [4]. In 2010, the Tokyo QKD network was built, and it comprised six optical network links, each developed by NTT, NEC, Mitsubishi Electric, AIT, IDQ, and Toshiba Research [14]. The world's first video conferencing with quantum cryptography was achieved by using this network. Furthermore, Nomura HD, Nomura Securities, NICT, Toshiba, and NEC collaborated on jointly verifying the efficacy and practicality of QKD technology by managing and overseeing the pre-existing Tokyo QKD network. Their aim was to strengthen the security of data communication and storage within the financial sector [15]. In 2013, the Tokyo Free Space Optics (FSO) testbed was constructed, connecting 7.8 km distance. In 2014, Japan's SOCRATES microsatellite was launched, and signal transmission to urban areas was established, which illustrates the viability of QKD in diverse environments. Later, in 2017, the world's first space quantum communication using this microsatellite was successfully demonstrated [16]. It transmits a laser signal to the ground at a rate of 10 Mbits/s from an altitude of 600 km at a speed of 7 km/s. In 2019, Continuous Variable (CV) QKD demonstrated the ability to generate a secure key rate of 27.2 kbps while accommodating 100 classical traffic channels co-propagating on a 10 km fiber with a 7 dB loss level [17]. Subsequently, in 2020, NEC, NICT, and ZenmuTech utilized QKD to encrypt the transmission of electronic medical record samples, successfully backing up the samples via a wide area network [18].

In India, the Indian Space Research Organization (ISRO) has made notable strides in QKD by successfully implementing the inter-building free space single-photon and entanglement-based QKD over a distance of 300 meters within the ISRO's Space Applications Centre (SAC) campus [19]. In 2022, in India, a joint team of experts from the Defense Research and Development Organization (DRDO) and the Indian Institute of Technology (IIT)-Delhi demonstrated a 100 km fiber-based QKD link with key rates up to 10 kbps using commercial-grade underground dark optical fiber [20]. Furthermore, in 2023, researchers at IIT-Delhi achieved a trusted-node-free quantum key distribution (QKD) up to 380 km in standard telecom fiber with a very low quantum bit error rate (QBER) [21]. Moreover, the Center for Development of Telematics (C-DOT) has deployed its fiber-based QKD solution between two government offices (Sanchar Bhawan, Department of Telecommunications and National Informatics Centre (NIC) Headquarters in New Delhi. The traffic between these two offices is encrypted using keys generated by the C-DOT QKD link, and the traffic has been operational since February 2023.

In 2022, an Indian QComm startup, QNu Labs, has successfully generated a pair of symmetric keys using their 150 km single hop - Armos QKD system and the Trusted Relay Node technology, covering a distance of 325 km. The innovation allows for the addition of any number of trusted nodes to the network without any distance barriers, thus extending secure communication to any communication node [22]. In 2023, MAQAN (Metro Area Quantum Access Network), a collaborative effort between IIT Madras, CDAC, SETS, and ERNET, successfully demonstrated India's first quantum network testbed connecting laboratories at IIT-Madras, ERNET, and SETS in a (1x2) star topology [23].

In 2020, the US launched a fiber optic quantum network spanning 26 miles, which interconnected Argonne National Laboratory and Batavia, Illinois, with a recent extension of 35 miles that connected the south side of Chicago to Argonne National Laboratory's quantum network [30]. Australia has increasingly focused on QKDs in recent years. In 2017, Quintessence Labs, an Australian company, received an AUD $3.26 million contract from the Australian Department of Defense to advance its QKD technology. This development marked one of Australia's first government-private sector partnerships within QKD technology, and since then, Australia's National Quantum Strategy has been introduced, with quantum communications being considered an integral vertical.

PQC Landscape in Quad Nations

PQC has emerged as a vital complement to QKD in enhancing the security landscape. Although QKD is theoretically unbreakable, it has some limitations, such as its dependence on high-grade optical fibers and restricted transmission range. On the other hand, PQC is a software-based approach that is ideal for use with handheld devices and offers more flexibility. Members of the Task Force suggest that a combination of QKD and PQC is crucial for future cryptographic frameworks. However, there are still challenges to overcome, particularly in terms of the heavy computing power and significant memory requirements needed for the PQC algorithms.

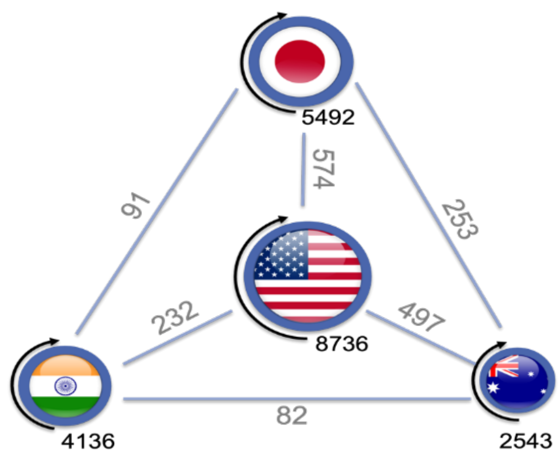
PQC methods have been developed and are currently undergoing standardization for implementation. Since 2016, the National Institute of Standards and Technology (NIST), a public initiative, has been working on developing replacements for encryption methods that are at risk. In 2022, NIST selected four PQC algorithms that the agency will standardize. These algorithms are CRYSTALS-Kyber for general encryption and CRYSTALS-Dilithium, FALCON, and SPHINCS+ for digital signatures. While the standard is still under development, NIST encourages security experts to explore the new algorithms and consider how their applications will use them. However, they should not yet integrate them into their systems, as the algorithms may undergo slight changes before the standard is finalized.

NIST is also collaborating with experts and international regulatory bodies, for instance, the International Organization for Standardization, which is developing its own standards. Many countries are also working on their PQC standards. In India, C-DOT has indigenously developed two PQC products- Quantum-safe IP Encryptor and Video IP Phone, which support PQC key exchange (Crystals Kyber) and signature (Crystals Dilithium) algorithms that have been selected for standardization at NIST. Successful proof-of-concept trials for both the PQC products have been conducted at various government offices/ministries like the Ministry of External Affairs (MEA), Cabinet Secretariat, Department of Telecommunications, etc. The Society for Electronic Transactions and Security (SETS), Chennai, has developed Certifying Authority (CA) software useful for enabling enterprises to leverage Public Key Infrastructure (PKI)-based digital signing primitives. SETS is currently enhancing the current CA solution with support for PQC-based digital signatures as well.

Moreover, to find vulnerabilities, if any, in QKD & PQC solutions developed by C-DOT and address the same, C-DOT came up with C-DOT Quantum Hackathon (CQuHACK 2023) with prize money of INR 1M for each successful break (extract a 256-bit key) for each QKD & PQC system. C-DOT received 4 entries for QKD and 3 entries for PQC. However, the prize money remained unclaimed. Furthermore, the Telecommunication Engineering Centre (TEC), an entity within the Department of Telecommunications of the Government of India, developed comprehensive Generic Requirements (GR) documents for Quantum Key Distribution Systems (TEC GR 91000:2022) in 2022 and Quantum-Safe (PQC) and Classical Cryptographic Systems (TEC GR 91010:2023) in 2023. These documents resulted from extensive consultation with multiple stakeholders and aimed to ensure the deployment of robust QKD & PQC solutions through thorough testing processes. The standard evolution process involved representatives from important academic organizations, start-ups, research and development centers, and industries in India. TEC, in collaboration with C-DOT and the Telecommunications Standards Development Society, India (TSDSI), hosted the International Quantum Communication Conclave (IQCC) in New Delhi in both 2023 and 2024.

QUAD Collaboration: Existing collaboration between Quad nations largely follows a centralized model, with the US acting as a central node. For instance, the number of quantum communication publications between individuals and pairs of Quad countries. As shown in Chart 1, for Australia, India, and Japan, most foreign governments, universities, or companies collaborate with the US.

Chart 1: Number of Quantum Communication Publications between individual and pair of Quad countries.



Top Challenges Faced by Quad Nations

Scientific/Technical Challenges: There are different challenges involved in building a quantum network and implementing quantum encryption protocols such as QKD. It depends on the specific platform used, such as fiber-based QKD or satellite-based QKD. While addressing each challenge separately could be too resource-intensive, this document aims to identify some common challenges across most quantum communication approaches.

1. **Technological Complexity and Infrastructure Development**: The Quad countries currently face a significant challenge in the insufficient availability of infrastructure for seamless integration and widespread adoption of quantum communication. This inadequacy is predominantly due to the intricate nature of hardware components and the demanding performance requirements of quantum communication technologies. Photon detectors, a crucial element in QKD technologies, exemplify these challenges. An

ideal photon detector must exhibit high detection efficiency, i.e., minimizing false negatives and false positives. Additionally, it needs to operate with low dead time and low timing jitter, thus demanding precision in design and implementation.

Another critical component, quantum memories, is a foundational building block for quantum networks. The challenges lie in achieving high memory efficiency, extended storage time, and efficient handling of entangled or single photon sources [8]. These requirements underscore the intricate nature of quantum communication technologies and demand specialized equipment, dedicated R&D laboratories, and sophisticated testing facilities for synthesizing and evaluating these critical building blocks of quantum communication technologies. Prioritizing these requirements for technological advancement is imperative to establish a comprehensive and interconnected infrastructure, thereby unlocking the complete potential of quantum communication technologies across the Quad countries.

2. **Workforce Skills and Training**: A lack of workforce and training has resulted in a critical challenge for quantum communication technologies, which demands a highly skilled workforce to tackle the complexities inherent in developing and sustaining essential hardware components. The interdisciplinary nature of the field, which blends electronics, physics, and mathematics, necessitates a multidisciplinary approach to the development of quantum systems. There are numerous job opportunities in quantum communication technologies, but there is a need for required skill sets and tailored training. This problem is primarily due to limited resources available for undergraduates and graduate students in quantum communication. This deficiency is exacerbated by the limited visibility of career options in the quantum field, as people are often unaware of the skills required. The mystique surrounding quantum theory further contributes to a hesitancy or unease in engaging with this transformative field. A few research institutes and universities offer quantum communication courses. For example, the University of South Australia, in collaboration with Arqit, is offering Ph.D. projects focusing on QKD in defense, space, and cyber technologies. In December of 2023, the Next Generation Quantum Graduates Program was announced, where Ph.D. students from 11 Australian universities will engage in projects aimed at enhancing Australia's larger quantum industry and enhancing quantum communications and cryptography as a focal point [31]. Further, a few research institutes and universities with quantum communication technologies-related courses and programs are mentioned in Table 2.

Table 2: Quantum Communication Research Centers across Quad nations.

Research Centers/Groups	University	Country
Quantum Computation and Communication Technology (CQC2T)	University of Melbourne	Australia
ARC Center of Excellence for Quantum Computation and Communication Technology	Royal Melbourne Institute of Technology (RMIT) University	Australia
Center for Quantum Information, Communication, and Computing	Indian Institute of Technology (IIT)-Madras	India
Initiative on Quantum Technologies (IQT)	Indian Institute of Science (IISc.), Bangalore	India
Quantum Science and Technology Program	Physics Research Laboratory (PRL), Ahmedabad	India
Quantum Communication Lab	Center for Development of Telematics (C-DOT)	India
Quantum ICT Laboratory	National Institute of Communication and Information Technology	Japan
OIST Center for Quantum Technologies (OCQT)	Okinawa Institute of Science and Technology (OIST)	Japan
Quantum Science, Networking, and Communications	University of Chicago	United States
Center for Quantum Networks (CQN)	University of Arizona	United States

3. **Quantum Technology Translation**: R&D areas often focus insufficiently on industrial applications, leading to the suboptimal translation of quantum communication technologies. This challenge is exacerbated by a notable gap between university research and practical industrial implementations. While university labs primarily concentrate on education, a crucial deficit exists in the specialized training related to key technologies like fiber optics, cryogenics, and microwave electronics, which are integral to advancing quantum communication technology. Consequently, industries encounter obstacles due to a shortage of engineers capable of fabricating and testing these novel technologies.

   Research shows that almost 33% of companies strongly demand hands-on experience with new laboratory technologies, such as aligning magneto-optical traps (MOTs) or laser systems. Furthermore, over 50% of companies reported a desire for on-demand short courses tailored to specific technologies, such as a month-long optical metrology course [9]. Hence, achieving a smoother transition of quantum communication technologies from R&D to commercial utilization necessitates fostering collaboration between industry and academia. This partnership is essential for training engineers and researchers in skills that directly align with the current needs of the quantum communication industry.

Market/Business Challenges: Quad nations have encountered challenges rooted in market dynamics, competition, and evolving consumer behavior. The landscape demands a nuanced understanding of business models to effectively integrate quantum communication technologies.

1. **Timelines and Costs of Quantum Communications Technologies Development**: Estimates for the timeline and costs of developing quantum communications technologies remain highly uncertain. Over the next decade, prototype technology development, including city-sized quantum networks, is anticipated to cost from $50 to $100 million, with possibilities of extending systems beyond a 100-mile radius within a decade. The maturation of foundational quantum technologies like transducers, quantum repeaters, and quantum memories, as well as space-based entanglement distribution systems, could start in the next five years. However, the timeline for commercial viability is uncertain. Developing a quantum internet is projected to span decades and cost at least $1 billion, with varying expert opinions on the timeline, ranging from 10 to 15 years for demonstrations of immature technologies [1].
2. **A slower rate of Quantum Communication Startups**: It is observed that the creation of quantum communication startups is slower when compared to quantum computing startups. The factors contributing to this trend include a less prominent investment landscape, the need for extensive infrastructure development, limited market understanding, and the necessity for global collaboration. As of 2022, there are 100 quantum communication startups, with only 27 of them being in Quad nations - the United States (20), Japan (2), Australia (2), and India (2). This number is significantly

smaller when compared to the 107 quantum computing startups across Quad nations in the same year [6].

3. **Funding and Resource Allocation**: Quantum communication technologies demand large-scale infrastructure development, such as upgraded satellites and optical networks. Thus, securing adequate funding and effectively allocating resources is paramount for driving R&D projects forward. Moreover, the advent of the quantum internet or quantum networks requires entirely new infrastructure to transmit quantum information over long distances; existing fiber networks and hardware are insufficient for its operation [1]. For instance, to establish a functional quantum network, tens of thousands of quantum repeaters will be required. However, building end-to-end hardware and quantum repeaters for a quantum network is no small task; rather, it will require large-scale national infrastructure projects. These projects will involve intricate collaborations among multiple vendors, research institutions, and governmental bodies, adding layers of complexity to the management of resources and partnerships. Additionally, the interdisciplinary nature of quantum communication research compounds the challenge, as it requires a diverse set of expertise, spanning from quantum physicists to optical/photonics engineers.

Resource/Supply Chain Challenges: One of the major significant challenges in developing and deploying quantum communication technologies is the scarcity of resources. Acquiring advanced technologies and materials essential for constructing quantum devices is a significant hurdle. These devices rely on specialized components that require exotic raw materials, some of which have limited global sources. For example, the production of high-quality periodically poled nonlinear crystals, such as KTP and LiNbO3, or quantum dots to build photon sources, is a complex and costly process. These high-end materials are only produced in a few technologically advanced countries, such as China [13]. Moreover, crucial components like superconducting nanowire single-photon detectors are produced in a few countries, such as Germany, Japan, North America, and Russia [13].

The supply chain of these components faces several interconnected challenges that can potentially disrupt its stability and evolution. One major concern is the presence of general restrictions, where the specialized nature of quantum technology and its dual-use applications subject it to heightened government scrutiny and regulation, hindering the flow of materials and technology. In response to these concerns, regulatory measures have been enacted, including export controls by both the United States and China on cryptography technologies. The United States, for instance, implemented regulatory actions aimed at curbing the proliferation of dual-use quantum technology applications. In November 2021, eight Chinese quantum technology firms were included in the Department of Commerce’s Entity List, imposing restrictions on American companies from supplying these entities without prior approval. Similarly, China introduced its Export Control Law in 2020, imposing limitations on the export of quantum technology, particularly for cryptography applications [13].

Additionally, the diverse technological paradigms and complexities within quantum communication necessitate specific components, materials, and expertise, adding layers of complexity to the supply chain. This complexity is exacerbated by potential disruptions, including limited access to key raw materials, manufacturing equipment, and technical expertise, as highlighted by commercial entities in the sector. Moreover, the rapid evolution of quantum technology introduces long-term stability challenges, as supply chains must continually adapt to market shifts and technological advancements. This dynamic environment underscores the need for strategic collaboration and innovation to address supply chain vulnerabilities and ensure the resilience of quantum communication infrastructure.

Regulatory Challenges: Navigating legal and regulatory obstacles is complex. It requires a delicate balance to ensure compliance with established regulations while propelling quantum communication initiatives forward.

1. *Information sharing*. As organizations adopt QKD/PQC, such as those in law enforcement and national security, they may hesitate to share information with those who have not transitioned to quantum communication technologies.
2. *Interoperability and Standardization*: Creating a Testing and Certification facility for interoperability requires standardized protocols, and achieving consensus on these in the quantum communication community can be challenging.
3. *Policy and Regulatory Frameworks*: Integrating quantum security into the national security strategy requires the development of robust policy frameworks and regulatory guidelines, which may be complex.

Priority Opportunities for the QUIN to Overcome Challenges

The Quantum Communications Task Force proposes several solutions to address the challenges faced by the Quad nations in quantum communication, with a focus on leveraging the Quad Investors Network (QUIN) effectively. Unlike a traditional think tank or investor entity, the QUIN serves as a network connecting investors, industry players, and innovators across the Quad nations. It plays a pivotal role in attracting more investors and engaging C-suite executives from leading and emerging industries. While the QUIN doesn't directly shape government policy, its collaborative platform facilitates the exchange of knowledge and insights that can inform government decisions.

Given this context, the Quantum Communications Task Force advocates for the following strategies to tackle the aforementioned challenges:

Recommendations	Implementation Needs	Potential Leaders
Transfer of Technologies Critical for Quantum Communication	▪ Establishing guidelines for "Quad Sovereignty" in technology collaboration. ▪ Facilitating technology transfer of controlled quantum communication technologies.	This necessitates coordinated efforts from regulatory bodies and governments of Quad nations to draft and agree upon policies ensuring secure and regulated transfer of quantum communication technologies. The role of the QUIN here will be to facilitate collaboration between stakeholders.
Public-Private Business Model	▪ Initiating pilot phases with government funding followed by private capital for scale and growth. ▪ Attracting private capital funds through proof of concept. ▪ Safeguard private investment into startups	Governments to allocate initial funding to kickstart pilot projects. Moreover, private sector companies to fund quantum communications startups and prototype. QUIN can facilitate partnerships between government-funded pilot projects and private investors to attract capital for scale and growth.
Free Flow of Capital	▪ Advocating policies supporting the unrestricted flow of capital for quantum communication initiatives. ▪ Strengthening the financial backbone of quantum communication technologies R&D.	A government can frame investment-friendly policies to create an environment conducive to investment in quantum communication technologies. Additionally, initiatives to attract private investment and financial institutions. QUIN can leverage its network of investment firms and industry associations to advocate and facilitate investment in quantum communication projects.

Reciprocity of Secure Partner Qualifications	▪ Defining standards for secure partner qualifications across Quad Nations (whitelisting). • Ensuring reciprocal recognition for a unified approach.	Government agencies and regulatory bodies should collaborate to establish consensus-driven common standards and qualifications for secure partners. This collaborative effort aims to ensure mutual trust and consistency in approaches to quantum communication security.
Manpower Training and Qualification Programs	▪ Development and implementation of training programs to enhance manpower skills in quantum communication across geographies.	Educational institutions, industry associations, and government agencies By leveraging its network, QUIN can facilitate the development and implementation of comprehensive training programs by securing funding support and engaging industry stakeholders.

Suggested Multilateral Collaborations

Optical Ground Stations for Satellite QKD:
- Collaborative development of optical ground stations to develop satellite-based QKD for fortified secure quantum communication channels.

Quantum Communication Test Bed:
- Pooling resources from each Quad nation to establish sophisticated quantum communication test beds that support both trusted and untrusted nodes in the QKD network.

Next-Generation Telecommunication Fibers for Quantum Communication:
- Multilateral cooperation in research and development of next-generation telecommunication fibers optimized for quantum communication, focusing on low-loss and multi-core technologies.

Materials for lasers, detectors, and nonlinear optics:
- Establishment of collaborative research projects and initiatives focusing on materials science for lasers, detectors, and nonlinear optics to address common challenges and accelerate progress in the field.

Post-Quantum Cryptography (PQC) - Crypto Agility:
- Joint efforts in the development of standards for crypto agility in PQC, strengthening the resilience of cryptographic systems through collaborative research.

References

[1] Government Accountability Office. (2021, October 19). GAO-22-104422, Quantum Computing and Communications: Status and Prospects. Government Accountability Office. Retrieved December 14, 2023, from https://www.gao.gov/assets/gao-22-104422.pdf

[2] Mavroeidis, V., Vishi, K., Zych, M. D., & Jøsang, A. (2018). The impact of quantum computing on present cryptography. International Journal of Advanced Computer Science and Applications, 9(3) doi:https://doi.org/10.14569/IJACSA.2018.090354

[3] Accenture Research, Untangling the future of quantum communications, https://www.accenture.com/content/dam/accenture/final/a-com-migration/r3-3/pdf/pdf-167/accenture-future-quantum-communications.pdf

[4] Stanley, M., Y. Gui, D. Unnikrishnan, S. R. G. Hall, and I. Fatadin. "Recent Progress in Quantum Key Distribution Network Deployments and Standards." In Journal of Physics: Conference Series, vol. 2416, no. 1, p. 012001. IOP Publishing, 2022

[5] Toshiba Launches Systems Aimed At $20 Billion Quantum Key Distribution Market

https://thequantuminsider.com/2020/10/19/toshiba-launches-systems-aimed-at-20-billion-quantum-key-distribution-market/

[6] McKinsey & Company, Quantum Technology Monitor - April 2024

[7] Report on First International Quantum Communication Conclave, New Delhi, India https://www.tec.gov.in/pdf/6GT/IQCC_Report_Released_by_Hon'ble_MoS.pdf

[8] OSA Industry Development Associates (OIDA) Quantum Photonics Roadmap, (2020).

[9] Fox, M. F., Zwickl, B. M., & Lewandowski, H. J. (2020). Preparing for the quantum revolution: What is the role of higher education? Physical Review Physics Education Research, 16(2), 020131.

[10] Overview on quantum initiatives worldwide – update mid-2021", Qureca, 19 July 2021, https://qureca.com/overview-on-quantum-initiatives-worldwide-update-mid-2021/.

[11] 4th Annual QC Global Market Forecast https://quantumconsortium.org/4th-annual-qc-global-market-forecast/

[12] Transitioning to a Quantum-Secure Economy, World Economic Forum (In collaboration with Deloitte), September 2022,
https://www3.weforum.org/docs/WEF_Transitioning%20to_a_Quantum_Secure_Economy_2022.pdf

[13] M.Harjani, S. Sharma, Will Quantum Supply Chains Fall Victim to Geopolitics? Institute of Defense and Strategic Studies of the S. Rajaratnam School of International Studies, NTU. https://www.rsis.edu.sg/wp-content/uploads/2022/08/IP22045-Harjani-Sharma-masthead-final.pdf

[14] M. Sasaki, "Field test of quantum key distribution in the Tokyo QKD Network", Optics express, 10387, vol. 19, 2010. https://opg.optica.org/oe/fulltext.cfm?uri=oe-19-11-10387&id=213840

[15] NICT press release, "Beginning Joint Verification Tests on quantum cryptography technology to enhance cybersecurity in the financial sector", 2021, https://www.nict.go.jp/en/press/2021/01/18-1.html

[16] Quantum ICT Collaboration Center, National Institute of Information and Communications Technology (NICT). https://www2.nict.go.jp/qictcc/en/about/result.html

[17] "Wavelength division multiplexing of continuous-variable quantum key distribution and 18.3Tbit/s data channels", Communications Physics, Vol. 2, 9, 2019,

[18] "Recent progress in quantum key distribution network deployments and standards," Stanley, M and Gui, Y and Unnikrishnan, D and Hall, SRG and Fatadin, IOP Publishing, 2022.

[19] Report on first international quantum communication conclave, Vigyan Bhawan, New Delhi. 2023. https://www.tec.gov.in/pdf/6GT/IQCC_Report_Released_by_Hon'ble_MoS.pdf

[20] Ministry of Defense Government of India, "DRDO and IIT Delhi scientists demonstrate Quantum Key Distribution between two cities 100 km" https://pib.gov.in/PressReleasePage.aspx?PRID=1800648

[21] Researchers at IIT Delhi Achieve Trusted-node-free Secure Quantum Communication for 380 km in Standard Telecom Fiber https://home.iitd.ac.in/show.php?id=193&in_sections=Press

[22] QNu Labs breaks the distance barrier in Quantum Key Distribution (QKD) technology, develops commercially ready new variant of Armos QKD system (News) https://www.smartstateindia.com/qnu-labs-breaks-the-distance-barrier-in-quantum-key-distribution-qkd-technology-develops-commercially-ready-new-variant-of-armos-qkd-system/

[23] Building a Metro Areas Quantum Access Network (MAQAN)

https://tec.gov.in/pdf/QC/Prof.%20Anil%20Prabhakar_2_6.pdf

[24] NIST Announces First Four Quantum-Resistant Cryptographic Algorithms https://www.nist.gov/news-events/news/2022/07/nist-announces-first-four-quantum-resistant-cryptographic-algorithms

[25] Albuainain, Aminah, et al. "Experimental Implementation of Shor's Quantum Algorithm to Break RSA." 2022 14th International Conference on Computational Intelligence and Communication Networks (CICN). IEEE, 2022.

[26] How a quantum computer could break 2048-bit RSA encryption in 8 hours https://www.technologyreview.com/2019/05/30/65724/how-a-quantum-computer-could-break-2048-bit-rsa-encryption-in-8-hours/

[27] Post-Quantum Cryptography, Wikipedia https://www.wikiwand.com/en/Post-quantum_cryptography

[28] Quantum Key Distribution, Wikipedia https://www.wikiwand.com/en/Quantum_key_distribution

[29] Mannalatha, Vaisakh, Sandeep Mishra, and Anirban Pathak. "A comprehensive review of quantum random number generators: Concepts, classification and the origin of randomness." Quantum Information Processing 22.12 (2023): 439.

[30] Universities Collaborate on Chicago's Quantum Network https://www.govtech.com/education/higher-ed/universities-collaborate-on-chicagos-quantum-network

[31] Towards Practical & Resilient Satellite-Based QKD For Space Networks: The University Of South Australia Offers An Exciting Opportunity To Apply For A Project-Based Ph.D. In Partnership With Arqit https://thequantuminsider.com/2022/10/11/towards-practical-resilient-satellite-based-qkd-for-space-networks-the-university-of-south-australia-offers-an-exciting-opportunity-to-apply-for-a-project-based-ph-d-in-partnership-with-arqit/

Methodology

Chart 1: Quantum communication publications by country for all time. The data was collected using the keyword "Quantum Communication" in the Web of Science, and the relevant numbers were extracted by applying country filters.

Quantum Sensing Task Force Report

Key Members: TF Leads: Celia Merzbacher[51], Nardo Manaloto[52]
TF Members: Dana Anderson[53], Kyle Hardman[54], Mark Luo[55], Ron Walsworth[56], Santu Sardar[57], Sendhil Raja S.[58], Takeshi Ohshima[59]
Invited Experts: Neil Wester[60], Sarah Sharp[61]
QUIN Members: Ryoto Sekine[62], Aneesh Medhekar[63], Asif Bhatti[64]

Executive Summary

Compared to quantum computing and communication, quantum sensing promises more near-term technological maturity. Despite this, the road to commercialization requires significant investment, policy changes, and scientific discovery. Specifically, the Task Force has identified that increased education of policymakers, investors, and researchers is critical, as well as developing mechanisms to efficiently de-risk investments. Given the many physical platforms for quantum sensing and their complex and dynamic supply chains, a united Quad can explore many more avenues than any one of them on their own. To this end Task Force presents priority opportunities for the QUIN to

1. Urge the Quad governments to resolve policy decisions on quantum technologies resulting from any joint Quad effort. Without high-level intervention on items including intellectual property, export controls and regulations, and national security concerns, the current landscape of highly regionalized investment and development will not change. [*Policy Related*]
2. Instigate a thorough study of the quantum sensing capabilities of each of the Quad nations. [*Policy* & *Commercialization Related*]
3. Host quantum sensing showcases where technology developers, end-users, and investors can interact, to increase interactions in a highly fragmented market. [*Commercialization Related*, *May require small funding*]

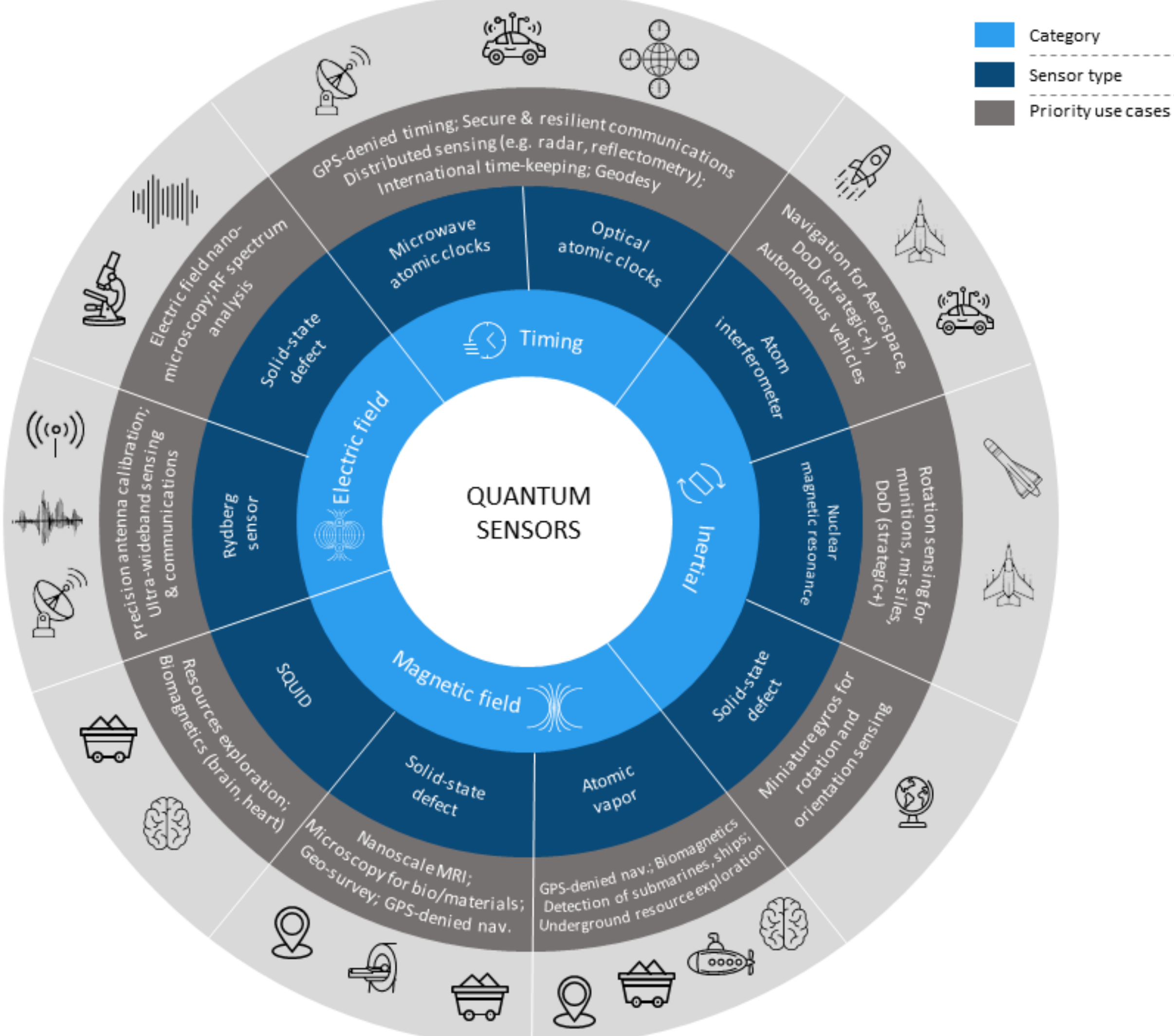
---

[51] Executive Director Quantum Economic Development Consortium
[52] Managing Partner, Qubits Ventures
[53] Founder and CSO of Infleqtion, Professor of Physics at UC-Boulder
[54] CEO of Nomad Atomics
[55] CEO of Quantum Brilliance
[56] Professor of Physics University of Maryland, Founding Director of the UMD Quantum Technology Center
[57] Director,DYSL-QT, Pune
[58] Head, Advanced Electro-Optics Systems Section, Raja Ramanna Centre for Advanced Technology, Indore
[59] Director of the Quantum Materials and Applications Research Center (QUARC), National Institutes for Quantum Science and Technology (QST)
[60] Head of Fabrication, Quanum Brilliance
[61] CEO, Frontier Sensing. Now at Quantum Brilliance
[62] QUAD Fellow. PhD from Caltech. Director of Technology Development at PINC Technologies Inc.
[63] Intern, America Fronier's Fund
[64] Interim Executive Director, QUIN

Current Context / Situational Assessment

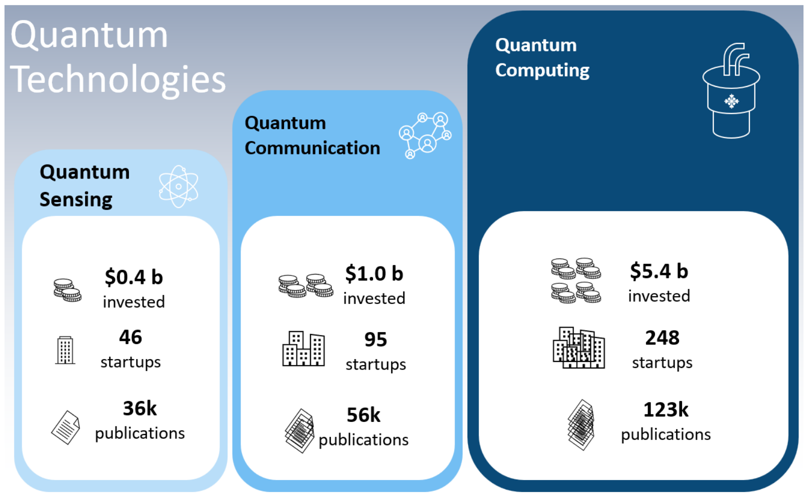
From atomic clocks used in GPS navigation to MRI scanners in hospitals, quantum sensors have already greatly benefited society. With further advancements in our understanding and capabilities with atoms, ions, and photons, we are now seeing a new generation of quantum sensors that take advantage of quantum states of light or matter to measure environmental states more precisely. This new generation of quantum sensors is expected to impact the fields of defense (e.g., GPS-denied navigation), medicine (e.g., enhanced neural activity mapping), and geology (e.g., uncovering new minerals and water resources), a small flavor of which is shown in Chart 1. This impact is demonstrated, for example, by the increased sensitivity to gravitational waves in the Laser Interferometer Gravitational-Wave Observatory (LIGO) mission.

Chart 1: Technologies and Applications Included in Quantum Sensing. This list is not exhaustive. Sensing categories such as temperature, pressure, and acceleration are omitted. Adapted from [3].



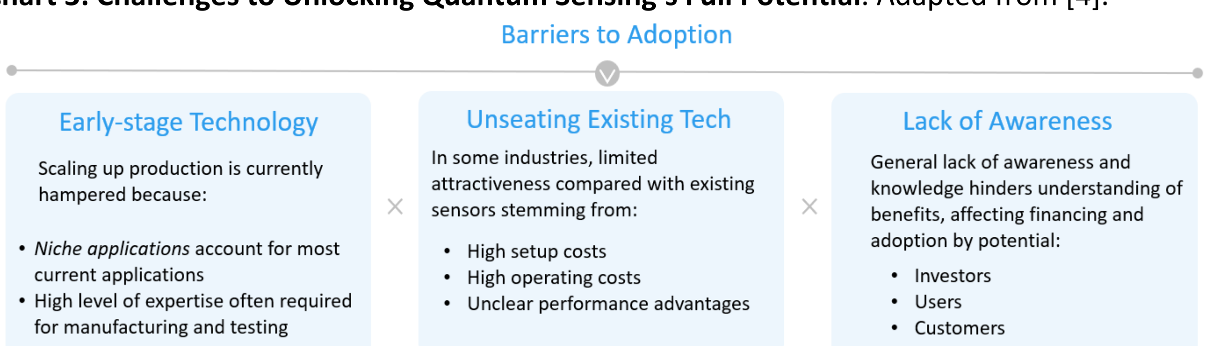
Yet despite being the closest to technological readiness, quantum sensing receives the least investment and academic publications, of the three quantum technology pillars of computing, communication, and sensing, as shown in Chart 2. Specifically, as of Dec. 2022, the amount of investment in these fields was $5.4b, $1.0b, and $0.4b, respectively, and the number of start-ups was correspondingly 248, 95, and 46 [1].

Chart 2: Levels of investment activity in main areas of quantum application. (See Methods).



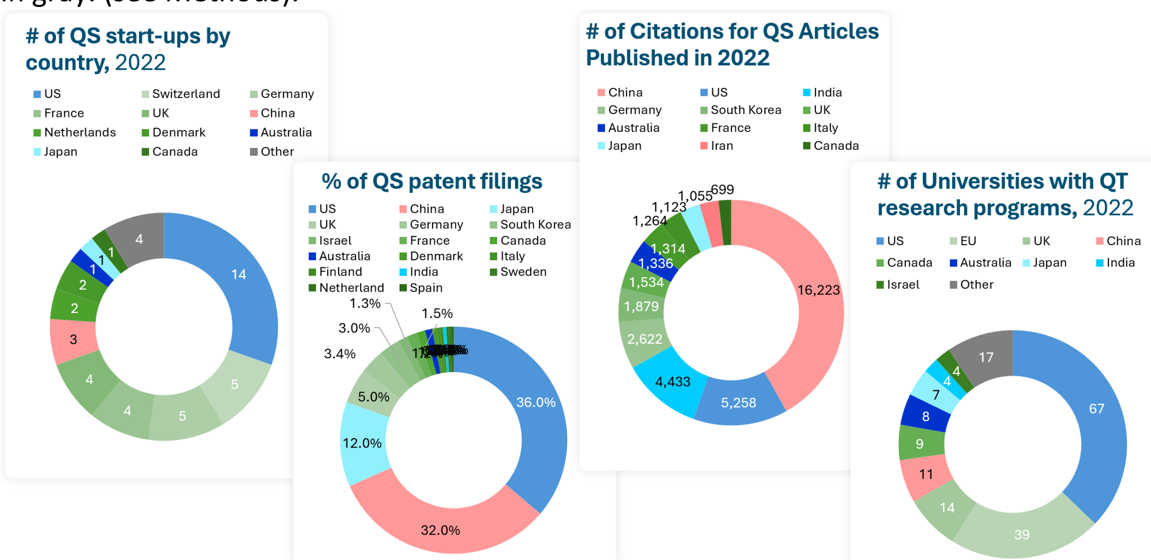
There are a few reasons for this discrepancy, as detailed in Chart 3. For one, as illustrated in Chart 1, there are many different quantum sensing platforms, and each is expected to be better suited for a different market. As a result, the quantum sensing market is highly fragmented. Second, the advantage of quantum sensors over existing classical systems is nuanced and is sometimes not clear-cut. Significantly more education of investors and exposure of developers to end users to determine the best applications are critical. Another barrier to adoption and financing is that many of these platforms require new material platforms and complex manufacturing processes.

Chart 3: Challenges to Unlocking Quantum Sensing's Full Potential. Adapted from [4].



The Quad nations are all players on the international stage of quantum technology but with different strengths and research ecosystems. In the United States quantum sensing technology is driven by both private and public investment. As shown in Chart 4, on the private side these include tech giants such as Microsoft. On the public side the NQI (National Quantum Initiative) and DoD (Department of Defense) provide significant investment. The US boasts by far the most start-ups (14 as of 2022), 15.4% of patents, and ranks highest in terms of most impactful journal publications (determined by h-index) in this space [1]. It is worthwhile noting however, that the ASPI (Australian Strategic Policy Institute) critical technology tracker shows the US to be tied with China in the fraction of highly cited publications on quantum sensing [9].

Chart 4: Situational Assessment of Quad Nations with respect to key metrics in Quantum Sensing (QS) and Quantum Technology (QT). Where appropriate, the Quad nations are highlighted in shades of blue, allied nations in shades of green, and strategic competitors are indicated in shades of red. Countries grouped under "other" are shaded in gray. (see Methods).



Top 10 Assignees of U.S. QS Patent Applications

Assignee	Microsoft	Equal1 Labs	Honeywell	MIT	NextGen Partners	Boeing	Caltech	Charles Stark Draper Lab.	Qubitekk	Raytheon
# of Patents	83	28	23	19	18	12	12	11	11	11

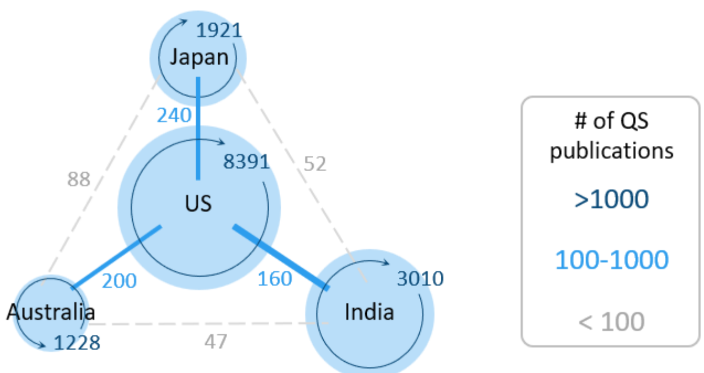
In Japan in contrast, 97% of quantum efforts ($1.9b) are stimulated by public investment. One of the hallmarks of this is run by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). Specifically, one of the branches in their Quantum Leap Flagship Program (MEXT Q-LEAP) is designated to "Quantum Metrology & Sensing" [7]. Corporate initiatives on the other hand, include those such as the Sumitomo-ColdQuanta Partnership and Japan Aviation Electronics Industry [8]. Unlike the US, Japan only has one notable start-up in QS [1]. However, it holds 13.6% of the world's quantum sensing patents (3rd most in the world) [1].

Compared to these two, Australia strikes a more equal balance between private and public investment [2]. While Nomad Atomics is its only sizable start-up dedicated to quantum sensing, Australia is rapidly trying to grow its quantum workforce and now boasts the sixth most universities in the world that offer quantum technology-related research programs [1].

In India development in quantum technologies is primarily driven by the government. In its recent National Quantum Mission ~$750 million has been dedicated over eight years to four quantum verticals, including sensing. While it lacks an environment for quantum sensing start-ups, as can be seen from the first panel in Chart 4, India's scientific publications in QS are widely read and cited, topped only by China and the US. India also boasts 82,110 masters in quantum technology-related fields in 2020, the second highest in the world [1]. However, India's retention rate during the transition from postgraduate studies to employment stands at approximately 70%, which is lower compared to that of most other nations [9]. Despite this, India attained its highest national ranking in quantum sensors compared to other quantum technologies, thanks to the contributions of its researchers in this field.

Existing collaborations between the Quad nations largely follow a hub-and-spoke model, with the US acting as the hub, as shown in Chart 5. In fact, Chart 5 makes clear that there are very few instances of direct collaboration in quantum sensing between Quad nations, excluding the US.

Chart 5: Number of QS Publications between individuals or pairs of Quad countries. (See Methods)



That being said, it should be stressed that continued collaboration and information sharing between the Quad nations with regard to quantum sensing is key to the improvement of their economic well-being and national security. Given the diverse nature of quantum sensing platforms, it is implausible for a single country to remain at the global cutting edge for all of them. The importance of this collaboration is further accentuated when noting that China owns 56.6% of the patents in quantum sensing from 2000-2022 (see Chart 4) and 43.5% of scientific publications in the past five years (up from 37% in the five years prior to that).

Top Challenges Faced by Quad Nations

- **Scientific/Technical Challenges**: While there are, of course, numerous scientific and technological challenges, these are often specific to the particular platform being used for quantum sensing – from NV centers to cold atoms to photonics. While the Task Force believes that facing each one of these challenges would be too resource-intensive – especially when the winning technology is still unclear – it has identified a few key challenges common to most approaches.

    1) **Insufficient support for quantum sensing start-ups to escape the so-called valley of death**. Many government-sponsored pipelines to develop quantum sensing technologies are insufficient to obtain commercialization. The example of the Chip-Scale Atomic Clock (CSAR) program by DARPA initiated in 2001 is a case in point. While a battery-powered portable atomic clock did emerge from the program, the aggressive deadlines set by the DARPA program did not allow for sufficient development of volume manufacturing. As a result, while the unit cost of a CSAC was $1.5k when it was first introduced, it has subsequently risen to $5k with three-month lead times [3]. Most quantum sensing technologies struggle to even reach this level of scale because the infrastructure to produce the new or exacting-spec components they require often do not exist and are costly to set up. The necessary supporting infrastructure is commonly not strictly quantum technology, such as integrated photonic foundries, lasers, vacuum technology, and low-noise electronics, and requires resources difficult to justify in a pure academic laboratory.
    2) **There remains a large gap between quantum sensing developers and potential users.** In fact, this has been flagged as the number one challenge in the reports by both the QED-C and NSTC (National Science & Technology Council) [3, 6]. Most initial drivers of quantum sensing technologies are fundamental research scientists whose mandate is to explore and discover, rather than to produce end products. Oftentimes they have no expertise in the markets their technology would like to penetrate, and as such, they have difficulty comparing their technologies with classical competing technologies and are unaware of the device specs required for field deployment. In fact, the NSTC has noted that the timelines and criteria for promotion, tenure, and publication do not align with that of tech-transfer. On the flip side it should also be noted that for end users quantum sensing technology has a high barrier of entry to understand and assess if it is suitable for their requirements.
    3) **Insufficient de-risking mechanisms for investors**, both private and public. It should also be noted that often it is unclear what the quantum advantage of a technology will be, but the technology requires significant financial and infrastructure investment to answer this question.

- **Resource/Supply Chain Challenges:** Given the heterogeneous approaches for quantum sensors with a large number of non-overlapping components, it is highly impractical that the Quad nations, let alone a single country, attempt to be completely self-sufficient in all areas of quantum sensors. Instead, the Quad governments should determine, based on recommendations from the QCoE Task Force, which key components they wish to maintain production capacity for, either directly or through allied nations. Especially since many small start-ups lack the resources to extensively monitor supply chains and the supply chain landscape rapidly changes as different technologies mature, the Quad governments should continue to maintain entities such as the Quantum Economic Development Consortium (QED-C), which aim to strengthen supply chains to promote robust industry. It might also be beneficial to monitor which key items are dominantly produced in China. A few categories that fit this description are nonlinear crystals for lasers [5] and novel material wafers that play an out-sized role in integrated photonics. In fact, a brief analysis of this kind was performed by the RAND Corporation in 2022 and is shown in Table 1. Note that the table is not intended to be complete. For example, it does not show the components that are available in the US or North America.

Table 1: Quantum Technology Components sourced from Asian and European Suppliers. Adapted from [5].

Quantum Technology Components Sourced from Asian Suppliers

Component	Country (Supplier)
Microcontrollers	Philippines, Taiwan, Malaysia, China
COTS electronics	China
COTS digital-to-analog converters	China
COTS analog-to-digital converters	China
COTS optics and raw materials for optics	China
Nonlinear crystals & wafers	China
Nonlinear Optics	Japan
Mirrors	China
Blue gallium nitride laser diodes	Japan (Nichia)
Cables	Japan (COAX Co.)
200 mm sapphire wafers	Japan (Kyocera)
Electron beam lithography tools	Japan
Distributed Bragg reflector laser diodes	Unnamed Asian Countries

Quantum Technology Components Sourced from European Suppliers

Component	Country (Supplier)
Single-photon detectors	Germany, Italy, France, Sweden
Laser diodes	Germany (Toptica Photonics)
Microcontrollers	Italy, France
Dilution refrigerators	Finland (Bluefors), UK (Oxford Inst.), Netherland (Leiden Cryogenics)
High Electron Mobility Transistor Amplifiers	Sweden (Low Noise Factory)
Optical lithography tools	Netherland (ASML)
Dielectric Glass Windows for vacuum chambers	Germany (Schott)
Fiber phase modulators	France
Double-angle evaporators	France
200 mm sapphire wafers	Russia
Monolithic integrated windows for vacuum chambers	UK (UK Atomic Energy Authority)
Entanglement sources	Unnamed European countries

- **Market/Business Challenges:** By 2030, the projected market for sensors is $170-200b. Of this, $3-5b is projected to be for quantum sensors [1, 4]. Achieving this level of market penetration, or even exceeding it, will largely depend on whether quantum sensing platforms can deliver in terms of providing better sensitivity than classical counterparts in a competitively sized and priced package.

  A significant market barrier for quantum sensing technologies lies in the fact that they will need to be developed for highly specialized applications. While the growth of a quantum vertical such as Quantum Computing may be driven by one model that has many applications across end-users, quantum sensing will require customization to the specific needs of each end-user. For example, quantum sensors used for medical imaging are expected to differ widely from those used for defense or geological exploration. This market barrier creates a multifaceted issue for the growth of the quantum sensing market. Since quantum sensing applications would span a wide range of industries, each sector could have its own unique challenges, making it difficult for quantum sensing companies to create a one-size-fits-all solution. This would require large-scale investment in multiple unique R&D projects to cater to each sector. The need for specialization and the lack of a single breakthrough would have further broad implications, limiting the scalability of quantum sensing solutions across different markets and potentially damaging the return on investment for companies in the sector. The need for specialization could, in fact, pose a prohibitively large barrier to entry of smaller early-stage companies as there could be high initial startup costs and slow potential adoption.

This is perhaps reflected in the fact that despite record investment, the rate of quantum technology startup creation as a whole slowed in 2022. This can be attributed to the lack of working use cases and insufficient development for commercial implementation, limiting application start-up creation. Furthermore, recent investor trends show an increasing preference for investment in scale-ups and late-stage start-ups, which inherently limits capital for early-stage startups.

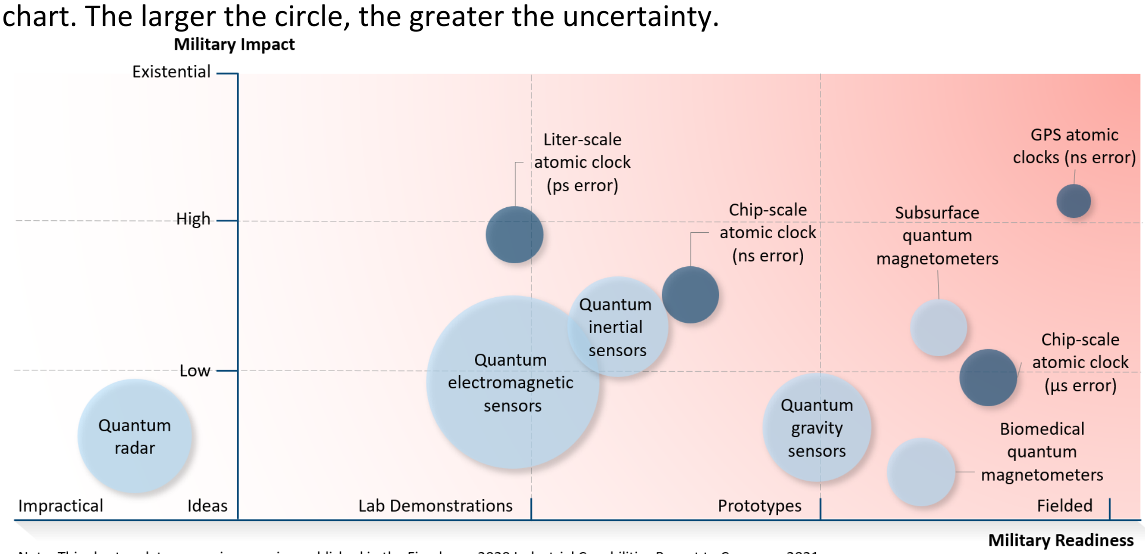
- **Regulatory Challenges:** Current export controls and restrictions on sharing sensitive information related to national security have created a difficult regulatory environment to navigate for early-stage quantum sensing companies and investors alike. The extent of the sensitivity of quantum sensing to national security can be gleaned from Chart 6, which was adapted from a RAND report originally submitted to the US Congress. Without the exemptions that are often provided by concrete and fully-formulated regulatory frameworks, there exists an environment where restrictions are the only governing policies. Existing bilateral cooperation agreements between the US and other Quad countries will continue to be limited by the restrictive export controls. With the US being the center point of the Quad alliance, US export controls are the leading regulatory concern. Even in the US, however, export controls on quantum sensors exist that hinder cross-border R&D collaboration [5].

  Furthermore, the U.S. International Traffic in Arms Regulations (ITAR), a set of restrictive safeguards for military technology, is a significant barrier for developing cross-border investments and partnerships in quantum sensing. Still, Australian and American lawmakers and officials are actively pushing for an exemption from U.S. arms regulations so that Australian companies would not be treated as foreign entities. While this provides some optimism for future collaborations between Australia and the U.S, as it currently stands, export controls heavily restrict the investment and collaborative environment without any outstanding regulatory frameworks that offer alternative solutions and exemptions.

With this background in mind, the following is a summary of the key challenges facing investors who would like to invest in quantum technologies:

- **Intellectual Property (IP) Rights**: Coordinating IP rights across different countries can be complex due to varying national laws and practices. There's a need for clear agreements on ownership, usage rights, and how to handle infringements. This complexity increases when dealing with technologies that could have both civilian and military applications.
- **Export Controls and Regulations**: Quantum technologies are often subject to strict export controls because of their potential military applications. Countries have their own control lists and regulations, which can make it challenging to share technology or even research findings. Navigating these controls requires comprehensive legal understanding and could limit collaboration or slow down the development process.
- **National Security Concerns:** As quantum technologies can significantly impact national security, countries may be cautious about sharing sensitive technologies or know-how. This can lead to trust issues between partners and might limit the scope of collaboration to less sensitive areas.
- **Compliance with International Norms**: As the quantum field evolves, so too do international norms and agreements regarding its development and use. Ensuring that joint projects remain compliant with these evolving standards can be an ongoing challenge.
- **Technology Transfer Restrictions**: Some countries impose restrictions on the transfer of advanced technologies to prevent their use in a manner that could harm national security. These restrictions can complicate collaboration and limit the ability of startups to operate globally.

Chart 6: Summary of Military Readiness and Impact of Various Quantum Technologies. Adapted from [5]. The dark blue shading denotes categories related to atomic clocks. The size of the circle represents uncertainty about where the technology falls on this chart. The larger the circle, the greater the uncertainty.



Note: This chart updates a previous version published in the Fiscal year 2020 Industrial Capabilities Report to Congress, 2021.
Source: Provided to RAND by the Office of the Undersecretary of Defense for Research and Engineering, and modified by the QUIN.

Priority Opportunities for the QUIN to Overcome Challenges

A proper discussion of what impact the QUIN can have on tackling the challenges to quantum sensing faced by the Quad begins by properly defining the QUIN. The QUIN (Quad Investors Network) is not a think tank. Nor is it an investor. Rather, it is a network of investors, industry, and innovators across the Quad nations. It has already brought, and will continue to bring in, more investors and C-suite executives of leading and emerging industries together. While it does not directly shape government policy, the very nature of the Quad construct allows it to educate and inform governments and the independent decisions they may make.

With this in mind, the Task Force discussed how the QUIN can have the largest impact. A major theme was that the QUIN should concentrate on playing to its strength, finding the best way to connect investors with innovators. There were a few suggestions on how to do this. While some proposals including a quantum sensing showcase, where investors and start-ups from the Quad nations could convene, and a Quad "SBIR" type program that could help de-risk investments for investors from the Quad were raised, ultimately the Task Force realized that implementing any Quad-based scheme for quantum technology must pass a few key barriers.

a. **Policy decisions on quantum technologies resulting from any joint Quad effort must be resolved at the government level**. The current landscape for quantum technologies, especially pertaining to IP, supply chain, and manufacturing is extremely fragmented and territorial. This is especially so as quantum technologies become further engrained in national strategies. A US investor for example, faces real barriers to investing in European quantum start-ups. For any joint venture resulting from multinational efforts such as the Quad there will be myriad policy-related complications. For example, which country will own the IP? How will the different involved countries share the IP license? Where will the start-up domicile and how will that affect the investing landscape? All of these questions and more, as detailed in the regulatory challenges in the previous section, should be cleared at the government level before individual investors and start-ups/companies partake in these multi-national endeavors.
   In particular, there have been ongoing discussions on key issues for quantum sensing technology regarding definition and control of dual use (civil, military) technologies, as well as barriers being set-up for export control. The QUIN should provide policy advice which finds a balance between the need to control sensitive technology and the ability to develop technology without unnecessary restrictions on the Quad nations. [*Policy Related*]

Once these policy-level questions are cleared, for quantum sensing the Task Force presents priority opportunities for the QUIN to

b. **Instigate a thorough study of the quantum sensing capabilities of each of the Quad nations**. There is a surprising dearth of studies mapping the existing quantum sensing capabilities of the Quad nations and how they intersect. Through organizations such as the QUIN and QED-C, the Quad nations should chart current capabilities, companies and developers, and roadmaps (near-term, mid-term, blue sky) and use these to help educate policy makers and connect developers of the technology. [*Policy & Commercialization Related*]

c. **Host conventions where quantum sensing technology developers, end-users, and investors can interact**. As mentioned previously in the report, quantum sensing faces the unique challenge that its market is highly fragmented. An advance in one type of quantum sensor does not necessarily benefit all the diverse applications of sensing. In many instances the killer applications of specific quantum sensing technologies have yet to be found. Thus, the Task Force recommends convening a quantum sensing showcase featuring startups and small businesses from the Quad nations, allowing venues where technology developers, end-users, and investors can interact. Such a showcase could happen alongside the Quad Leaders Summit where Quantum could be a theme. [*Commercialization Related, May require small funding*]

References

[1] "Quantum Technology Monitor." McKinsey, 2023.

[2] Rand Report: https://apps.dtic.mil/sti/trecms/pdf/AD1214987.pdf

[3] "Quantum Sensing Use Cases." QED-C report, 2022.

[4] Jean-François Bobier, et al., "Making Sense of Quantum Sensing." BCG, 2023.

[5] Edward Parker, et al., "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology." Santa Monica, CA: RAND Corporation, 2022.

[6] "Bringing Quantum Sensors to Fruition". National Science & Technology Council, 2022.

[7] "MEXT - Quantum Leap Flagship Program(MEXT Q-LEAP)"

[8] "Technology Spotlight: Quantum Sensors in Japan." J. Pickles (2023)

[9] "How is + performing + in Quantum sensors." ASPI Critical Technology Monitor (2024)

Methodology

Chart 2: The investment values and start-up numbers are those till the end of 2022. They were adapted from [1]. The number of publications reflects those till the end of 2022 and were collected using the Keywords "Quantum Sensing" in Web of Science.

Chart 4: For the panel titled "# of Citations for QS Articles Published in 2022," the number of academic journal citations was taken from the Web of Science on Feb. 25, 2024, using the Keyword "Quantum Sensing" coupled with the appropriate country filters. The other panels were adapted from [1] and [5].

Chart 5: Entries indicate the number of Quantum Sensing Publications over all time, including the countries listed in the row and column of the table. The data was collected by using the Keywords of "Quantum Sensing" in Web of Science and then extracting the relevant numbers by applying country filters.