Strategy
Paper-4

Quantum Technologies for Karnataka

Karnataka Science and Technology Academy
Department of Science & Technology
Government of Karnataka

MAY 2025

Strategy Paper

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Bengaluru

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Karnataka Science and Technology Academy

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Preface

Karnataka Science and Technology Academy (KSTA), an autonomous organization under the Department of Science and Technology, Government of Karnataka has long been working to provide supportive information for shaping the scientific and technological trajectory of the state by consistently publishing policy, strategy, status, and approach papers on topics of contemporary importance. These papers act as vital resources for policymakers, researchers, academicians, and industry leaders, offering direction and insight to foster innovation and propel progress in emerging and sunrise sectors.

As quantum technology evolves at a remarkable pace, it is poised to become a transformational force with profound and far-reaching applications in many fields and domains. Recognizing the enormous potential of quantum technology, this strategy paper seeks to provide a detailed and forward-thinking roadmap for its development within Karnataka.

During his visit to KSTA for the KSTA Award and Fellowship function in February 2023, **Prof. Ajay Kumar Sood**, Principal Scientific Advisor to the Government of India, suggested bringing out a strategy paper to accelerate the development of this emerging and game-changing technology. Following his advice, **Prof. S. Ayyappan**, Former Chairman of KSTA, proposed the formation of an expert committee to develop the strategy paper on quantum technology.

In response, an expert committee was constituted, with **Prof. A. R. Usha Devi**, Senior Professor, Department of Physics, Bangalore University as the Chair and **Shri Sreenath Rathnakumar**, Scientist/Engineer 'SG', ISTRAC, ISRO as the Member Secretary. The committee included members from renowned academic and research institutions both within India and abroad. Through a series of online and in-person meetings, the committee thoroughly deliberated on the advancement of this frontier technology and has now finalized the strategy paper.

This strategy paper presents a well-structured approach to capitalize on the opportunities within quantum technology, while simultaneously addressing the challenges that accompany its development. Recognizing its immense potential, the document envisions establishing Karnataka as a global leader in this field by outlining a comprehensive roadmap for the advancement of quantum technology in the state. It highlights key milestones in education, research, industry collaboration, and startup support, all of which are aimed at positioning Karnataka at the forefront of this emerging sector.

I hope this strategy paper will serve as a valuable reference for stakeholders and contribute to making Karnataka a global hub for quantum innovation.

Dr A. M. Ramesh
Chief Executive Officer, Karnataka Science and Technology/
Convener, Expert Committee on Quantum Technology

Foreword

Quantum technology has witnessed meteoric rise of interest across the globe. Complex computing, long distance communication, cybersecurity would all be undergoing revolutionary technological changes and advance socio-economic conditions. Countries across the globe have already made a huge head start in quantum computing, quantum cryptography, and quantum materials, recognizing the transformative potential of quantum technologies.

At this crucial juncture of technology transformation, India has recognized the immense potential of quantum technology and impact of its revolutionary scientific breakthroughs on various sectors like health, finance, drug design, machine learning, space, national security and so on. On 19th April 2023, India announced its Rs. 6003 crore National Quantum Mission (NQM) with an aim to seed and nurture quantum technology research and development (R&D) over a span of eight years (2023-31). Karnataka, with its strong foundation in science, technology, and innovation, is uniquely poised to accelerate advancements in quantum technology research. The state's world-class academic and research institutions, dynamic startup ecosystem, and robust industry collaborations create an ideal environment to propel quantum technology forward.

This strategy paper presents a comprehensive roadmap for strengthening quantum education and research at all levels—from undergraduate to doctoral programs—ensuring a skilled workforce for the future. It underscores the need for dedicated centers of excellence, sustainable funding mechanisms, and strong research-academia-industry-government partnerships to drive innovation. Recognizing the crucial role of startups in translating research into real-world applications, the paper also highlights incentives, incubation support, and policy frameworks to nurture quantum entrepreneurship.

I commend KSTA for taking the initiative to publish a strategy paper on quantum technology.

Dr A R Usha Devi
Chairperson
Expert Committee on Quantum Technology
Karnataka Science and Technology Academy (KSTA)

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1.0 Introduction

Fig. 1 Concept of Qunatum Technology for Karnataka

Quantum technologies (QT) have the potential to revolutionize entire industries, advance human society, and address some of the world's most pressing challenges. Innovations in healthcare, technology, energy production, finance, cybersecurity and beyond will benefit society as a whole and should be shared to enhance global well-being, ensure environmental sustainability, and support future generations.

Quantum technologies, including quantum computing, quantum sensing & imaging, quantum communications, and networking are creating new opportunities across various sectors. They are already influencing key economic areas, leading to novel solutions for previously unsolved problems, introducing new industry players and fostering innovative business models. Beyond quantum computers, these technologies encompass quantum sensing, quantum networking, quantum-safe cybersecurity, and quantum simulation.

Quantum technologies promise abilities to transform various aspects of business and society. Recent advancements in QT have been generating growing interest from nations, regions and organizations in the global arena. This interest is largely driven by the potential of quantum technologies to solve problems that classical computers have not and may never be able to address. The early adopter advantage in this relatively nascent field offers opportunities to strategically explore and benefit from the transformative potential of QT.

To ensure that QT is developed and deployed for the common good, it is crucial to adopt well-considered, scientifically sound, inclusive and socioeconomically holistic strategies. Learning from past experiences and being proactive in our approach would indeed help maximizing the benefits of quantum technologies for all.

1.1 The National Quantum Mission (NQM)

Fig. 2 "Adopting quantum technologies is not a choice any longer today, it's a question of getting in at the earliest" - Prof. Ajay Kumar Sood, Principal Scientific Advisor (PSA), GoI

On 19th April 2023, the Union Cabinet of Government of India approved **The National Quantum Mission (NQM)** with an objective to nurture and create a vibrant and innovative quantum technology ecosystem within the country. India is the seventh country after the US, Austria, Finland, France, Canada, and China to have taken this significant step to be a leading player in the development and commercialization of quantum technologies. With a substantial budget allocation of Rs. 6003.615 crore spanning over eight years (2023-24 to 2030-31), the NQM aims to lay a solid foundation in the field of quantum technologies, positioning India among the top nations committed to translational research, invention of new products, commercialization of services, and creation of skilled quantum workforce. Ultimately, the initiative aspires to drive technological breakthroughs that can significantly impact various sectors, including healthcare, finance, and defence, thereby contributing to India's broader vision of becoming a global hub for quantum technology.

It is essential for the state of Karnataka to align with the objectives and achievements of the NQM. This alignment will create coherence and synergy in Karnataka's initiatives to advance quantum technology. By adopting the NQM as a guiding framework, Karnataka can strengthen its strategy, ensuring a meaningful contribution to the national agenda for quantum technology development. Karnataka can also play a significant lead role in the future as a QT leader as it offers vast opportunities in this field.

1.2 Karnataka State – pioneer in various strides

Fig. 3 Karnataka State

Karnataka, a vibrant state in southwest of India, epitomizes a blend of culture, history, and innovation. From Coorg's picturesque coffee plantations to Mysuru's majestic palaces, Karnataka showcases a rich heritage. Bengaluru, being India's Silicon Valley, anchors the state's IT, biotech, and startup sectors. Karnataka's diverse terrain features lush forests, cascading waterfalls, and pristine beaches, complemented by a thriving arts scene and renowned hospitality. Seamlessly melding tradition with modernity, Karnataka offers a captivating experience, from ancient temples to cutting-edge industries.

Karnataka has emerged as a beacon of scientific excellence in India. The state hosts a dynamic network of research institutions, universities, and innovation hubs that drive pioneering scientific exploration and breakthroughs. Bengaluru, the state capital, houses esteemed institutions like the Indian Institute of Science (IISc), Raman Research Institute (RRI), National Centre for Biological Sciences (NCBS), Bangalore University (BU), Indian Institute of Astrophysics (IIA), Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), University of Agricultural Sciences (UAS) Bangalore and the International Institute of Information Technology (IIIT), Bangalore. Karnataka's prowess extends to biotechnology with facilities like Biocon Park and Genomics Center, while its aerospace capabilities are bolstered by organizations such as Indian Space Research Organization (ISRO), Defence Research and Development Organisation (DRDO) and Bharat Electronics Limited (BEL). With its conducive environment, skilled workforce, and robust governmental support, Karnataka stands as a premier science hub, attracting global scientists, researchers, innovators and entrepreneurs.

Renowned as a pioneer in India's tech journey, Karnataka has solidified its status as the Information Technology (IT) capital, biotech hub, and nanotechnology citadel. Its capital city, Bengaluru, hosts a multitude of startups, multinationals, and research institutions, fostering innovation and growth. Supported by a favourable ecosystem, skilled workforce, and government backing, Karnataka excels across these domains. As emerging technologies such as Artificial Intelligence (AI) and quantum computing gain traction, Karnataka is poised to lead in these areas as well. The State is in the forefront for various development sectors and it has the potential of emerging as a model for other States. Continued investments in infrastructure, research, and talent development will further cement Karnataka's position as a premier QT destination, leveraging the expertise, technology readiness in this area, contributing substantially to the national initiative and to meet strategic demands.

1.3 Quantum Technologies for Karnataka (QT4K)

Fig. 4 Quantum for Karnataka - Conceptual Design

The State of Karnataka has achieved major strides in e-governance and increased efficiency and transparency in Governance. Recognizing its leadership in technology and innovation, Karnataka should prioritize the development of quantum technology. As the next frontier in computing, cryptography and communication, Quantum Technology for Karnataka (QT4K) will secure Karnataka's competitive edge in the global tech landscape. Embracing quantum technology early can drive significant economic growth by fostering new industries, creating necessary workforce, generating revenue streams and employability. This strategic investment will enrich Karnataka's innovation ecosystem, drawing startups, entrepreneurs, and investors while strengthening its position in defence, aerospace, finance, healthcare and advanced manufacturing.

Recent advancements in quantum technologies have sparked growing interest from various countries, regions, and organizations. This interest is fuelled by the technology's potential to solve problems that classical computers cannot address. As quantum technology is still in its early stages, early adopters have a unique opportunity to strategically explore and leverage its benefits.

To ensure that quantum technology is developed and deployed effectively, it is crucial to adopt well-thought-out, scientifically rigorous, and socioeconomically inclusive strategies in this direction. Therefore, Karnataka Science and Technology Academy (KSTA) proposes to develop a strategy paper on Quantum Technologies for Karnataka (QT4K) to articulate a roadmap for harnessing the potential of the new technology -- thus advancing the role of Karnataka as a pioneer in this direction.

1.4 Quantum Technology Strategy Paper

Developing a quantum technology strategy paper for Karnataka is crucial as the state is well-positioned to leverage its established strengths in this transformative field. Karnataka has already distinguished itself as a leader in IT, biotechnology, and research, supported by a robust ecosystem of universities, research institutions, and tech giants. The launch of the National Quantum Mission (NQM) by the Government of India, which promises substantial funding and support for quantum research and development, presents Karnataka with a unique opportunity to spearhead and leapfrog in the implementation of quantum technology.

A comprehensive strategy paper would help align Karnataka's resources, talent, workforce and infrastructure with the ambitious goals of National Mission on Quantum Technologies & Applications (NM-QTA). By ensuring alignment between state and national efforts, Karnataka can enhance its impact in advancing quantum technology. This strategic coordination will not only bolster Karnataka's scientific and technological capabilities but also make it more attractive for global collaborations, investments, and talent. By positioning itself as a leader in quantum technology innovation, Karnataka can indeed drive inclusive economic growth and establish itself as a hub of cutting-edge technological advancements in India and beyond. The proposed strategy paper by the Karnataka Science and Technology Academy (KSTA) aims to prepare a coherent roadmap with a vision to elevate Karnataka's scientific standing and to reinforce its position as a beacon of technological advancement and economic prosperity.

1.5 Karnataka Science and Technology Academy (KSTA)

KSTA is an autonomous organization under the Department of Science and Technology, Government of Karnataka. Established in July 2005 under the chairmanship of the distinguished space scientist and Padma Vibhushan awardee, Prof. U. R. Rao, Former Chairman, Indian Space Research Organization (ISRO) and Secretary, Department of Space (DOS). KSTA was established to advance STEAM (Science, Technology, Engineering, Agriculture, and Mathematics) education at various levels and to promote science among the general public in the state of Karnataka.

Since its inception, KSTA has organized a diverse array of integrated STEAM educational and outreach programs throughout Karnataka. These initiatives have provided valuable platforms for enhancing teaching and learning across all educational levels, from high school to university, and have fostered a spirit of inquiry and scientific temper among students. KSTA’s programs effectively engage both students and the public statewide.

Key programs include the Annual Science and Technology Conference, the Science and Technology Conference in Kannada, and the Prof. C.N.R. Rao Lifetime Achievement Award in STEAM. Other notable awards are the Lifetime Achievement Award in STEAM Communication in Kannada, the Dr. S.K. Shiva Kumar Award for undergraduate students, the Prof. U.R. Rao Award for postgraduate students, and the KSTA Award for Innovation by the General Public. KSTA's initiatives also encompass Digital Content Generation, the Postgraduate Special Lecture Series, Certificate Courses, and various competitions such as quizzes, essays, and science modelling. Additionally, KSTA collaborates with R&D institutions, provides small grants for short-term studies and science promotion, offers Academy Fellowships and Associateships, and publishes policy, strategy, status, and approach papers on critical topics including science communication, higher education in science, COVID-19, horticulture, mineral exploration, etc.

To prepare a comprehensive strategy paper on quantum technology for Karnataka, an expert committee was formed under the leadership of Dr. A. R. Usha Devi, Senior Professor in the Department of Physics, Bangalore University, Bengaluru. The committee's mandate was to discuss, analyze, and formulate actionable strategies, along with key recommendations, to promote the development and advancement of quantum technology in the state. Comprising 12 experts, the committee held several meetings, both online and offline, where members deliberated on various aspects of quantum technology and collaboratively drafted the strategy paper.

2.0 Quantum Technology: A Global Scenario

Quantum technology is rapidly evolving as a transformative field with significant global implications. It encompasses areas such as quantum computing, quantum communication, and quantum sensing, each promising breakthroughs that could revolutionize industries ranging from cybersecurity to pharmaceuticals. Countries around the world are investing heavily in quantum research, recognizing its potential to enhance computational power, improve data security, and enable unprecedented levels of precision in measurements. Collaborative international efforts and partnerships are emerging, as nations strive to secure a competitive edge in this cutting-edge domain. As advancements continue, quantum technology is poised to play a pivotal role in shaping the future of technology and science on a global scale.

2.1 Europe

Quantum Information has evolved from being of pure academic interest to a favourite domain for developing new emerging technologies in the recent years[1,2]. With advent of the second quantum revolution in 1994[3], focusing on control and manipulation of quantum systems, the possibility of employing quantum solutions to push the limits of existing technology emerged[4,5]. The academic community in Europe has been actively conducting research in quantum physics (QP), pioneering several key aspects of the field since the end of 20th century. Though it was only in 2016, that the European Commission recognized its worthiness[6] for technological developments its flagship program was launched in 2018, bridging the gap between research institution, industry and public funders which is a long-term research and

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[1] Rainer Kaltenbaek, Antonio Acin, Laszlo Bacsardi, Paolo Bianco, Philippe Bouyer, Eleni Diamanti, Christoph Marquardt, Yasser Omar, Valerio Pruneri, Ernst Rasel, et al. Quantum technologies in space. *Experimental Astronomy,* 51(3):1677–1694, 2021.

[2] Peter Knight and Ian Walmsley. UK national quantum technology programme. *Quantum Science and Technology,* 4(4):040502, 2019.

[3] Peter W Shor. Algorithms for quantum computation: discrete logarithms and factoring. In *Proceedings 35th annual symposium on foundations of computer science*, pages 124–134. IEEE, 1994.

[4] Antonio Acin, Immanuel Bloch, Harry Buhrman, Tommaso Calarco, Christopher Eichler, Jens Eisert, Daniel Esteve, Nicolas Gisin, Steffen J Glaser, Fedor Jelezko, et al. The quantum technologies roadmap: a European community view. *New Journal of Physics*, 20(8):080201, 2018.

[5] Oskar van Deventer, Nicolas Spethmann, Marius Loeffler, Michele Amoretti, Rob van den Brink, Natalia Bruno, Paolo Comi, Noel Farrugia, Marco Gramegna, Andreas Jenet, et al. Towards European standards for quantum technologies. *EPJ Quantum Technology*, 9(1):33, 2022.

[6] Quantum technologies flagships. digital-strategy.ec.europa.eu.

innovation initiative that aims to put Europe at the forefront of the second quantum revolution.

The unique physical principles of QP had led to unexpected applications such as unconditionally secure quantum communication, quantum Turing machines, quantum algorithms, simulating biological systems, and quantum computing[7]. But there was a certain scepticism with respect to using them for industrial purposes.

In 2016, a quantum manifesto[8] completely changed this scenario by endorsing quantum information as a major solution to current technological hazards and beyond. About 3400 individuals from academia and industry across the globe supported the declaration. As a result, the European Commission appointed 24 individuals (12 from academia and 12 from industry) as the high-level steering committee to deliver a research strategy outlining implementation and governance guidelines specific to quantum technology (QT). Finally, with a desire to build upon existing scientific excellence to achieve technological dominance to sustain as a prosperous and secure continent, the European Union (EU) recognized QT as an emerging future technology.

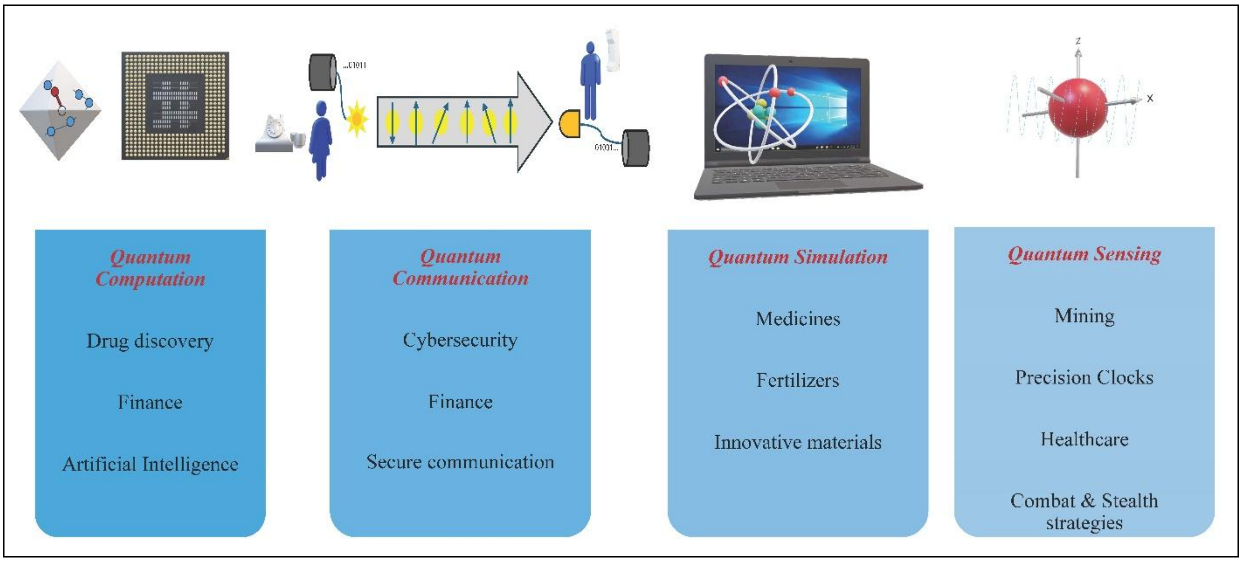

Fig. 5 Representation of the four main branches of QT as recognized by the EU for investment towards development of QT for industry and commercial applications. Illustration and applications with respect to each area is also presented.

With a mission to encourage cross country cooperation, interdisciplinary research, industry-academia exchange and pioneering QT, the EU

[7] Michael A Nielsen and Isaac L Chuang. *Quantum computation and quantum information.* Cambridge university press, 2010.

[8] Quantum manifesto. qtflagship.cnr.it.

commission allocated[9] €1-billion for the next 10 years towards QT research. Under this initiative, quantum computing, quantum communication, quantum simulation and quantum sensing or metrology were recognized as the four main pillars of QT. About 20 projects across Europe were funded for a period of 3 years under the first call for proposals in 2017 with €132−million from industry, academia and public funders[10]. Identifying the disruptive nature of QT in influencing the consumer market, security, industry and international relations, specific applications were expected to be the target. Namely, quantum cybersecurity, drug discovery, artificial intelligence, innovative materials, finance, fertilizers, mining, healthcare, combat and stealth strategies. The dual benefit (civil and military) of the QT was one the major driving forces behind this.

At the end of 2021, it was reported that 236 organizations across EU were performing research related to QT with 1500 scientists. A total of 105 patents had been filed with about 64 of them being granted. Also, about 1536 publications in peer-reviewed journals had been declared[11]. Until 2023, EU had funded about 24 consortia of industry and academia with €150−million. Within the EU's Quantum Flagship, projects focused on developing ion-trap quantum computing (AQTION)[12], quantum sensors based on nitrogen vacancy centres in ultra-pure diamonds (ASTERIQS within Horizon 2020)[13] and development of quantum internet ecosystem[14] in EU (QIA) deserve special mention. In addition to the funding available under the quantum flagship mission, several other calls for research proposals were advertised across EU.

- The QuantEra project[15] with € 88.9−million constitutes 41 research funding organizations from 31 different countries. Since 2017, this funding body has published 4 calls for research proposals. The programme is dedicated to advancing innovation and excellence in scientific research within QT while encouraging industry collaboration, commercialization, patenting and intellectual property to facilitate knowledge transfer from academia to industry.

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[9] Davide Castelvecchi. Europe shows first cards in € 1-billion quantum bet. *Nature,* 563(7729):14–15, 2018.

[10] First projects selected for the European initiative on quantum technologies.https://www.cnrs.fr/en/press/first-projects-selected-european-initiative-quantumtechnologies.

[11] The quantum insider. thequantuminsider.com.

[12] An ion-trap quantum computer for europe. aqtion.eu/.

[13] Advancing science and technology through diamond quantum sensing. asteriqs.eu/.

[14] Quantum internet alliance. quantuminternetalliance.org/.

[15] Quantera. quantera.eu/.

- The Horizon Europe[16] with a funding of € 93.5−billion between 2021−2027 supports economic and industrial growth, job creation and engaging EU's talent pool by better dissemination of research outcomes. The uniqueness of this programme is their "Go Green" policy which approaches climate change and sustainability related issues from a technological perspective.
- The CHIST-ERA call[17] for funding new and emerging information and communication technology in Europe with an approximate funding of € 100−million for a period of 3 years. This body has funded 22 diverse topics so far with 20 participating countries within and outside EU (Taiwan, Turkey, United Kingdom).

Other noteworthy activities throughout EU fostering QT development were workshops, conferences, training of human resources in preparation for the future and quantum hackathons. Diversity, equality, ethics and policy related awareness and safe space for everyone is also promoted[18,19]. Additionally, a rise in support for women in quantum[20,21] has been observed with dialogues on safe space, maternity related issues, pay scale and recruitment. Finally, in 2023, it was reported that about 147 start-ups based on QT exist in EU, of which a 60 of them are related to quantum[14] computing. By 2025, this number is expected to rise to about 197. Alice & Bob, RiverLane, Id Quantique, Quantum Cybersecurity Group, PASQAL, Quantinuum, Qtlabs, and ORCA Computing are few well-known companies in Europe.

2.2 America

The America, without any dispute, has the richest landscape of research and development of quantum technologies. Consequently, the USA and Canada, the two prominent North American nations in terms of technologies, are hosting swiftly evolving Quantum Technology industries that could be of

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[16] Horizon europe. research-and-innovation.ec.europa.eu.

[17] Chistera. chistera.eu/.

[18] Ana Bel´en Sainz. Q-turn: changing paradigms in quantum science. *Quantum Science and Technology,* 7(4):044004, 2022.

[19] inqlude project. https://inqlude.ug.edu.pl/.

[20] Women in quantum. onequantum.org/women-in-quantum/.

[21] Almut Beige and et. al. Women for quantum – manifesto of values. arXiv:2407.02612,2024.

economic importance. On the other hand, the landscape seems to be sparsely populated in the south Americas and mostly restricted to academia.

In the following we will discuss the quantum technology scenario of the United States of America (USA) and Canada in some detail. The agenda here is to provide an overview on the role of government policies and academia-industry partnership in advancing the QT. Also, a glimpse of the economy associated with the industry is presented.

2.2.1 United States of America (USA)

The idea of quantum computing in the USA blossomed with a lecture delivered by Richard P. Feynmann at the MIT Computer Science and Artificial Intelligence Laboratory in May 1981. There he proposed the idea of harnessing the quantum effect to simulate quantum systems that are too hard to simulate using classical computers. Such ideas were also put forward by American Physicist Paul Benioff and Russian mathematician Yuri Manin.

Initiatives of The US Government: Taking forward the idea a step closer to materialization, the US government was the first to conduct a workshop on quantum computing in 1994 which was held at National Institute of Standards and Technology (NIST). Following the event, in 1996 the government and the Army Research Laboratory issued the first public call for research proposals in quantum information processing. Since then, the government has made a number of strategic investments in Quantum Computing (QC) research and development through various initiatives. The government's investments are aimed at advancing this technology to solve some of the most challenging problems in science, engineering and national security. Research is currently aimed at applying quantum computing technology to improve outcomes in drug discovery and cryptography, as well as financial and climate modelling.

The most important in recent times is the National Quantum Initiative Act signed into law in 2018 by the President Donald Trump. The program is coordinated by The National Quantum Coordination Office with the aim of advancing quantum technology, particularly quantum computing and offers support for a number of government agencies and national laboratories that host research and development programs connected to quantum science and technology. Some prominent national laboratories are Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory and Oak Ridge National Laboratory. The program also supports private institutes like MIT, Caltech, Stanford, Harward and many more. The national act also actively involves a total of 23 federal agencies like Defence Advanced Research Projects Agency (DARPA), US Air Force, US Army, National Institute of Standards and Technology (NIST) and National Aeronautics and Space Administration (NASA). Every agency, institute and laboratory brings in its unique capability and requirement to the legislation.

The National Quantum Initiative (NQI) is a whole-of-government approach to ensuring American leadership in quantum information science. The National Strategic Overview for Quantum Information Science (QIS) outlines the US strategy for QIS R&D, with an emphasis on the science, workforce, industry, infrastructure, security, and international cooperation. The strategy focuses on:

- Getting the science right by understanding the applications and timelines by which QIS will benefit society, and the roadblocks we must overcome to get there.
- Enhancing competitiveness by accelerating technology development toward useful economic and mission applications of QIS and working with international partners, while also protecting national security.
- Enabling people by building the necessary talent pathways and ensuring that QIS creates new opportunities for all Americans.

To accomplish such quantum mission, the USA government has been generous. The budget allotment was $449−million in 2019, $918−million in 2022 and $884−million in 2023. Other than the government, private venture capitalists have been actively funding the quantum computing startups.

Private Sector: The government quantum strategies, policies and funding have led to incubation of exclusive quantum technology based private startups in the USA. PsiQ, IonQ, Regetti, Quantum Computing Inc, Riverlane are some of the shining examples of quantum computing startups. Importantly, many of such startups are spinoffs from the academia underpinning the importance of academia-industry partnerships. The startups are funded by venture capitalists and government agencies.

Apart from the startups, the participation of traditional information technology industrial players like IBM, Google, Amazon and Microsoft is of immense importance. IBM has built superconducting circuit-based commercial quantum computers, while Google has its 53-qubit superconducting Sycamore quantum processor. Microsoft offers featuring solutions, software and hardware through Azure. Others like Honeywell known for aircraft engines too have ventured into the industry. Honeywell Quantum Solutions and Cambridge Quantum have combined to form Quantinuum – the world's largest integrated quantum computing company.

2.2.2 Canada

Another North American nation that leads when it comes to research and the commercial aspects of quantum technologies is Canada. Like the USA, Canada too has a national quantum technology program known *as National Quantum Strategy*. The aim of the program is to support Canada's quantum technology industry and consolidate its position among leaders in this competitive landscape. The program sets out three key missions:

- Make Canada a world leader in the continued development, deployment and use of quantum computing hardware and software—to the benefit of Canadian industry, governments and citizens.
- Ensure the privacy and cybersecurity of Canadians in a quantum-enabled world through a national secure quantum communications network and a post-quantum cryptography initiative.
- Enable the Government of Canada and key industries to be developers and early adopters of new quantum sensing technologies.

Under the national of strategy, five principal quantum technologies would be pursued rigorously: Quantum Computer, Quantum Software, Quantum Communication, Quantum Sensors and Quantum Materials. The budget allocation to achieve the goal has been $360-million in the year 2021-2022. To foster these missions and other quantum initiatives, the program is built on three pillars:

Research - Supporting basic and applied research to realize new solutions and new innovations: When it comes to research, Canada has a very strong infrastructure in terms of quantum research institutes and labs. Some significant ones are Université de Sherbrooke—Institute quantique, University of British Columbia—Advanced Materials and Process Engineering Laboratory Quantum Information Science—Quantum Matter Institute, University of Calgary—Institute for Quantum Science and Technology, University of Toronto—Centre for Quantum Information and Quantum Control and University of Waterloo—Institute for Quantum Computing.

Talent** – **Developing, attracting and retaining the critical talent from within Canada and around the world to build the quantum sector: Increasing industry-academia collaboration was noted as a way to draw research talent into industry, increase commercialization, and ensure strong readiness to engage and create value from quantum applications. Training and internship programs that provide work experience and cross-disciplinary skillsets are also identified as key for the program.

The Canadian government also realises the need to expand efforts to attract international talent. For this, creating mobility programs that offer international training and internships, adopting immigration measures, developing agreements with other countries, and facilitating access to international talent to complement Canada's home-grown supply are being planned.

Commercialization – ***Translating research into scalable, commercial products and services that can benefit Canadians, our industries and the world:*** Canada has expertise in many technologies with near-term commercial opportunity, including quantum sensors, which can be used to increase the competitive advantage of mining and defence sectors; quantum communications and cryptography; and quantum computing hardware and software, including algorithm design.

Quantum technologies are evolving quickly; however, they have lengthy development timelines and require long-term R&D support. Even when a quantum innovation reaches the proof-of-concept stage, intensive research is still needed to scale it into a commercially viable technology. This underpins the importance of industry-academia-government collaboration throughout the development lifecycle.

As Canada's domestic market is small, its quantum strategy needs to leverage international partnerships and markets. Given the modest number of large Canadian first-buyer companies, the Government of Canada would be a first buyer. Such government procurements will be pivotal to de-risk product development and secure commercial success.

Furthermore, it is in the top ten countries worldwide in planned public funding for quantum technology at more than $1.9 billion, a number that is growing but still behind China with $15 billion, the EU with $7.2 billion and the US with $7.7 billion.

Private Sector: Given the strong R&D hosted by Canada it is not surprising that the home of the first quantum computing company in existence, D-Wave is Canadian. D-wave stands as a symbol of success of academia-industry-government partnership. In the province of Ontario that stretches roughly from Waterloo to Toronto, where many of its quantum startups, incubators, accelerators, venture capitalists, and research institutes are located is known as Canadian quantum valley. Some European players like ORCA computing have setup their branches there.

As of now, Canada hosts nearly 25 quantum technology startups and the number could be growing given the ecosystem set in place. Some other well-known industrial leaders are Xanadu AI Quantum Technologies. The company recently, in 2023, received a fund of $30M from Canadian government. Xanadu is building a quantum photonic processor and an open-source full-stack quantum software platform called Strawberry Fields for photonic quantum computing. In June 2022, Xanadu's Borealis programmable photonic quantum computer with 216 squeezed-state qubits demonstrated quantum computational advantage. The achievement is a significant milestone on the path to building a large-scale, fault-tolerant quantum computer. Borealis is available to the end users through company's cloud services.

Another noteworthy spinoff from the *Silicon Quantum Technology Lab* at Simon Fraser University is the *Photonic Inc.* which focuses on designing and manufacturing silicon-based, high-quality quantum technologies. Another eco-system player 1QBit develops general-purpose algorithms for quantum computing hardware. Initially, 1QBit's focus was on NISQ-era applications but it has increasingly moved now to providing enabling software across the stack. InfinityQ is another example startup focused on developing quantum analog computing solutions. Its first-gen quantum-analog computer, InfinityQube, uses analog electronics, operating at room temperature, to exploit certain quantum effects. The company claim to specialize in solving highly complex problems across various industries including finance, pharmaceuticals, logistics and chemistry. The analog quantum computer is available to the end consumer via the company's cloud interface.

Currently, Canada is home for nearly 25 startups and the number is expected to grow in future. The nation also aims to create and expand a sustainable economy around the quantum technology industry. While competing on a level playing field with the USA and China may seem daunting, Canada aspires to be a significant player in the quantum technology landscape, striving to match or surpass the achievements of other countries.

2.3 Asia

In this section, we present an overview of the quantum missions of various Asian countries, excluding India, and highlight their motivations for investing in quantum technology.

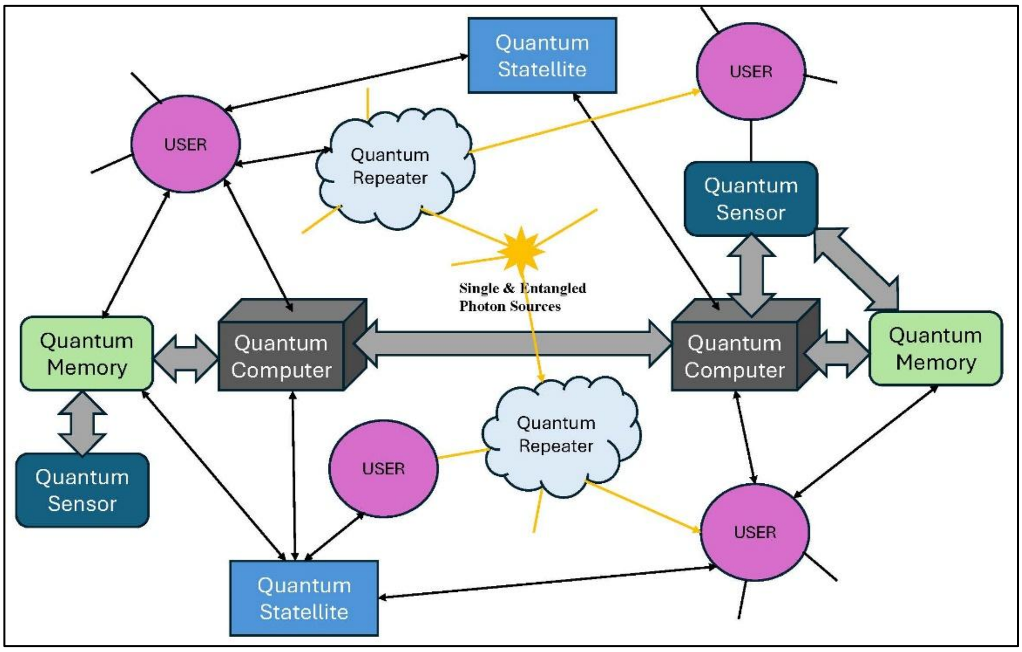

Fig. 6 Illustration of a quantum network where each node is connected to each other via a quantum channel (Fiber-optic cables known as terrestrial links or free-space via satellites known as space links) running quantum communication protocols. Quantum repeaters are stationed at regular intervals to maintain the strength of quantum signals undergoing decoherence in the presence of noise. A central unit consisting of single and entangled photon sources generate and distribute single and entangled pair of photons to different nodes on the network. Each node has access to quantum computers to perform computation, quantum memory to store and access quantum states when desired and quantum sensors for sensing applications. The nodes are also equipped with quantum detector units and in some cases quantum random number generators. All the nodes and service providers on this network have access to an authenticated classical channel for classical communication.

2.3.1 Singapore

The government of Singapore identified the importance of quantum science and technology and established the Center for Quantum Technology (CQT) in 2007. It has been planned to invest about $222−million over the next five years to fuel quantum technology research and talent development make it the most quantum safe country in the world[22]. Under the National Quantum Strategy (NQS), Singapore aims to build quantum processors for advancing artificial intelligence (AI), new materials for batteries, drug and pharmacy applications. The mission focuses on four main initiatives to achieve this.

[22] Singapore boosts quantum computing investment. www.aseanbriefing.com.

- ***Scientific Excellence***: Universities and research centers (e.g. CQT, National University of Singapore) along with Agency for Science, Technology and Research (A∗STAR) have been declared as national research and development hubs to fulfil the agenda of NQS.

- ***Engineering Capabilities:*** The Quantum Engineering program in Singapore will include new calls for proposals related to Quantum Communication, Quantum Sensing, Quantum Processors, Quantum Computation and Simulation. The National Quantum Sensor Program will be established to develop navigation timing, biological sensing and remote sensing for industrial applications. Similarly, expertise in designing of quantum processors using ion-traps, neutral atom arrays, Photonics and control electronics will be addressed under The National Quantum Processor Initiative. In addition to these, other existing programs to strengthen academia and industry collaboration are,
  1. National Quantum Computing Hub to build quantum computers and develop highly skilled manpower to access it[23].
  2. National Quantum Federated Foundry to design, fabricate and characterize micro- and Nano- devices that are essential hardware required for QT[24].
  3. National Quantum Safe-Network is a program that works on providing quantum-safe communication systems for use across Singapore. Validating the security associated with a quantum protocol and its realization before integrating it with existing communication network is carried out[25].

- ***Talent Development***: The National Quantum Scholarship Scheme (NQSS) provides funding for 100 PhD and Master's students to develop quantum ready workforce over the next five years.

- ***Innovation and Enterprise Collaborations through the National Quantum Office***: Singapore has 11 start-ups related to QT where

[23] National quantum computing hub, singapore. https://www.nqch.sg/.

[24] National quantum federated foundry, singapore. www.a-star.edu.sg.

[25] National quantum-safe network, singapore. https://www.nqsn.sg/.

investment will be made to create a dynamic quantum ecosystem through strong collaboration with industry and support local firms.

2.3.2 Japan

The Quantum Strategic Industry Alliance for Revolution (Q-STAR) was founded in 2021 to speed-up the development and commercialization of QT in Japan.

It is interesting to note that the government is more inclined towards Quantum Computing and has invested about $30−million towards it. The possible reason behind this might be their long-standing expertise in this area. The first ever experimental demonstration of a quantum computer by Y. Nakamura et.al.[26] propelled Japan to this pioneering position. Through a technology and an integration map for QT, key research areas for technological innovation will be identified. A gate-based approach to quantum computing and solid-state quantum sensing along with hybridization of these systems will be prioritized. In addition, integration with quantum communication and quantum AI is also set as a goal. The national QT hubs are expected to meet these goals through basic research, demonstration of key technology aspects and human resource development. Also, 17 start-ups are reported in Japan.

While the Japanese mission for QT in general is similar to most other countries around the world, they differ majorly in terms of one particular objective. International co-operation with USA and EU is included as a key agenda in their national quantum strategy. Japan aims to strengthen ties abroad by developing early bilateral and multilateral co-operation for the purpose of trade and security[27] e.g., Japan-US-EU Symposium held in 2019.

2.3.3 China

The Quantum Mission of China dates back to 2006 as a part of their Five-year plan. About $150−million was used to fund research on single state detection and interaction, long distance quantum communication and

[26] Yasunobu Nakamura, Yu A Pashkin, and JS Tsai. Coherent control of macroscopic quantum states in a single-cooper-pair box. nature, 398(6730):786–788, 1999.

[27] Integrated Innovation Strategy Promotion Council. Quantum technology and innovation strategy (final report) (in japanese). Technical report, Japan, Jan. 2020.

demonstration of key technological aspects and their verification at space scale[28]. With promising outcomes, China further enhanced their support towards QT research (focussing on metrology, quantum key distribution, space and industry applications) in their five-year plan in 2011 with $490−million and in 2016 with $337−million. The source of money for funding is believed to be through the government organizations. Several milestones have been achieved through their Quantum Experiments at Space Scale (QUESS) mission such as long-distance quantum communication, establishment of a backbone for terrestrial quantum network, demonstration of intercontinental quantum key distribution and testing the loop holes in fundamental tests of QP. The country became the first to generate entanglement onboard satellites in space and distribute it to ground stations. Additionally, there are 22 start-ups in China mostly based on quantum computing. Also, the nation has been involved in research and experiments on underwater quantum key distribution (UQKD), including using decoy-state BB84 protocols and continuous-variable (CV) QKD. UQKD is still mainly limited to lab experiments and proof-of-concept prototypes. And theoretical studies and experiments indicate that UQKD could be used in underwater applications that are tens to hundreds of meters apart.

2.3.4 Israel

The country has established the QUEST (Quantum Entanglement in Science and Technology) centre for development of QT[29]. Defence, academic institutions and government organizations are expected to take part and deliver in this mission. Around $336−million was allocated in 2018 for the same. One of the main focuses for Israel is building a quantum computer with 30 − 40 QBits and integrating it with classical systems.

2.3.5 Russia

With support from the government and industry, Russia announced $663 −million funding for quantum science and technology as part of their digital technology initiative[30]. About 120 researchers are involved in this venture.

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[28] Qiang Zhang, Feihu Xu, Li Li, Nai-Le Liu, and Jian-Wei Pan. Quantum information research in china. Quantum Science and Technology, 4(4):040503, 2019.

[29] Quest,israel. quest.biu.ac.il.

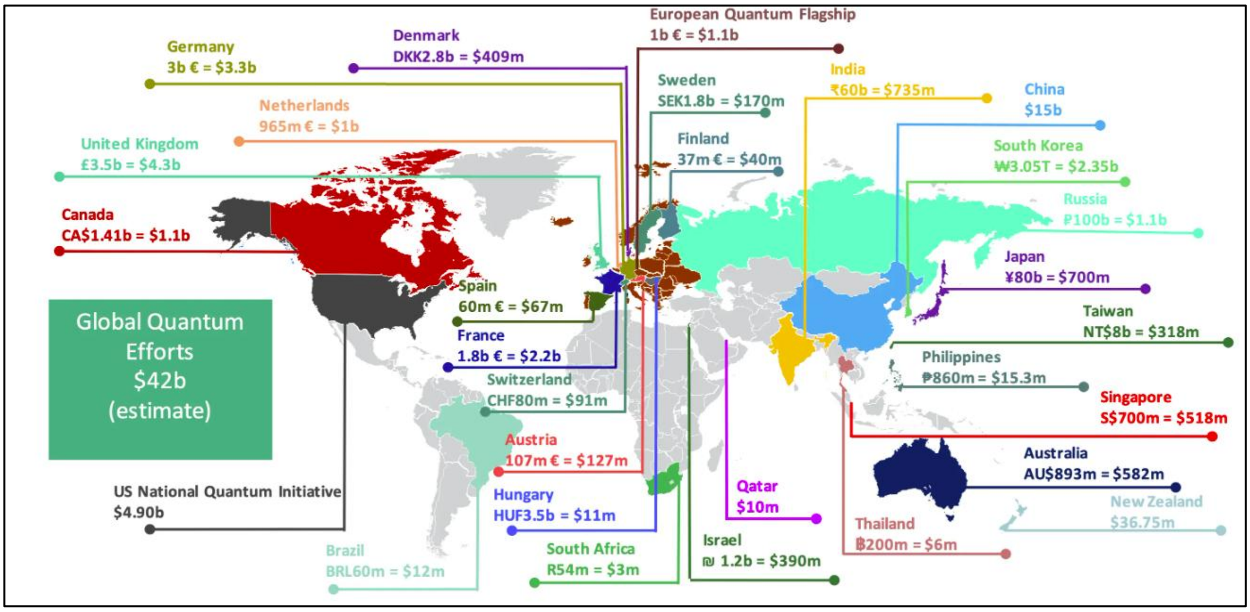

Fig. 7 World Map depicting countries and their investment in quantum technologies

It is planned to build a quantum computer with about 50-100 qubits and achieve quantum communication across 7000 kms. In addition, Russia is looking for active collaborative efforts with India and China regarding development of QT[30].

[30] Russian scientists eye Brics (Brazil, Russia, India, China and South Africa) quantum lab:

http://timesofindia.indiatimes.com/articleshow/102328661.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst

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3.0 Landscape of Quantum Technology in India

The contributions of Indian researchers to the field of quantum mechanics are widely acknowledged, with prominent examples including those of Prof. S.N. Bose and Sir C.V. Raman, among many others.

- Beyond any ambiguity various experiments have confirmed that all observed elementary particles in nature are described by the principles of quantum mechanics. All the known particles in this vast universe are broadly classified either as Bosons, named after S. N. Bose or Fermions.
- Raman Effect plays an important role in understanding light scattering and quantum effects at the molecular level.

Over the years, many Indian researchers have significantly contributed to the transition of quantum mechanics from theoretical understanding to practical technological applications. From the outset, the Indian research community has recognized the transformative role of quantum mechanics in information processing and computing, actively advancing the field to its current level of maturity. Notably, the strong community in quantum optics and mathematical physics in India has been instrumental in fostering the growth of quantum information research. Today, numerous research groups across the country are studying quantum information theory, with several recent initiatives focused on developing technology for quantum devices. Recognition of the emerging trend and long-term impact of quantum technology by Indian science and technology organizations has led to several pilot projects in the country over the past few years, fostering an ecosystem for a comprehensive quantum technology development program. Today, this has resulted in the launch of an ambitious National Quantum Mission by the Department of Science and Technology, Government of India. However, compared to various other countries which have similar programs towards developing quantum technology and creating an ecosystem for the same, we still have a long way to go. Our available human resource for developing QT is still many folds smaller than required to make a big impact. The number of research groups is still very small and funding investment towards research and development is still meagre when compared to the investments made by other economically better countries. In addition to the National quantum mission, state governments and industry should in parallel invest both toward research and development and to train human resources to contribute to the field.

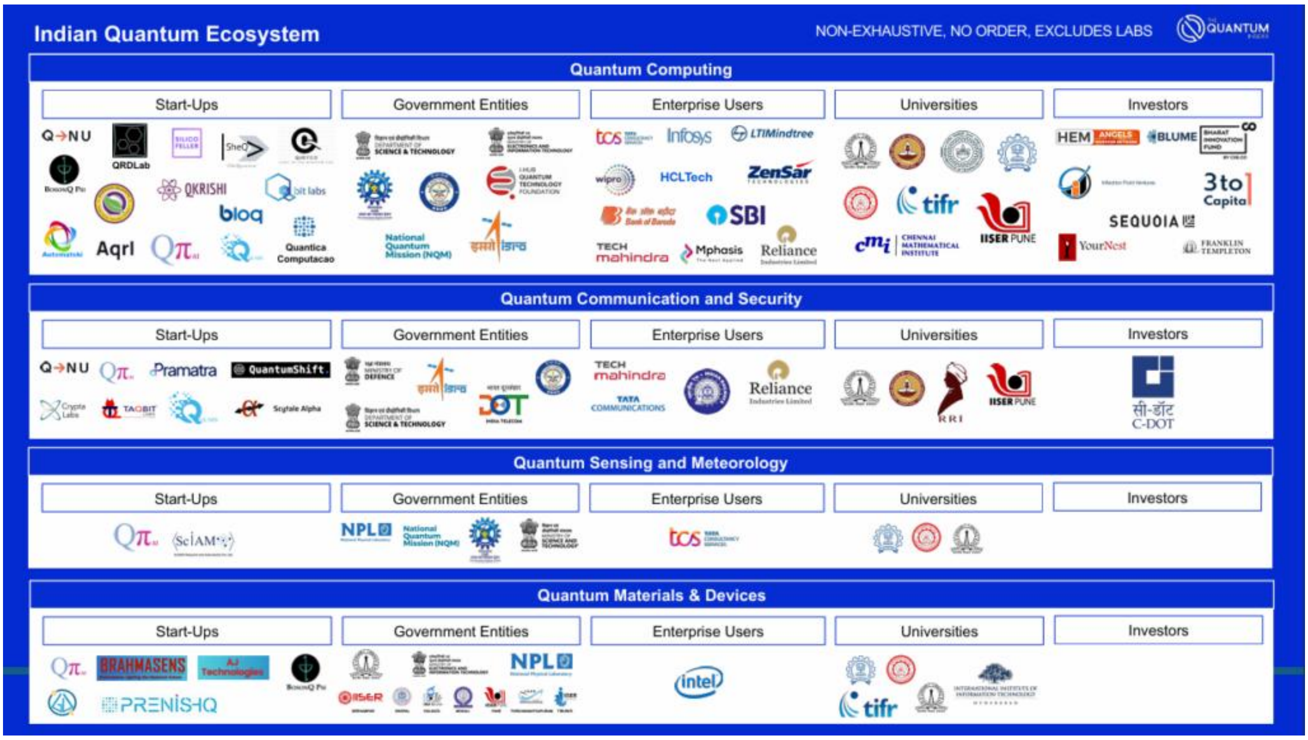


Fig. 8 Indian Quantum Ecosystem : Representing various verticals and horizons of the quantum sectors excluding R&D labs
Image Credit: Quantum Insider, 27 Nov 2024

3.1 Academic and research institutes landscapes

In comparison to many countries with smaller economies and fewer researchers, India's quantum information community is relatively small, comprising approximately 110 principal investigators and independent researchers, including those in universities and some with overlapping interests. This limited representation is evident even within prominent Indian scientific research institutes and organizations.

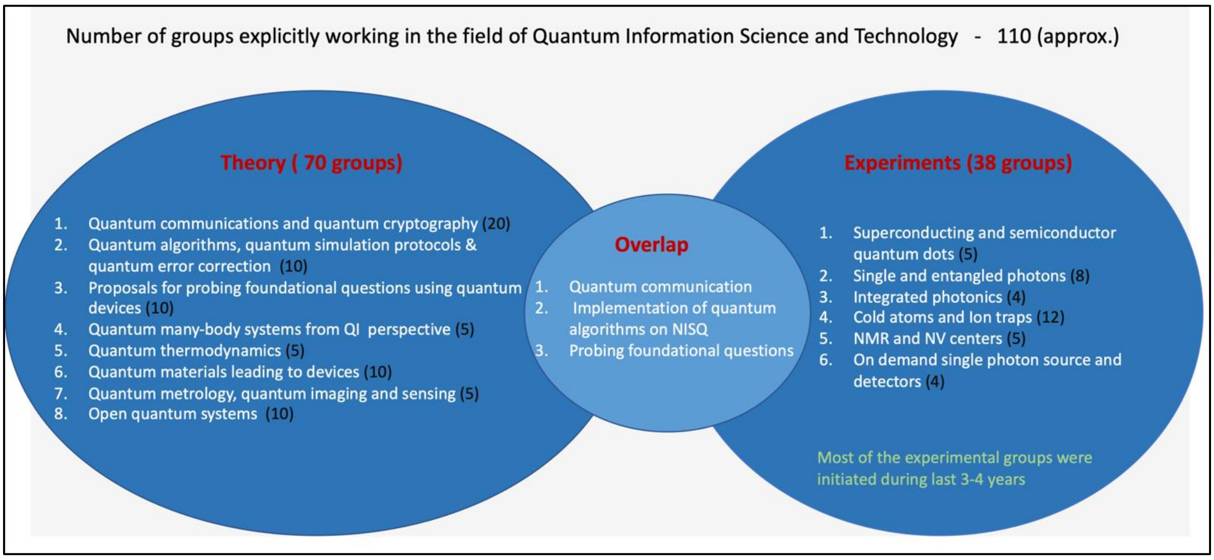


Fig. 9 Number of Groups explicitly working in the field of Quantum Information Science and Technology – 110 (approx.)

Tab.1 Research topics and the number of academic groups contributing to the advancement of quantum technologies.

Institute	Areas of Research
Indian Institute of Sciences, Bengaluru	1. Superconducting qubits 2. Experiments with single & entangled photons (Photonic qubits / computation) 3. Quantum algorithms 4. Integrated photonics 5. Quantum materials
Indian Institute of Technology, Madras (is part of IBM quantum network)	1. Quantum many bodies system from Quantum information perspective 2. Quantum error correction 3. Quantum communications (Fiber based, weak coherent pulse) 4. Integrated photonics
Tata Institute for Fundamental Research, Mumbai	1. Superconducting qubits Quantum communication (QKD) 2. Trapped Ions 3. Quantum Materials
Indian Institute of Science Education and Research - Pune	1. Cold atoms and Ion traps 2. NMR and NV center systems 3. Quantum sensing using cold atoms
Indian Institute of Science Education and Research - Mohali	1. Quantum information processing using NMR 2. Experiments with single and entangled photons (quantum imaging) 3. Quantum Information theory
Raman Research Institute, Bengaluru	1. Quantum communications (free space, entanglement-based protocols) 2. Cold atoms and Ion traps
Physical Research Laboratory, Ahmedabad	3. Quantum communications (free space, entanglement-based protocols)
Harishchandra Research Institute (HRI) - Allahabad Indian Statistical Institute, Bose Institute - Kolkota, Institute of Mathematical Sciences Chennai, IIIT Hyderabad, IISER-Trivandrum, IIT-Jodhpur, SN Bose Centre for Basis Sciences	1. Many body quantum systems from quantum information perspective 2. Quantum Information theory, Quantum algorithms, 3. Quantum cryptography and quantum communication protocols
Indian Institute of Technology, Mumbai	1. NV centers 2. Semiconductor based qubits 3. Quantum thermodynamics 4. Quantum materials

Institute	Areas of Research
Indian Institute of Technology, Kanpur	1. Experiments with entangled photons (OAM states and other quantum optics experiments)
Indian Institute of Technology, Delhi	1. Quantum communication (using weak coherent pulse) 2. Experiments with single and entangled photons
Raja Ramanna Centre for Advanced Technology, Indore	1. Atom optics, Cold atoms and Ion traps, cold atom gravimetry 2. Quantum Metrology, sub-SQL interferometry 3. Squeezed light source development
Bhabha Atomic Research Center, Mumbai, Defence Institute of Advances Technology Pune, IUCAA - Pune, NPL- Delhi	1. Cold atoms and Ion traps 2. Quantum sensing using cold atoms 3. Atom-Optics experiment using **"trapped-ion optical clock"** 4. Quantum nano-photonics metrology
Other IITs, IISERs, Universities, Govt. R & D laboratories	1. Four to six PIs explicitly work in the field of quantum information theory and closely related experiments.

The Indian research community has made significant contributions to foundational and theoretical understanding, with somewhat less focus on experimental work. Significant theoretical advancements have been made in characterizing and understanding entanglement, quantum information processing tasks and quantum computations.

The following are the key research areas in which the Indian scientific community is well-represented:

1. Quantum Entanglement Theory
2. Foundations of Quantum Mechanics
3. Quantum Open Quantum Systems and Thermodynamics
4. Many-Body Qunatum Information
5. Quantum Algorithms
6. Quantum Simulations
7. Topological Methods and Quantum Error Correction
8. Quantum Communications including Quantum Cryptography
9. Continuous Variable Qunatum Information

It is essential to expand into underrepresented areas such as computational models, architectures, photon-based technologies, quantum memory, quantum measurements, sensing, and imaging (quantum metrology).

Various government programs have already initiated efforts in these domains.

3.2 Programs launched by various Indian government organizations

3.2.1 Quantum Enabled Science and Technology (QuEST), Department of Science and Technology (DST), Inida.

Launched in 2019, QuEST aims to enhance the capabilities of Indian research groups in the broad field of quantum technology. Following a peer review process, a total of 51 projects were supported. They were categorized into four themes:

A. Quantum Information Technologies with Photonic Devices (24 projects).
B. Quantum Information Technologies with Nitrogen Vacancy and Magnetic Resonance (9 projects).
C. Quantum Information Technologies with Ion-trap and Optical-lattice Devices (9 projects).
D. Quantum Technologies with Superconducting Devices & Quantum Dots (9 projects).

These initiatives by the Department of Science and Technology (DST) have paved the way for the evolution of the program into a large-scale national mission. Research groups and various government organizations collaborated to develop a detailed project report for the National Quantum Mission (NQM) under DST guidelines. This was overseen by Principal Scientific Advisor (PSA) to the Government of India. In 2023 it was approved by the Union cabinet and put to motion almost immediately.

3.2.2 National Quantum Mission (NQM), Department of Science and Technology (DST), India

The goal of the National Quantum Mission (NQM), which the Union Cabinet authorized on April 19, 2023, is to seed, nurture, scale up scientific and industry R&D, and establish a vibrant and inventive ecosystem in quantum technology (QT). The NQM is approved by Govt. of India at a cost Rs. 6003.65 crore from 2023–2024 to 2030-2031. This would foster the nation's ecosystem, spur economic growth driven by quantum technology, and position India as a pioneer in advancing quantum technologies and applications (QTA). The Mission's goals include creating intermediate-scale quantum computers in eight years using 50–1000 physical qubits across various platforms, including photonics and superconducting technologies. Long-distance secure quantum communications with other nations, inter-city quantum key distribution over 2000 km, multi-node secure quantum communications, and satellite-based secure quantum communications between ground stations within India, among the Mission's products are quantum networks with quantum memories.

Four Thematic Hubs (T-Hubs) in the following disciplines are established at prestigious academic and national R&D institutes as part of the mission implementation. The hubs will encourage R&D in assigned areas and concentrate on producing new knowledge through basic and applied research under the verticals:

1. Quantum Computing
2. Quantum Communication
3. Quantum Sensing & Metrology
4. Quantum Materials & Devices

3.2.3 Activities of Defence Research and Development Organization (DRDO)

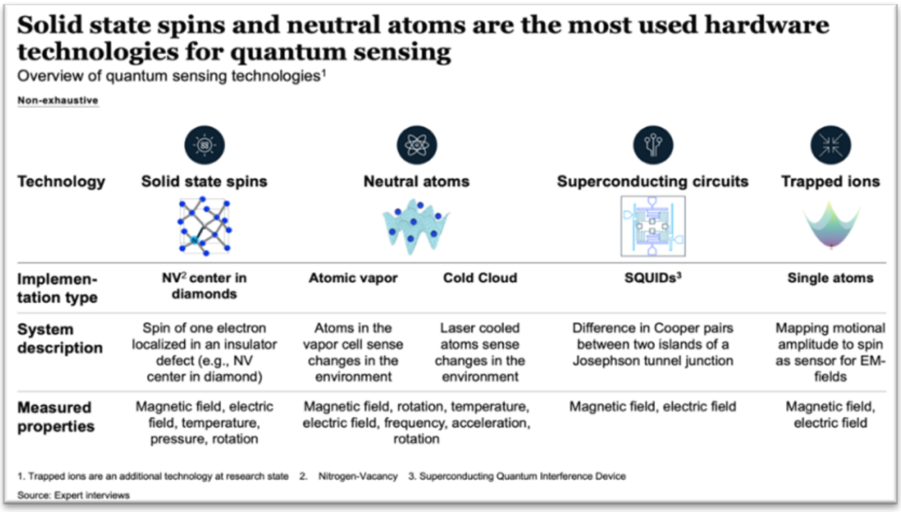
a) ***DRDO Young Scientist laboratory – Quantum technology:*** Established to foster young talent, DRDO Young Scientist Laboratory focuses on developing cutting-edge solutions in areas such as quantum computing, quantum cryptography, and quantum sensing. By providing a platform for young scientists to explore and experiment, the laboratory seeks to enhance India's capabilities in quantum technologies.

b) A 6-qubit superconducting quantum computer has been developed by the Defence Research and Development Organisation (DRDO) in collaboration with the Tata Institute of Fundamental Research (TIFR) and Tata Consultancy Services (TCS). This state-of-the-art quantum computer leverages superconducting circuits to manipulate quantum bits (qubits), enabling advanced quantum computations. The collaboration combines expertise from research and industry, aiming to enhance India's capabilities in quantum technology.

3.2.4 Quantum Technology Centers at IISc (Quantum Sensing) and IIT Delhi (Quantum Communication)

The Quantum Technology Center at the Indian Institute of Science (IISc) focuses on quantum sensing, exploring advanced techniques for measuring physical quantities with unprecedented precision. Researchers at this center work on developing sensors that leverage quantum principles to enhance capabilities in areas such as navigation, biomedical imaging, and environmental monitoring.

At IIT Delhi, the Quantum Technology Center specializes in quantum communication, aiming to develop secure communication systems based on quantum cryptography. This center is dedicated to advancing research in quantum key distribution and other protocols that utilize quantum mechanics



Solid state spins and neutral atoms are the most used hardware technologies for quantum sensing

Overview of quantum sensing technologies[1]

Non-exhaustive

Technology	Solid state spins	Neutral atoms		Superconducting circuits	Trapped ions
Implementation type	NV[2] center in diamonds	Atomic vapor	Cold Cloud	SQUIDs[3]	Single atoms
System description	Spin of one electron localized in an insulator defect (e.g., NV center in diamond)	Atoms in the vapor cell sense changes in the environment	Laser cooled atoms sense changes in the environment	Difference in Cooper pairs between two islands of a Josephson tunnel junction	Mapping motional amplitude to spin as sensor for EM-fields
Measured properties	Magnetic field, electric field, temperature, pressure, rotation	Magnetic field, rotation, temperature, electric field, frequency, acceleration, rotation		Magnetic field, electric field	Magnetic field, electric field

1. Trapped ions are an additional technology at research state 2. Nitrogen-Vacancy 3. Superconducting Quantum Interference Device

Source: Expert interviews

Fig. 10 Solid state spins and neutral atoms are widely used in hardware technologies for quantum sensing

to ensure secure information transfer, with potential applications in defense, finance, and telecommunications. Together, these centers represent India's commitment to advancing quantum technologies for a range of practical applications.

3.2.5 Ministry of Electronics and Information Technology (MeitY)

MeitY has launched several initiatives to promote the development and application of quantum technologies:

- It is a part of the broader national initiative to establish a Quantum Mission aimed at advancing research, development, and application of quantum technologies, including quantum computing, communication, and sensing.

- Provides funding support for various research projects and collaborations between academic institutions and industry to foster innovation in quantum technologies.
- The Ministry is also focused on building a skilled workforce by offering training programs and workshops on quantum computing and related fields to students and professionals.
- MeitY supports the creation of Centers of Excellence in quantum technologies at leading institutions to facilitate cutting-edge research and development.

MeitY has supported the establishment of a multi-institutional Center of Excellence in Quantum Technology at the Indian Institute of Science (IISc). The three institutes that are part of the center are IISc, Centre for Development of Advanced Computing (CDAC) and Raman Research Institute (RRI), which are based in Bengaluru. This Center of Excellence focuses on developing superconducting Qubits, quantum simulators and quantum communication.

Furthermore, CDAC, a body under MeiTY, has its own quantum accelerator project and they are in the process of setting up a superconducting quantum computing facility at their electronic city campus in Bengaluru.

3.2.6 Projects on Quantum Key Distribution in collaboration with Department of Space (DOS)

On January 27, 2022, researchers from two leading laboratories of the Department of Space (DOS)—the Space Applications Centre (SAC) and the Physical Research Laboratory (PRL)—successfully showcased real-time Quantum Key Distribution (QKD) based on quantum entanglement over a 300-meter atmospheric channel. This milestone included the secure transmission of text and images, along with quantum-assisted two-way video calling. The demonstration was conducted at SAC in Ahmedabad, linking two buildings that were 300 meters apart, representing a significant advancement in quantum communication technology.

The Quantum Experiments using Satellite Technology (QuEST) project is a collaborative effort between the Raman Research Institute (RRI) and the UR Rao Satellite Centre of ISRO, initiated in 2017. The project aims to explore and implement quantum communication technologies using satellite systems. Specifically, it focuses on demonstrating quantum key distribution (QKD) over long distances, which is essential for secure communication. In April 2023, a successful demonstration of secure communication was achieved between a stationary source and a moving receiver using Quantum Key Distribution (QKD). This breakthrough demonstration could pave the way for secure ground-to-satellite quantum communication in the future. The new program to launch Quantum Satellite for Secure Applications using Quantum and Optical Technologies (SAQTI) and Opto Quantum Communication satellite is also conceived by ISRO in coming days. This mission aims to demonstrate satellite-based quantum communication and satellite based optical communication through Low Earth Orbiting Platforms. Additionally, it aims to perform QKD between Indian ground stations along with high-speed data communication between Space to ground and ground to space.

3.2.7 Department of Telecommunication - National Working Group on Quantum Technology (NWG-QT)

The Telecommunication Engineering Centre (TEC) of the Department of Telecommunications has established a *National Working Group on Quantum Technology (NWG-QT)* during 2022 to create a focused and coordinated strategy for developing standards in Quantum Technology and to contribute to global standardization efforts, while prioritizing national interests.

The NWG-QT aims to engage all stakeholders in Quantum Technology, including academia, industry, startups, research and development organizations, service providers, and government entities, to collaboratively develop standards in this domain.

3.2.8 The Quantum Research Park (QuRP)

The Quantum Research Park (QuRP), a center for quantum computing and related technologies, is managed by the Foundation for Science Innovation and Development (FSID) at IISc, with support from the Karnataka Innovation and Technology Society (KITS) under the Government of Karnataka. It engages in a variety of activities like Q-Daksha Student Internship Program (to provide opportunity for aspiring students to engage and witness Quantum Technology research at IISc.), Q-Karyashala (Workshop for providing hands-on training and education to students, researchers, and professionals interested in quantum technology), QuanTalks (a series of discussions and seminars featuring expert speakers from academia, industry, and research who share insights on recent advancements, research findings, and future directions in quantum science and technology) and so on.

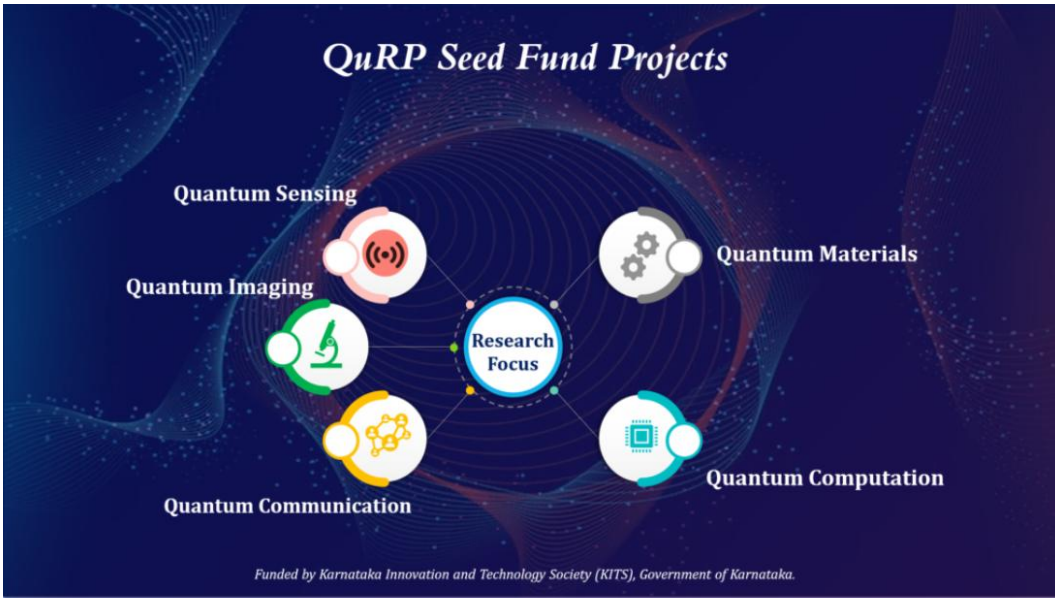


Fig. 11 QuRP seed fund projects - different fields

3.2.9 Private Sector and Start-ups

India's quantum technology ecosystem is rapidly developing, driven by both government initiatives and private sector innovation. Several key industries, ranging from established tech giants to emerging startups, are focusing on a wide array of quantum-related fields including quantum computing, quantum cryptography, communication, and sensing. Some notable programs and initiatives are listed here:

- **Tata Consultancy Services (TCS)**: TCS has been developing a **Quantum Computing Platform** to integrate quantum technology into business processes, aiming to solve problems that are computationally intractable for classical computers. Towards this direction, TCS has partnered with leading global quantum research labs and institutes, including IITs and IISc, to build a talent pool in quantum technologies.
- **HCL** has partnered with global tech giants like IBM and Google to tap into quantum computing capabilities with a focus on transforming the software solutions they provide to clients in sectors like banking, energy, and healthcare using quantum technology.
- **Wipro**: Headquartered in Bangalore, Karnataka, India, the multinational corporation Wipro is exploring the use of quantum computing for industries such as finance, healthcare, energy, and

logistics. Wipro has signed a Memorandum of Understanding (MoU) with Tel Aviv University for research and analysis in quantum science and technology. According to the MoU, Tel Aviv University's Center for Quantum Science & Technology (QuanTAU) faculty members will work with Wipro to analyse potential applications of quantum computing for its largest clients.

- **Infosys:** *Infosys Quantum Living Labs (QLL)* is an initiative by Infosys that provides clients with a platform to explore and implement quantum computing use cases, accelerating the adoption of quantum technologies across industries. QLL offers a collaborative environment where businesses can experiment with the all-powerful quantum advancements, solve complex challenges, and develop practical solutions leveraging quantum computing.
- **QNu Labs, Bengaluru** (https://qnulabs.com)**:** An Indian startup, launched during 2016, focuses on developing quantum-safe cryptographic solutions. QNu Labs is helping businesses and governments secure their communications and digital infrastructure in the emerging quantum era. They have developed experimental kits for exposing UG/PG students on QI protocols.
- **QpiAI, Bengaluru** (https://qpiai.tech): A start-up company (established during 2019) QPiAI focuses on leveraging quantum computing and artificial intelligence (AI) so as to create innovative solutions in various industries.
- **BosonQ Psi, Bengaluru** (https://www.bosonqpsi.com/): Founded in 2020, BosonQ Psi is focusing on the development of quantum-powered engineering simulation software called BQPhy. **(**The name BosonQ Psi pays tribute to the great Indian physicist Dr. Satyendra Nath Bose).
- **QRDLab**, **Kolkata** (https://www.qrdlab.in/)**:** This company is an industry-first initiative promoting quantum education, research and consultancy in different areas of quantum computing. QRDLab aims towards translating nascent research ideas and advancing entire Quantum Computing technology stack in India.
- **QuLabs, Hyderabad** (https://qulabs.ai/): Started in 2018, QuLabs Software (India) Pvt. Ltd. aims to create a completely secure internet and communication at optimal speed and security.
- **Mphasis** (https://www.mphasis.com/), an applied technology services company based in Bengaluru, has partnered with IIT Madras to foster innovation and support the growth of startups, develop talent, and

provide scholarships. This collaboration aims to create a robust ecosystem for emerging technologies, including quantum computing, and AI. By funding startups and supporting research initiatives, Mphasis and IIT Madras are working together to accelerate technological advancements and help scale solutions.

In summary, India is well on its way to making substantial contributions to the global quantum revolution, with real-world applications set to emerge during next two decades.

4.0 Establishing Karnataka as a premier destination for quantum technologies

Establishing Karnataka as a premier destination for quantum technologies requires a comprehensive strategy that fosters sustainable talent development, collaboration between academia, industry & government state-of-the-art infrastructure, innovation hubs & outreach activities.

4.1 Sustainable talent development

The rapid expansion of knowledge in fields like quantum technology (QT), artificial intelligence (AI), and biotechnology (BT) has a profound impact on the development of new, realizable technologies. As these advancements translate into innovative products and services, they reshape industries, requiring a highly skilled workforce to harness their potential. The ability to adapt to and leverage these technological changes is crucial for ensuring sustained economic growth and global competitiveness. As such, it is essential to identify emerging research trends and technologies in order to align workforce demand and supply, ensuring a smooth transition without disruptions, and to mitigate the risk of falling behind in the rapidly evolving technological landscape. Sustainable talent development for quantum technology in Karnataka requires a multi-pronged approach, involving education, hands-on experience, industry-academia collaboration, and long-term policy support.

Quantum technology has emerged through the domain of quantum information science, which forms the foundation for advancements in areas like quantum computing, quantum cryptography, and quantum communication. As such, quantum theory when studied in the language of information theory brought forth a whole new dimension in the way we see the world around us. Many queer aspects such as the Uncertainty relation, Superposition/Coherence, Entanglement were seen as resources through which real time applications in the security of communication, simulation of microscopic happenings etc. could be envisioned.

The early quantum revolution started around the first quarter of the 20th century with the famous names of Max Planck, Albert Einstein, Werner Heisenberg, Erwin Schrodinger, Paul M Dirac, Max Born, etc. to name a few. This led to the then technological revolutions ushering in the laser, atomic clocks, semiconductors, medical imaging devices like the MRI. At the turn of this new century, however, revisiting foundational aspects of quantum theory gained much importance and has led to what is being considered as the *second quantum revolution*.

It becomes pertinent and timely to create awareness amongst the various stakeholders regarding the disruption in the skilled workforce due to the rise of quantum technology. Here are some points of concern substantiating this:

- **Talent gap:** Even though harnessing all the quantum advantage in technology domains is still in its nascent stage, addressing talent gap to equip the workforce to be quantum ready is of high priority and has the potential to impact the economy of a nation. The article titled *"Quantum computing funding remains strong, but talent gap raises concern"* [31] (June 15, 2022), written by Mateusz Masiowski, Niko Mohr, Henning Soller, and Matija Zesko, addresses the growing concerns about the talent gap in the quantum technology landscape.
- **Educational and training challenges:** The rapid pace of quantum technology is creating an increasing demand for a highly specialized workforce. The lack of qualified personnel could slow down advancements and limit the potential development of the technologies. This emphasizes the pressing demand for targeted initiatives towards educational reforms, training programs, and stronger industry-academia collaboration to prepare the next generation of quantum professionals. Designing educational programs and training initiatives to effectively prepare the workforce with required skills for quantum-related roles is the need of the hour.

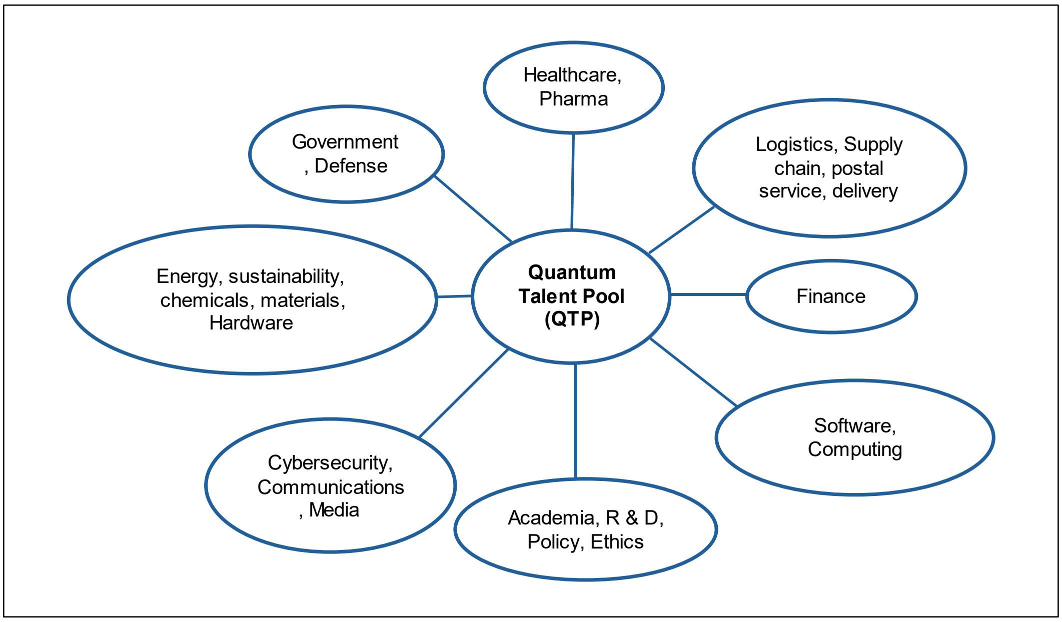


Fig. 12 Quantum Technology Protocol

[31] Mateusz Masiowski, Niko Mohr, Henning Soller, and Matija Zesko, "Quantum computing funding remains strong, but talent gap raises concern", June 15, 2022.

- **Access to Infrastructure**: Limited access to quantum technology infrastructure could restrict the ability of organizations to keep up with developments in the field, further increasing disparities in workforce readiness.
- **Networking**: Limited access/opportunities to meet the resource persons and discuss the direction of projects, training-young scholars on various aspects of QT.

Furthermore, the rapid development of quantum technology presents challenges in predicting its full impact. The workforce may need to adapt quickly to new discoveries and breakthroughs. The following three examples correspond to comprehensive talent development and sustainability programs envisioned with the focus of developing and making the talent pool quantum ready for the future, overcoming the deficiency of the required skilled workforce.

A. **The United States of America**: National security being one of their focus areas, one of the main tasks to create, foster and nurture and retain talent is in building workforce to drive national and global innovation and security (https://www.fdd.org/analysis/op_eds/2024/05/09/quantum-talent-development-retention-a-strategy-for-national-security/).
Starting with K-12 (the equivalent of the Pre-University Course) they have initiated programs like ***Pathways to Quantum* (**https://www.pqic.org/pathways***)*** to *"…. provide students with an introduction to quantum via a virtual course, followed by a week-long in-person experience visiting workplaces engaged in different parts of the quantum ecosystem including business and marketing, communications, policy, research, and more. Previous sites included IonQ, The MITRE Corporation, George Mason University, and the University of Maryland, Information Technology and Innovation Foundation, and George Washington University."*

B. **Singapore**: Singapore has started, the National Quantum Computing Hub (NQCH) which is a joint initiative of the Centre for Quantum Technologies at the National University of Singapore, the Institute of High-Performance Computing at the Agency for Science, Technology and Research (A*STAR) and the National Supercomputing Centre Singapore. The idea being to build capabilities, foster community and collaborations for entering the next era of computing. Under NQCH, *Quantum Talent* is an online learning platform (https://qutalent.org/en/) *"…with the aim of bolstering new and growing communities by sharing information about the world of quantum computing both locally and internationally. Quantum Talent offers interactive online short courses as well as stand-alone videos on a growing list of topics."*

C. **Netherlands** (https://quantumdelta.nl/)*:* The Dutch think that *"quantum revolution is a scientific, engineering and commercial challenge unlike any other in history***. Quantum Delta NL** *is well-positioned to contribute to a historic opportunity in quantum by accelerating quantum technology developments in the Netherlands and establishing a collaborative ecosystem that fosters international collaborations with the world's top scientific institutions, businesses, students, and professionals."* They have initiated the ***Quantum Delta NL*** empower the career with the quantum advantage. The three centers at Delft/Leiden, Amsterdam, Twente and Eindhoven aim at training students and teachers through facilitating projects and internships to make them ready for a quantum professional environment, create atmosphere to translate scientifically acquired knowledge into practical applications, link Netherlands' educational institutions with quantum and related technology companies. The unique point of this endeavour being that "*Regional centres work closely together with both regional educational institutions and with partners from industry and other societal stakeholders*."

Karnataka, particularly Bengaluru, leveraging its strong academic, research, and industrial ecosystem, has begun with significant strides in the field of quantum technology. Bengaluru's status as India's *Silicon Valley* has been instrumental in attracting major tech players such as IBM, Intel, and Microsoft, who have initiated collaborations with local academic institutions to foster quantum research. Here are a few notable developments in this connection:

- ***Quantum Research Park (QuRP)***: The foundation for science innovation and development, Indian Institute of Science (IISc) along with Karnataka Innovation and Technology Society, Government of Karnataka formed the hub ***QuRP*** to create and inspire scientific innovation in the field of quantum computing and related technologies. QuRP envisions skill development, mentorship, and industry/startup collaborations in quantum technologies. They arrange Q-Karyashala workshops, Q-Daksha internship program and popular science talks (QuanTalks).

a) ***Q-Daksha:*** The highlight of this program being that it is earmarked for students from Karnataka only (with the eligibility being third- or fourth-year BE/BTech students or first or second year MSc/MTech pursuing students are eligible. The course duration is 4-8 weeks).

b) ***Q-Karyashala*****:** A workshop aimed to deepen understanding of quantum technology related topics with pedagogical talks from experts, lab visits, hands on and interactive sessions. The eligible participants being senior undergraduate, postgraduate, and research students, faculty, and researchers from Karnataka, along with industry experts.

- **Educational Programs in Quantum Technology :**
  MTech in Quantum Technology at the **Indian Institute of Science (IISc), Bengaluru**. This is one of the premier post-graduate-level courses (2021 onwards) designed to address the growing demand for skilled professionals in quantum technologies. This course offers an excellent opportunity for students to specialize in one of the most transformative and high-impact fields of modern science and technology. By providing both strong theoretical foundations and practical training, the program prepares graduates to contribute significantly to the rapidly advancing quantum technology sector. Other programs include M.Tech in Quantum Technology program at **IIST, Thiruvananthapuram**; **IISER Pune** has started MS program in Quantum Technology in 2024. **IIT Delhi** offers a certification program in quantum computing and machine learning. **IIT Madras** is offering quantum science and technologies as a specialization in their dual-degree program. Recently. **All India Council for Technical Education (AICTE)** and the Department of Science and Technology (DST) have unveiled a model curriculum for an undergraduate (UG) minor programme in quantum technologies.

For Karnataka to establish itself as a premier destination for quantum technology, a holistic approach that involves strengthening research infrastructure, developing a skilled workforce, fostering industry-academia collaborations, and supporting quantum startups is essential.

With its strong tech ecosystem, academic institutions, and government support, Karnataka is well-positioned to become a global leader in the quantum technology space. Here are some specific suggestions to create innovative ecosystem and sustainable talent development in Karnataka:

<u>**Na**mma **Qu**antum Science & **T**echnology **T**raining **I**nstitute **(NaQu TanTI)**</u>

- **ನಾಕು ತಂತಿ (NaQu TanTI) Regional hubs for Quantum Technology across Karnataka**: To create a robust ecosystem for quantum technology and develop sustainable talent in Karnataka, establishing regional centers across the state can play a crucial role.

- Hubs for skill development in quantum technology may be initiated at four key regions across Karnataka viz., Hubli/Dharwad, Mysore/Bengaluru, Chitradurga and Mangaluru/Udupi naming them as ನಾಕು ತಂತಿ (NaQu Tanti) of quantum technology. These regional hubs create an inclusive, sustainable ecosystem giving access to emerging fields like quantum technology to younger generation throughout Karnataka.

  i. **ನಾಕು ತಂತಿ-(NaQu TanTI)** regional hubs should focus on recruiting highly skilled, dedicated, and ethically grounded team of research faculty. It must be equipped with state-of-the-art - laboratories and provide efficient, high-speed processes for ordering, procuring, and repairing equipment. The centers should also prioritize nurturing students with a motto of becoming experts in a specific area while possessing a broad understanding of various related fields.
  ii. **ನಾಕು ತಂತಿ-(NaQu TanTI)** regional innovative hubs could create platforms for the ease of access of quantum science and technology knowledge and awareness programs for seeding, nurturing and developing regional and local students. Regional students should feel more supported and encouraged to thrive in quantum technology, in contrast to the often intimidating and overwhelming environment of established urban research institutions.
  iii. State Universities of Karnataka should be closely connected to **ನಾಕು ತಂತಿ-(NaQu TanTI)** innovative hubs for quantum technology, with the goal of evolving into centers of excellence for quantum technology in the coming years.
  iv. Regional and decentralized quantum startups should be actively encouraged and supported by **ನಾಕು ತಂತಿ-(NaQu TanTI)** hubs, fostering innovation and entrepreneurship in local communities. These initiatives can empower women and non-binary

individuals by providing equal employment opportunities in the quantum technology sector[32]. Additionally, the growth of quantum startups can contribute to the local economy by creating jobs, boosting regional tourism, and attracting talent and investment to the area, ultimately driving economic development in the region.

v. Quantum Research-Education-Advancement-Programme (Q-REAP) analogous to the JN Planetarium, Bengaluru's REAP[33] with a focus on creating quantum science and technology education awareness for region specific undergraduate students could be organized by ನಾಕು ತಂತಿ.

vi. Developing ನಾಕು ತಂತಿ website along the lines of the ***Quantum Talent*** (https://qutalent.org/en/) of Singapore or the quantum delta NL (https://quantumdelta.nl/) of the Netherlands catering to the development and sustaining the awareness of quantum technology initiatives. This website should be hosting contents developed through several talks, courses, quizzes etc.

vii. **Introducing and offering Quantum science and technology as a specialization course in MSc programs and embedding it as a necessary paper in all the streams of Engineering giving importance alongside to AI/machine learning as well**. Along with quantum technologies, machine learning aspects too need to be focused and developed. As such, a new course streamlined to cater to feed the requirement of a skilled workforce could well be focused on Quantum science and technology empowered with machine learning aspects.

However, Karnataka should highlight the importance of funding basic research on quantum foundations and not abandon it. In fact, this funding for quantum foundational research was what Europe did (from late 90s till early 2020s) before the push for investing towards commercial realization of quantum technology got started from industry and government initiatives alike.

[32] According to The Economic Survey 2023-24, more than 45% of the recognized start-ups are emerging out of tier two/three cities & more than 47% of the recognized start-ups have at least one-woman director.

[33] REAP at JN Planetarium is held concurrently with regular under graduate college education for interested students for 3 years only during weekends.

4.2 Fostering national/international collaboration between academia, industry and the government

Any serious attempt to attract and hold the attention of young talent in the field of quantum technologies (or any other, for that matter) must include an element of innovation. This is to happen at the industrial scale, which requires collaboration between all stakeholders, namely, the government and industry, and above all, the academics. In particular, academics must note several recent government initiatives in this direction, including setting up of research parks at institutions of national importance, that already provides a framework for establishing good collaboration.

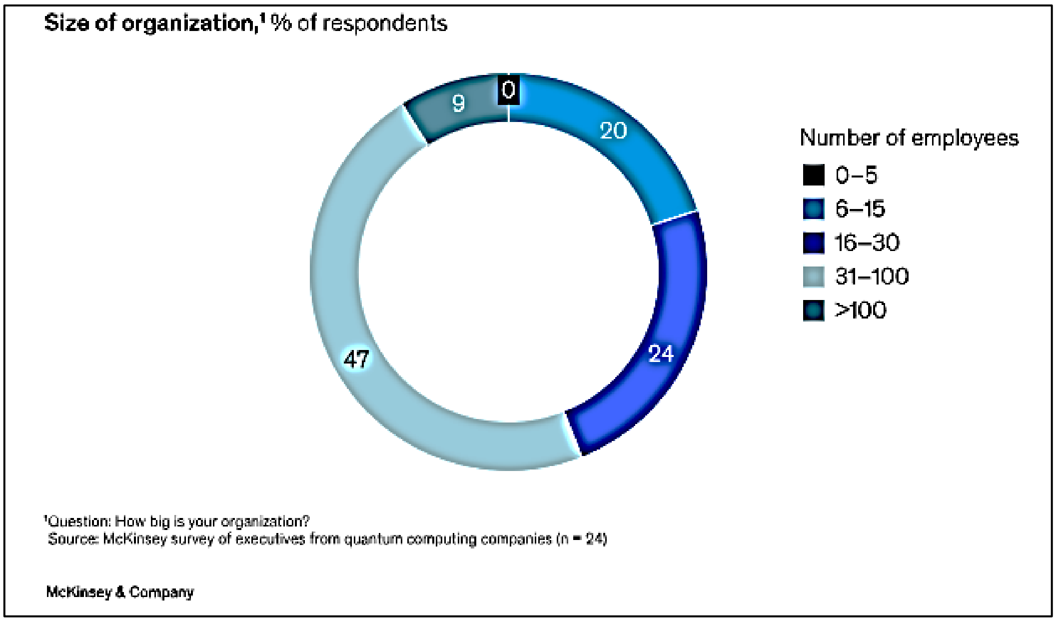


Fig. 13 Size of organization, 1 % if respondents

[1]Courtesy: Quantum computing: The time to act is now, McKinsey & Company, Quantum Technology Monitor - February 2024

The lack of collaboration between traditional academic institutions and large governmental or industrial organizations is a significant challenge. This disconnect results in missed opportunities for innovation, commercialization, and the growth of high-tech industries. To address this, a three-pronged policy strategy could be implemented to foster collaboration and accelerate advancements in quantum technology.

I. **Policies Enabling Industry:** Government of India has recently emphasized the need for rapid and larger-scale innovation, for which traditional industrial setups lack the technical expertise, entrepreneurial leadership, and laws. Recognizing that startups could fill this gap has led to a number of initiatives, which can potentially be aided by the involvement of academia.

A. **Startup India Initiative:** This flagship program, launched in 2016, aims to promote entrepreneurship and innovation by providing various benefits like tax exemptions, self-certification compliance, a dedicated Startup India Hub, and access to government schemes. Under the Digital India campaign, tech startups are encouraged to promote digital infrastructure. Many states, such as Karnataka and Telangana, have their startup policies, offering additional incentives and support. Such support should be extended to QT related startups.
B. **Make in India (MII):** The Make in India (MII) campaign encourages innovation within the country by enforcing specific compulsory requirements and providing incentives for setting up manufacturing units. This ultimately helps create an ecosystem for diverse and rapid innovation in many emerging areas, including quantum technology.

II. Policies Enabling Academia

A. **Atal Innovation Mission (AIM)** encourages innovation and entrepreneurship among startups, researchers, and students. It includes programs such as Atal Tinkering Labs (ATLs), e.g., at Kendriya Vidyalaya IIT Powai and Atal Incubation Centers (AICs). Students could use this to solve startup-specific problems guided by researchers.
B. **Research and Development (R&D) Support:** Various government bodies, such as the Department of Science and Technology (DST) and the Biotechnology Industry Research Assistance Council (BIRAC), provide grants and funding for R&D projects.
C. **Uchhatar Avishkar Yojana (UAY)** promotes skill development and innovation by encouraging academia-industry collaboration through funding projects that address industry-oriented problems. UAY focuses on creating solutions with the potential to be monetized.

III. Policies Enabling Collaboration

A. **Scheme for Promotion of Academic and Research Collaboration (SPARC)** promotes internationalization by encouraging collaboration between foreign institutions and Indian higher education institutions (HEIs), supporting faculty exchange, and facilitating joint research projects. IIT Kharagpur is nodal institute for SPARC.
B. **Impacting Research Innovation & Technology (IMPRINT):** IMPRINT focuses on research and development in engineering and

technology. It encourages collaboration between academia and industry to focus on R & D that addresses real-world challenges. DST, specifically Anusandhan National Research Foundation (ANRF) acts as the nodal agency for IMPRINT.

It is to be noted that on-campus research parks have been created as a platform for their researchers to collaborate and exchange knowledge with startups, industry partners, and the government. These offer mentorship, infrastructure, and networking opportunities. The IITs at Chennai, Mumbai, Delhi, Kanpur, and Kharagpur have set up such research parks.

The University Grants Commission (UGC) guidelines on a sustainable and vibrant university-industry linkage system stress the importance of creating sustainable partnerships, enlarging employability, and advancing entrepreneurship. Furthermore, the National Education Policy (NEP) 2020 can provide a basis for academic researchers, universities, and industry to participate in a flexible and dynamic multidisciplinary education system.

Facilitation for collaboration between Indian and foreign research institutions and universities by provisions for joint research projects, bilateral agreements, and student exchange programs should be utilized suitably.

Here are a few examples of projects built on successful collaborations:

A. **Smart Cities Mission**: This mission involves collaboration between academic institutions, municipal corporations, and private enterprises to make Indian cities citizen-friendly and sustainable. Projects under it include smart solutions for waste management, infrastructure, transportation, and energy-efficient consumption.
B. **National Supercomputing Mission (NSM):** A joint initiative of DST and the Ministry of Electronics and Information Technology (MeitY), the NSM involves collaboration between government institutions, IITs, NITs, and other academic research institutions to promote supercomputing research and facilities.
C. **Clean Ganga Mission (Namami Gange)** involves collaborating government agencies with academic institutions and NGOs to clean and revitalize the River Ganga. The project requires research on pollution control, water quality, and sustainable river management.
D. **National Skill Development Corporation (NSDC):** This corporation collaborates with vocational training institutes, industry partners, and universities to provide vocational training and skill development across multiple sectors. Projects under it include apprenticeship programs, skill centers, and industry-oriented certifications.

E. **Defence Research and Development Organization (DRDO)** collaborates with academic research institutions via schemes such as Grants-in-aid projects and CARS, granted via established Centers of Excellence (CoE). Projects under it mainly involve defense technology development especially in missile technology, radar systems, and cybersecurity.
F. **Partnerships between Institutes, Universities and Industry:** Joint projects focused on material science, renewable energy, and manufacturing processes, collaborative actions and programs can be taken-up on pilot mode and later worked out on scaling up the programs and projects.

4.3 Collaboration opportunities in the state of Karnataka

Advancements in Quantum Technologies rely on collaborations between various sections of society, including scientists, engineers, industrialists, government, and other organizations especially involved in academics and R&D. The primary objective of these collaborations among diverse stakeholders is to enhance the proliferation of quantum technologies, from laboratory realization to widespread commercialization. Such collaborations will give way to raising the skilled workforce and developing standards to embrace the quantum era.

Karnataka has the potential to nurture and nourish such collaborations among various sections of society:

1) World-class researchers and academicians in institutions like the Indian Institute of Science (Bengaluru), Raman Research Institute (Bengaluru), Universities (across the state), Indian Institute of Technology (Dharwad), Indian Institute of Information Technologies (Bengaluru and Dharwad), Indian Space and Research Organization (Bengaluru and other places), Defence and Research Organization (Bengaluru and other places), privately recognized universities and engineering colleges from across the state.
2) Several Information Technology Industry giants, such as Accenture, Adobe, Amazon, Capgemini, Cisco, Cognizant, Dell, Google, HCL, Honeywell, HP, IBM, Infosys, Intuit, Labs, Microsoft, Mindtree, Mphasis, Oracle, SAP Software, TCS, Tech Mahindra, Trident, Wipro, and many more, have decades of presence in the state of Karnataka.
3) Other sections of industries include biotech, finance, data and analytics, e-commerce, artificial intelligence, production companies, marketing, health & start-ups.

The academic institutions, R&D organisations and industries have great potential to collaborate, to develop and commercialize quantum technologies through investment in industry-ready quantum technologies with potential user bases. Karnataka state can potentially become a leader in hosting the cluster of companies invested in developing quantum technologies and their commercialization.

Through further encouragement from the Government of Karnataka, more Industries, especially the existing leaders in IT and aligned companies, could be encouraged to invest in developing quantum technologies in Karnataka in collaboration with the four regional hubs of quantum technology in the State.

The "vocal for local" mantra is an essential approach for fostering collaboration between local universities, R&D organisations, government bodies, and industries to address local challenges while keeping a global vision in mind. It emphasizes not just localized innovation but also positioning these solutions for international relevance and scalability. This approach can be particularly powerful when leveraged to tackle emerging technologies such as quantum technologies.

4.4 Outreach initiatives in Quantum Technology

The shortage of skilled and trained workforce in the scientific community in India is a significant hurdle for the development of quantum technologies (https://quantumcomputingreport.com/the-indian-quantum-ecosystem-2022-2023-executive-summary).To this end substantial investments must be made in educational and training programs to attract and retain talent, which is essential for sustaining and progressing quantum research. Both the central and state governments should collaborate to initiate outreach activities targeting students and the broader public, raising awareness about the vast potential of quantum technology. Such initiatives can inspire parents to encourage their children to pursue careers in this emerging field. Introducing quantum concepts at early school levels can ignite students' curiosity and passion for the technology, fostering the next generation of innovators and researchers.

Outreach programs with an objective, *to create awareness, spark interest, and build a pipeline of skilled individuals for quantum science and technology*, need to focus on educating and inspiring both young students and the general public. These programs aim to bridge the knowledge gap, highlight the importance of quantum technologies, and provide hands-on learning opportunities for all age groups.

A. **Inclusion of quantum science and technology in the school curriculum (QT - ಕಲಿ ನಲಿ):** The School education up to the higher secondary level (up to 10th standard) covers science subjects only at the basic level. Students will be able to understand the nuances of quantum physics as a foundational subject and the mathematical tools necessary to work with it when they pursue higher education. In the lower/higher secondary school level, an overview can be given to the students by including well thought out and structured lessons in the curriculum. Lessons that do not require deeper understanding of the subject but gives comprehensive introduction to the history and evolution of quantum information science & technology (QIST) are recommended. In the post-secondary level (11th and 12th; commonly named 1st and 2nd PUC), introducing one or two modules on the basic concepts of quantum science is a welcome move. United Kingdom, Australia, Germany and so on have introduced[34] quantum science in their higher secondary and post-secondary school levels, as early as 2019. Karnataka could become the first State in India to introduce dedicated modules on QIST in its post-secondary school curriculum.

B. **Q-Kalike magazine:** Science magazines play a vital role in increasing awareness, promoting education, fostering engagement and encouraging collaboration in the field of quantum information science and technology. To enhance outreach efforts, popular science publications in both Kannada and English should be promoted in schools and colleges across Karnataka. The bimonthly Kannada science magazine ***Vijnana Loka***, published by the Karnataka Science and Technology Academy (KSTA), is distributed to Pre-University and undergraduate colleges in Karnataka. This bimonthly magazine features Kannada articles related to science and technological advancements and emerging technologies.
Additionally, ***Resonance-Journal of Science Education***, published by the Indian Academy of Sciences, caters to interested students and

[34] H. K. E. Stadermann, E. van den Berg, and M. J. Goedhart, Analysis of secondary school quantum physics curricula of 15 different countries: ``Different perspectives on a challenging topic'' Physical Review Physics Education Research **15**, 010130 (2019)

teachers of science in general. The Indian Association of Physics Teachers (IAPT) also publishes a monthly bulletin ***Physics News*** covering contemporary topics. Encouragement for including devoted sections/contents on Quantum Information Science and Technology (QIST) & dedicated special issues on the subject is recommended. To this end, it may be highlighted that the IISc Quantum Technology Initiative has recently launched annual publication of ***QUANTNEWS*** (https://iqti.iisc.ac.in/iqti-newsletter/), newsletter which highlights advancements in quantum computing and outreach programs taken up at IISc. Teachers should encourage students to read these magazines regularly through science clubs to spark their interest. **ನಾಕು ತಂತಿ-(NaQuTanTI)** regional hubs may initiate publishing their QIST activities through science magazines, ***Q-Kalike*** and make it available to local students and faculty members.

C. **Q-Dhwani radio talks and podcasts**: Organizing short radio talks and creating podcasts (in both kannada and english) dedicated to quantum information science and technology serves as an excellent outreach program in this field. Educators and experts may be requested to deliver non-technical, informative talks that spark interest through these platforms. School and colleges should facilitate group listening of these talks followed by group discussions on Q-Dhwani to enhance collective focus and engagement in QIST at all levels.

D. **Developing QT4K Website (Quantum Technology for Karnataka):** There have been concerted efforts by institutions and the scientific community to educate school children about Quantum Information Science and Technology (QIST). Resources such as pedagogic quantum games, user-friendly & executable programs demonstrating simple quantum phenomena, e-books and educational videos on QIST are being developed globally[34]. Many of these resources are readily available online and are widely used in various countries to educate students and the public. In addition to guiding users on how to access and utilize these online resources, creating QIST contents and making it available on a dedicated website **QT4K** (Quantum Technology for Karnataka), is going to be an excellent outreach initiative.

E. QIST Festivals: Organizing annual/biannual Quantum Information Science and Technology (QIST) festivals in Karnataka would be a highly effective outreach initiative. These interdisciplinary science festivals can showcase the latest advancements in quantum research and its applications through interactive exhibits, workshops, and seminars. They can feature live demonstrations, hands-on activities, and discussions by quantum experts to engage students, teachers, researchers and the general public. By bringing together academicians, industry professionals, and students, these festivals can foster collaboration, inspire interest in quantum technologies, and raise awareness about their potential impact on various sectors.

F. QT4K (Quantum Technology for Karnataka) Hackathons: Organizing QT4K hackathons at various levels—local, regional, or statewide— is going to be an exciting and impactful outreach initiative to engage students, researchers, and the tech community in the state. These hackathons could focus on solving real-world problems using quantum technologies, encouraging participants to develop innovative solutions in areas like quantum computing, cryptography, and machine learning. By providing access to quantum programming platforms, mentorship from experts, and collaboration opportunities, these events would not only help participants hone their skills but also spark interest in quantum technology. They would offer a platform for networking, learning, and discovering potential career opportunities in the emerging field of quantum science and technology.

G. Illustrative Experimental Models and Kits for QIST: To enhance the understanding of Quantum Information Science and Technology (QIST) concepts, developing illustrative experimental models and kits at **ನಾಕು ತಂತಿ-(NaQuTanTI)** regional hubs would be a valuable outreach tool. These kits could include simple, hands-on experiments to demonstrate quantum principles such as superposition, entanglement, and quantum interference. These simple kits may be developed for bulk supply to schools, colleges of Karnataka by suitable start-up companies initiated for this purpose. Students will be able to engage with quantum phenomena in a practical, accessible way with the help of these illustrative kits which can serve as a bridge between theoretical knowledge and real-world quantum scenario. This is going to be a great effort towards fostering curiosity and deepen interest of young students in the area of quantum technologies.

In addition to these, outreach programs specifically designed in areas of QIST for students pursuing graduate/postgraduate/Engineering studies, developing interdisciplinary dual-degree programs on QIST at the undergraduate science and engineering level in Karnataka would equip students for taking up full-fledged programs in quantum technology at the post-graduate stage. Consequently, interdisciplinary post-graduate programs focused on Quantum Information Science and Technology (QIST) needs to be established in Karnataka as a crucial initiative to develop a skilled workforce in quantum technologies. These programs can integrate physics, computer science, engineering, and mathematics to provide a comprehensive understanding of quantum principles and their applications. They should be initiated at all state universities and engineering colleges of repute.

By expanding and collectively networking various outreach efforts, Karnataka can establish itself as a leader in QIST education and research, aligning its initiatives with the national and global actions to advance QIST, while empowering future generations to contribute to and shape the quantum technology revolution.

Epilogue

Quantum technologies (QT) hold immense potential to revolutionize industries by offering transformative advancements in healthcare, energy, finance, cybersecurity, and more. Innovations in quantum computing, sensing, imaging, and communication promise solutions to complex global challenges that surpass the capabilities of classical technologies. As countries worldwide strive to lead in this domain, the rapid progress in QT underscores its growing importance on the global stage.

India's approval of the National Quantum Mission (NQM) in April 2023 marks a pivotal step in building a robust quantum ecosystem. With a substantial investment of ₹6,003.65 crore over eight years, this mission positions India as a significant player in quantum research and commercialization, emphasizing advancements in healthcare, defense, and finance. Establishing four thematic hubs dedicated to quantum computing, communication, sensing, and materials further strengthens this initiative, paving the way for inter-city and satellite-based quantum communication networks and quantum computing capabilities with 50–100 QBits.

Globally, countries like the USA and Canada lead quantum research and commercialization, supported by significant government funding and academic-industry collaborations. The USA's National Quantum Initiative Act (2018) and Canada's National Quantum Strategy underscore their commitment to fostering innovation, developing talent, and ensuring leadership in this field. Similarly, Asian nations like Singapore, Japan, China, and Israel have made substantial investments in quantum technologies, focusing on secure communication, sensing, and computational advancements. These efforts highlight the strategic importance of QT in achieving scientific, economic, and national security goals.

India, with its rich legacy of contributions to quantum mechanics by pioneers like S.N. Bose and C.V. Raman, has made significant strides in quantum research. Initiatives like the "Quantum Enabled Science and Technology" (QuEST) program and the efforts of institutions such as the Indian Institute of Science (IISc) and Indian Institutes of Technology (IITs) have laid the foundation for advanced research in quantum information, quantum devices, and secure communication. However, challenges persist, including limited funding, infrastructure, and skilled talent compared to other global leaders. Addressing these gaps through state-level investments, industry collaborations, and talent development is essential to propel India's quantum landscape forward.

Education and outreach are critical to sustaining long-term growth in QT. Introducing quantum concepts into school curricula at the higher secondary level can spark early interest and build foundational knowledge. Hands-on initiatives, such as delivering experimental kits to high school students, organizing hackathons, and offering interdisciplinary degree programs, can equip the next generation with practical skills. Public engagement programs like Q-Kalike magazines, Q-Dhwani radio talks, and QIST festivals can further raise awareness and foster enthusiasm for quantum science among students and the general public.

Karnataka is uniquely positioned to drive India's quantum mission forward, leveraging its reputation for technological excellence. The state boasts a rich scientific ecosystem, featuring prestigious institutions like the Indian Institute of Science (IISc), Indian Space Research Organization (ISRO), Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Raman Research Institute (RRI), National Center for Biological Sciences (NCBS), and Centre for Nano and Soft Matter Sciences (CeNS), along with a thriving IT and biotech sector and premier educational institutes in Bengaluru and beyond. By fostering partnerships between government, academia, and industry, Karnataka can nurture startups, attract global collaborations, and drive innovation. Aligning the state's strategy with the National Quantum Mission (NQM) will further enhance its role in advancing quantum technologies and promoting inclusive growth in tier II and III cities.

Karnataka, as a hub for science and technology, has the potential to lead in establishing a quantum ecosystem. Developing Centers of Excellence in 4–5 locations across the state can encourage research among undergraduate and postgraduate students, research scholars, and young teaching faculty. These centers can focus on niche areas of quantum technology, creating an environment conducive to innovation and experimentation. Additionally, by aligning with the "Vocal for Local" initiative, Karnataka can leverage its resources to address regional challenges and develop scalable solutions for global markets.

The expansion of quantum technology must not remain confined to Bengaluru; it is imperative to ensure its growth across tier II and III cities in Karnataka. This decentralized approach will democratize access to advanced technologies, foster regional development, and create new employment opportunities. Furthermore, integrating quantum technologies with industries like electronics, IT, biotech, AI, and manufacturing can boost economic growth while addressing critical societal challenges.

Thus, quantum technology represents a transformative other force with the potential to redefine multiple sectors. By promoting education, nurturing talent, and encouraging collaborations, the state can play a pivotal role in advancing both national and global quantum ecosystems. Through sustained efforts and strategic investments, Karnataka can emerge as a global leader in quantum research, innovation, and commercialization, ensuring brighter and technologically empowered future generations.

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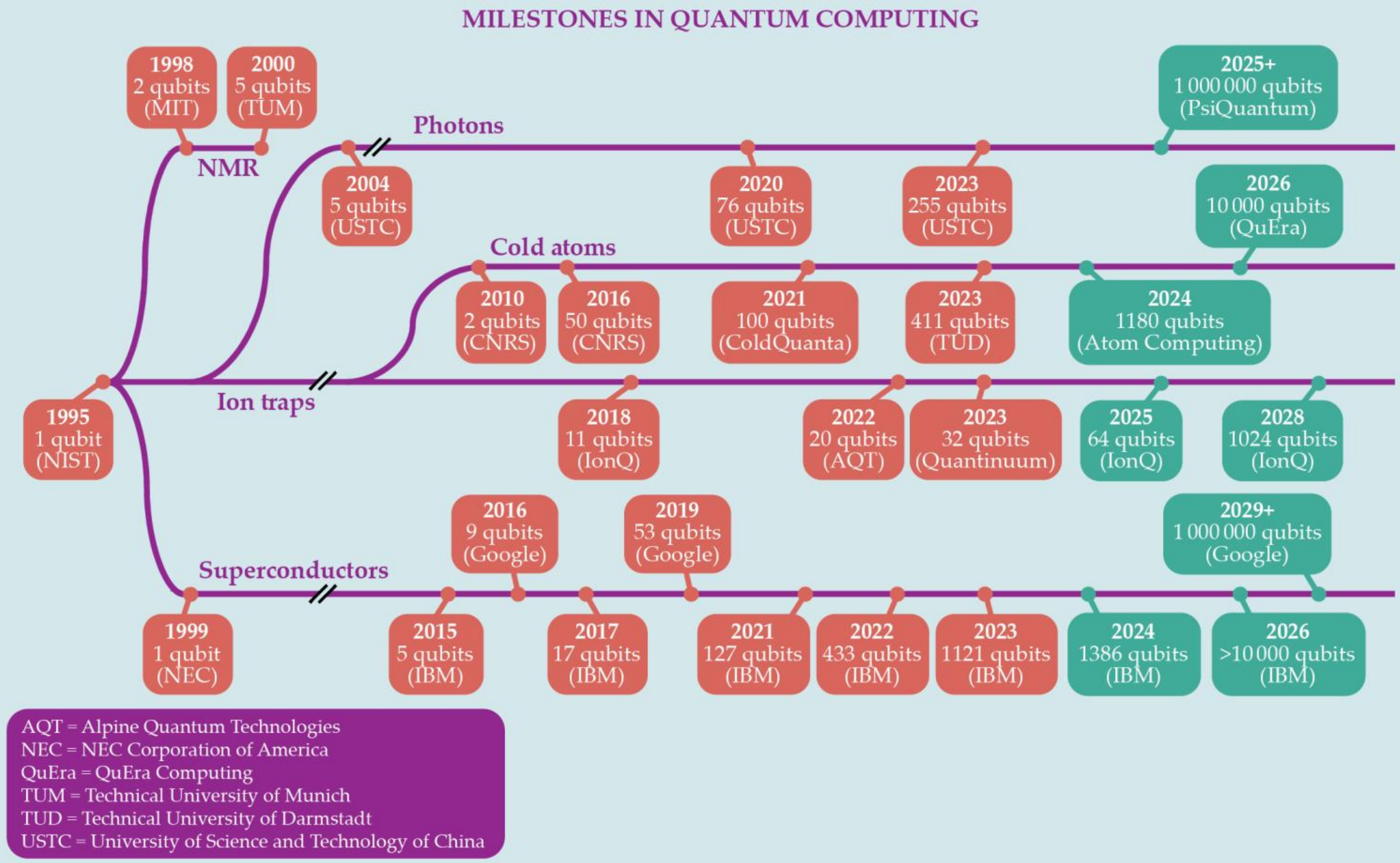

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