India's Challenges and Opportunities in the Quantum Era

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Introduction

When Google announced "quantum supremacy" in 2019,[1] there was a sudden global wave of programmes and strategies to develop quantum technologies and demonstrate their applicability. What was once enigmatic and elusive had now been demonstrated in the tangible world. In the course of this century, and even later, technologies will be developed based on the fundamentals of quantum mechanics that will carry the potential to change human life as we know it.[2] For the last four decades, scientific and technological advancements have been made in the realm of quantum science. Today, we stand on the cusp of the "second quantum revolution." Now, states and tech firms have started investing billions of dollars into building quantum computers that will allow researchers, scientists and technologists to solve problems that classical computers would take hundreds of years to solve.

Against this backdrop, it is important to study the implications of quantum computing on emerging technological development. Quantum capabilities will disrupt modern-day cryptography, alter the way business and commerce are conducted, and dramatically change the methods of information transfer.[3] Given the potential of quantum computing in strengthening national security, states are formulating strategies to speed up quantum technological development.[4] From the West to the Indo-Pacific, nearly all major economies have rolled out their national missions and programmes to accelerate research and development in quantum computing. India formally entered the race when it announced its National Mission on Quantum Technology and Applications (NM-QTA) in the Union Budget 2020.

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1 John Martinis, "Quantum Supremacy Using a Programmable Superconducting Processor," Google AI Blog, 2022, https://ai.googleblog.com/2019/10/quantum-supremacy-using-programmable.html

2 Ronald de Wolf, "The Potential Impact of Quantum Computers on Society," arXiv, 2017, https://arxiv.org/abs/1712.05380

3 de Wolf, "The Potential Impact of Quantum Computers on Society"

4 Scott Buchholz et al., "The Realist's Guide to Quantum Technology and National Security," Deloitte Insights, 2020, https://www2.deloitte.com/us/en/insights/industry/public-sector/the-impact-of-quantum-technology-on-national-security.html

This report attempts to elucidate the progress of quantum technologies in India till date. It also presents a detailed Theory of Change framework—posited by Carol Weiss—to evaluate the outcomes of the country's quantum mission. (See Annex 1 for a brief explanation of the framework.) In analysing the challenges impeding India's progress, this report utilises insights gained from consultations with experts from industry, scholars, graduates, and PhD students from quantum laboratories in different parts of India, and entrepreneurs working in India's quantum startup space. The analysis relies on the PESTLE framework, formulated by Francis Aguilar in the 1960s to study the implications of political, economic, social, technological, legal, and environmental/ethical factors on an organisation or a process or a public policy. (Annex 2 gives a brief description of the framework.)

This report also makes recommendations for overcoming the challenges. These include the need for states and tech firms to formulate rules, guidelines and accords for the ethical use of quantum computing.

I

The Emergence of Quantum Science and Its Applications

In the early 20th century, physicists—such as Max Planck, Niels Bohr, Albert Einstein, Werner Heisenberg, Erwin Schrödinger, and Louis de Broglie—started exploring matter to the subatomic level, giving birth to a new field of physical sciences known as quantum physics. The foundational work done by Planck on the quantisation of energy[5] revolutionised classical mechanics and led to the emergence of quantum mechanics.

A number of technological innovations emerged as a result of the new theories postulated in the "first generation"[6] of quantum science. In the 21st century, as computers became ubiquitous, the "second generation" of quantum science came into being. At present, tech firms, states, academia, and technologists are building on the principles of quantum physics to improve computing capabilities. Quantum technology and quantum computing are based on the very principles of quantum mechanics. There are certain properties of matter, like momentum and position, that cannot be precisely calculated, allowing room for a quantum system where a particle can exist as a combination of multiple states until it is measured and the specific state is recorded.

The core phenomena of quantum physics—i.e., superposition, the uncertainty principle, entanglement and tunnelling—when used with computing will play a crucial role in developing quantum technologies such as quantum communication systems. In modern-day computing, information is relayed and stored in binary digits or bits—i.e., 0 or 1. In quantum computers, information-sharing and storage are done in qubits, which exist as 0 or 1 or a combination of both. This implies that quantum computers will have far more computational capabilities and storage capacity, allowing for exponential processing prowess.

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5 "Max Planck: Originator Of Quantum Theory," European Space Agency, 2022, https://www.esa.int/Science_Exploration/Space_Science/Planck/Max_Planck_Originator_of_quantum_theory

6 Jonathan P. Dowling and Gerard J. Milburn, "Quantum Technology: The Second Quantum Revolution," arXiv, 2002, https://arxiv.org/pdf/quant-ph/0206091.pdf

What makes quantum technologies different?

By virtue of being based on quantum mechanics, quantum computing and related technologies will be different from the applications of classical computing. A key difference is in the massive implications that quantum technologies will have on encryption of data, data storage, and data transfer. This could lead to national security concerns and threats to safekeeping of confidential information of both states and people.[7] Till date, most emerging technologies have had remarkable impact on the conduct of business and commerce but the disruptive potential of quantum technologies will have implications on cybersecurity and geopolitics.[8,9] The global quantum race will not be restricted to achieving quantum supremacy, but also in using quantum capabilities to withstand quantum-led cyber-attacks by adversaries, and simultaneously building quantum capacities to launch such attacks.

Another discipline that makes quantum technologies stand out from other emerging technologies is quantum information. Experts suggest that it will be impossible to perfectly copy quantum information from one device to another. This falls under the ambit of the "quantum cloning principle", which states that after information is copied, superposition is broken, rendering the copied information and the qubit becomes useless for any further computation.[10] This will ensure that quantum information is difficult to hack or trace to perfection, and reduce eavesdropping in communication.

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7 Walid Rjaibi, Sridhar Muppidi, and Mary O'Brien, *Quantum Computing and Cybersecurity: How to Capitalise on Opportunities and Sidestep Risks,* IBM, 2018, https://www.ibm.com/thought-leadership/institute-business-value/report/quantumsecurity

8 Alex Capri, *Quantum Computing: A New Frontier in Techno-Nationalism,* Hinrich Foundation, 2021, https://www.hinrichfoundation.com/research/wp/tech/quantum-computing-a-new-frontier-in-techno-nationalism/

9 Alice Pannier, Strategic Calculation: *High-Performance Computing and Quantum Computing in Europe's Quest for Technological Power,* Études de l'Ifri, 2021, https://www.ifri.org/sites/default/files/atoms/files/pannier_strategic_calculation_2021.pdf

10 Heng Fan et al., "Quantum Cloning Machines and the Applications," arXiv, 2014, https://arxiv.org/pdf/1301.2956.pdf

Quantum science will also lead to dramatic improvements in meteorology and sensing given heightened incision, precision and accuracy. Scientists and researchers are of the view that as computer power increases, magnetic resonance imaging (MRI) machines will be reduced to the size of cellphones[11] and navigation will also be based on quantum capabilities.[12] They also anticipate quantum simulations to be a game-changer in 21st-century technological developments.

Applications of quantum computing

a. Near-term applications

In the short term, noisy intermediate-scale quantum (NISQ) computers will be more viable. These will be able to carry out quantum computations, though not without errors. These systems will be able to carry out complex calculations that would take a classical computer more time and resources.

b. Medium-term applications

Small quantum computers with more qubits (in hundreds) that will be able to carry out computations in quantum chemistry, quantum optimisation and quantum machine learning.

c. Long-term applications

These will be fault-tolerant computers, with low error rates, which can execute tasks beyond the reach of classical computers. Applications will include simulations in physics and chemistry, quantum resistant cryptography, and breaking public-key encryption.

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11 Michio Kaku, *The Future of the Mind* (Doubleday, 2014), pp. 199–201.

12 Donghui Feng, "Review of Quantum Navigation," *IOP Conference Series: Earth and Environmental Science* 27, no. 3 (2019), https://iopscience.iop.org/article/10.1088/1755-1315/237/3/032027

Early applications of quantum computing

Areas such as business, commerce, health and finance could experience a paradigm shift with progress in quantum computing and related technology development.[13] Most quantum use cases and applications will be based on one of the four known models of quantum computing—quantum simulations, optimisation, factorisation, and linear algebra. Some industries will take up quantum technologies more easily than others—e.g., banking and finance, drug discovery and development, manufacturing, and cybersecurity and information technology.[14]

a. Banking and finance

In the finance sector, there are many challenges that are addressed by the use of combinatorics. These range from formulation of derivatives, credit rankings, securities management to algorithmic trading. Financial institutions deal with these challenges by simplifying them with the use of combinatorics that reduces the number of possible solutions. This makes these problems more manageable. Because classical machines have limited computational capacities, at times, the most optimal solution to a problem is never found. Quantum computing and algorithms can address this as these can suggest more solutions and make it easier to pick the most feasible one.

When it comes to banking, quantum computers will provide optimised portfolio and risk management. Quantum-optimised loan management can give insights into interest rates, assist in freeing held-up capital, and in general, improve bank offerings.[15]

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13 Matteo Biondi et al. *Quantum Computing Use Cases Are Getting Real—What You Need to Know,* McKinsey & Company, 2021, https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-computing-use-cases-are-getting-real-what-you-need-to-know

14 McKinsey & Company, *A Game Plan for Quantum Computing, 2020,* https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/A%20game%20plan%20for%20quantum%20computing/A-game-plan-for-quantum-computing-v3.pdf

15 Feng, "Review of Quantum Navigation"

b. Drug discovery and development

Drug development is based on the discovery of molecules and the ability to manipulate them. Since this happens at the subatomic level, quantum mechanics inevitably comes into play. With advancements in chemistry, a vast number of molecules have been discovered, which has further led to an exponential rise in the ways that these can be manipulated, configured and combined. Since this becomes a challenge in combinatorics, quantum computing can easily simulate new molecular models that the present computing capabilities cannot. This will have a dramatic impact on the discovery of new drugs and directed medication. Quantum simulations can also reduce dependency on trial and error, making the process of drug development more efficient.[16]

c. Manufacturing

Manufacturing sectors like automotives and heavy machinery can benefit from quantum computing. New design techniques, greater efficiency of supply chains, reduction in losses in logistics, increased production and enhanced management can be brought about with the use of quantum computers. Manufacturing also involves process management and finding the most cost-optimal solutions, and quantum simulations and algorithms can easily find the best solution.[17]

d. Cybersecurity and information technology

The most dramatic impact of quantum computing and allied technologies will be on the exchange, storage and transfer of information. Coupled with the ability of quantum computers to break the most robust encryption systems of the day, which is the RSA-2048 encryption, quantum computers will also

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16 Matthias Evers, Anna Heid, and Ivan Ostojic, "Pharma's Digital RX: Quantum Computing in Drug Research and Development," McKinsey & Company, 2021. https://www.mckinsey.com/industries/life-sciences/our-insights/pharmas-digital-rx-quantum-computing-in-drug-research-and-development

17 Feng, "Review of Quantum Navigation"

evolve new paradigms of cybersecurity. There are two ways to secure the cyberspace in the quantum age: one, build on post-quantum cryptography algorithms[18] that can safeguard classical computers from quantum-led cyber-attacks; two, build on new encryption standards, like quantum key distribution (QKD),[19] based on the principles of quantum computing. Both these methods have their advantages and disadvantages but will prove to be successful in securing information from cyber-attacks launched by quantum machines.

Cybersecurity and information technology have garnered attention from governments and the private sector in the last few years. Quantum policies and missions around the world are heavily tilted towards this aspect of quantum technology development, as this will have a notable impact on military, defence and space systems as well.

The promise of developing a quantum computer has enamoured both the scientific community and the general public alike. The prospects of building a machine that can execute Shor's algorithm[20] and manipulate large integers have made researchers and scientists take giant leaps in quantum technology development. However, it must be noted that quantum computing will not solve all problems of the modern world. A machine of that magnitude will offer dramatic computational speeds to only specific problems, especially those that are based on optimisation.

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18 Prachi Mishra, "Cybersecurity in the Quantum Age," Observer Research Foundation, 2022, https://www.orfonline.org/expert-speak/cybersecurity-in-the-quantum-age/

19 "Quantum Key Distribution (QKD)," Quantum Flagship, 2022, https://qt.eu/discover-quantum/underlying-principles/quantum-key-distribution-qkd/

20 "Shor's Algorithm," IBM Quantum, 2021, https://quantum-computing.ibm.com/composer/docs/iqx/guide/shors-algorithm

II

Quantum Development in India

Governments and tech firms in different parts of the world have invested billions of dollars into quantum science research and application development.[21] India entered the club of nations with quantum technology development in 2017.[20]

The first effort of the Indian government in accelerating the development of indigenous quantum capabilities was undertaken in 2017 by the Department of Science and Technology (DST), when its Interdisciplinary Cyber Physical Systems (ICPS) division launched the research programme, Quantum Information Science and Technology (QuST).[22] The programme identified quantum technologies as a frontier technology, paving the way for subsequent programmes, and the national mission launched in 2020. The vision of the QuST as outlined by the planners was "to revolutionize the future computation and communication systems which will ultimately have a huge impact on the Nation and our society as a whole"[20] (See Table 1).

Table 1. Objectives of the QuST, 2017

Development of a quantum computer and demonstration of quantum capabilities
Research and development of quantum communication (including cryptography)
Harnessing technologies based on quantum computing
Research and development of advanced quantum information systems

21 World Economic Forum, *State of Quantum Computing: Building a Quantum Economy,* 2022, https://www.weforum.org/reports/state-of-quantum-computing-building-a-quantum-economy/

22 Department of Science & Technology, "Interdisciplinary Cyber Physical Systems (ICPS) Division – Detailed Call for Proposals (CFP) under ICPS Programme," Ministry of Science & Technology, Govt. of India, 2017. https://dst.gov.in/sites/default/files/QuST%20-%20CFP1.pdf

The programme encourages scientists and academicians in the quantum space to develop capabilities using key processing techniques like photonics, superconducting materials, and trapped ions. As an outcome of the programme, quantum laboratories across India now use these techniques to understand their advantages and disadvantages, and test them for scalability, stability, complexity, and computation costs.

In 2018, the DST renamed QuST as Quantum Enabled Science and Technology (QuEST) and sanctioned an outlay of INR 80 crores (approx. US$10 million) for a period of three years.[23] In April 2022, the first QuEST National Symposium was held at IIIT-H to discuss the progress of quantum science research and development in India and deliberate on new ideas in quantum technologies, overall, and in quantum information theory.[24]

In 2020, India formally entered the global quantum race as it announced the National Mission on Quantum Technologies and Applications (NM-QTA) in the Union Budget.[25] While the mission is yet to be rolled out in its entirety, there have been notable developments in the field in the last few years, primarily, development of indigenous quantum communication technologies, and the evolution of India's quantum ecosystem. (See Annex 3.)

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23 Shweta Ganjoo, "India Starts Working on Quantum Computers, Kicks-Off Rs 80 Crore Project to Build Machines of Future," *India Today,* January 11, 2019, https://www.indiatoday.in/technology/news/story/india-starts-working-on-quantum-computers-1428902-2019-01-11

24 Quantum Enabled Science and Technology National Symposium, 2022, https://cqst.iiit.ac.in/quest/

25 Department of Science & Technology, "Budget 2020 Announces Rs 8000 Cr National Mission on Quantum Technologies & Applications," Ministry of Science & Technology, Govt. of India, 2022, https://dst.gov.in/budget-2020-announces-rs-8000-cr-national-mission-quantum-technologies-applications

Table 2. Milestones in NM-QTA

Jan 2023	Two-day symposium held at the Centre for Development of Advanced Computing (C-DAC), Pune, on "Quantum Computing Ecosystem: Basic Building Blocks." Participation from across the globe and representation of each part of the quantum ecosystem was noted.[26]
Dec 2022	QETCI signed an MoU with T-Hub (Telangana startup accelerator) to mentor early-stage startups working in the quantum space.[27] Quantum Science and Technology Hackathon (Q-STH) results published. A total of 132 entries and 37 prototype submissions were received by QETCI.[28]
Sept 2022	QETCI organised a hackathon in collaboration with the Indian government's principal scientific adviser's office. The hackathon was designed to aid students and young researchers to develop quantum applications to solve real-world problems.[29] Indian Institute of Technology (IIT), Madras, joined the IBM Quantum Network to advance development of quantum technologies for Indian industries.[30]

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26 "Symposium of Quantum Computing Ecosystem: Basic Building Blocks," Centre for Development of Advanced Computing, 2023.

27 "QETCI, T-Hub Sign Pact to Support Start-Ups Working on Quantum Technologies," *The Hindu Business Line,* 2022, https://www.thehindubusinessline.com/info-tech/qetci-t-hub-sign-pact-to-support-start-ups-working-on-quantum-technologies/article66230003.ece

28 Fareeha Almas, *Report on the Quantum Science and Technology Hackathon 2022,* Quantum Ecosystems and Technology Council of India, 2022, https://qetci.org/report-on-the-quantum-science-and-technology-hackathon-2022/

29 "Quantum Science and Technology Hackathon 2022," Office of the Principal Scientific Adviser to the Govt. of India, 202, https://quantum-science-and-technology-hackathon-2022.hackerearth.com/

30 "IIT Madras Joins IBM Quantum Network," IBM India Newsroom, 2022, https://in.newsroom.ibm.com/2022-09-12-IIT-Madras-joins-IBM-Quantum-Network

Aug 2022	The Indian Army issued a formal request for proposal to Bengaluru-based startup QNu Labs for deployment of the latter's QKD communication system.[31] QpiAI, a Bengaluru-based startup, announced its AI-enabled QpiAISenseTM platform that would help maintain requisite cryogenic conditions for operating qubits.[32]
Jul 2022	Indian IT giant Tech Mahindra and Mahindra University collaborated to establish a new "Makers Lab" to aid research and development in quantum technologies, AI and Metaverse.[33]
Mar 2022	Defence Research and Development Organisation (DRDO), along with IIT Delhi, successfully demonstrated quantum communication using QKD in the state of Uttar Pradesh, from Prayagraj to Vindhyachal. The quantum communication channel spreads over 100 km.[34]
Jan 2022	The Space Application Centre (SAC) and Physical Research Laboratory, Ahmedabad, demonstrated quantum entanglement and showcased hack-proof quantum communication based on QKD between two points 300m apart.[35]

31 Huma Siddiqui, "India @ 75: Achieves Key Milestone in Quantum Technology," *The Financial Express,* 2022, https://www.financialexpress.com/defence/india-75-achieves-key-milestone-in-quantum-technology/2630587/

32 "QpiAI Announces AI-Enabled QpiAISense™ Platform for Worldwide Deployment," Mint, 2022, https://www.livemint.com/brand-stories/qpiai-announces-ai-enabled-qpiaisense-platform-for-worldwide-deployment-11661343071436.html

33 "Tech Mahindra, Mahindra University to Set Up Lab for Metaverse, Quantum," Press Trust of India, 2022, https://www.outlookindia.com/business/tech-mahindra-mahindra-university-to-set-up-lab-for-metaverse-quantum-computing-news-211445

34 "DRDO and IIT Delhi Scientists Demonstrate Quantum Key Distribution Between Two Cities 100 Kilometres Apart," Defence Research and Development Organisation, 2022, https://www.drdo.gov.in/press-release/drdo-and-iit-delhi-scientists-demonstrate-quantum-key-distribution-between-two-cities

35 "Department of Space Demonstrates Entanglement Based Quantum Communication Over 300M Free Space Along With Real Time Cryptographic Applications," ISRO, 2022, https://www.isro.gov.in/DeptofSpace.html

Jan 2022	Indian IT giant Tata Consultancy Services marked its entry into the domestic quantum sector by issuing a request for information (RFI) to understand the country's quantum community and to establish mutually beneficial associations with academia, startups and other tech companies.[36]
Dec 2021	The Indian Army set up a quantum computing lab and an AI resource centre in Mhow, Madhya Pradesh. It is projected to spearhead R& D in quantum cryptography and communication. The lab and the AI centre are backed by the National Security Council Secretariat.[37]
Oct 2021	After demonstrating a communication solution based on QKD, the Centre for Development of Telematics (C-DOT) launched its own quantum communication lab. The solution showcased by C-DoT can support over 100 km of optical fibre-based communication.[38]
Sep 2021	Indian IT firm Infosys announced its collaboration with Amazon Web Services (AWS) to build quantum computing capabilities. It pledged to use Amazon Braket to build quantum business use cases on the cloud.[39]

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36 "TCS Research & Innovation RFI on Quantum Computing," Office of the Principal Scientific Adviser to the Govt. of India, 2022, https://www.psa.gov.in/innerPage/psa-initiatives-covid/tcs-research-innovation-rfi-quantum-computing/3537

37 "Indian Army Establishes Quantum Laboratory at Mhow (MP)," Press Information Bureau, 2021, https://pib.gov.in/Pressreleaseshare.aspx?PRID=1786012

38 "Secretary Telecom Shri K. Rajaraman Visits C-DOT; Inaugurates Futuristic Quantum Communication Lab," Press Information Bureau, 2022, https://www.pib.gov.in/PressReleasePage.aspx?PRID=1762590

39 "Infosys to Develop Quantum Computing Capabilities on Amazon Web Services," Press Trust of India, 2021, https://www.thehindubusinessline.com/info-tech/infosys-to-develop-quantum-computing-capabilities-on-amazon-web-services/article36608775.ece

Aug 2021	IIT, Roorkee, in collaboration with IISc, Bengaluru, and C-DAC, developed India's first quantum simulation toolkit, QSim, which was launched at the national level by the Ministry of Electronics and Information Technology. The toolkit's objective is to provide a platform for researchers, academics and students to gain hands-on experience in coding quantum algorithms and problem solving.[40]
Jul 2021	The C-DAC and Defence Institute of Advanced Technology agreed to build quantum computers. The development of indigenous quantum capabilities would take place in Pune.[41]
Mar 2021	The DST and over 10 research groups from IISER, Pune, launched the I-Hub Quantum Foundation to foster state-of-the-art quantum R& D in India. It is based in Pune and acts as the kernel of the quantum ecosystem.[42]

40 "India's First Quantum Computer Simulator (Qsim) Toolkit Launched by Meity," Indiaai, 2021, https://indiaai.gov.in/news/india-s-first-quantum-computer-simulator-qsim-toolkit-launched-by-meity

41 "DIAT, C-DAC Ink MoU for Development of Quantum Computers," *The Indian Express,* 2021, https://indianexpress.com/article/cities/pune/diat-c-dac-ink-mou-for-development-of-quantum-computers-7429059/

42 "I-Hub Quantum Technology Foundation Set Up at IISER Pune," IISER Pune, 2021, https://www.iiserpune.ac.in/news/post/i-hub-quantum-technology-foundation-set-up-at-iiser-pune/231

Jan 2021	The Ministry of Electronics and Information Technology (MeitY) collaborated with AWS to expedite the involvement of the private sector in quantum computing and application development in India. Together, they launched a Quantum Computing Applications Lab that will leverage the industrial expertise of AWS to build on India's quantum mission.[43]
Dec 2020	The DRDO achieved a milestone after its Young Scientist Lab for Quantum Technologies in Mumbai built a quantum random number generator. The system can detect and process random quantum events and translate them into an array of binary digits.[44]

Indian universities and research institutes have also made strides in both the theoretical and the experimental aspects of quantum science development. These include quantum-sensing experiments using nitrogen vacancy in Prof Kasturi Saha's lab at IIT Bombay; and cryogenic experiments in Prof Anil Shaji and Prof Madhu Thalakulam's lab at IISER Thiruvananthapuram.

43 "Building the First Quantum Computing Applications Lab in India," AWS Public Sector Blog, 2021, https://aws.amazon.com/blogs/publicsector/building-first-quantum-computing-applications-lab-india/

44 "DRDO Young Scientists Laboratory Develops Quantum Based Technology for Random Number Generation," Press Information Bureau, 2022, https://www.pib.gov.in/PressReleasePage.aspx?PRID=1684381

Field visits and the author's interactions with scientists working in these laboratories found that collaboration is key[45] in the development of India's indigenous quantum capabilities. The QuEST programme marked the onset of building domestic quantum capabilities in India. Along with scientific, technological and research development, it also aided in setting up the foundational infrastructure and experimental set-ups. Most academicians[46] are of the view that the programme has helped in peer learning, improved collaboration and brought together the best minds in India to work on the joint mission of developing an indigenous quantum computer and evolving applications through it.

45 The author visited quantum labs in India at IISER, Thiruvananthapuram, in May 2022; IIT-Bombay in May 2022; IISc, Bengaluru, in June 2022; IIIT, Hyderabad, in June 2022; and Physical Research Laboratory, Ahmedabad, in July 2022.

46 Based on interviews with Prof. Anil Shaji and Prof. Kasturi Saha at IISER, Thiruvananthapuram, and IIT-Bombay, respectively, in May 2022.

III

India's Mission for Quantum Tech: Vision vs. On-Ground Progress

India's aspirations in quantum technologies took a formal shape with the QuEST programme launched in 2017. Like most governments,[47] India decided to initiate a mission that would encompass all frontiers of quantum science R&D and thereby, make India quantum tech-ready.

In her budget speech of 2020, Finance Minister Nirmala Sitharaman announced India's National Mission on Quantum Technologies and Applications (NM-QTA), which was given an outlay of INR 8,000 crore for a period of five years. It comes under the purview of the Prime Minister's Science and Technology Innovation Advisory Council (PM-STIAC) and is driven through the Principal Scientific Advisor's office.[48]

In this chapter, two key sources of information have been used: one, the Draft Concept Note on the NM-QTA;[49] two, answers given in the Lok Sabha related to the topic.[50] The mission is in the approval stage at the time of writing this report. The Concept Note is a guiding document which has been analysed here to present an initial assessment of the Mission.

A. Vision

The mission aims to build indigenous quantum capabilities, train human resources, boost translational research, and drive entrepreneurship in the country. It seeks to strengthen foundational science research and assist in technological development in the field of quantum science to address issues of critical national importance like securing India's cyberspace and developing indigenous quantum hardware capabilities.

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47 Like the United States, Canada, Germany, the UK, Australia, Japan, Singapore, South Korea, China and the European Union.

48 "Draft Concept Note — National Mission on Quantum Technology & Applications (NM-QTA)," Technology Information, Forecasting and Assessment Council, 2019, https://tifac.org.in/images/nmqta/concept_note12.06.19.pdf

49 The author visited quantum labs in India at IISER, Thiruvananthapuram, in May 2022; IIT-Bombay in May 2022; IISc, Bengaluru, in June 2022; IIIT, Hyderabad, in June 2022; and Physical Research Laboratory, Ahmedabad, in July 2022.

50 "National Mission on Quantum Technologies & Applications," Lok Sabha, Parliament-Question/Answer Publishing System, n.d. http://164.100.24.220/loksabhaquestions/annex/176/AU1883.pdf

B. Focus areas for quantum science R&D

Research and development in the field of quantum tech can be categorised into two: theoretical research and experimental research.[51] In India, academicians and scientific institutions are focused on both these aspects. There are a number of quantum labs across India that work on different aspects of the discipline and are collaborating to solve problems, assist other stakeholders in the quantum ecosystem with their expertise and knowledge, and share their research for translational outcomes.[52] The following paragraphs summarise the core research areas that India endeavours to develop.

a. Theoretical research

Computation

Quantum algorithms have improved computational and processing capabilities exponentially, paving the way for systems that can outpace conventional computers in performing complex and time-intensive tasks. The algorithms that have changed the course of quantum computing include Fourier transformation,[53] quantum walk,[54] Grover's algorithm,[55] Shor's algorithm[56] and Hamiltonian evolution. Research pathways in this field are the development of algorithms which can assist in quantum application development like pattern recognition and photon sampling.

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51 "DRDO and IIT Delhi Scientists Demonstrate Quantum Key Distribution Between Two Cities 100 Kilometres Apart"

52 Translational outcomes can be viewed as more direct and applicable outcomes of foundational research which can be commercialised and scaled.

53 An integral transform, Fourier transform, is able to decompose a wave (signal) into its components and their frequencies.

54 Quantum walks are used to exponentially improve the efficiency and speed of classical algorithms.

55 Grover's algorithm provides a quantum computer with the ability to expedite search in huge databases.

56 Shor's algorithm says that factorisation of primes can be carried out in polynomial time, which could have severe data security implications (as cryptographic algos are based on the prime factorisation of large numbers).

Simulations

At the core of the second quantum revolution is the ability of quantum computers to translate theories and models of quantum physics at the application level. This requires number theory, sampling and protocols to verify if the results obtained from a quantum computer are correct. This opens up opportunities for research in this field as classical verification methods cannot test for the veracity of quantum computing.

Quantum Information

Quantum computers will radically change information processing, storage and transmission. This implies that it would be relevant to study the state of quantum systems. One of the fundamentals of quantum information processing is "no cloning"—i.e., no quantum information can be perfectly copied from one system and/or application to another. Such areas of research are underway in Indian universities, research institutes and labs.[57,58,59]

Quantum foundations

Quantum foundations is a sub-discipline of quantum science that explores the mathematical underpinnings of quantum theory so that the present understanding of quantum science can be more deeply understood.

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57 "Quantum Information & Computation," Center for Security, Theory & Algorithmic Research, IIIT-H, https://cstar.iiit.ac.in/research-areas/quantum-information-computation/

58 "Quantum Computation and Information Syllabus," School of Technology and Computer Science, Tata Institute of Fundamental Research, 2014, https://www.tcs.tifr.res.in/academics/courses/quantum-computation-and-information

59 Anil Shaji, "Computational Studies of Atomic & Molecular Processes in Noisy Environments," Center for Computation, Modelling and Simulation, 2014, http://ccms.iisertvm.ac.in/anil/research-qit.html

Error Correction

Quantum devices, including computers, are highly sensitive to environmental noise. These are not stable at all cryogenic conditions and thus need specific error-correction codes to make the environment noise-free and stable. In this area of research, Indian scientists and researchers are working on methods of quantum control and feedback and on hardware that can be noise-tolerant to a certain degree.[60]

Communication

Over the last few years, Indian scientists and communication experts have demonstrated the relay of information using quantum communication algorithms and systems, like QKD over short distances.[61] Innovating and developing encryption paradigms that can secure information from quantum-led cyber-attacks is also a priority. There is immense scope of improving QKD and relay models for longer distances (over 100 km). Further, there is need to give greater impetus to post-quantum cryptography. These research enquiries are underway in a number of Indian universities, physics labs and defence research organisations. Quantum communication will be able to revolutionise information transfer and safeguard communication channels dramatically. Quantum-enabled communication will also be able to safeguard information of critical importance such as financial data, confidential location-based information and other sensitive national information.

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60 See, for instance, the Quantum Measurement and Control Laboratory, Tata Institute of Fundamental Research, Mumbai, India (https://www.tifr.res.in/~quantro/people.html). Research in these disciplines is not limited to the cited universities and research institutes. These have been cited only as examples.

61 Siddiqui, "India @ 75: Achieves Key Milestone in Quantum Technology"

b. Experimental research

Quantum dots and impurities at the atomic level

Quantum dots are colloidal semiconductor particles with sizes at nano scales and have optical and electronic properties that behave as individual qubits. Various applications of these particles have been utilised till date, such as in precision medication, imaging, and more accurate diagnosis. Experimental research based on phosphorus impurities in silicon particles and nitrogen vacancies in diamonds underway at Prof Kasturi Saha's lab in IIT, Bombay, could result in groundbreaking discoveries.

Quantum optics

This finds heavy application in quantum optical communication where individual quanta of light (photons) interact with other subatomic particles. These optical devices offer stability that makes them suitable for experimentation. The Mission seeks to promote research in this area of quantum science.

Ion traps

An ion trap is a method to isolate charged particles or ions from the external environment using electromagnetic fields. The applications of ion traps can be found in spectrometry and controlling the states of qubits. Several enterprises in certain parts of the globe have developed quantum computers on the trapped ion technique.[62] However, there is a need to study their stability and efficiency against other techniques/processors.

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62 Global companies like Honeywell, IonQ and Oxford Ionics use the trapped-ion method for developing quantum computers.

Superconducting qubits

Quantum computers based on superconducting qubits architecture have proven to be the most efficient till date. Tech firms like Google and Intel have reported significant advances in quantum computing, like quantum supremacy using superconducting quantum computers. There is scope for research in the design of qubits, quantum control, implementation of error correction algorithms and readout techniques. The Mission provides a thrust to these areas of research.

Topological qubits

Quantum topology is a new stream of mathematics that links quantum mechanics and topology. A computer based on that theory will employ charged particles called 'anyons' that are seen to provide high levels of error correction. Microsoft has chosen topological qubits for building their quantum computer and arriving on quantum competency. Their applicability has not been proven till date, opening research avenues for Indian experimental physicists.

Cryogenics of quantum computing

Qubits are highly sensitive to temperature and detected at close to absolute-zero temperatures and low energy levels. This calls for systems to be built that can maintain these specific temperature conditions for the functioning of a quantum computer. At present, refrigeration systems with several layers of cooling and cables can introduce thermal noise that can destabilise qubits. A number of experimental labs[63] in India are working on developing such systems that can maintain the stability of qubits while offering them the requisite cryogenic conditions.

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63 For example, Prof. Madhu Thalakulam's lab at IISER Thiruvananthapuram focuses on cryogenic experiments in quantum science.

c. 'Theory of Change' for the Mission

A *Theory of Change* framework is imperative to get a measure of the impact of the Mission. This framework would also stand testimony to the effectiveness of the Mission and whether or not the efforts are aligned with the vision. This section offers a bird's-eye view of the inputs, outputs and outcomes of the Mission components, based on the "Draft Concept Note".

Table 3. Theory of Change in Technology Development

Objectives	Inputs	Outputs	Outcomes
Knowledge generation	Funds	New information and knowledge	Intellectual property; new quantum use cases; human resource development
Product development	Funds	Prototypes	Intellectual property; new quantum use cases; human resource development; academia-industry linkages
Product delivery	Funds	Products and services	Intellectual property; human resource development; academia—industry linkages; commercial applications of quantum tech

Table 4. Theory of Change in Human Resource Development

Objectives	Inputs	Outputs	Outcomes
Internships, fellowships and apprenticeships	Funds	Innovation and problem solving by students and young professionals	Specifically trained task force
Trainings for faculty	Funds	Greater exposure; pointed skill development; and enhancement in faculty members	Intellectual property; mentorship and tutorship to young students; advanced research
Professorships	Funds, faculty positions	Professors with specialised concentrations	Intellectual property; research aptitude; new courses at all university levels on various aspects of quantum science

Table 5. Theory of Change in Innovation, Entrepreneurship, and Startup Ecosystem

Objectives	Inputs	Outputs	Outcomes
Hackathons and other such competitions	Funds	Prototypes; new ideas	Startups; innovators; employment; business use cases
Technology Business Incubator (TBI)	Funds	Quantum-based enterprises and tech firms	Startups; innovators; employment; business use cases; new commercial use cases of quantum tech
Startup ecosystem development	Funds	Well-connected investors, entrepreneurs, academics, scientists, students, businesses, and government	Startups; innovators; employment; awareness; new scientific and commercial use cases

Table 6. Theory of Change in International Collaboration

Objectives	Inputs	Outputs	Outcomes
Global partnerships in scientific research	Funds; research enquiry; experimental and/or theoretical inputs	Exchange of knowledge; joint work on areas of common interest	Research papers in journals of international credence; global recognition of India's scientific acumen; wider ecosystem
Collaborations in technology development and transfer of technology	Funds; expertise and/or experience in technology	Products and services; training modules; technology solutions	Business opportunities; new commercial use cases; new market avenues; wider ecosystem; global recognition

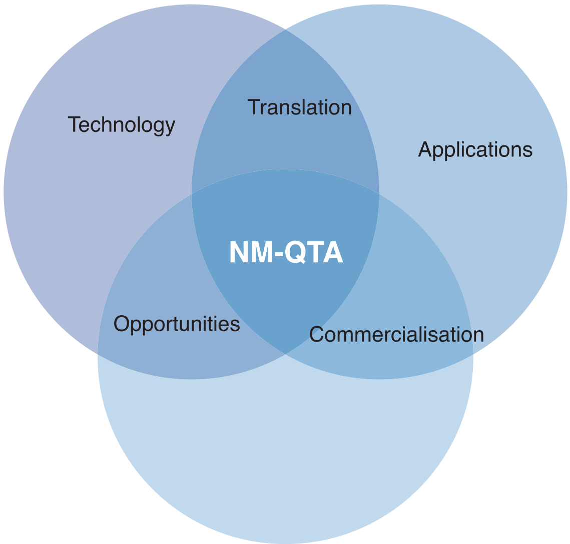
Table 7. Theory of Change in Centre for Development of Quantum Technology (C-DoQ)

Objectives	Inputs	Outputs	Outcomes
Development of a centre that offers new knowledge, new education modules, human resource development, proofs of concept of new tech use cases, products and services	Funds; research enquiry; experimental and/or theoretical inputs	Physical infrastructure; new information and scientific results; courses designed for students at university and school levels; technology applications and use cases; prototypes; commercialised quantum tech	A nodal agency to manage quantum technology development; quantum education; wider ecosystem; trained professionals; intellectual property; quantum labs and centres of excellence; ready acceptance of quantum technologies

B. Management of the Mission

Quantum computing is an interdisciplinary science that involves physics, technology, linguistics, and computing. The Indian Mission on quantum tech attempts to leverage domestic talent and expertise in these fields to build up the country's native quantum capabilities. The draft Concept Note identifies five key aspects that will drive foundational research and technological development in this field. (See Fig. 1).

Fig. 1. The Five Wings of the NM-QTA



Source: Draft Concept Note on NM-QTA, TIFAC.[64]

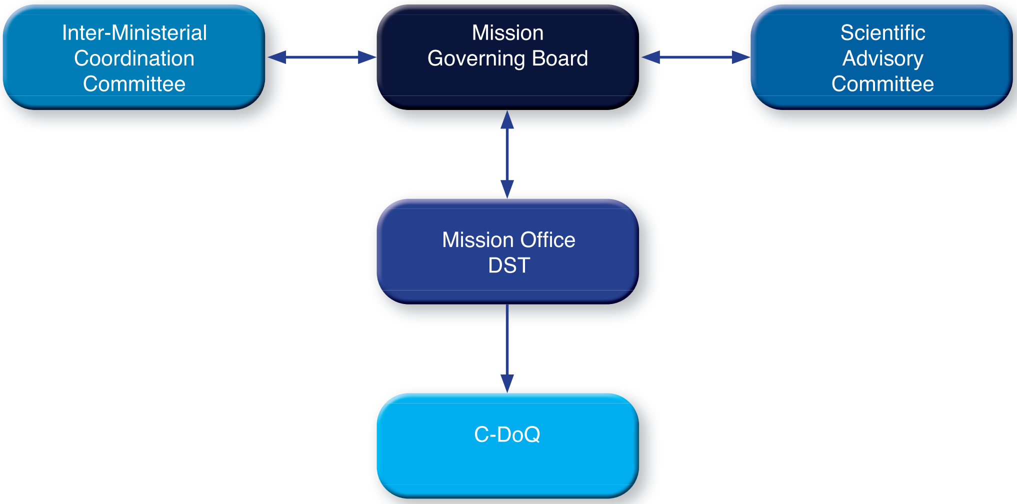
A special purpose vehicle called the Centre for Development of Quantum Technology (C-DOQ) will be responsible for the management of these five aspects of quantum science research in India. Facilities will be set up across the country to cater to these aspects.

It will also spearhead coordination between various ministries and departments such as MeitY and the Department of Heavy Industry that are critical for the commercialisation of the technology. C-DOQ will also be responsible for setting-up Technology Business Incubators (TBIs) that will provide requisite services to all of these wings irrespective of their physical proximity to a TBI. C-DOQ will be responsible for developing centres of excellence, generating new knowledge and information, producing quantum-related education material for different education levels, and innovating development of new business use cases.

64 "Draft Concept Note — National Mission on Quantum Technology & Applications (NM-QTA)"

The working of the quantum ecosystem in India will be ensured by the Scientific Advisory Committee (SAC) and the Inter Departmental Stakeholders Committee (IDSC).[65] The Mission proposes setting up a Mission Governing Board (MGB) that will be supported by various committees. (See Fig. 2).

Fig 2. Management of Quantum Science Research and Technological Development in India



Source: Draft Concept Note on National Mission on Quantum Technologies and Applications (NM-QTA) provided by the Technology Information Forecasting and Assessment Council (TIFAC), Department of Science and Technology.[66]

The Mission Governing Board (MGB) will be an apex body tasked with framing and issuing guidelines for the implementation of the Mission.[42] It will work in coordination with various committees such as a subject experts committee, a cluster committee and an international advisory committee to understand the requirements of the Mission and approve them. It will also be responsible for gauging the nature of support required by various stakeholders and reviewing their work. The purpose of the Mission Office under the DST is to link the governing board and the stakeholder ecosystem

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65 The IDSC is interchangeably referred to as the Inter-Ministerial Coordination Committee.

66 "Draft Concept Note — National Mission on Quantum Technology & Applications (NM-QTA)"

of the mission. It is tasked with informing those involved in the mission with its progress. For instance, the Office will set up a cloud-based online portal to facilitate communication between industry experts, academics, scientists, students, entrepreneurs, and civil society in all matters of quantum science research and technological development. The online platform will also track the progress of various aspects of quantum science, including publications, grants, fellowships, patents, and projects.

a. Key stakeholders in the quantum ecosystem

The stakeholders of the quantum ecosystem will comprise four categories: government agencies and departments; industry experts; academia; and entrepreneurs. These will be responsible for the direct planning and implementation of the mission, while every citizen is viewed as an indirect beneficiary.

To bring the stakeholders together, the QETCI has been set up. Through periodic meetings catalysed by the council, the quantum ecosystem of India is getting a thrust.

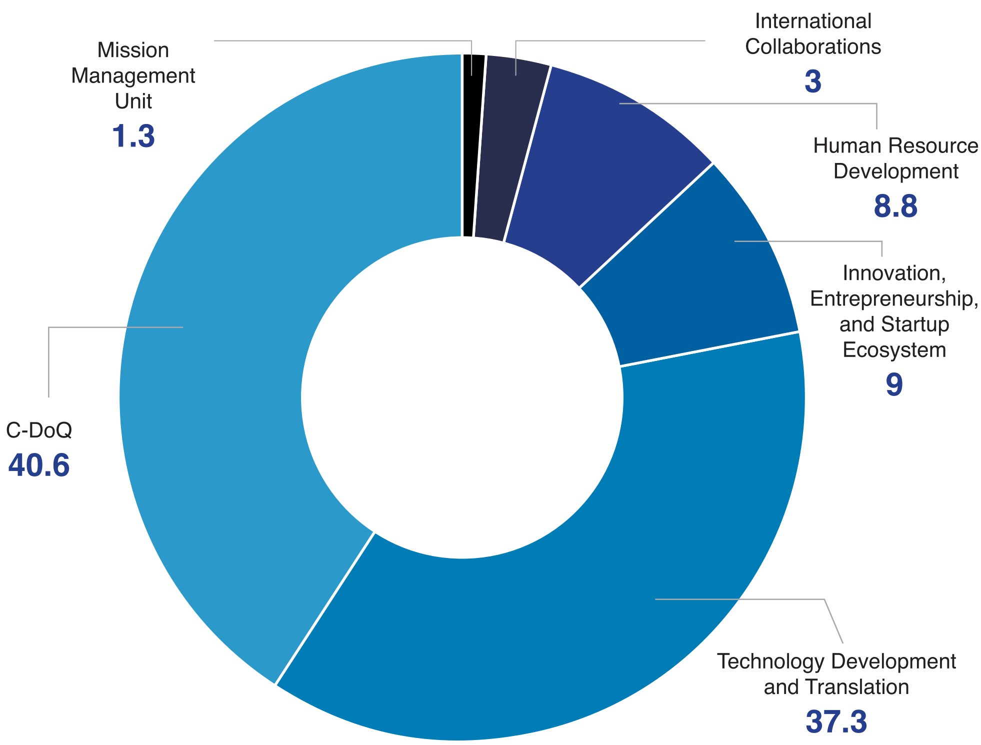
C. Financing the Mission

According to the planners of the mission, the entire amount sanctioned in the Union Budget for financing the schemes related to quantum science will be sourced from public funds and no private funding is indicated.

Where will the money go?

The Union Budget heads of the mission that will be funded from the financial years 2020 to 2024, along with their budgetary allocation, are shown in Fig. 6. This is based on the figures and the budget heads provided in the mission's Draft Concept Note.

Fig. 3. Budgetary Heads Under the Mission and Their Stipulated Expenditure in Percentage Share (2020—2024)



Source: Draft Concept Note on NM-QTA as provided by the TIFAC, Department of Science and Technology .[67]

Note: As per the reply to a parliamentary question, no funds were made available in FY 2020-21. The figure here is based on the estimates provided in the "Draft Concept Note".

As highlighted in the mission's vision document, C-DoQ has been allocated nearly 40 percent of the budgetary outlay. This is followed by technology development which includes commercialisation of the technology and identification of business use cases that will be contextual to India. The Union Budget has also given impetus to entrepreneurship and the development of homegrown companies and innovators. (Table 3 shows the original cost estimates. These have not been disbursed as of writing.)

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67 "Draft Concept Note — National Mission on Quantum Technology & Applications (NM-QTA)"

Table 8. Cost Estimates of India's Quantum Mission (in INR crore)

Budget Head	1st Year	2nd Year	3rd Year	4th Year	5th Year	Total
C-DOQ	500	700	1,250	600	200	3,250
Tech development and translation	130	250	900	1,200	500	2,980
Innovation, entrepreneurs and startup ecosystem	150	200	220	100	50	720
Human resource development	100	150	250	150	50	700
International collaborations	0	50	70	80	50	250
Mission management unit	100	0	0	0	0	100

Source: Draft Concept Note on NM-QTA as provided by the TIFAC, Department of Science and Technology.[68]

68 "Draft Concept Note — National Mission on Quantum Technology & Applications (NM-QTA)"

B. NM-QTA's Progress

The budget of the Mission was announced in February 2020 and its main strategy was planned in the subsequent months. However, at the time of writing this report, the allocated financial resources have yet to be disbursed towards the budget heads. Academics, scientists, entrepreneurs, and students told this author that they have not received the funds allocated to them. This has implications on the progress of the mission. For instance, delayed funding impedes experiments critical to the cryogenics of quantum computing. Researchers and scientists could not procure the required equipment and components for their work. Stalled funding also means that human resource development would lag and the translation of pure scientific research for commercial purposes cannot be carried out as per the mission's timeline.

Apart from delays in funding, focused strategies to implement the vision are also absent. After the mission was announced in 2020, listing India's aspirations in the quantum domain, there have been no new schemes, programmes, or legislative actions to deploy implementation. According to a July 2021 Parliamentary question posed in the Lok Sabha apropos the progress of the mission, the Minister of Science and Technology (Independent Charge) clarified that the DST had prepared a Detailed Project Report (DPR) and the mission would be approved soon.[69] The DPR lists the following as the objectives of the mission:

a. Build quantum computers and quantum information processors with 50 qubits or more.
b. Build a sustainable quantum ecosystem that can thrive on self-reliance. Build on requisite intellectual property (IP) laws.
c. QKD protocol for free space and fibre-based media will be developed. Quantum communication and quantum internet to be built as well.
d. Reduce sensitivity in measurements of rotations and accelerations in space, military and civil applications by designing and developing quantum sensors.
e. Design and development of new quantum materials.
f. Stimulate economic growth, foster employment generation, and cater to societal development.

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69 Like the United States, Canada, Germany, the UK, Australia, Japan, Singapore, South Korea, China and the European Union.

According to the reply, the mission will be implemented as a private-public partnership (PPP). The framework for identification for private collaborators has been formulated.

The mission considers quantum technology as just another emerging technology, reflecting the lack of focus on foundational science and a hasty approach to translate scientific results to business applications. While the mission aims to improve India's readiness for quantum applications, relevant agencies must acknowledge that the bedrock of translational applications (or applied research that yields applications for the good of humanity) is pure scientific research.

Due to the unprecedented impact of the COVID-19 pandemic on supply chains, innovation, communication, institutional capacity building, global outreach preparation, and multilateral association formation, there could have been delays in starting off the mission. The pandemic's impact could be attributed in part to the mismatch between ground progress and the mission's timeline. The relevant agencies must expedite the flow of resources to quantum labs, academics, scientists, entrepreneurs, and students, and get the mission back on track.

IV

Challenges and Opportunities for India's Quantum Advance

India's mission on quantum technologies envisions designing and building quantum capabilities at home. From manufacturing chips to fabricating qubits to carrying out cryogenic experiments, the mission seeks to advance all aspects of quantum science—i.e., experimental and theoretical—to give India a competitive advantage. However, there are many challenges for India to emerge as a leader in this domain in the coming decade as gaps exist at both the policy and implementation levels. These deficiencies arise due to the absence of holistic policymaking, and lack of financial resources, coupled with the delay in rolling out the Mission in the stated time frame.

A. Financing the mission

1. There is no separate funding for the mission. The mission's finances will be drawn from ministerial budgets.

At first glance, the mission's budget may seem astronomical. With INR 8,000 cr being allocated to the Indian scientific and research community to build an indigenous quantum computer, it would appear to be a giant leap forward in India's quantum technology footprint. However, as mentioned earlier, the allocation has yet to be transferred to the scientific and the entrepreneurial communities. Experts made clear that the allocation will not be made separately towards the mission but will be extracted from the departmental and the ministerial allocations made every year to various Union ministries and departments.

For instance, the Department of Space, which has demonstrated quantum communication using entanglement,[70] will have to draw out funds from its annual financial statement for the duration of the mission to continue working on its experiments. This can impact the progress of the mission and other undertakings of the department. Additionally, this has the quantum community in limbo. The mission objectives and deliverables need to be met as per the detailed plan, but due to delays in handing out the allocated budget, scientists and researchers are unable to meet the deadlines.

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70 Quantum entanglement is a process by which two or more subatomic particles are generated in a way that the state of one particle can give the state of the other particle(s), like its spin or momentum.

2. The opportunity cost of import restrictions is high.

A number of key experiments carried out in Indian quantum labs need components and specific equipment that are not available domestically. Quantum chips and cryogenic equipment like dilution refrigerators, for example, need to be imported. However, India's import restrictions, trade barriers, and other protectionist measures have impeded the acquisition of these components. Some scientists have said that because of these issues, there have been lags of the order of ten months to over a year in setting up experiments.

3. Investment is scanty for producing quantum components within India and manufacturing continues to be a legacy problem for India's tech advance.

Quantum computing is one of the focus areas of India's quantum mission. Building a quantum computer indigenously will require expertise, massive investments, a controlled environment, and dedicated quantum hardware. In contrast to a classical computer, a quantum computer is built on qubits, quantum data planes, quantum registers, and reversible gates. It will also require a quantum processing unit that uses principles of quantum mechanics such as entanglement and superposition to perform tasks. Some of these tasks will be more cost-intensive than others. For instance, building registers and control processors will not be as cost-heavy as building qubits and chips.

It thus becomes imperative to review the costs associated with making these components and identify the magnitude of investments needed to meet the expectations of the NM-QTA.

a. **Quantum-bit (qubit) simulation methods:** At the core of a quantum computer are qubits that can be simulated through methods like using photonics, trapped ions, superconducting materials, or semiconducting materials. At present, tech companies are using superconducting materials or photonics to achieve qubit simulation. However, it is not certain which method will eventually become the most optimal and sustainable. Estimates from stakeholders suggest that building a single qubit costs around US$10,000. Google demonstrated quantum advantage by deploying a 54-qubit processor, Sycamore,[71] and China arrived at the same using 56-qubit and 60-qubit processors.[72] IBM's quantum computer, Eagle, works on a 127-qubit processor.[73] These tech firms and universities designed and manufactured qubits in their own labs, spending billions of dollars in the process. India's NM-QTA envisions a functional quantum computer of 5 qubits at the experimental stage.

b. **The overall costs of building a quantum computer from scratch:** The generally accepted threshold number of qubits of a functional and viable quantum computer is 49.[74] Such a computer and those developed with more qubits will be of universal utility. Experts suggest that the hardware costs of making such a machine is around US$10 billion. To attain this threshold, tech firms around the world will not just need to build hardware but also invest in software programs and ensure that these machines are kept at specific temperatures to maintain their stability.[75] As an example, IBM has invested US$38 billion in the last five years in developing practical quantum capabilities.[76]

c. In India, investments in this emerging technology are scanty. According to the country's Technology Information Forecasting and Assessment Council (TIFAC), 37 percent of the budget for India's quantum mission—nearly US$400 million or INR 3,000 cr—has

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71 Martinis, "Quantum Supremacy Using a Programmable Superconducting Processor"

72 Qingling Zhu et al. "Quantum Computational Advantage Via 60-Qubit 24-Cycle Random Circuit Sampling," arXiv, 2021, https://arxiv.org/abs/2109.03494

73 Jerry Chow, Oliver Dial, and Jay Gambetta, "IBM Quantum Breaks the 100-Qubit Processor Barrier," IBM Research Blog, 2021, https://research.ibm.com/blog/127-qubit-quantum-processor-eagle

74 Daniel Gottesman, "Threshold for Fault-Tolerant Computation," Daniel Gottesman, 1997, https://www2.perimeterinstitute.ca/personal/dgottesman/threshold.html

75 Sabine Hossenfelder, "Quantum Supremacy Is Coming. It Won't Change the World," *The Guardian,* 2019, https://www.theguardian.com/technology/2019/aug/02/quantum-supremacy-computers

76 Jessa Tan, "IBM Sees Quantum Computing Going Mainstream Within Five Years," *CNBC*, 2018, https://www.cnbc.com/2018/03/30/ibm-sees-quantum-computing-going-mainstream-within-five-years.html

been diverted towards technological development and translation of quantum computers over a span of five years. Along with this investment, the DST announced in 2017 an investment of around INR 80 cr (US$10 million) spanning over three years in building quantum computers from scratch. While these investments can account for the development of a few components at home, India will eventually end up spending a hefty percentage of the mission's allocation in transfer-of-technology (T-o-T). India will still have to rely on heavy imports from other quantum players for its technical and hardware requirements. While many scientists and technologists may not see this as an impediment, T-o-T will present a Catch-22 situation: ideally, it should be considered the last resort for India's quantum aspirations; however, since intellectual property is a net-zero for India, T-o-T becomes an absolute essential for India's quantum ambitions. Interactions with Indian startups, tech firms, and research labs suggest that manufacturing of the most critical components of a quantum computer has not taken off with full thrust. A huge proportion of India's quantum efforts are focused on building software that can run quantum simulations. Not enough impetus is given to manufacturing these components locally. Moreover, for India to manufacture these components, funding avenues will have to be broadened. For instance, Intel's fabrication labs that build chips are estimated to cost around US$7 billion to build and maintain, which is roughly seven times India's quantum mission budget.[77] Tech giants like Google and IBM have invested heavily in building quantum computers without relying much on US government spending. At present, India does not have a fabrication lab of its own to produce quantum chips. Small fabrication facilities for experiments exist in a few institutes in India, like IIT-Bombay and IISc, Bengaluru, but they cannot produce chips at an industrial scale.

77 Stephen Shankland, "What It's Like Inside a $7 Billion Intel Fab," *CNET*, 2021, https://www.cnet.com/tech/computing/what-its-like-inside-a-7-billion-intel-fab/

B. Commercialisation of quantum technology

Western nations and China are getting ahead in the race by pledging to build commercial-grade quantum computers that can be deployed in businesses, defence, and industrial applications. In 2018, Google previewed its 72-qubit processor, Bristlecone, to provide researchers with functional and commercial quantum computers in the coming years.[78] A Chinese startup has built a 2-qubit desktop quantum computer priced at US$5,000 for school and university students.[79] Both Google and China have invested in multi-billion-dollar quantum campuses to move from the proof-of-concept stage to second-generation quantum computing.

To exert tech sovereignty, India needs not only to manufacture key components locally for building indigenous quantum capabilities but also strategise on scaling quantum computing to commercial levels in the coming years.[80] As observed in the case of quantum leaders, private investment is key to the development and operation of these computers. A lack of investment and policies that bolster manufacturing of electronic equipment and components locally has been an age-old problem in India. With each technological revolution, India is faced with these twin issues. India's investments and funding towards quantum computing is not on par with the global first-movers. In most leading regions,[81] formal quantum missions and strategies were shaped much later after investments from the private sector have flowed in. However, in India, funding is scarce and the private sector's involvement is not as requisite as it should be. Indian enterprises like Infosys and Reliance have only recently begun to take part in quantum computing development, in contrast to US and China tech giants that have been spearheading their countries' global quantum revolution since the early 2010s.

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78 Julian Kelly, "A Preview of Bristlecone, Google's New Quantum Processor," Google AI Blog, 2018, https://ai.googleblog.com/2018/03/a-preview-of-bristlecone-googles-new.html

79 "A Desktop Quantum Computer for Just $5,000,"Discover Magazine, 2021, https://www.discovermagazine.com/technology/a-desktop-quantum-computer-for-just-usd5-000

80 "From Quantum Computing to AI, Indian Science Congress Looks Forward to Lead Industry 4.0," *NewsOnAIR,* 2023, https://newsonair.com/2023/01/03/from-quantum-computing-to-ai-indian-science-congress-looks-forward-to-lead-industry-4-0/

81 Like in the United States, the European Union, the UK and China.

1. **Management of logistics and operations, and maintenance of quantum machines will also require heavy investments.**
   Quantum mega machines are highly capital-intensive, as has been highlighted by researchers who built Google's Sycamore and the Chinese developers who achieved quantum supremacy using both superconducting materials and photonics. Apart from manufacturing quantum computers, significant costs will be involved in operating and maintaining them. For instance, Google notes that communication between Sycamore and quantum chips takes place via hundreds of cables that each cost around US$1,000 for a 2-foot length.[82] Additionally, quantum computers have a very high heat load and keeping these cool is a significant challenge. These require constant power supply to keep cryogenic systems in place and India will have to develop infrastructure to ensure the maintenance of these machines. According to researchers in the Google Quantum AI Lab, their quantum machines expend most of the power consumed in keeping temperatures in check.

2. **The need to incentivise investment in Indian quantum startups and labs is evident.**
   The building blocks of many technologies are missing in India. In the long run, laxity in the Union government's approach to addressing these challenges will hamper India's transition from an importer of technology to an exporter. The government should also seek to immediately determine the focus areas of investment, for instance, whether the government wants to invest in R&D that will make India industry-ready, or if there needs to be greater R&D focus on foundational science.

   The second generation of quantum science development offers an opportunity to address these issues and strengthen India's place in the world as a manufacturer of quantum computers. Since technological development cannot solely rely on government funding,[83] there is a need to ascertain how the quantum ecosystem can thrive on its own. These challenges can only be resolved with consistent R&D, a steady stream of investment, and evolving expertise in the quantum space.

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82 Stephen Shankland, "Google's Quantum Supremacy Is Only the First Taste of a Computing Revolution," *CNET*, 2022, https://www.cnet.com/tech/computing/google-quantum-supremacy-only-first-taste-of-computing-revolution/

83 World Economic Forum, *Private or Public: What's Really Driving Technological Innovation?,* https://www.weforum.org/agenda/2020/08/democratizing-innovation

C. The problem of personnel

The NM-QTA seeks to build a quantum workforce by training teachers; formulating specialised courses for undergraduate, graduate, and PhD students; instituting specialised departments and centres for quantum research in universities; and establishing fellowships, internships, and apprenticeships for students. The budget allocated for this gargantuan task, as outlined in the draft Concept Note, is about 9 percent. While the budgetary allocation could fall short, these initiatives for personnel development are missing some key indicators, which will be discussed in turn in the succeeding paragraphs.

1. Academia is overburdened.

There are about 50 researchers, scientists, and academics directly engaged with the development of quantum technologies in India. They need to teach and mentor the next generation of quantum experts while carrying out experiments, meeting the NM-QTA targets, and publishing academic research papers. Since the number of academic papers make up for a key metric in appointments and promotions of academic staff, innovation and discovery often take a backseat. Most of them believe that there is a need for exponential growth in the number of academics and researchers to ease pressure on academia.[84] Compared with China, where the number of researchers and academics in each quantum lab is about 50[85] (including personnel adept at maintaining quantum computers), the Indian scientific community falls short in skilled and trained workforce. This has a profound impact on directed tutorship in specialisations of quantum science. Teaching is critical for skilling quantum experts, but it has not garnered enough thrust. For instance, professors are expected to train eight to 10 students in their fields of quantum science every year but due to the massive workload, the quality of training cannot be guaranteed.

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84 Based on the author's interviews at IIT-Bombay; IISER, Thiruvananthapuram; IISc, Bengaluru; and IIIT-H from May to July 2022.

85 Samarth Bansal, "Why India Is Falling Behind in the Y2Q Race," Mint, 2020. https://www.livemint.com/technology/tech-news/why-india-is-falling-behind-in-the-y2q-race-11579018170008.html

2. **The quantum industry is underdeveloped.**
At present, there are very few opportunities in the field in India for postgraduate students and PhD fellows specialising in quantum science. According to professors that this author spoke to for this report, most PhD students, after graduating from Indian universities, choose postdoctoral fellowships overseas.[86] There are few startups that work in quantum science and even fewer private sector jobs. Because the industry—academia connection is also not well-established, the second generation of quantum science is not leading to employment generation as had been planned under the Mission. One crucial reason that the industry is not participating in the development of quantum science and its applications is because the outcomes of the technological advance are uncertain. Some academics believe that since the mission is more commercially aligned, the industry should step up and invest in the emerging technology. For instance, Google and IBM invest heavily in R&D[87,88] that has given support to academia and has helped shape a sound connection between industry and pure scientific research. Indian industry and tech giants are unable to match this gold standard.

3. **Getting past Tier-I universities and colleges.**
With the current state of quantum science development in India, there is considerable chance that the technology becomes exclusively available and accessible to Tier-I colleges and universities of the country. There are professors and scientists who mentioned that the older IITs, IISc, centrally funded universities in general, and a handful of the relatively new reputable institutions like IIT-Hyderabad get the biggest share of resources and facilities for the development of quantum science. Tier-II and -III universities struggle for funding, setting up labs, and attracting

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86 Based on interviews at IIIT-H and Physical Research Laboratory, Ahmedabad, in June 2022 and July 2022, respectively.

87 Prableen Bajpai, "Which Companies Spend the Most in Research and Development (R&D)?," Nasdaq, 2021, https://www.nasdaq.com/articles/which-companies-spend-the-most-in-research-and-development-rd-2021-06-21

88 Thomas Alsop, "IBM Research, Development, and Engineering Expenditure Worldwide from 2005 to 2021," Statista, 2022, https://www.statista.com/statistics/274821/ibms-expenditure-on-research-and-development-since-2005/

talent for pure scientific research and technological development. They are also often faced with administrative hurdles. While a few researchers also believe that the mission has led to a stronger participation of all universities, their litmus test lies in the number of their students who become gainfully employed after graduating.

4. **Education and skills gap.**
   Various issues face the quantum science community in designing new educational courses and training modules that will help develop an educated and skilled quantum workforce. Most young professors and teachers feel that there is a lack of inclusiveness when it comes to framing new courses. They are seldom consulted to shape the vision of quantum education in India. The NM-QTA seeks to introduce new courses in quantum technology at the undergraduate, postgraduate, and doctorate levels, which will only cater to either the theoretical or the experimental aspect of quantum science, making them purely scientific. These are not interdisciplinary in nature. This strategy will have a long-term impact on the ethical use of technology as students will not be exposed to the societal implications of the technologies they create.

5. **Support staff is neglected.**
   Apart from researchers, scientists and academics, every quantum lab needs skilled personnel who can build, operate and maintain quantum machines. Support staff like lab technicians and assistants are underpaid and are often not educationally qualified for the job. In the United States, for instance, lab technicians have a PhD and are paid as per industry standards. Similar is the case in China. This aspect of skilled personnel is overlooked in India.

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89 Vikram Sarabhai was the principal architect of the Indian Space Research Organisation (ISRO). He pioneered the Indian space odyssey and set up several premier institutes of higher education such as the Physical Research Lab in Ahmedabad and the Indian Institute of Management, Ahmedabad.

Satish Dhawan was an Indian mathematician and physicist who pioneered the development of experimental fluid dynamics in India. He was instrumental in the development of several of India's satellite programs.

Homi J. Bhabha was the principal architect of India's nuclear program. He also founded the Tata Institute of Fundamental Research in Mumbai and set up the Atomic Energy Commission of India.

6. **Single-minded approach to innovation is amiss.**

   India's indigenous space and nuclear programmes have met with success owing to the dedicated efforts of individuals like Vikram Sarabhai,[89] Satish Dhawan and Homi J. Bhabha. As observed by scientists and academics of the present day, India has not emerged as a leader in semiconductor and other technologies because efforts are in silos and not directed towards the on-ground scientific progress. There is inertia in investing in pure science, and it is true for the quantum mission as well.

   India's quantum ecosystem, though well-knit and collaborative, will need to reassess its strategy for building a quantum-ready workforce. Most of the quantum technology startups today are not led by those who have expertise in the field. Since the industry—academia linkages are weaker, entrepreneurs tend to overcommit on building quantum technologies that seem infeasible to researchers at the moment.

D. Innovation

India's quantum mission has laid out several outcomes in its *Theory of Change* framework, but these are generic in nature and cannot be effectively used to assess on-ground progress. For instance, mere mention of the "generation of intellectual property" is not a metric of innovation. Proper metrics would account for innovation: number of jobs created; number of quality research papers published in top-ranked academic journals; number of startups incubated each year; and exceptional solutions to societal problems. These are, however, lacking in the NM-QTA's vision.

1. **India's patent tally is zero.**

   The number of patents filed by Indian engineers and scientists working for IBM India in the quantum space was over 900 in 2019;[90] the number of patents filed by Indian firms, startups, or research institutes was nil. A significant percentage of patents awarded to IBM was from their India office. (See Figures 7 and 8 for the top patent awardees in quantum computing and quantum cryptography.)

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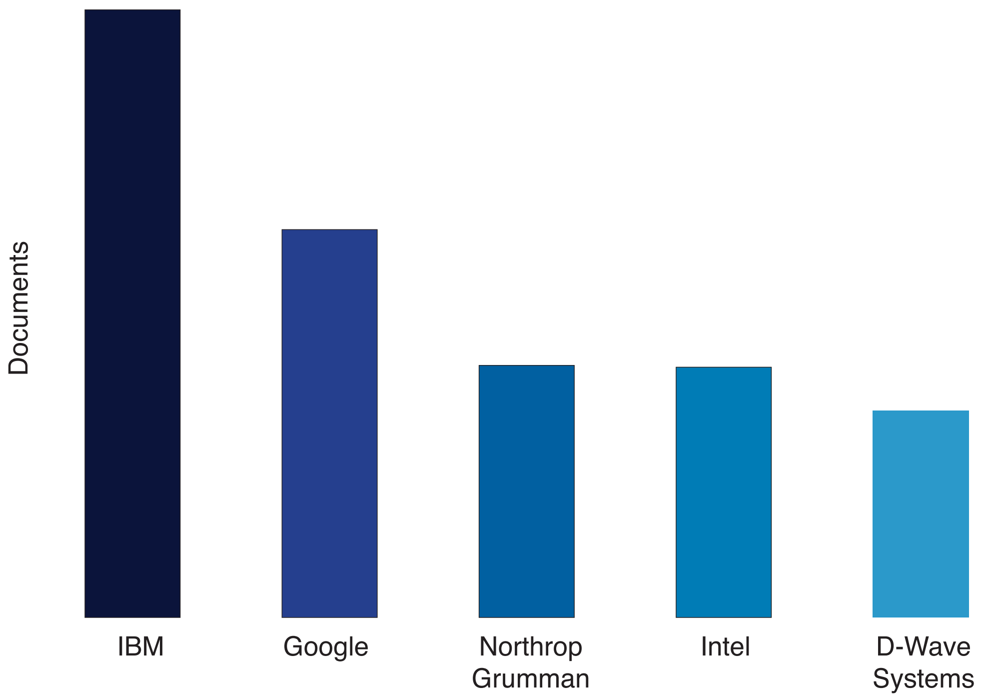
90 "India Contributes 900 Patents to IBM'S Global Innovation Pool," *The Hindu,* 2020, https://www.thehindu.com/business/india-contributes-900-patents-to-ibms-global-innovation-pool/article30569940.ece

Fig. 4. Top Patent Awardees in Quantum Computing, by Company (2021).

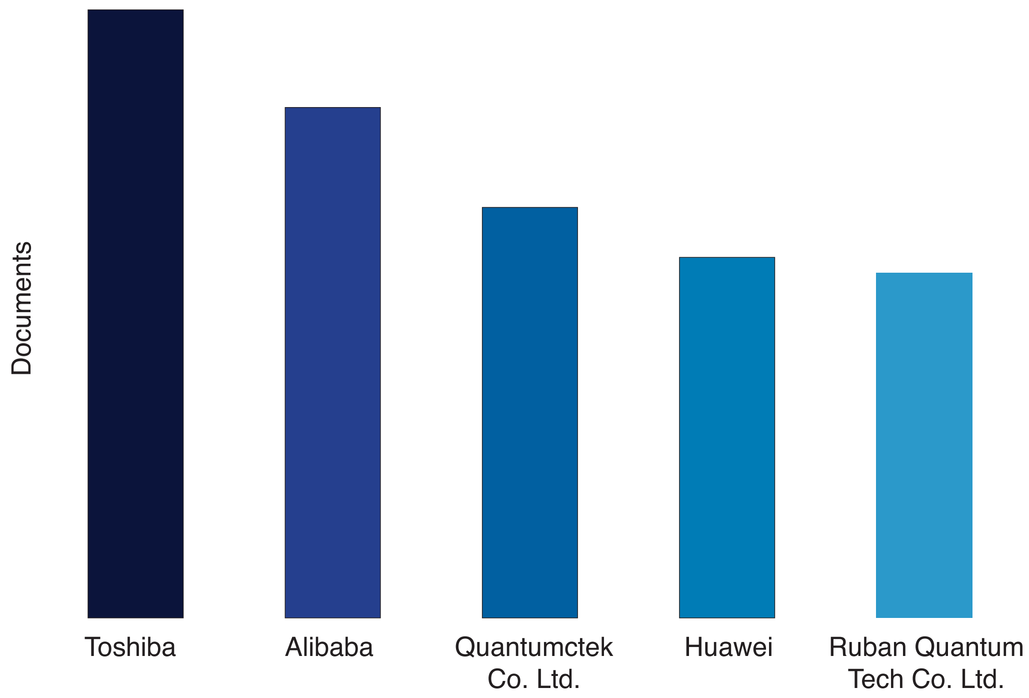


Global firms with the most quantum computing patents.

Source: Quantum Technologies: A Review of the Patent Landscape 2021.[91]

91 Alex Mathew, *Quantum Technologies: A Review of the Patent Landscape,* Arxiv, https://arxiv.org/pdf/2102.04552.pdf

Fig. 5. Top Patent Awardees in Quantum Cryptography, by Company (2021)



Global firms with the most quantum cryptography patents.

Source: Quantum Technologies: A Review of the Patent Landscape 2021.[92]

2. **Lack of patent offices in universities.**
   A crucial reason behind the lack of patents filed by research centres in India is the absence of patent offices in universities, apart from a few IITs. Students and researchers are not provided the support to register their intellectual property. The task of filing patents requires cumbersome legal work and students opt out of these additional responsibilities. Some students this author spoke to also stated that filing patents through a centralised system requires manoeuvring arduous bureaucratic hurdles that eventually drain resources and time that they could use in experiments and academic work.

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92 Mathew, *Quantum Technologies: A Review of the Patent Landscape*

3. **Delays in sanctioning labs to new scientists.**
   Quantum science is vast and there are many avenues of technological development that have opened fairly recently. Several young professors who are also academically equipped to carry out research in quantum science stated that they face hurdles and administrative blockages in setting up experimental research. This has a snowball effect in slowing innovation and the achievement of NM-QTA's objectives.

4. **Missing open innovation platforms.**
   Quantum science research areas are niche, and the problems they seek to solve cannot be limited to research labs and the academic environment. Indeed, most emerging technologies have evolved because of cross-collaboration and innovation platforms that were available to students, technologists, the industrial workforce, academics, and scientists. For instance, Kaggle,[93] an open innovation platform that carries millions of datasets for data scientists, has paved the way for organisations and students to bridge the skill gap, nurture talent, and offer innovative solutions to complex problems. Kaggle also hosts online competitions and hackathons that help pave the way for enhanced international cooperation. Indigenous open innovation platforms like Qiskit,[94] which was released by IBM in 2017, are absent in India. Indian industry would also need contextualised solutions for its problems, and such a platform would be useful.

5. **Metrics to gauge progress are loosely defined.**
   Tech firms and states are working on the second generation of quantum computers that will be industry-ready. Since none of these checkpoints can be accomplished in the short term, a proper framework to gauge timely progress should be in place. The objectives of NM-QTA, as stated in the vision statement, seem generic in nature. Lack of clarity will also have a negative impact on application development. As of today, it is

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93 Kaggle, https://www.kaggle.com/

94 Qiskit, https://qiskit.org/

not clear whether the Union government wants to focus on long-term applications such as developing quantum computers with sensors, or near-term applications like quantum communication and QKD. As most academics would agree, this lack of clarity has led to dispersed efforts within the quantum community.[95]

E. Policy communication is lagging

Consultations with graduates and young researchers in the quantum space revealed that most of them are not aware of the Indian quantum mission, its objectives, and its overarching framework. While the Mission was announced in the budget session of 2020, it has not been communicated effectively to all the relevant stakeholders in the quantum ecosystem. A similar observation was made for civil society experts, especially those who champion data privacy, cybersecurity and India's IT policies. Even after two years of the announcement of the mission, it is largely limited to academia and a handful of startups. The mission was never opened for inputs from academia or the industry or other relevant stakeholders in the quantum ecosystem. This suggests that several key aspects of decision-making could be amiss in the mission.

95 Based on interviews during field visits to India's quantum labs (May to July 2022).

V

Recommendations

While there is strong optimism in the community towards the uptake of the NM-QTA, there are a number of pressure points where India will need to reassess its quantum tech strategy.

1. **Rethinking investments**

   For India to manufacture quantum components locally, appropriate infrastructure will have to be developed. For example, for producing chips, fabrication labs will have to be set up. During field visits, this author found that India does not have an industrial-scale fabrication facility, albeit there are a few for carrying out experiments. The government will need to incentivise various players to invest in long-term infrastructure development that will not just help resurrect India's manufacturing sector but also strengthen its geopolitical position in producing quantum equipment.

   To this end, India can frame lucrative policies that attract foreign and Indian investors alike. Current initiatives like the Scheme for Promotion of Manufacturing of Electronic Components and Semiconductors (SPECS),[96] Modified Special Incentive Package Scheme (M-SIPS),[97] and Production-Linked Incentive (PLI) Scheme could also be extended to quantum technologies. Insurance to manufacturing firms, especially startups, can be provided. Attractive loans can be planned for micro, small and medium enterprises (MSMEs) to kickstart manufacturing of quantum components in the country. Startup missions in states could be leveraged to empower manufacturing locally. For instance, the Kerala Startup Mission initiated setting up the first super fabrication lab[98] in the country that can produce any machinery. Devolving power to states will also improve ease of doing business, reduce centralised paperwork and generate employment for locals.

96 "Scheme for Promotion of Manufacturing of Electronic Components and Semiconductors (SPECS)," Ministry of Electronics and Information Technology, https://www.meity.gov.in/esdm/SPECS

97 "Modified Special Incentive Package Scheme (M-SIPS)." Ministry of Electronics and Information Technology, https://www.meity.gov.in/esdm/incentive-schemes

98 Fablab Kerala, https://fablabkerala.in/

Some academics and scientists are of the view that there is a need to direct more funding towards foundational science. Because research in quantum science is still in the early stages, handing out more funds to academia (both theoretical and experimental) will lead to more experiments, attract more talent, add to innovation and strengthen India's knowledge base. Initiatives like the National Research Foundation may have good intentions, but they need to be sped up. Further, delays caused by bureaucratic hurdles must be reduced significantly. For this, the government can develop a single portal or assign a single point-of-contact to all academics in the quantum space to communicate with the government.

At this stage, pure science should be given priority and the government must work towards easing the hurdles.

2. **Reframing policies and restructuring leadership for quantum science research**

   No policy can exist in silos and that holds true for India's quantum mission. Economic measures and foreign policy must be aligned with the country's technology policies. If the government chooses to impose restrictions on the import of electronic equipment, it should either relax these norms for purposes of scientific research or bolster their domestic manufacturing, so that R&D and academia do not suffer.

   Importantly, unlike other technologies that can be managed by generalist bureaucrats, quantum technologies should be directly managed by scientists who will be given the key role in decision-making and framing pointed policies for quantum science. Since they know their field best, it will be easier for both the government and the quantum community to match pace with the NM-QTA's objectives, deliver outcomes on time, reduce siloed communication, and meet the requirements of scientists in a timely fashion.

3. **Synergising for a quantum-ready workforce**

   There are many facets of building a quantum-ready workforce that the government, private sector, academia and the R&D sector must consider. Merely tutoring students in quantum science will not suffice. Since quantum technologies will affect various current technologies, there is a need to bring technologists and experts from different sectors to participate in the transition. For instance, the telecommunications sector should be made part of key scientific discourses that take place around quantum-enabled encryption. The voice of telecommunication experts is critical in understanding the future of quantum communication and must be accommodated. The government can then facilitate a network of networks comprising experts from academia, industry, government, civil society and the R&D sector to ensure a holistic adoption of quantum technologies.

As discussed in the previous chapter, the support staff that will deal with the day-to-day functioning of quantum machines, their maintenance, and their operation will need to be trained. The government can rope in industrial training institutes and skills-based institutions to impart focused training, modules, and certified courses for this purpose. At present, these could be directed towards training in quantum software. These should be carried out in parallel to technological and scientific development.

India should not blindly replicate practices in the West in developing its quantum industrial workforce. Instead, it should focus on its core strengths in quantum communication, sensing and quantum information, and invest resources to develop a directed workforce. The private sector, which has only recently shown interest in the Indian quantum space, will be pivotal in catering to this. To deepen the trust of industry in quantum science and research, academia and the R&D sector can provide them periodic proof-of-concept. This will not only make research more credible, feasible, and plausible but also finetune participation strategies of the private sector. Indian technology firms like Infosys, Tata Consultancy Services, and Wipro—which have sufficient state-of-the-art infrastructure and wide outreach in university campuses—can then offer placement opportunities to young graduates and make quantum computing and technological development commonplace in the country.

At present, academic fellowships in the quantum space are scant, selective and highly scientific. Their scope can be broadened by making them inclusive towards tech policy professionals, sociologists, liberal arts graduates, communication professionals and those involved in India's national security, including defence personnel.

Academia, the R&D sector and industry must act together to create a sustainable job market lest the many who graduate with quantum education end up not being able to join the workforce.

4. Developing a quantum-enriched curriculum

A number of experts in academia and industry that this author spoke to, recommended that quantum science be taught from the primary school level. This will pique young minds and cater to the long-term vision of indigenous quantum research. While these courses can be accommodated within the National Education Policy 2020, there is also a need to include courses around the ethics and philosophy of quantum technologies.

At the university level, several top institutes of India, like IISc, Bengaluru, IIT-Bombay and IISERs have started niche courses on quantum science for graduates. State governments can seek their assistance and set up such courses at state colleges and universities. Moreover, to develop a quantum-aware workforce, private universities that are lower-tier should also offer specialised courses in quantum science. Again, leading universities can foster the setting-up of labs and research groups. This would also require state governments to develop capacity (in both academic and infrastructure) to improve skills in the quantum space.

India will also need to move away from solely software development courses and offer both types of courses: those that focus on quantum hardware development and those focused on quantum information science and software development.

Restructuring education will be critical in the long haul. Since quantum technological development is interdisciplinary, thoughtfully carved out quantum education can be a game-changer in India's quantum advance in this century.

5. **Making innovation a primary focus for the quantum community**

   Several facets of quantum science and technology development are resource-intensive and collaborations are inevitable. The government should bolster innovation through enhanced collaboration between industry—academia—R&D connect. There is a pressing need to formulate IP laws for emerging technologies. The government should also leverage on current agencies like the Competition Commission of India (CCI) and the Bureau of Indian Standards (BIS) to expedite algorithm standardisation and innovation, and to set out standards for commercialisation of quantum technologies. This would also help private firms understand gaps in technology areas and the readiness of the quantum workforce in the uptake of these technologies.

   When it comes to increasing India’s patent tally, patent offices should be set up for universities, research labs, R&D institutions and research firms where development of technology is prominent. This will not just accelerate patent filing but also ease the pressure on academics and graduate students. The technicalities of patent filing, like articulate writing and understanding of IP rights (IPR) laws, might not be an asset of every professor or researcher. This could be facilitated by the DST in India. Further, innovation needs to be incentivised. The government could announce prizes, bigger grant checks, subsidised purchase of critical equipment and other such initiatives for those who are granted patents.

   Open innovation platforms must also be developed within the quantum community and should be planned in a way that these gain transnational presence. Since contextualised technology translations are the need of the day, innovation must be at the core of the mission. Commercialisation could then follow.

Conclusion

Quantum technological development has progressed steadily in the last few decades. As the global race to quantum supremacy gains relevance in this "techade", nations and tech firms are investing billions of dollars into developing this emerging technology. However, quantum science and technologies will vary significantly from others like AI, blockchain and IoT. Therefore, the set of challenges and their solutions will be different for quantum technologies.

India's foremost policy for quantum science development was initiated in 2017 after the Department of Science and Technology announced the QuEST Program with a budgetary outlay of INR 80 cr. While the program was instrumental in establishing a few key experimental labs and initiating proofs of concept, it is only through the National Mission on Quantum Technologies and Applications (NM-QTA) that a quantum stakeholder ecosystem has been underway and relevant R&D has picked up. It has been allocated INR 8,000 cr for a period of five years, from 2020 to 2024.

The Mission's vision and intention is to develop India's quantum capabilities. However, the funds have not reached the relevant quantum stakeholders till date. At present, the mission's vision and its implementation are faced with many gaps at both the policy and the execution levels. The imperative is to identify these gaps and roll out measures to address them. Challenges such as filing patents, funneling investments, and framing pointed policies for quantum hardware and software development need to be addressed. As quantum technologies will be based on robust foundational research, it is also imperative for relevant agencies to advance in a meticulous manner towards future research rather than solely focusing on application development. The mission must strive to achieve all three categories of application building. It is also essential that the indicators to track the progress of the mission are defined with more granularity and communicated effectively to various stakeholders of the quantum ecosystem.

Unlike in other emerging technologies, such as AI and blockchain, where India could not drive global discourse and decision-making, quantum tech offers India a unique advantage. India, like other economies that have quantum strategies and policies in place, can leverage its global position through multilateral organisations like the G20 and the Quad to spearhead global quantum science and technology development.

At present, the focus of the Mission is not clear to many stakeholders in the ecosystem. Consultations with these stakeholders resulted in gauging the on-ground progress of the Mission and what needs to be done to make it a success. As the Indian quantum ecosystem continues to grow and evolve and technological advancement gathers pace, it is important that the telos of the mission is central to all these developments. Indeed, these challenges are more of opportunities rather than bottlenecks.

About the Author

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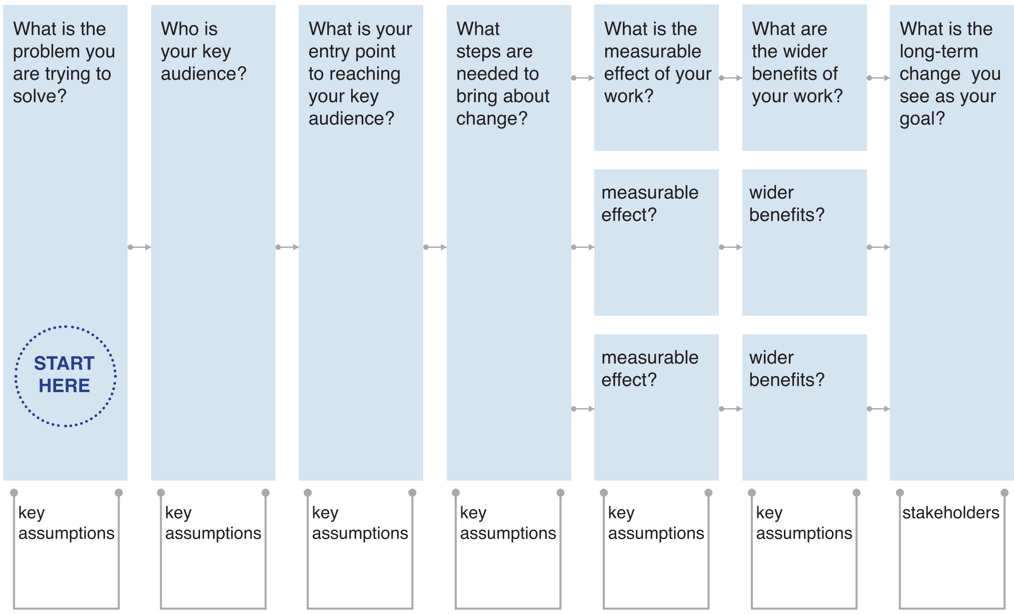
Appendix 1

Theory of Change

Theory of change essentially explains the process by which the outcomes of a programme, policy or scheme will be achieved. The framework breaks down the desired outcomes into long-term and short-term goals, identifies assumptions and lays down interventions to achieve these. It proposes a step-by-step approach to attain the desired objectives. Fig. (i) presents the Theory of Change framework.

Fig. (i). Theory of Change framework.



Source: EduSpots.org

The framework is useful when evaluating the efficacy of any policy or programme. It also allows for policy planners to structure policy objectives more succinctly and assign realistic timelines. Usually, the framework requires many rounds of iterations and leaves immense scope for accommodating new ideas of approaching the problem.

Appendix 2

PESTLE framework

The PESTLE framework is used for understanding the implications of a policy or a programme.

P	E	S	T	L	E
political	economic	social	technological	legal	environmental (or ethical)

It can be used to recognise risks that might arise as a result of the policy or programme that is put in place. It is also widely used for pre-empting any negative consequences of a policy, a scheme or a programme on the well-being of people or society in general.

As a matter of practice, the framework should be used in consultation with all stakeholders in the policy ecosystem. This should also be employed after collecting data from the grassroots and should not be merely deployed using anecdotes.

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