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LANDSCAPE OF INDIAN R&D IN QUANTUM TECHNOLOGIES

2024

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Foreword by Kris Gopalakrishnan

Till the end of the 20th century quantum technologies was considered an esoteric domain, and limited to experiments in a few labs around the world. This has changed in the 21st century, and we are now witnessing a slew of high-profile applications of quantum technologies. In fact, the Nobel Prize in Chemistry 2023 rewarded the discovery and development of quantum dots, which are used to illuminate computer monitors and television screens (QLED technology) and could contribute to flexible electronics, tiny sensors, thinner solar cells and encrypted quantum communication.

In 2011 D-Wave launched D-Wave One, the first commercially available quantum computer. IBM's first commercial superconducting quantum computer, the IBM Quantum System One, was launched in 2019 with 20 qubits. IBM'S Condor, a superconducting quantum computer with more than 1,000 qubits was released in December 2023.

In 2017, a quantum cryptography key was shared between Beijing and Vienna using a satellite so that that the presidents of the Chinese Academy of Sciences and Austrian Academy of Sciences could communicate using a very secure video link.

In 2020, Samsung and SK Telecom launched the Galaxy A Quantum smartphone, with a quantum random number generation chipset. In other words, the communications were secured to a degree that is almost un-hackable using classical computing methods.

Today, quantum technologies are being considered for a myriad of products and solutions. These range from the strategic defence and security to more accurate global navigation systems to hand-held MRIs. Not surprisingly, it is estimated that the top twelve countries have invested about USD 38.6 billion in quantum technologies as part of current programmes. While the ongoing global race to dominate AI is well underway, the global race to dominate quantum technologies has just begun.

The Indian government is aware of the importance of building national capability in quantum technologies. The Indian higher educational institutions, national labs, industry, and start-ups are enthused about this task. India has a strong foundation in science and technology research and development (R&D) which will serve as launch-pad for quantum technologies. If we treat quantum technologies as a national priority, we will succeed in building world-class capabilities like we have done in domains like IT services and space research.

This landscape study on quantum technologies in India has identified important impact areas to focus for its R&D and translation. This should help spark a dialogue among researchers, policy makers, industry, and science philanthropists in India on fine tuning the announced National Quantum Mission (NQM).

India needs double down on the NQM to aim high. As Richard Feynman said in his seminal paper titled "Simulating Physics with Computers",[1]

"And I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

I believe that our world-class researchers are ready for this challenge with vital support from the NQM.

Kris Gopalakrishnan

Chairman itihaasa Research and Digital, Co-founder Infosys

Executive Summary

Quantum technologies is the practical application of quantum physics in devices or algorithms. The important domains in quantum technologies include:

1. **Quantum computers**
2. **Quantum communications**
3. **Quantum sensing and metrology**
4. **Quantum materials and devices**

Quantum computing uses quantum bits (qubits) and the principles of quantum mechanics as the fundamental unit of information to perform calculations. The principles of quantum physics are used to measure movement, position, time, electric field, magnetic field, gravitational field, etc. accurately. Such measurements are called quantum sensing and metrology. The principles of quantum mechanics are also used to transmit information using qubits. This is quantum communications. Quantum materials are substances that exhibit exotic electronic, magnetic, or optical properties arising from quantum mechanical effects. They are the underlying materials used in devices powering quantum computing, quantum sensing and metrology, and quantum communications.

Some of the key applications of quantum technologies include the following:

Quantum computing

- quantum computers in designing new drugs, AI & machine learning
- quantum safe cryptography or post quantum cryptography (PQC)
- quantum random number generators (QRNG) in Monte Carlo simulations

Quantum communications

- quantum key distribution (QKD)
- quantum satellite communication
- quantum Internet

Quantum sensors and metrology

- atomic clocks
- nuclear magnetic resonance (NMR) spectrometers
- atomic force microscopes

Quantum technologies are likely to influence many aspects of human life. This makes quantum technologies strategic, and almost every developed country is investing in mastering these technologies. Current worldwide investments in quantum technologies from the top 12 countries focussing on this domain are estimated to be about USD 38.6 billion. [2,3]

	Country	Estimated Quantum Investments (Quantum Resources and Careers)	Estimated Quantum Investments (McKinsey & Co.)
1	China	15.00	15.3
2	United Kingdom	4.30	1.3
3	United States of America	3.75	3.7
4	Germany	3.30	3.8
5	South Korea	2.35	-
6	France	2.20	2.2
7	Russia	1.45	0.7
8	European Union	1.10	8.4
9	Canada	1.10	1.1
10	Netherlands	0.90	0.9
11	India	0.74	1.0
12	Japan	0.70	1.8

Country-level estimated quantum investments (in billion USD, as of 2023)

The USA, China, and the European Union (EU) are the R&D leaders in quantum technologies. India has reasons to be optimistic to become a leader since quantum technologies are still evolving, and there is an opportunity to leapfrog. The presence of world-class principal investigators (PIs) and R&D teams, and the large National Quantum Mission (NQM) makes India well-poised to become a global leader.

India has a strong R&D foundation accumulated over multiple decades in quantum phenomena, superconductivity, condensed matter physics, quantum optics, quantum materials, etc. India has also benefitted from the past R&D missions including the Nano Misson, pilot projects in quantum technologies initiated by the Office of the Principal Scientific Adviser, Department of Science and Technology's (DST's) Interdisciplinary Cyber Physical Systems (ICPS) division's Quantum Information Science and Technology (QuST) programme, DST's Quantum Enabled Science and Technology (QuEST) programme, the National Mission on Quantum Technologies & Applications (NM-QTA) blueprint, and the proposed NQM.

We interviewed twenty principal investigators (PIs) working in quantum technologies, two founders of quantum technology startups, and one R&D program manager for this study.

Currently, there are about 110 to 145 PIs working on quantum technologies in the top Indian higher educational institutions and national labs. These PIs support about 75 to 100 post docs, and about 300 to 400 PhD students. There are also about 50 to 100 MTech students in programs focused on subjects that are close to quantum technologies. In addition, there are about 200 PIs working in different domains of physics, material science, electronics, computer science, etc. allied to quantum technologies. They support over 1000 students / researchers in these allied domains.

Estimated number of Indian researchers and students in quantum technologies

110-145 PIs	**75-100** Post Docs
300-400 PhD Students	**50-100** MTech Students
~200 PIs in domains allied to quantum technologies	**>1000** Post Docs, PhD and MTech Students in domains allied to quantum technologies

A Web of Science data-based analysis of papers by researchers from Max Planck Institute on quantum technologies between 2000 and 2018 indicates that India has published 1,711 papers while China published 12,110 papers and the USA 13,489 papers. The USA is ranked first, China second, and India tenth in terms of papers published.[4] If the top 10% most cited papers are considered, the USA ranks first, China third, and India twentieth.

Based on analysis of Web of Science data for the period between 2018 and 2022, China leads the world in research quality in quantum communications, and the USA leads in quantum computing and quantum sensors. With respect to research quality, India ranks in the top 10 in quantum sensors (#6), and outside the top 10 in quantum computing (#11) and quantum communication (#16). In one sub-domain of quantum computing, i.e., post-quantum cryptography, India is in the top 5 in the world with respect to research quality (#5).[5] With respect to research quantity, Indian ranks in the top 5 in quantum computing, quantum communications, and quantum sensors.

A machine learning driven patent analysis study on Reclura's patent database of patents between 2015 and 2020, indicated that India had 339 patents in quantum technologies compared to 23,335 for China, and 8,935 for the USA. [6] China is ranked first, the USA second, and India ninth by patents published.

Indian R&D in quantum computing is working with different technologies like superconducting qubits, ion-trap qubits, semiconductor qubits, and nuclear magnetic resonance qubits. India is also working on the software elements of quantum computing like developing simulators for quantum computers. Indian capability in the quantum communications domain is probably closer to the global best when compared to other domains of quantum technologies. Indian R&D has demonstrated its capabilities in both fiber-based and free space quantum communications. Indian R&D has also developed prototypes of different types of quantum sensors. The focus is also to shift its basis for metrology standards from artifact-based to quantum standards. In quantum materials and devices, the focus of Indian R&D is to identify the different materials best suited for devices used in different applications in the other three quantum domains.

Recommendations:

Focus on higher education and training

- The NQM may want to explore ramping up MTech programs in electronics, communication and applied physics to include super specializations in microwave and optical technologies.
- The NQM should also include teaching related projects in its portfolio of funded projects.
- The blended offline and online education model is a realistic way to impart quality education to a large number of students on quantum technologies.

Attract the best talent

- The NQM should allow hubs to select promising undergraduate students and sponsor them for a PhD in quantum technologies at institutes like IISc, IITs, and IISERs. After their PhD, the hubs get them back, and offer them positions as postdocs in the research projects they are sponsoring in different institutions.
- The NQM may have to indicate a complete career path in India in quantum technologies. The NQM may need to facilitate a S&T cadre in the hubs similar to the ISRO and BARC model of the researcher and technologist cadres.
- Attracting the best postdocs from around the world helps to jumpstart R&D.

Jump-start translational research

- It is important for the NQM to identify national priority use-cases upfront to enlist industry partners from the initial stages of defining applications.
- The NQM must encourage and train boundary spanners from industry, startups, and higher educational institutions.
- The NQM hubs can invest in teams to translate promising technologies in lower TRL to a higher TRL. It also needs to quickly ramp-up experimental facilities.

Foster multi-disciplinary collaborations

- Creating and translating a quantum technology requires physicists, material science engineers, electronics engineers, mechanical engineers, computer scientists, etc. to work together.
- The NQM should analyse the European model where a multi-disciplinary team of PIs nurture a quantum technologies lab, and adopt the best practices contextualized to the Indian context.
- The NQM should also explore including a larger community of Indian citizens to discuss the impact of quantum technologies.

Create effective and efficient hubs

- The NQM needs to identify if the hub is a virtual collection of higher educational institutions and national labs, or it is a physical centre located in the premises of one of the organizations that constitute that hub.
- The NQM hubs should prioritise establishing national experimental facilities equipped with top-of-the-line scientific instruments.

- The NQM hubs may need to emulate the best practices of Indian mission mode application-oriented organizations like ISRO, BARC, NM-ICPS, etc. and best-in-class international organizations.

Smoothen the procedural challenges

- The NQM should consider an exemption from the GTE process in equipment and raw material procurement.
- Importing materials for R&D may need a special channel that includes speedy customs clearance.
- The NQM should include funds required for maintaining and repairing the equipment upfront as obtaining funds post-facto for maintenance can be arduous.

1. Introduction

India has leapfrogged in building a world class capability in information technology (IT). The capability in IT has powered India's economic development in the past three decades. IT now contributes to 7.5% of India's GDP.[6] While this is a significant achievement, India cannot afford to be complacent since IT is evolving rapidly. India has realized the impact of this change and is investing in emerging domains like artificial intelligence and machine learning (AI/ML). While the jury is still out on how well India has taken advantage of its dominant position in IT to acquire a capability in AI/ML, there is another change taking place.

A new domain is advancing at an accelerating pace, and looks promising to illuminate both our understanding of the fundamental building blocks of matter as well as advance IT. This domain is quantum technologies, the practical application of quantum physics in useful devices or algorithms. These are sophisticated technologies that help us to control and measure quantum particles at an individual level.

Why are quantum physics and technologies important? The best answer is probably in the introduction to the chapter on photons and matter waves in the classic well-loved textbook *Fundamentals of Physics* (endearingly called *Resnick and Halliday* after the authors).[7]

"Quantum physics, as our new subject is called, answers such questions as: Why do the stars shine? Why do the elements exhibit the order that is so apparent in the periodic table? How do transistors and other microelectronic devices work? Why does copper conduct electricity but glass does not? In fact, scientists and engineers have applied quantum physics in almost every aspect of everyday life, from medical instrumentation to transportation systems to entertainment industries. Indeed, because quantum physics accounts for all of chemistry, including biochemistry, we need to understand it if we are to understand life itself.

Some of the predictions of quantum physics seem strange even to the physicists and philosophers who study its foundations. Still, experiment after experiment has proved the theory correct, and many have exposed even stranger aspects of the theory. The quantum world is an amusement park full of wonderful rides that are guaranteed to shake up the commonsense world view you have developed since childhood."

Our objective for this study is to provide a nucleus for starting a dialogue among stakeholders that results in concrete action plans to significantly impact Indian R&D in quantum technologies and its translation in India.

The report is organized as follows. Section 2 provides a brief overview of quantum physics and quantum technologies. Section 3 is on the global missions in quantum technologies and the implications for India. Section 4 is a summary of the evolution of Indian R&D in quantum technologies and the national missions in quantum technologies. Section 5 analyses the current state of R&D in quantum technologies across four domains of quantum computing, quantum communications, quantum sensing and metrology, and quantum materials and devices. This section also provides an outline of the state of translational R&D, estimates the number of principal investigators, and India's track record in research publications and patents. Section 6 provides a set of recommendations that will enhance the impact of the National Quantum Mission (NQM).

2. Quantum physics and quantum technologies

2.1. A very brief overview of quantum physics and quantum technologies

Over a century ago, physicists observed certain phenomena especially in very small scales of atomic and sub-atomic particles which could not be explained by the existing classical physics theories. To explain those observations, they had to invent a new theory which we now know as quantum physics.

A quantum is the smallest discrete unit of a physical phenomenon. It is quantifiable and measurable. For example, a quantum of light is a photon, and a quantum of energy carried by a photon is determined by its frequency and Planck's constant. According to quantum physics, sub-atomic particles exist in quantum states that typically represent their position and momentum.

Quantum physics is useful to describe quantum phenomena which are usually at the sub-atomic and atomic scales. In macroscopic scales classical theories work well, like in the context of a cricket ball as it leaves a bowler's hand or a car travelling on the road, and quantum physics does not provide new insights.

Some of the important principles of quantum physics are:

- Superposition: Quantum physics allows a particle to be in a superposition of different states, typically of position and momentum.
- Entanglement: A group of particles interact such that the quantum state of each particle of the group cannot be described independently of the state of other particles, including when the particles are separated by a large distance.
- Tunnelling: A particle or atom can pass through a potential energy barrier that it does not have the energy to cross based on classical physics.
- Squeezing: Heisenberg's uncertainty principle states that we can't precisely know both the position and momentum of a particle at the same time. A state is squeezed when the noise in one variable, say position, is reduced below a limit at the expense of the increased noise in momentum, so that the uncertainty principle is not violated.

Quantum technologies comprise four domains

1. Quantum computing
2. Quantum communications
3. Quantum sensing and metrology
4. Quantum materials and devices

1. Quantum computing uses quantum bits (qubits) and the principles of quantum mechanics as the fundamental unit of information to perform calculations. Qubits are represented as 0, 1, or any quantum superposition of those states. This is different from classical computing, where bits represented by 0 and 1 are the fundamental unit of information.
2. The principles of quantum mechanics used to transmit information using qubits. This has led to the domain called quantum communications. The promise of quantum communications is that if a hacker tries to observe these qubits while in transit, their quantum state collapses. A hacker cannot tamper with the qubits without leaving behind a trail.
3. The principles of quantum physics are also used to measure movement, position, time, electric field, magnetic field, gravitational field, etc. very accurately. Such measurements are called quantum sensing and metrology.
4. Quantum materials are substances that exhibit exotic electronic, magnetic, or optical properties arising from quantum mechanical effects. They are the underlying materials that are used in devices powering quantum computing, quantum sensing and metrology, and quantum communications.

Each of these domains spawns many technologies. For example, qubits can be created by leveraging one of many different technologies.

- Electrons in superconducting circuits: In superconducting circuits, where current can flow without resistance, quantum states are encoded in the energy levels of the superconducting elements.
- Nuclear spin: Qubits can be created by using the spin states of nuclei, using techniques like Nuclear Magnetic Resonance (NMR) and Electron Spin Resonance (ESR).
- Trapped ions: Qubits, in ion trap quantum computers, are created by trapping individual ions (charged atoms) using electromagnetic fields. Laser beams are used to manipulate and measure the quantum states of these ions.
- Diamond Defect Centres: Certain defects in diamond crystals, like nitrogen-vacancy (NV) centres, can serve as qubits. The electron spin of the defect centre can be controlled and measured using magnetic fields and lasers.
- Other technologies include quantum dots, photon polarization, topological qubits, semiconductor qubits, and others.

2.2. Applications of quantum technologies

Quantum computing

Quantum computers can be used to model atomic and molecular phenomena, design new kind of drugs and catalysts, and discover new enzymes, proteins, etc. Medical diagnostics and treatment can be revolutionized with quantum technologies because the underlying processes are at the atomic and molecular scale. Programming a quantum computer requires an intimate understating of quantum principles. High level programming environments for quantum computing make it easier even for users without a knowledge of quantum principles to write programs that can run on a quantum computer.

Given the low stability of some quantum devices due to the small coherence times of milliseconds or microseconds when the qubits are available for calculations, the way a quantum application will be architected will be different from traditional computers. Such applications will not run for days or weeks together on a quantum computer like they do on a supercomputer. The quantum applications will be hybrid systems – a combination of quantum and classical systems. Users will break the problem into subroutines, and run some of them, one by one, on a quantum computer where it can complete the subroutines in very little time. The results may be stored in a classical domain and used later in an application or subroutine.

> Consider the following scenario of working with a quantum computer. A programmer, using a laptop, writes a program to implement factorization. She uses the Python-based Qiskit SDK, an opensource software development kit for working with quantum computers. That program gets compiled on a classical computer in the cloud, which then sends a subroutine to the quantum computer. This is done in the form of transmitting microwave signals into qubit-gates to execute that command. This is what gets executed on the quantum computer. Everything else prior to this step is carried out on a classical computer.

Just like in the case of classical computing, the demand for large quantum computers is likely to come from computing platform companies, universities, and labs.

Quantum computing as a service offered by companies like IBM is one model to percolate the use of quantum computers. Consider IBM's proposed 100 X 100 challenge, which would be the state-of-the-art for a quantum computer in the world. In 2024, IBM plans to offer a tool capable of calculating unbiased observables of circuits with 100 qubits and depth-100 gate operations in a reasonable runtime.[8] Thus, the most sophisticated quantum computer will demonstrate using 100 qubits and 100 gates, whereas a transistor in a classical computer, packs millions of gates at the same time, to solve a problem. The number of gates in the two computers should not be compared directly since the power of a quantum computer increases exponentially in proportion to the number of qubits while the power of a classical computer has a 1:1 relationship with the number of transistors. Further, it has been proven mathematically and demonstrated that certain types of problems (such as factorization, search etc.) can be solved on quantum computers exponentially faster.

Not all problems in all domains can be reduced to a quantum physics related problem. For instance, there is a common misconception that Brownian motion models used in financial markets is a quantum phenomenon. It is not, and is based on conventional probability theory. The immediate quantum application in finance domain is seen in determining how much faster the trades can be completed. Newer theories and models, such as quantum game theory, have been proposed that go beyond conventional probabilistic or statistical analysis. They can be applied, for instance, by the government for policy making in order to improve the efficiency of the market.[9]

An emerging field in quantum computing is **quantum AI and ML**. IBM researchers have found mathematical proof of a potential quantum advantage for quantum machine learning. The advantage comes from the fact that one can construct a family of datasets for which only quantum computers can recognize the intrinsic labelling patterns, while for classical computers the dataset looks like random noise.[10] The advantages may be in the form of increased efficiency, accuracy, or reduced training costs.

For instance, quantum AI/ML algorithms seem to be much more efficient at computer vision like identifying a picture of a cat, or identifying road signs as compared to classical machine learning systems. IBM researchers have found that quantum computers require an order of magnitude lesser amount of data to train – tens of pictures of a cat as compared to 10,000 pictures for an ML system. Quantum computers are more accurate as well – they can distinguish a cat from a cheetah (close cousins) more accurately than classical ML systems.

Researchers in the autonomous-vehicles lab at a quantum computing company, IonQ, and the automobile major, Hyundai, developed quantum machine-learning algorithms that can differentiate ten road signs. The quantum-based model used just 60 parameters to achieve the same accuracy as a classical neural network using 59,000 parameters.[11]

One domain in computer science that will be revolutionised with quantum computing is cryptography. Quantum computers pose a threat to traditional cryptographic methods, which rely on mathematical techniques like factorization. They have the potential to break existing encryption schemes efficiently. There is a need for **quantum safe cryptography or post quantum cryptography (PQC)** to make classical cryptographic systems that are able to resist attacks from both classical computers and quantum computers. PQC is not quantum technology. It makes use of different cryptography algorithms, such as hash-based, code-based, lattice-based cryptography and so on. PQC is resistant to quantum algorithms such as Shor's algorithm and Grover's algorithm.[12]

Quantum Random Number Generators (QRNG), a type of quantum device, can be used in the financial services sector to seed the Monte Carlo simulation to assess pricing and risk for financial products like options, fixed income securities, and interest rate derivatives. QRNG is better than the current methods of generating random numbers and provides truly random numbers for improving the accuracy of Monte Carlo simulations.

When problems can be solved faster using quantum computers, it leads to **quantum-advantage**. This refers to the potential computational advantage that quantum computers and devices may have over classical computers and devices for solving certain types of problems. The trick is to find the quantum principles to model the solution to a problem. A corollary is that quantum-advantage is problem-dependent. While quantum computers have the potential to outperform classical computers for specific problems, they do not necessarily provide an advantage for all types of computations.

A question that arises is the following. If quantum technologies provide a solution that cannot otherwise be obtained by classical methods, how do we know that the solution is indeed a solution. For example, one paradox in quantum computing is: If a quantum experiment solves a problem which is proven to be intractable for classical computers, how can one verify the outcome of the experiment?[13]

The task of ensuring the correct functioning of a quantum device in terms of the accuracy of the output is referred to as certification or sometimes verification. There are a number of methods to certify or verify a quantum system.[14] Let us consider a few of them.

- Blind Quantum Computing allows someone who only has classical computational resources to delegate their computation to a quantum server in such a way that the server cannot learn anything about the client's inputs, outputs, and computation.[15] In this, the verification has computations as tests or traps which the verifier can check (they include verification protocols such as single-prover prepare-and-send, single-prover receive-and-measure, and multi-prover entanglement-based). If the provers attempt to deviate, they will trigger these traps and prompt the verifier to reject.

- Quantum self-testing is a method to infer the underlying physics of a quantum experiment in a black box or device-independent quantum information processing scenario.[16]
- Benchmarking: This assigns a reproducible performance measure to a quantum device. For example, in ion trap technology, the performance benchmarking measures include the stability of the trap frequency, the duration of a gate operation, and the stability of the control lasers. Similarly, for superconducting technologies, the precision of the Josephson, anharmonicity, and gate duration, are equally relevant to performance.[17]
- Tomographic reconstruction in quantum certification refers to the process of reconstructing the complete quantum state or process from measurement data.

Quantum communications

Quantum communication can provide fundamentally secure communication channels. The data we transmit today are classical bits. Qubits can be used to encrypt and decrypt the communication with bits. **Quantum Key Distribution (QKD)** is sending keys to decrypt the information that are encoded and transmitted in a quantum state using qubits. Using QKD protocols, such as BB84, it can create unbreakable encryption keys. These keys are secure against attacks, even if an adversary has a powerful quantum computer. At some point in the future, we may have a **Quantum Internet** which will consist of quantum computers and quantum communication protocols. This will be the preferred way to connect quantum computers.

Quantum communications will initially benefit defence and government sectors who process and transmit classified data. QKD and PQC will be useful to securely transmit personal data between collector organizations, data centres, and user organizations, especially in the context of stringent personal data protection laws enacted in many countries. QKD has a huge potential in the financial and healthcare services industries that need the most secure network for transmitting authentication, digital signatures, and secure access control related information. QKD and PQC can also become critical in an increasingly IoT enabled world. IoT in the healthcare domain like pace makers, and in the transportation sector like autonomous cars will benefit from secure transmissions facilitated by QKD and PQC.

Quantum Secure Direct Communication (QSDC), an alternative to QKD for secure communication, is designed for secure direct communication between two parties without the need to establish a shared encryption key beforehand. QSDC requires a quantum channel using an optical fiber or a quantum satellite link to send quantum-encoded information between the sender and receiver. **Quantum Satellite Communication** extends quantum communication to satellite-based systems, enabling secure communication over long distances.

Organizations such as National Institute of Standards and Technology (NIST), USA, are involved in specifying such quantum certification protocols and standards. For instance, in 2022, NIST announced the world's first four quantum-resistant cryptographic algorithms. The selection follows a six-year effort managed by NIST to devise and then vet encryption methods that could resist an attack from a future all-powerful quantum computer.[18]

Quantum sensing and metrology

Atomic clocks are quantum sensors that measure time with a high degree of precision. The atomic clocks, in satellites are communicating with mobile devices, keep time with high accuracy. This time-accuracy can be converted into high accuracy of location. Thus, if we improve the atomic clock, the resolution of satellite navigation systems will increase and the map applications on our mobile phones can become more detailed and accurate. Such capabilities are also very helpful in improving precision for surveillance for defence and government.

In instruments such as **NMR spectrometers** and **Magnetic Resonance Imaging (MRI) devices** for medical diagnostics, the measurements are a response of the system to the presence of a magnetic field. And to get a good response, we require a high magnetic field. This requirement typically results in the large sizes of conventional diagnostic devices. With quantum sensors for measuring magnetic field at much greater accuracy and sensitivity, we can cut down on the strength of the magnetic field which is applied from outside. Thus, it is possible to convert an MRI machine into a hand-held instrument with the same precision.

Interferometers are high-precision instruments used to detect changes in the gravitational field. This can help us determine what is buried in the earth. Such measurements may be used to detect specific minerals, discover the presence of a natural oil reservoir, or determine the presence of a landmine.

Similarly, quantum devices may be used in the measurement of electromagnetic fields. Examples include **quantum radars** for military applications and **quantum microscopes** for medical applications. Such devices help improve the signal to noise ratios, which are very important in detecting objects in a noisy environment, and result in improved imaging resolutions.

Atomic force microscopes are used to detect and measure the mechanic and magnetic properties of various materials. Quantum sensors can also be used for in-vivo biological detection of temperature differences in cells due to cancer or any other medical condition.

Nature may also be leveraging quantum effects to enhance the efficiency or functionality of a variety of organisms to gain a biological advantage. Consider photosynthetic light harvesting in green-sulphur bacteria. Almost every photon (nearly 100%) that is absorbed is successfully transferred to the reaction centre in the bacteria through a specialized structure called the Fenna-Matthews-Olson (FMO) complex. We have evidence of quantum coherent energy transfer in the FMO complex. Consider the case of avian magnetoreception – the ability of certain bird species to navigate by the earth's magnetic field and which is transduced by a magnetically sensitive chemical reaction that relies on subtle quantum effects. A new area of research, **quantum biology**, has emerged that is looking at developing nature-inspired, bio-mimetic quantum technologies for areas such as efficient energy harvesting or long-coherence-time chemical reactions.[19]

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As we can see from their potential impact, quantum technologies are likely to influence many aspects of human life. This makes quantum technologies strategic, and almost every developed country is investing in mastering these technologies.

3. Global quantum missions

Current worldwide investments are estimated to be over USD 38.6 billion (see Table 1 for country-level estimated quantum investments).[20,21]

	Country	Estimated Quantum Investments (Quantum Resources and Careers)	Estimated Quantum Investments (McKinsey & Co.)
1	China	15.00	15.3
2	United Kingdom	4.30	1.3
3	United States of America	3.75	3.7
4	Germany	3.30	3.8
5	South Korea	2.35	-
6	France	2.20	2.2
7	Russia	1.45	0.7
8	European Union	1.10	8.4
9	Canada	1.10	1.1
10	Netherlands	0.90	0.9
11	India	0.74	1.0
12	Japan	0.70	1.8

Table 1: Country-level estimated quantum investments (in billion USD, as of 2023)

Let us consider the quantum missions from China, the European Union (EU), United Kingdom (UK) and the United States (USA).

3.1. China

China has made significant progress in quantum technologies. It is difficult to know exactly how much China has invested, but it is estimated to be about USD 15 billion.

Key highlights of the Chinese quantum technologies program include:

- Quantum computational advantage in two mainstream technologies 1) a 66-qubit superconducting quantum computing system, and 2) a quantum computer using the photonics quantum computing technology.[22]
- In quantum communications, China is ahead of the rest of the world. They have demonstrated quantum states transmission between two ground stations at a distance of 1,200 kilometres via a quantum scientific experiment satellite, and have established a 2,000 kilometres quantum communication line between Beijing and Shanghai.[23]
- China has become the third country, besides the USA and Canada, with the ability to manufacture a quantum computer for commercial use.

3.2. European Union

The EU started its Quantum Flagship program, like they did for graphene and brain research, in 2018 with a funding of about USD 1 billion over ten years. Halfway into the program, EU has increased its funding commitment by 75%. The member states of the European Union have their own national program on quantum. Over the last decade the EU states have invested about USD 7 billion in quantum technology and research activities.

The long-term objectives of EU's Quantum Flagship include: [24]

- Quantum Internet: Distributed quantum computers, and quantum sensors interconnected via quantum communication networks.
- EuroQCI: a quantum communication infrastructure and building a European cybersecurity shield
- EuroHPC: Deploying a quantum computing infrastructure all over the EU

3.3. United Kingdom (UK)

The UK government published its National Quantum Strategy and committed about USD 3 billion over the ten years from 2024.[25] It includes investments in programme of missions in quantum computing, and positioning, navigation, and timing, and to develop research hubs in quantum computing, communications, sensing, imaging and timing.

This builds on UK's National Quantum Technologies Programme (NQTP), first formed in 2014. It has invested in:

- Research through the Quantum Research Hubs, a national network of four university-led Quantum Technology Hubs and over 30 research organisations
- New centres / institutions such as the National Quantum Computing Centre (NQCC), the Quantum Metrology Institute at the National Physical Laboratory (NPL) and so on.

3.4. United States (USA)

The USA conducted the first government workshop on quantum computing in 1994. The National Quantum Initiative (NQI), started in 2018 with an investment of USD 2.6 billion, aims to establish American leadership in Quantum Information Science (QIS), at the intersection of quantum physics and information science, and create QIS-ready workforce.

Key highlights of NQI include: [26]

- Over 2000 QIS R&D grants have been given under NQI, which engage over 1000 scientists and engineers from over 250 different institutions including 14 quantum research centres.
- The Quantum Economic Development Consortium, an industry-led consortium established as part of the NQI, has over 150 companies.

3.5. Implications for the Indian quantum mission

There are about 17 countries in the world which have announced their formal quantum missions or national programs on quantum technologies. 3 countries have quantum strategies under development while 12 others have significant government-funded initiatives. But more than 150 countries do not yet have a quantum strategy.[27] With respect to companies and startups in quantum technologies, the USA leads with 59 startups, followed by EU (53),[28] UK (50),[29] China (30),[30] and Canada (17).

With respect to India, it is commendable that it is among the 17 countries with formal national quantum missions, and is among the top 12 countries in terms of committed investments. At the same time, we must recognise that India is lagging the global leaders in quantum technologies, and needs to ramp-up both R&D and translational aspects to catch up with them.

There are reasons to be optimistic since quantum technologies are still evolving, and there is an opportunity for India to leapfrog. We have benefited from the nano and quantum initiatives over the years. Thanks to our world-class principal investigators (PIs) and the upcoming NQM, India is poised well. India has had a rich legacy of research in quantum physics and technologies dating back to the early 20th century.

4. Evolution of quantum technologies in India

4.1. A snapshot of the evolution of Indian R&D in quantum technologies

Quantum phenomena and superconductivity

S.N. Bose sent a paper on "Planck's Law and the hypothesis of light quanta" (now called photons) to Albert Einstein in 1923-24, who then went on to propose pioneering ideas such as quantum statistics and Bose – Einstein condensates. The Raman effect, that measured the effect of light scattering and changes in wavelength in the 1920s, was important to the understanding of the then emerging quantum theory. An explanation of the scattering required the use of photons and their change in energy as they interacted with the atoms in a particular molecule.

There have been a number of other important research developments in India related to superconductivity – K.S. Singwi (TIFR) – phonon induced pairing, electron-lattice interaction and superconductivity; R Srinivasan, G Rangarajan (IIT Madras) – superconductivity in Cheverel Phase compounds; J. Yakhmi (BARC) – superconducting wires; N. Kumar, K.P. Sinha, Nandini (IISc) - photoinduced superconductivity; P.N. Ganguly and C.N.R. Rao (IIT Kanpur and IISc) – liquid superconductors; G. Baskaran (Institute of Mathematical Sciences)– resonating valence bond theory (RVB) to describe high-temperature superconductivity; and others. [31]

Condensed matter physics and quantum optics

Condensed matter physics and quantum optics were a research focus for PIs in India from the latter part of the 20th century. NMR based quantum computing research by Anil Kumar's team at the Department of Physics in IISc successfully demonstrated one of the first implementations of NMR Quantum Information Processing – distillation of pseudo pure states, implementation of logical operations and gates on two, three, and four qubit systems based on nuclear magnetic resonance in the 1990s. Vasant Natarajan's team also at the Department of Physics at IISc developed their own semiconductor laser-based frequency tunable light sources, precision electronics, and ultra-high vacuum systems with hardware sourced from pan-Indian suppliers from the 1990s. In addition, they also developed an optical tweezer system which is the foundation for ion-trap based qubits. G. S. Agarwal and his team worked on different aspects of quantum optics at TIFR, IIT Bombay, University of Hyderabad, PRL, etc. from the 1970s.

Quantum materials

Quantum materials has a vibrant legacy in India. Several funding mechanisms were dedicated towards developing and understand materials for furthering the knowledge of fundamental physics. Through the 1980s with superconductors, through the 1990s with magnetoresistive sensors, to the 2000s with new classes of 2D materials, materials research and the corresponding R&D infrastructure became sophisticated.

The R&D on materials accelerated thanks to DST's Nano Science and Technology Program that started in 1997.[32] This program resulted in setting up R&D centres in the mid-2000s. The Nano Science and Technology Initiative started in 2001 with a funding of INR 60 crores. In 2007, the government launched a 5-year program called Nano Mission with wider objectives and larger funding of USD 250 million. And followed it up with Nano Mission Phase II. In 2013, India ranked third in the number of papers published in the nano science and technology domain, behind only China and the USA. Patent applications from India in this domain in 2013 saw a ten-fold growth as compared to 2006.[33]

From the mid-2000s, R&D teams focused on materials in the Nano Misson started developing devices. National Centres for Nanofabrication and Nanoelectronics were established in IISc and IIT Bombay. The knowledge and skills from the Nano Mission were proposed to be carried forward by the quantum technologies initiatives in India.

4.2. A snapshot of the evolution of Indian national quantum programs

Report on quantum technologies by Office of the Principal Scientific Adviser

Around 2015-16, the Office of the Principal Scientific Adviser to Government of India put together a team of researchers to prepare a report on quantum technologies for India. The report identified four research areas – quantum cryptography, satellite-based quantum cryptography, quantum computing, and quantum sensing. Two pilot projects were supported, one at IISc and another at IIT Madras. The latter project, which was on differential phase shift quantum key distribution, eventually led to a spin-off, QuNu Labs.

DST's Quantum Information Science and Technology (QuST)

The Department of Science and Technology's (DST's) Interdisciplinary Cyber Physical Systems (ICPS) issued a call for research proposals under the title Quantum Information Science and Technology (QuST) covering five focus areas in 2017.[34]

1. Quantum information technologies with photonic devices.
2. Quantum information technologies with solid state, nitrogen vacancy, magnetic resonance.
3. Quantum information technologies with ion-trap and optical-lattice devices.
4. Quantum information technologies with superconducting qubit devices and quantum dot devices.
5. Mathematical and fundamental aspects of quantum computation and quantum information.

Since 2018, the first four focus areas of QuST continued as the DST's Quantum Enabled Science and Technology (QuEST) initiative.

Given that the ICPS was the umbrella initiative, the focus was on harnessing the principles of quantum systems for information processing. The entire ICPS initiative had an allocation of INR 20 crores during 2017-18.[35] The QuST projects were funded from this budget, and the important deliverables included:

- Design of quantum register
- 4-qubit quantum computer initially and possibility to scale up no of qubits
- Gate implementation and quantum algorithm realization
- 4-qubit quantum entangled state
- Generation of entangled states between two locations
- Multiparty entanglement generation, detection, and quantification
- De-coherence effects on entanglement generation, development of methods to overcome the same, and their demonstration
- Demonstration of quantum teleportation, remote state preparation, and quantum dense coding
- Demonstration of quantum key generation between two locations and its security analysis

DST's Quantum Enabled Science and Technology (QuEST)

In 2018, India launched Quantum Enabled Science and Technology (QuEST), a multi-institutional networked program of the Department of Science and Technology (DST). QuEST funded 51 projects with a budget of INR 250 Cr[36] and covered quantum technologies development across four themes:

1. Quantum Information Technologies with Photonic Devices
2. Quantum Information Technologies with Nitrogen Vacancy and Magnetic Resonance
3. Quantum Information Technologies with Ion-trap and Optical-lattice Devices
4. Quantum Technologies with Superconducting Devices & Quantum Dots

The deliverables at the end of the financial year 2021 from the QueST program were:[37]

- Quantum computation with NMR & solid-state qubits like Nitrogen/Silicon vacancies
- Generation & characterization of entanglement
- Development of decoherence mitigation strategies
- Development of quantum sensors based on Nitrogen Vacancy Centers (NVC)
- Development of quantum enhanced and quantum inspired technologies
- Ultra-cold & trapped atoms/ions
- Quantum Technologies with superconducting & quantum dot devices

While these projects were, in general, a repetition of known global quantum experiments, QuEST boosted the research in quantum areas. It enhanced the interaction within the Indian quantum ecosystem, between Indian and global researchers in the domain, and helped the government identify the national quantum labs and experts.

In 2018, ISRO in collaboration with RRI (Raman Research Institute), started the Quantum Experiments Using Satellite Technology (QUEST) program. This was India's first project on satellite-based long distance quantum communications. In 2021, the program demonstrated free-space QKD, 50m apart and 300m apart in line of sight, and supported hack-proof live videoconferencing.[38] Around the same time, DRDO (Defence Research and Development Organisation) developed a quantum technology roadmap keeping India's defence requirements in mind.

In 2019, the Technology Information, Forecasting and Assessment Council (TIFAC), DST, published a note on National Mission on Quantum Technology and Applications, and indicated nine focus domains:[39]

1. Frontier research in Quantum Science & Technology
2. Information and quantum mechanics
3. Quantum matters and material
4. Quantum computing
5. Quantum communication
6. Quantum cryptography
7. Quantum metrology
8. Quantum Sensing
9. Quantum-enhanced imaging

In 2020, following the QuEST program, India established a full-fledged national quantum hub, the I-HUB Quantum Technology Foundation (I-HUB QTF), in IISER Pune under the aegis of the National Mission on Interdisciplinary Cyber-Physical Systems (NM-ICPS) with a budget of INR 170 crores dedicated to development of quantum technologies. [40] The flagship projects of the hub include development of ion-trap based quantum computer and gravity sensor (gravimeter). It follows a hub and spoke model by funding in-house core projects at the hub, projects in collaboration with other institutes and projects at other institutes respectively.

National Mission on Quantum Technologies & Applications (NM-QTA)

The government of India, in its Budget 2020, announced a National Mission on Quantum Technologies & Applications (NM-QTA) with a total budget outlay of INR 8000 crores for a period of five years to be implemented by the DST. The government planned to create four quantum research parks and 21 quantum hubs in the country. There were about 40 to 50 academic institutions involved in quantum technologies research. The areas of focus for the NM-QTA were fundamental science and research, translation and technology development, human resource generation, innovation and start-ups.[41]

National Quantum Mission (NQM)

In 2023, the Union Cabinet approved the NQM, the latest avatar of the NM-QTA, at a total cost of INR 6000 crores.[42] The four domains of quantum technologies include (**1) quantum computing, (2) quantum communication, (3) quantum sensing and metrology, and (4) quantum materials and devices**. The tangible mission objectives include,

1. Developing intermediate-scale quantum computers with 50-1000 physical qubits in 8 years in various platforms like superconducting and photonic technology
2. Satellite-based secure quantum communications between ground stations over a range of 2000km within India, long-distance secure quantum communications with other countries, inter-city quantum key distribution over 2000km
3. Multi-node quantum networks with quantum memories
4. Developing magnetometers with high sensitivity in atomic systems, atomic clocks, single photon sources/detectors, and entangled photon sources
5. Supporting the design and synthesis of quantum materials such as superconductors, novel semiconductor structures, and topological materials for the fabrication of quantum devices

NQM is different in its design and scope as compared to some of the recent national missions like the nano mission, which was focused on fundamental research. The NQM envisages the development of a technology which requires fundamental research and their translation into applications. And as a result, scientists, engineers, business professionals, and policy makers from higher educational institutions, national labs, industry, startups, and government will all have to work in harmony for the success of NQM.

Given the existing R&D foundation for quantum physics and technologies in India, R&D in quantum technologies has witnessed a steady advance in recent years.

5. Current state of quantum technologies in India

5.1. Estimating the size of the R&D professionals

We interviewed twenty PIs working in quantum technologies, two founders of quantum technology startups, and one R&D program manager for this study. Refer to Appendix for a list of the experts interviewed. We asked them to provide an estimate of PIs in the four domains of quantum technology in India.

Domains in quantum technologies	Estimated number of PIs in top Indian higher educational institutions and national labs
Quantum computing	About 5 to 10 in hardware, and about 40 to 50 in software
Quantum communications	About 10 to 15
Quantum sensing and metrology	About 15 to 20
Quantum materials and devices	About 40 to 50

Table 2: Estimated number of PIs in quantum technologies in India

There are about 110 to 145 PIs working in diverse sub-domains in quantum computing, quantum communication, quantum sensing and metrology, and quantum materials and devices. They support about 75 to 100 post docs, and about 300 to 400 PhD students. There are also about 50 to 100 MTech students in programs focused on subjects that are close to quantum technologies.

In addition, there are about 200 PIs working in different domains of physics, material science, electronics, computer science, etc. allied to quantum technologies. They support over 1000 students / researchers in these allied domains.

5.2. Papers and patents

Most PIs believe that India has done well in theoretical research aspects of the four domains and almost on par with the best in the world. India has some catching up to do in the applied research aspects of these four domains. Applied research is the foundation for translational R&D. India needs to focus on building capabilities to propel applied research to a best-in-class level, and to nurture translational research.

A Web of Science based analysis of papers by researchers from Max Planck Institute on quantum technologies between 2000 and 2018 indicates that India has published 1,711 papers while China published 12,110 papers and the USA 13,489 papers. The USA is ranked first, China second, and India tenth in terms of papers published.[43] If the top 10% most cited papers are considered, the USA ranks first, China third, and India twentieth.

An analysis, by researchers at the Australian Strategic Policy Institute, of data from Web of Science for the period 2018 to 2022 shows the quantity (which is the number of publications) and quality (which is the proportion of papers in the top 10% most highly cited research reports) of quantum research across various countries (see Figure 2).[44]

Country	Quantum Computing		Quantum Communications		Quantum Sensors	
	Research Quantity (%)	Research Quality (in the top %)	Research Quantity (%)	Research Quality (in the top %)	Research Quantity (%)	Research Quality (in the top %)
China	22.8	15	38.1	31.5	24.5	23.3
USA	21.3	33.9	12.5	16.7	15.4	23.7
UK	4.1	6.2	5.1	7.7	3.6	4.3
Germany	4.8	5.5	4.5	6.5	7.6	7.8
Japan	4.1	4	3.1	2.2	4.9	4.3
India	5.2	2	3.8	1.2	5.3	3.9

Figure 1: Quantity and quality of quantum research of countries for the period 2018 and 2022
(Source: Australian Strategic Policy Institute Critical Technology Tracker)

While China leads the world in research quality in quantum communications, the USA leads in quantum computing and quantum sensors. With respect to research quality, India ranks in the top 10 in quantum sensors (#6), and outside the top 10 in quantum computing (#11) and quantum communication (#16). In one sub-domain of quantum computing, i.e., post-quantum cryptography, India is in the top 5 in the world with respect to research quality (#5). With respect to research quantity, Indian ranks in the top 5 in quantum computing, quantum communications, and quantum sensors.

A machine learning driven patent analysis study on Reclura's patent database of patents between 2015 and 2020, indicated that India had 339 patents in quantum technologies compared to 23,335 for China, and 8,935 for the USA.[45] China is ranked first, the USA second, and India ninth by patents published.

Patents have not been a focus area for Indian PIs and their teams so far. They are more incentivized to publish papers targeted at the top-ranked journals. Publications in the top journals are also the primary objective for Indian postdocs and PhD students. Unless there is a special institutional focus for patents, like the explicit focus on translation proposed in the NQM, it is difficult to change the status quo. PIs and their teams may require institutional support in the form of assistance from patent analysts and patent lawyers to file for patents.

Indian patenting in quantum technologies is still evolving. In many cases, patenting is an after-thought. A formal landscape analysis of patents in a domain is not a common practice in Indian R&D. This analysis is a useful information when making decisions on translating a technology. A useful aspect while translating technologies from a lab to a product is to have a bouquet or pool of patents that gives a comprehensive cover for a business entity interested in licensing the patents. Identifying patents with other assignees that need to be licensed along with this bouquet will also be useful for a prospective licensee. Many PIs believe that patenting will pick up in the medium term when the experimental R&D in quantum technologies moves into the translation phase.

The current Indian R&D landscape in quantum computing, quantum communication, quantum sensing and metrology, and quantum materials and devices appear promising. In the next four sections, we present an illustrative snapshot of these R&D in India.

5.3. A snapshot of Indian R&D in quantum computing

The NQM is aiming for a 50 to 1,000 qubits computer by the end of the decade. Based on the current context, some PIs believe that constructing a superconducting quantum computer with 1,000 qubits by the end of the decade is an ambitious grand national challenge. To go beyond hundreds of qubits requires India to leapfrog and catch-up on the lead other countries have. Focused investments and larger teams facilitated by the NQM are required to fabricate a 1,000 qubits quantum computer by the end of the decade.

A team in **TIFR works on superconducting qubits** and related areas. Their focus is on novel qubit designs, quantum error correction, quantum simulations, quantum limited parametric amplifiers, weak quantum measurements, nanomechanical systems in the quantum regime, etc. Superconducting qubits typically work at milli Kelvin temperatures. The initial focus of this team was focused on the building blocks, new kinds of devices for a superconducting quantum computer. This is one of the well-funded teams in India. This team has built a three qubits superconducting quantum computer, and is building another with more superconducting qubits.

Currently, superconducting qubits seems to be the leading technology for quantum computers. This is dominant technology used by the leaders in quantum computing hardware like IBM and Google. The USA, for example, has a head start of working on the building blocks of this technology for the past four decades.

Another technology for quantum computing that is being pursued in India is **ion-trap qubits**. A team in **IISER Pune** focuses on using ultracold atoms and ions for quantum computing. While India is on par with the global leaders in this ion-trap technology in terms of know-how, there is a gap in terms of scaling up the experimental systems. Just like with supercomputing qubits, 90% of the subsystems need to be imported. The IISER team plans to build an ion trap quantum computer with about 20 qubits.

A team in **IISER Thiruvananthapuram** works on **semiconductor qubits**. Currently, these qubits operate at milli-Kelvin temperatures and their coherence times (time-frames that the qubits are stable and available) are typically longer than superconducting qubits. Taking their operational temperatures beyond 1K is an active area of research, which would minimize the cryogenic instrumentation requirements, a major technical challenge as far as scalability is concerned. Since these are spin based qubits, they tend to fluctuate under the influence of magnetic fields.

A team at **IISER Pune** designed a quantum register for two, three and four **NMR qubits** using singlet states, which are special long-lived states in NMR. Another team at **IISER Mohali** leveraged a single qutrit (a qutrit or quantum-trit is a 3-level quantum system as opposed to a qubit which is a 2-level orthogonal state system) to perform a quantum computation.[46]

Let us consider some of the key challenges that the Indian researchers are addressing. Apart from the ultra-low temperature that is required for quantum computers using superconducting qubits, there is another challenge. Quantum systems are fragile and coherence times collapse in microseconds or milliseconds time-frames depending on the underlying technology. Architecting the quantum systems, for longer coherence times is a challenge.

Solid state devices operate typically with coherence times in the order of 100 microseconds. In NMR devices, the coherence time is of the order of seconds or minutes. But these devices are not easily scalable to assemble multiple devices to make a larger quantum computer.

In the software sub-domain, **QSim Toolkit**, developed at **IISc**, is one of the first initiatives to address the common challenge of advancing the quantum computing research frontiers and its education in India. The QSim offers a quantum computer simulator integrated with a GUI based workbench in which one can create quantum circuits and quantum programs. The QSim toolkit is released as an open-source project. It is designed to work on any laptop, and run a 10 to 12 qubit system. It is a collaborative project with the IISc team developing the software libraries, a CDAC team building the graphical user interface, and an IIT Roorkee team creating tutorials based on the software.

Indian higher educational institutions have access to quantum computing on the cloud. These institutions have started to **develop quantum computing applications**. For example, **IIT Madras** has signed up agreements with IBM, D-Wave, and Amazon.

- IBM has released 433 qubits on the cloud. The 1000 qubit system, released in late 2023 will also be available to members of its Quantum Network.
- D-Wave, which builds quantum annealers that are different from gate-based quantum computers, has released 5000+ qubits, and its Leap cloud service supports real-world size applications with up to 1 million variables and 100,000 constraints.[47]
- Amazon Braket is a fully managed quantum computing service, and offers customers with different types of quantum hardware technologies – gate-based superconducting processors (from Rigetti and OQC), gate-based ion-trap processors (from IonQ), and neutral atom-based quantum processors (from QuEra Computing).[48]

5.4. A snapshot of Indian R&D in quantum communications

R&D teams in India are working on both fiber based and free space quantum communications. In free space quantum communications, teams are working on both terrestrial and extra-terrestrial communications. In fiber-based quantum communication, teams are working on using existing fiber infrastructure with low loss for shorter distances. Indian capability in the quantum communications domain is probably closer to the global best when compared to other domains of quantum technologies. The NQM should look to quickly ramp-up the R&D capabilities in quantum communication, and push for more translation.

RRI has a team working on experimental secure quantum communications including **QKD in free space**. They collaborate with ISRO, and have demonstrated secure communication between a stationary source and a moving receiver. This sets the foundation for ground to satellite quantum communication. RRI has developed a pointing, acquisition, and tracking system. This group has a BBM92 protocol implementation over a free-space channel. They are also working on integrated photonics-based QKD.

A team in the **Physical Research Laboratory's (PRL)** has demonstrated **free-space** implementation of BB84 and BBM92 QKD protocols over 200 meters and can go up to kilometre scale distances. They use entangled photon source for QKD which is now becoming a dominant globally preferred technology. The laser driver circuit and QRNG has been developed within PRL.

An **IIT Madras** team working on **fiber-based quantum communications**. They have demonstrated a standards-based metro area quantum access network between different sites in Chennai. They are working on a fiber-based quantum Internet with local access that can connect Bangalore with Chennai and New Delhi. The Bangalore to New Delhi fiber-based quantum communication network will be among the longest in the world when operational based on current publicly available data on similar networks around the world.

The Ministry of Electronics and Information Technology funded project, MAQAN (Metro Area Quantum Access Network) is an example of the hub and spoke approach. It is India's first quantum network testbed in a 1 x 2 topology. In mid-2023, MAQAN demonstrated quantum secure key for video transmission over a classical link. This project involved four partners, each of whom brought different capabilities.

- IIT Madras – differential phase shift QKD, coherent one-way QKD which is a solution to extend the achievable distance of practical QKD, quantum queues, quantum information
- C-DAC (Centre for Development of Advanced Computing) at Bengaluru and Trivandrum – hardware, controls, firmware, software defined network
- SETS (Society for Electronic Transaction and Security) Chennai – FPGA firmware related activities such as sifting, error correction, and privacy amplification, post quantum cryptography
- ERNET (Educational and Research Network of India) Chennai – link monitoring and network management

The next ambitious phase of the project is called Quantum Internet with Local Access (QuILA). It is to build a quantum network between Chennai and Bengaluru (550 KM) and Bengaluru to New Delhi (2200 KM), with about 25 secure nodes every 100 to 200 KM. This project also envisages creating MAQANs in Chennai, Bengaluru, Hyderabad, Bhopal and New Delhi.

Private Indian universities like **Jaypee Institute of Information Technology**, a deemed to be university, also have a team working on **fiber-based quantum communications**.

Quantum communications can power a network of quantum computers to create a secure, high-performance, quantum cloud computing infrastructure in the future. Quantum communication products like single photon generators and receivers, QKD systems have the potential of mass adoption like networking products of today.

One of the important aspects is to involve the user organizations, especially in space, defence, telecom hardware, and telecom services sectors, to work with the quantum communications R&D groups to ensure that their technology, from TRL (Technology Readiness Level) 3 or 4 onwards, is transferable into products and solutions.

Quantum communications R&D in IIT Madras was the foundation for **QuNu Labs**, a translational startup, which is now focusing on QRNGs and QKD.[49] There is a global market potential for these products that is only likely to spike with the proliferation in quantum computing. India's quantum communications startups need to focus develop products like single photon detectors, QRNGs, etc. with indigenous subsystems and firmware that seem to meet the requirements of domestic customers. The startups should obtain the best global certifications for these products, and also make them globally cost competitive.

A translational benchmark for India's efforts in quantum communication is **ID Quantique** that was a spin-off founded by four PIs in the University of Geneva in 2001.[50] In 2018, ID Quantique raised USD 65 million from SK Telecom, South Korea in 2018. ID Quantique helped SK Telecom develop the world's smallest QRNG, and this was used in Samsung's Galaxy A Quantum, the world's first quantum random number generator smartphone.

5.5. A snapshot of Indian R&D in quantum sensing and metrology

Quantum sensing and metrology can make high precision measurements of acceleration, velocity, position, time, electric field, and magnetic field. This has applications in atomic clocks, gravity meters, interferometers, imagers, microscopes, radars, navigation, etc.

A group in **RRI** is working on techniques on **laser cooling** of specific atoms and molecules. They are trapping these molecules, manipulating them, and detecting them non-destructively. This has fundamental applications in quantum sensing. Another group in RRI is working on **quantum mixers** with an objective to understand the quantum many-body physics with applications in quantum sensing and quantum information processing. They are also working on **spin correlation spectroscopy** to develop high precision magnetometers. Other quantum research centres working in the area of cold atoms include **NISER Bhubaneswar** and **Raja Ramanna Centre for Advanced Technology (RRCAT)**.

The **ion-trap team in IISER Pune** working on quantum computers also works on quantum metrology and sensing. They work on distributed quantum information processing using atom-plasmon coupling, gravimeters based on atom interferometry, optical atomic clock based on the narrow linewidth transition in strontium.

Research by teams in **IIT Bombay** and **IISER Bhopal** focus on magnetometry using NV centres in diamonds. The technology can be engineered into products in form factors that are useful for practical applications. These can result in miniaturized MRI for deep tissue imaging. Other interesting applications of NV centres in diamonds used in quantum sensing include fault detection in the semiconductor industry and thermal imaging.

A team in **IUCAA** (Inter-University Centre for Astronomy and Astrophysics) is developing **atom-optics** experiments using a trapped-ion optical clock. They are developing optical reference that has applications in classical as well as quantum communications, accurate calibration of the optical spectrographs, phase synchronization of the geographically distributed detectors, etc. They have the ability for networking optical clocks across different locations.

The quantum metrology group in **NPL** (National Physical Laboratory) is working on quantum devices based on **superconducting nanowires and junctions**. An application of this research is superconducting nanowire single photon detector that is capable of detection of single photons with wide wavelength range. From a metrology perspective, this technology superconducting nanowires is one of the promising methods to establish a quantum current standard. The programmable Josephson voltage standard developed by the group is used to accurately measure voltage on par with the best standards bodies in the world. The group has also developed the capability for an accurate resistance standard.

One of the major challenges in quantum sensing and metrology is to engineer the lab prototypes into miniaturized and robust products. Experimental setups need to be miniaturized and ruggedized. While Indian R&D capability is very good, there is still a gap in translating R&D into products. An example of a translational startup in the metrology domain is **ColdQuanta**, a spin-off from the NIST.[51] ColdQuanta has productized magneto optical traps, trapped ion devices, cold atom sources, etc.

5.6. A snapshot of Indian R&D in quantum materials and devices

The quantum material and devices research can develop a new materials and devices with translational potential in the near to medium term like devices for single photon detectors, which are used in quantum processors, atomic force microscopes, etc. Novel materials for magnetic memories have applications in the emerging field of neuromorphic devices.

A team in **IISc** investigates structural, **electrical and magnetic properties of various nanoscale systems**, in a wide variety of materials. The basic research includes fundamental quantum mechanical effects on charge and spin states in nano systems. Their applied research focuses on carbon-based electronics, critical behaviour in smart materials, to new schemes of sensing with nano and micro-electromechanical sensors. In short, this domain identifies the different materials best suited for different applications in the other quantum domains. For example, the IISc group has identified a novel design of a material that can be utilized to count photon in an optical pulse with single photon resolution.

Another team in **IISc** have developed a **True Random Number Generator (TRNG) on a chip**. Its min entropy, a parameter used to measure the performance of TRNGs, was found to be 0.98 per a standard set by NIST and is amongst the highest reported globally. There are many other R&D teams in India working on condensed matter physics, some of which can come under the umbrella of quantum materials and devices.

Some PIs in the other quantum technologies domains believe that quantum materials and devices should be well integrated with the other three application domains. They believe that R&D teams focusing on quantum materials and devices, may need to collaborate with R&D teams working quantum computing, quantum communications, and quantum sensing and metrology. For example, there is no Indian supply of very pure Silicon-Germanium used for semiconducting qubits. This is one area where PIs working in quantum materials and devices can collaborate with those working in quantum computing.

5.7. Current state of translational research

Many PIs believe that translation works best in a vertically integrated mission-mode program. Many PIs ask the question whether they should take the lead in translation. They all however agree that there should be a tight hand-off between their R&D team and the translation team, and a parallel knowledge transfer run before the translation team takes over.

Some of the products that India is ready to produce or close to translating include single photon detectors, FPGA (Field-Programmable Gate Array) boards, power supplies, laser systems, measurement devices like voltmeters and ammeters, mirrors and lenses, artificial diamonds, etc. These are all not quantum technologies, but they are in-demand products with a wide variety of applications. The focus should be on benchmarked performance, quality, and global cost competitiveness of these products so that these can cater to markets outside India as well.

For example, a team in **IISc** have developed **Scalable Quantum Control and Readout System (SQ-CARS)**, using Xilinx RFSoC FPGA board, for control and readout of the quantum states of the qubits. SQ-CARS provides a scalable and user-friendly platform to carry out advanced quantum experiments at reduced cost especially when compared to imported alternatives.

In the medium term, we are likely to see many more products in quantum technologies getting translated from R&D. These are likely to include atomic clocks, quantum computers with a few qubits, atomic force microscopes, cameras, laser systems, etc.

Translation implies using the technology into a marketable product, and does not stop at a lab-level table-top sized PoC (Proof of Concept). For example, if a sensor has applications in space, the PoC is in a form factor that can fit and withstand the environment in space as appropriate. Taking a technology from a lower TRL to a higher TRL requires rigorous engineering with the expertise in miniaturization, compliance with the requisite standards, and design for industrial scale production.

Organizations like DRDO have a prior experience in translating R&D into products. They are interested in the translation of quantum communications technology for its applications in encryption-decryption, secured communications. They are also interested in the translation of quantum technologies like sensors and detectors. About 25% of their overall R&D funding is earmarked for R&D projects in higher educational institutions and national labs. There is a special focus in DRDO on moving technologies from TRL 5 or 6 to products in TRL 9, and qualifying these products.

The **DRDO Industry Academia Centres of Excellence (DIA-CoEs)** are a step in this direction. The DIA-CoEs in IISc and IIT Delhi are working in the domains of quantum sensing and metrology, and quantum photonics respectively. While the focus on the DIA-CoEs is up to TRL 5 or 6, the aim is to translate these technologies into implementable systems and products that are at a higher TRL. The DRDO's qualification system are useful for startups to validate their products. Some of the quantum technologies that the DIA-COEs are working on are magnetometers, quantum random number generator on a chip, room temperature NV centres, quantum computing algorithms, etc. There is a focus on miniaturization and ruggedization of products. The DIA-CoEs should be an integral part of the translational plans of the NQM.

Another example is the **DRDO Young Scientist Laboratory – Quantum Technologies (DYSL-QT)** set up in 2020 in Pune.[52] The young scientist labs are staffed and led by scientists who are under 35 years of age. The focus of the quantum technologies lab is quantum computing systems, quantum random number generators, quantum communication systems and exploring quantum sensing technologies. Their mission is to explore quantum technologies and improve the TRL from 1 to 5 and subsequently to 9 in quantum computing, quantum communications and quantum sensing technologies. The interlinkages between DYSL-QT and other labs within and outside DRDO, higher education institutions, and industry need to be strengthened under the NQM. It is also important to nurture links between DYSL-QT and the startup ecosystem.

Translation through startups and industry seem viable models for PIs. The technologies that have immediate industrial applications like quantum computing and quantum communications are seen as a natural fit with translation through startups and industry. Quantum sensing and metrology, and quantum materials are seen as better translated using government organizations like DRDO, ISRO, and CSIR (Council of Scientific & Industrial Research) given their immediate use in strategic applications.

Some PIs believe that there is a need for change in the perception in technical higher educational institutions that only papers in top ranked journals are recognized output from their R&D. The focus, especially among experimental PIs, also needs to focus on productizing PoCs. The focus should be on both understanding the science and technologies, building PoCs, and enable their translation into products.

While all PIs are inclined towards translational startups, the PIs in research labs like RRI, PRL and the IISERs pointed out that their organizations do not yet have an in-house incubation program. These organizations need to get connected with the incubation programs in the IITs and IISc.

The French startup, **Muquans**, is an example of how translational research has resulted in a one-of-a-kind company in the world.[53] The founders have PhDs from University Paris, Ecole Normale Supérieure, and Institut d'Optique. They have worked in R&D teams at both higher educational institutions and industry. Muquans is probably the only company in the world that have a commercially available robust and sensitive quantum gravimeter and quantum clock.

India has built a good foundation in quantum technologies. The proposed NQM provides the ideal launch-pad for the R&D ecosystem to forge ahead. We have identified the focus areas that need special attention to provide the impact required for India to reach a leadership position in quantum technologies.

6. Nurturing Indian quantum technologies R&D for high-impact

6.1. Focus on higher education and training

A global comparison of education programs in quantum technologies in 2022 indicates that it is a focus area in many countries. [54]

- There are about 162 universities and institutions worldwide with educational programs and research activities in quantum technologies.
- Specialized doctoral training programs and institutions exist such as the Central Doctoral Training programme by University College London, the International Graduate School for Quantum Technologies in the UK, Quantum Science and Technologies at the European Campus (QUSTEC), the Centre for Quantum Technologies in Singapore, and the QuTech Academy in the Netherlands.
- There are 40 universities worldwide providing master's degrees in quantum science and technology, mostly concentrated in North America (12) and Europe (21). About 450 quantum technology master's level graduates are produced yearly.

In India, the older IITs (IIT Kharagpur, IIT Bombay, IIT Kanpur, IIT Madras, IIT Delhi), IISc, and a few IISERs (IISER Pune, IISER Mohali, and IISER Kolkata) offer educational programs on quantum technologies. For instance,

- Two institutions in India offer programs for M. Tech. in Quantum – IISc and Defence Institute of Advanced Technologies
    - IISc started an M. Tech. in Quantum Technologies in 2021, a first in the country
    - DIAT, under DRDO, offers an M. Tech. in Quantum Technologies
- IISER Pune has launched in 2024 a Master of Science (MS) program in Quantum Technologies
- IIT Madras offers a specialization in quantum science and technologies in its dual-degree program
- IISER Kolkata organized a summer school on quantum information and quantum technology in 2021
- The Centre for Quantum Engineering, Research and Education at TCG CREST, a private entity, in collaboration with the Academy of Scientific and Innovative Research offers a PhD in Science program with an emphasis on quantum sciences and technologies with emphasis on quantum computing and quantum sensing

A couple of domains that seem closely intertwined with quantum technologies are microwave and optical technologies. **The NQM may want to explore ramping up MTech programs in electronics, communication and applied physics to include super specializations in microwave and optical technologies.**

These are super specialties in the different engineering disciplines, or in the case of optical engineers multidisciplinary involving physics and electronics engineering. A competent engineering pool in these domains need to be nurtured. The initial demand will come from the NQM hubs and the labs in higher educational institutions and national labs. Industry and startups are likely to have a back-ended demand for these engineers.

A comparison of graduates from fields that are related to quantum technologies – such as biochemistry,

chemistry, electronics and chemical engineering, information and communications technology, mathematics and statistics, and physics – shows that India stands second to EU worldwide.[55] These graduates will still need focused training on different aspects of quantum technologies to make them a relevant workforce in the field.

Country	Number of graduates in quantum technology-relevant fields
European Union (EU)	135,511
India	82,110
China	57,693
United States (USA)	45,087
Russia	23,450
United Kingdom (UK)	14,601

Table 3: Number of graduates and density in quantum technology-relevant fields 2020 (Source: McKinsey)

While the overall number of students in India is impressive, the elephant in the room is that other than the IITs, IISc, IISERs, and a few other top tier technical institutions, there is a scarcity of faculty to train students in the quantum technologies. **NQM should also include teaching related projects in its portfolio of funded projects**. Teaching programs can also explore grants from industry's corporate social responsibility funding. The proposed National Research Foundation (NRF) may also play a role in ramping up the R&D and teaching quality in multiple fields, including quantum technologies, in the Indian university system. There is a requirement of national experimental facilities in quantum technologies in different parts of India that can offer advanced experimental physics courses for students, especially Masters and PhD students, in the universities in that geographical region. **The NQM hubs can explore housing these national experimental facilities in quantum technologies.**

The blended offline and online education model is a realistic way to impart quality education to a large number of students on quantum technologies. One idea is to create a bouquet of online courses in quantum technologies in NPTEL and SWAYAM. This will benefit students from colleges and universities which do not have full-fledged or trained faculty. In such a model, widespread access to the national experimental facilities and quantum computing simulators students will become essential.

IBM has made access to five and seven qubit quantum computers on its cloud freely available to users. Of the half a million users across the world, 20% to 25% are from India. IBM has also developed Qiskit, an open-source software, that allows one to easily design experiments and applications and run them on real quantum computers or classical simulators. We must make available the Indian quantum computing software and textbooks in local languages. **The Indian quantum computing software community has translated the Qiskit textbook into four Indian languages now – Tamil, Malayalam, Gujarati, and Hindi. IBM partnered with IIT Madras to offer a quantum computing course on NPTEL, which attracted over 15,000 registrations in two years.**

Many PIs are concerned about training a large number of students without assessing the real demand from universities, labs, and industry. **A gradual ramp-up in training may be better than creating a large pool from the beginning.** The PIs believe that they can forecast the demand in universities and labs, but they are not sure about how many will be absorbed by industry. For example, not all programmers in the Indian IT industry writing applications running on quantum computers need be trained in quantum technologies.

One of the stated goals of NQM is to have a 20,000 to 25,000 strong workforce in quantum technologies. This needs to be planned and revised continuously by the NQM for each of the domains. For example, some of the PIs estimated the numbers in quantum computing by the end of the decade.

- Those who know how to build a quantum computer in India. A few hundreds to a thousand. This could be the PhDs and MTechs.
- Those who are can program the firmware of the quantum computer. In the thousands. This could be the MTechs, B.Techs, and BEs.
- Those who can write applications (in a language like Python) on the quantum computer. In the tens of thousands. This could potentially be any college graduate.

In the current context, there is a lack of India based employment opportunities in quantum technologies. This is the opposite to the global context where there is shortage of talent. In one analysis, of the 750 vacancies in quantum technologies available in 2022, 62% demanded candidates with a PhD degree.[56] The Indian PhDs who get trained in the top-tier higher educational institutions, and publish in top journals are able to get employment as postdocs in foreign universities or as professionals in global companies focussing on quantum and related technologies.

6.2. Attract the best talent

The NQM should allow hubs to select promising undergraduate students and sponsor them for a PhD in quantum technologies at institutes like IISc, IITs, and IISERs. After their PhD, the hubs get them back, and offer them positions as postdocs in the research projects they are sponsoring in different institutions. The postdocs can then explore opportunities to become faculty members in the higher educational institutions or scientists in the national labs or opt for jobs in industry. The PhDs and postdocs who are interested in translating that research can build the products as part of translational startups that will be seed-funded by the NQM hubs.

A hot field like quantum technologies is likely to have a robust global demand for trained workforce**. NQM may have to indicate a complete career path in India in quantum technologies.** This is like the post-MTech/PhD to retirement career path available at organizations like ISRO and BARC. There may be merit in this integrated approach and concentrate the specialist workforce.

Postdocs are the current Achilles heel in quantum technologies. The translational focus of the NQM may make the problem worse. Working on refining existing technologies of applications usually does not result in top-notch journal papers, which is the most important professional objective for postdocs. The top higher educational institutions in India currently recruit faculty primarily based on their publication record. An Indian postdoc option focusing on translation needs to be made attractive.

Attracting the best postdocs from around the world helps to jumpstart R&D. For example, the PIs working on superconducting and semiconducting qubits in India have trained as postdocs with the best labs in the world in those domains. They are fluent with the technologies, architecting the experimental setup, and operating the experimental setup. Well networked PIs also know the sources from where they can procure hard to obtain high quality materials. These is typically not produced in industrial scale, and is often procured from labs in other countries that usually do not advertise that they produce these materials.

A disruptive idea is to attract the best PhDs from across the world who are trained at the best universities and labs in the world as postdocs in India's quantum technology projects. This would mean an Indian industry benchmarked salary, and include one travel to their home location a year. **The NQM should explore using industry's corporate social responsibility funds, and science philanthropy to support such a program.**

The key factors that influence Indian PhDs in quantum technologies to stay in India for a postdoc or go abroad are salary levels and regular salary payment, job security for at least three years, and the fact that a global lab exposure is often an un-written pre-condition for a good faculty job in India. Another perception among Indian PhDs is that they usually do not want to do a post-doc in an institution that is perceived to be ranked lower than their PhD granting institution even though the lab they are considering may be top-ranked. **The NQM can support Indian postdocs affiliated to Indian institutions with a sabbatical in an international top-ranked lab for up to a year, and explore using industry's corporate social responsibility funds, and science philanthropy to support such a program.** This will ensure that postdocs get an opportunity to work in the best international labs, and help Indian labs to assimilate current cutting-edge technologies. Many PIs indicated that the Chinese follow this practice to get a first-hand knowledge of cutting-edge technologies, and quickly leap-frog.

The NQM may need to facilitate a S&T cadre in the hubs similar to the ISRO and BARC model of the researcher and technologist cadres. A new category of technical professionals may be required. Professionals who are involved in the developmental aspects of technology. They include activities such as optimizing parameters of a development process, refining an existing processes and protocols with an objective of identifying promising outcomes for translation, and translating these outcomes into products. **NQM needs to make technology development positions lucrative as a career option, and bring into its fold professionals from different backgrounds.**

6.3. Jump-start translational research

The NQM's focus on applications provides an opportunity to build a national-scale translation capability. It is imperative that the Indian industry, including startups, participates and contributes to the mission's projects from inception. One model that the NQM can pursue is to encourage translation of quantum technologies is to explore coupling them to national priority use cases.

India is home to over 1.4 billion citizens. It is important that we are self-sufficient in inventing medicines that cater to our current and emerging healthcare needs, and ensuring that our healthcare costs are under control. Inventing new molecules that become effective medicines is increasingly becoming computing intensive. One of the applications for our quantum computers can be new drug discovery. This use case provides an opportunity for companies in our pharmaceutical and IT industries, including startups, to contribute to the translational aspects of NQM.

Another possible use case is using quantum sensing to develop inertial sensors that can help provide accurate global navigation capabilities for our defence forces. Quantum sensors can provide in-situ, real-time calibration, and thereby reduce the reliance on transmitting and receiving signals from global navigation satellite systems that may not have the required coverage. This also provides an opportunity for industry to supply advanced systems to our defence forces. **It is important for NQM to identify national priority use cases upfront to enlist industry partners from the initial stages of defining applications.**[57]

Translation needs to be managed like a business project with plans for product development, staffing, budgets, etc. If the translation is through startups, incubators may need to be brought on board upfront to support the PIs. The first step is to educate PIs about the commercial use cases and business potential of quantum technologies. While this happens as a one-off today, the incubators in the top higher education institutions need to make this a sustained program. **Organizations focused on capability-building in academic translational research and innovation like the Gopalakrishnan Deshpande Foundation are required to nurture focused translation programs in the NQM hubs.**

Sometimes, it is beneficial to separate R&D and translation with tight hand-offs. Industry sector specific translation organizations can be set up in the NQM hubs. This requires building a talent pool with a flair for translation with expertise in product engineering, product management, manufacturing operations, supply chain management, etc.

Another important aspect for the success of translation is the presence of boundary spanners. These are professionals in universities who understand the demands of industry and startups, and professionals in industry and startups who understand how R&D in higher educational institutions works. The boundary spanners play an important role of a bridge between the R&D teams and higher educational institutions on one hand and industry and startups on the other. **The NQM must encourage and train boundary spanners from industry, startups, and higher educational institutions.**[58]

The NQM should remove the impediments prevent India from moving from lower TRL to higher TRL in quantum technologies. An important reason for this challenge is that the focus of most PIs and their teams is to publish papers in the top journals. This is possible when experiments are novel. It is difficult to publish refinements of known techniques or the productization of R&D. **NQM hubs can invest in teams to translate promising technologies in lower TRL to a higher TRL.** These teams should develop a manufacture-ready prototype along with associated process documents and a bill of materials. The process to license these technologies to a startup or an established firm should be made easy. The professionals in the teams working on translation should also be given opportunities to startup.

One lesson from the global quantum missions is their ability to translate quantum technologies into products almost immediately after the technology is developed. CERN's (European Organisation for Nuclear Research) Knowledge Transfer group helps transfer its technology and know-how such as superconductivity, microelectronics, cryogenics, vacuum, data monitoring and management tools, etc. to create innovations for society. It has also created CERN Venture Connect, a platform to help deep-tech founders with the right technologies and investor networks.[59] More than 30 European startups are supported.[60] India has to create such a research ecosystem where scientific advances and technology deliverables are directly connected to the entrepreneurial ecosystem and product markets. **NQM has to adopt an operating model in a dynamic manner, where informed bets are made on translating promising technologies at TRL 3 as they emerge from R&D.**

Once this decision is taken, the plan for translation must be stitched together immediately with sufficient time for a knowledge transfer between the R&D and translation teams. The USA, EU, and more recently China have achieved success in this hand-off between R&D and translation teams in their critical technology programs. One interesting model is the Russian Skolkovo Innovation Center where a team of business-oriented product managers help assess the market and productize technologies which have gone beyond TRL 3.[61]

Many PIs feel that the path to translation of quantum technologies may take up to a decade. A realistic roadmap for them is for NQM to focus on TRLs 1, 2, and 3 in the first three years, focus on TRLs 4, 5, and 6 during the fourth and fifth years, and reach TRL 7 and beyond by the seventh year. Certain technologies where India has a head-start like quantum communication may witness an accelerated translational journey. **For this time-bound translation to happen, the NQM needs to quickly ramp-up experimental facilities.** The most important aspect is the mindset change in the entire ecosystem to work on a mission-mode to make translation happen.

Translational startups are likely to become an important aspect of productizing quantum technologies. **Seed funding from the NQM will help translational startups in the initial years.** There are very few angels and VCs looking to fund quantum technologies especially in the hardware domain. It appears that startups working in the domain of modelling or simulations for quantum computing are more likely to obtain funding. **Those angels and VCs who are interested in investing in quantum technologies should be made part of the NQM hub ecosystem.**

Startups in quantum technologies believe that R&D should deal with the proof of science that needs to get translated into proof of technology and commercial viability in the startups. A sustainable startup needs to have a proof of businesses. **The key challenge that startups in quantum technologies face is to enhance the PoC from R&D in a lab at a higher educational institution to meet typical commercial specification, and to miniaturize Indian technology on a chip or integrate them into an existing product.** Sometimes they also have the challenge getting an Indian product to meet global standards.

The startups want a better intertwined collaboration with PIs rather than the typical current arm's length collaboration model. **These startups are also keen that the NQM has a program to allocate grants to combined teams of startups and R&D teams where both are equal partners in the project.** From the startups' perspective this helps them to productize the technology better and quicker.

The startups would also like the NQM to help them obtain pilots with government user organizations. In the case of quantum technologies, some of the products developed in India may have only a few global prior use cases even in a developed country. This makes it imperative that user organizations especially in the government are primed to pilot these technologies.

Many PIs also seem to indicate a preference for translational startups in quantum technologies. According to them this is a sure shot way of getting a qualified technical team in the startups. They are in general wary of the fact that the current hype around quantum can lead to VC funding in startups that do not have the requisite technical prowess. For example, the technologies for fabricating quantum computers based on any one of the technologies currently exists only in Indian higher education institutions and national labs.

Some PIs are of the opinion that quantum computing and quantum communications are more amenable for translation into commercial applications compared to quantum sensing and metrology and quantum materials. On the other hand, quantum sensing and metrology and quantum materials may initially find applications in strategic sectors like defence and space. These may be attractive to a select number of companies who work in these sectors.

NQM should also facilitate more international multi-institutional collaborations that have industry partners. IIT Bombay joining the Chicago Quantum Exchange as an international partner is a welcome development. The members include top science and technology American universities like the University of Chicago, University of Illinois Urbana-Champaign, etc.; top American labs like Fermilab and Argonne National Laboratory; a slew of industry partners like IBM, Microsoft, etc.; and international universities like Technion – Israel Institute of Technology, QuTech – Netherlands, etc.

One Indian industry of interest is information technology (IT) services. **NQM should encourage the Indian IT services companies, who are developing service offerings in quantum technologies for their global clients, to actively participate in the mission.** The Infosys Quantum Living Labs offers innovative solutions to its clients by leveraging quantum technology. Infosys has built partnerships with companies like IBM and AWS (Amazon Braket), and startups like QCWare, QPiAI and Quintessence Labs in the quantum technologies space.[62] For instance, an Infosys - QPiAI algorithm enables a 60% cost reduction in vehicle routing optimization.[63] TCS has launched a virtual TCS Quantum Computing Lab on Amazon Web Services to develop, and test enterprise business solutions and accelerate the adoption of quantum computing.[64] ACM's Winter School on Quantum Computing - 2022 was sponsored by TCS Research. In 2024, TCS and IIT Bombay announced a collaboration to develop India's first Quantum Diamond Microchip Imager, a quantum imaging platform for the non-destructive examination of chips.

HCL's Q-Labs, has formed a partnership with Microsoft Azure Quantum to create on-cloud examples of quantum technologies. HCL and the Sydney Quantum Academy (comprising a partnership of Macquarie University, the University of New South Wales, the University of Technology Sydney, and the University of Sydney) have signed a MoU to help accelerate the development of the quantum technology ecosystem in Australia.[65] Wipro has signed a Memorandum of Understanding (MoU) with Israel's Tel Aviv University for research and analysis in quantum science and technology.[66]

6.4. Foster multi-disciplinary collaborations

One important lesson from the global missions is that they have a research ecosystem with a multi-disciplinary team of researchers working together on a nationally important challenge. Consider the composition of many research groups in the global quantum missions. They may have researchers from multi-disciplines such as:

- Physicists working on an experimental quantum device
- Material scientists growing the best quality high purity substrate for the device
- Mechanical and electronics engineers who architect an experimental setup
- Electronics and microwave communication engineers who create the systems that link between the quantum device and classical electronics for drawing the output

Creating and translating a quantum technology requires physicists, material science engineers, electronics engineers, mechanical engineers, computer scientists, etc. to work together. NQM needs to foster multi-disciplinary collaboration among PIs in different science and technology domains. A good of such a collaboration in the Indian context is ISRO. We need to learn from ISRO on how to make multi-disciplinary teams work well.[67] For successful translation we also need PIs from multiple disciplines to work together. IISc launched its Quantum Technology Initiative (IQTI) in September 2020, with multi-disciplinary R&D focus. This includes core hardware and back-end engineering support to algorithms for cryptography and machine learning, bringing expertise in core quantum technology, theoretical and modelling support, and peripheral technology development and engineering backup. IISc, in collaboration with the Government of Karnataka, established a Quantum Research Park.[68]

While the classification of quantum technologies into four domains (quantum computing, quantum communications, quantum sensing and metrology, and quantum materials and devices) is useful from a user application perspective, it is beneficial to have an organization where PIs in all these domains work together. The Division of Quantum Physics and Quantum Information in the University of Science and Technology of China have a diverse mix of PIs.[69] This lab has had many global firsts in demonstrating multiple quantum technologies.

Many PIs mentioned that there is a higher proportion of engineering PIs working on quantum missions in other countries compared to India. They also indicated that about 40% of the PIs in countries like Germany and Finland are non-Physics PIs. European labs (especially those in France and Germany) are led by multiple PIs from different complementary disciplines. These PIs collaborate to start and sustain the lab. **The NQM should analyse the European model where a multi-disciplinary team of PIs nurture a quantum technologies lab, and adopt the best practices contextualized to the Indian context.**

While it is important for the PIs, government departments, S&T policy professionals, industry, and startups to collaborate, at some point the **NQM should also explore including a larger community of Indian citizens to discuss the impact of quantum technologies.** This can be modelled on the lines of the Geneva Science and Diplomacy Anticipator (GESDA).[70] The Open Quantum Institute, GESDA explores how to develop use cases in quantum technologies that can accelerate meeting UN Sustainable Development Goals. [71]

6.5. Create effective and efficient hubs

It appears that NQM envisages setting up a multi-organizational hub for each of the four domains in quantum technologies. The operating model may evolve once the NQM is launched, and how the hubs are to be set-up. **NQM needs to identify if the hub is a virtual collection of higher educational institutions and national labs, or it is a physical centre located in the premises of one of the organizations that constitute that hub.** The hubs will need clarity on whether they manage a fixed allocated budget or will they need to compete for budgets among themselves based on their past performance and future activities.

The most important capability of a hub is to fund R&D and translation projects. The largest slice of the budgets of the hubs should be for funding R&D and translation projects. A process of evaluating proposals in the hub should be transparent and give a fair chance to PIs from institutions that are not part of the hub to obtain funding. This may also become one of the key aspects of the success of the hubs and the NQM.

Another important capability that the NQM needs to develop in the hubs are national experimental

facilities with top-of-the-line scientific equipment. This facility will have three main roles. First, to efficiently operate, maintain, and repair expensive imported equipment. For example, maintaining imported electron beam lithography equipment, dilution refrigerator, stylus profilometers, etc. can be done in partnership with the global manufacturers. This will help reduce the downtime of equipment and bring down the cost of maintenance. Second, the facility will also fabricate indigenous equipment in collaboration with partner organizations including industry and startups where PIs agree that a world-class expertise exists. For example, Indian expertise exits to fabricate vacuum chambers, room temperature RF measurement setups, UV mask aligners, etc. Third, these will also serve as national experiential facilities for both R&D and to train students.

An important facet is to ensure that a high proportion of the allocated budget goes into direct costs for R&D projects, and setting up and maintaining world-class experimental facilities. All efforts should be taken to keep indirect expenses optimal by not reinventing the wheel in non-core aspects. For example, spends on administrative overheads should be minimized by leveraging best practices from similar national and international missions, existing organizations, and automation where possible.

The National Mission on Interdisciplinary Cyber Physical Systems (NM-ICPS) is pioneering the multi-organizational hub and spoke model.[72] There are twenty-five hubs, that exist in higher educational institution, with each focusing on a different domain of cyber physical systems. Other higher educational institutions that are interested in a particular domain can join the hubs as spokes. NM-ICPS aims at development of technology platforms to carry out R&D, translational research, product development, incubating, and supporting startups as well as commercialization.

One global reference point for the hub and spoke model is UK's National Quantum Technologies Programme (NQTP). Through its four quantum hubs led by the Universities of York, Birmingham, Glasgow, and Oxford, it has created a thriving academic and industrial quantum community. It has led to the successful transfer of knowledge and technology into many UK companies, created around 50 quantum technology start-ups, nurtured a skilled quantum workforce that includes over 470 quantum PhDs, and attracted more venture capital investment per capita into quantum technology than any other country.[73] The program has claimed many world-firsts, the first industrial demonstrations of a quantum gravimeter, the first chip-to-chip QKD encrypted transmission, and achieving world record performance in ion trap quantum computing.

NQM hubs may need to emulate the best practices of Indian mission mode application-oriented organizations like ISRO, BARC, NM-ICPS, etc. and best-in-class international organizations. There is a compelling argument that India did not take the Department of Space and ISRO or Department of Nuclear Energy and BARC model of an integrated approach in semiconductors, and hence did not develop a capability in this domain. Given the strategic importance of NQM, it is imperative to make the hub model work well.

NQM hubs should take the lead in collaborations with quantum technologies research hubs and programs in other countries. The focus of these collaborations should be nurturing relationships between R&D teams. And should involve access and sharing of lab infrastructure. For example, India PIs may require access to foundries that are in other labs outside India.

6.6. Smoothen the procedural challenges

Most of the components and raw materials for quantum technologies R&D is imported. India imports critical high quality raw material for making devices, special glass, oxygen free copper, lithography equipment, dilution refrigerators, etc. The high proportion of import has its own challenges. **The price for imported scientific equipment is quoted in foreign currencies (typically USD or Euro), and budgets for NQM will be allocated in INR. Adverse exchange rate movements over time can imply that more of the budget is consumed for purchase of imported equipment. The NQM may want to maintain a buffer budget to compensate for these adverse exchange rate fluctuations.**

Another impediment is procurement related. For purchase of any scientific equipment worth over INR 5 lakhs, higher educational institutions have to go through a new Global Tendering Enquiry (GTE) process. A domestic tender has to be floated to identify domestic manufacturers or service providers for the products or services for which approval is being sought for issuance of global tenders.[74] PIs indicate that the GTE process introduces delays of about two to six months in the procurement process which is a big impediment when it comes to time-bound mission-mode projects. **All PIs have uniformly suggested that the NQM should consider an exemption from the GTE process in equipment and raw material procurement.**

While previously the Government of India offered a subsidy in tax rates for purchase of R&D components and raw material, it removed this subsidy in 2022. Tax rates on scientific and technical instruments to public research institutes went up from 5% to 12% or 18% GST on equipment they purchase. Thus, the money available to be spent on scientific purposes effectively comes down.

Many PIs indicated that importing materials for R&D may need a special channel that includes speedy customs clearance. One of the oft quoted examples was the challenge faced in importing artificial diamonds for R&D. PIs have stated that there is a disconnect between the scientific departments of the government and the customs department on the difference between artificial diamonds for R&D and for jewellery. It often takes months to release these artificial diamonds and requires multiple back and forth between the PIs, DST, and Customs.

Another procedural challenge relates to the maintenance of equipment. Most of this equipment is imported and there are typically no maintenance engineers of the equipment vendors based in India. If an imported laser is damaged or misaligned, it needs to be sent back to the vendor abroad for repairs and such a process may take over four months. The lab, which would typically have only one of such equipment, would be essentially shut during this period as no experimental work would be possible. **The NQM should include funds required for maintaining and repairing the equipment upfront as obtaining funds post-facto for maintenance can be arduous. Sending equipment outside Indian for maintenance is expensive and time consuming.** As indicated earlier, the central facilities in the NQM hubs should enter into partnerships with the global manufacturers to maintain repair equipment in India.

Many of the components and raw materials required for quantum technologies R&D is now imported. As on now, there are no restrictions in importing these. **The geopolitical context needs to be carefully monitored by the NQM, and in case there is an impact in importing from a particular country, alternate sources need to be activated.** While components are imported, India has the expertise to assemble these components into certain types of equipment like some types of lenses, vacuum chambers, electronics systems, etc.

7. Appendix: List of experts interviewed for this study

Anil Prabhakar, *IIT Madras*

Anirban Phatak, *JIIT*

Apoorva Patel, *IISc*

Arindam Ghosh, *IISc*

Ganapathy Baskaran, *IMSc*

Kasturi Saha, *IIT Bombay*

Kausik Majumdar, IISc

Kavita Dorai, *IISER Mohali*

L. V. (Venkat) Subramaniam, *IBM Research India*

Madhu Thalakulam, *IISER Thiruvananthapuram*

Pravin Vaity, *Qtesslab*

R. P. Singh, *PRL*

R. Vijayaraghavan, *TIFR*

S. D. Sudarsan, *CDAC*

Sadiq Rangwala, *RRI*

Saptarishi Chaudhuri, *RRI*

Satyakesh Dubey, *CSIR-NPL*

Subhadeep De, *IUCAA*

Sudhir Kamath, *DRDO-IISc*

Sunil Gupta, *QuNu Labs*

Umakant Rapol, *IISER Pune*

Urbasi Sinha, *RRI*

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About itihaasa Research and Digital

itihaasa Research and Digital (www.itihaasa.com) is a non-profit Section 8 company that aims to understand the evolution of technologies and innovation in India. We have published reports on the landscape of AI / ML research and brain science research in India. We have worked as a knowledge partner for the U.S. - India Artificial Intelligence (USIAI) initiative of the Indo-U.S. Science and Technology Forum (IUSSTF).

Kris Gopalakrishnan, co-founder Infosys, is the founder and Chairman of itihaasa Research and Digital. Our flagship project is itihaasa history of Indian IT, a first-of-its-kind free digital museum that recounts the history of Indian IT since the 1950s. This makes the incredible history of Indian IT accessible to an audience across the world and is available on https://itihaasa.com/History. We have also published the book *Against All Odds: The IT Story of India*.

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Disclaimer: This report reflects insights from select expert and PIs. Not all experts and PIs in this domain were interviewed.