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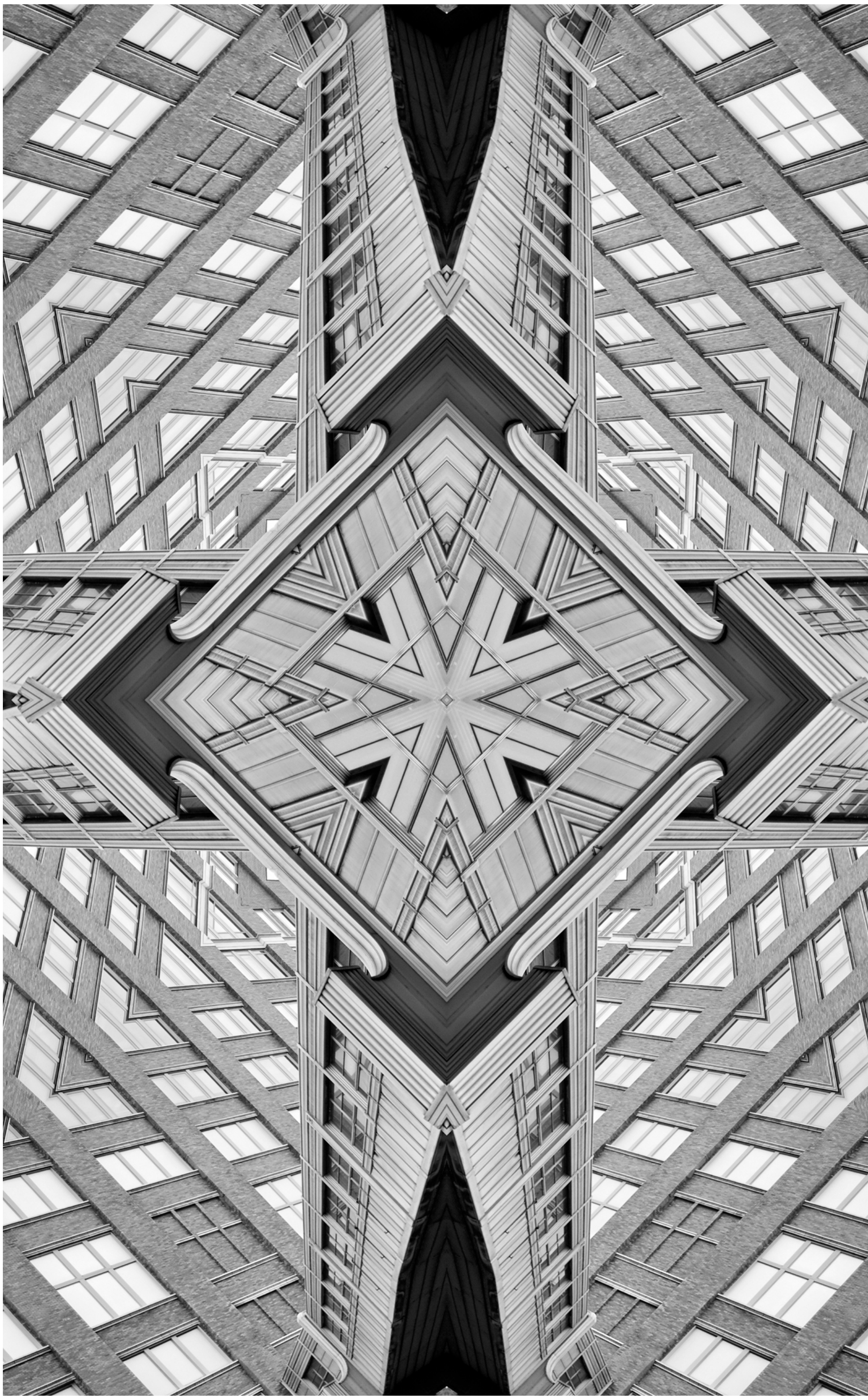

Quantum Computing: Current Scenario and Future Prospects

Prateek Tripathi

Abstract

Quantum computing (QC) forms one of the cornerstones of emerging technologies as we know them today. The technology has seen rapid progress over the years, but practical hurdles remain. The recent boom in Artificial Intelligence and the corresponding boost it has provided to classical algorithms also presents an additional hurdle for quantum algorithms. Countries like the United States, China, and Canada have made significant strides in QC and have managed to indigenously develop quantum computers. India, for its part, approved its National Quantum Mission in April 2023, and while it will likely provide the thrust that the technology needs to prosper within the country, it lays out objectives which are rather modest, and could benefit tremendously from a broader and more ambitious vision.

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Introduction

Since its inception in 1900,[1] quantum theory has found its use in most technologies, from transistors to superconductors. The development of microprocessors in the 1970s led to a rapid increase in the processing power of computers, but classical computers remained unequipped to simulate quantum systems. Computing with quantum systems was proposed by Richard Feynman[2] in one of his lectures in 1982. Today, most of the discussion around "emerging technologies" is centred around quantum computing (QC), primarily due to its increased computing speed and the fact that it can break most current encryption protocols. Quantum computers can perform calculations beyond the capabilities of classical computers, and therefore, find applications in various fields. However, despite the availability of early QC capability, there are significant practical and technological hurdles that need to be overcome before utility-scale QC can be achieved.

Quantum computers use systems obeying the laws of quantum mechanics to perform similar functions as classical computers, although there are differences at an operational level. The quantum scale has distinct advantages for computation, especially because quantum computers use quantum bits, or qubits, instead of classical bits.[3] Bits are carriers of information and can take on either a 0 or 1 value, whereas a qubit can take a 0 or 1 or a superposition of both. The "principle of superposition" is a fundamental property of the quantum scale.[4] Because qubits can exist simultaneously as 0 and 1 (mathematically, any linear combination of 0s and 1s), unlike classical bits, they significantly increase information-carrying capacity, thus boosting the speed of quantum computers compared to their classical counterparts.

Several paradigms and hardware implementations have been adopted for quantum computers, although no single approach has emerged superior. Two common approaches are adiabatic quantum computation (AQC) and gate model QC.

AQC and Quantum Annealing

'Adiabatic' means that a system is not permitted to exchange energy with the surrounding environment. The relaxation of this requirement results in quantum annealing (QA).[5] The QA model is already commercially available.

Optimisation problems in the real world can be framed as energy-minimisation problems in physics. QA uses quantum physics to solve these problems and arrive at the optimal solution. The first commercial quantum computers, which were produced by D-Wave, were of the QA type.[6] QA computers are currently being used to solve select real-world problems, including optimisation, scheduling, machine learning, and simulations.

Gate Model QC

When discussing quantum computers, it is usually the gate model QC that is being referred to.[7] Similar to classical computers, gate model QC relies on passing qubits through a sequence of logic gates to perform the computation; however, quantum logic gates are significantly more complex than their classical counterparts.

> "Despite the availability of early QC capability, there are practical and technological hurdles to achieving utility-scale QC."

Practical Limitations of Quantum Computers

The primary obstacle that QC must overcome is the problem of "noise" or "decoherence."[8] Quantum systems interact with the external environment via vibrations, temperature fluctuations, and electromagnetic fields, which causes information carried by qubits to decay over time. While the complete isolation of any quantum system is impossible, these interactions can be minimised. The interaction of qubits with the surrounding environment needs to be limited as efficiently as possible in order to allow sufficient time for computation. This can be addressed by quantum error correction, which also allows greater fidelity from quantum computation.[9] According to recent estimates, each functional or "logical" qubit requires more than 1,000 physical qubits to perform state-of-the-art error correction, though this is an area of active research with progress being made on a continual basis.[10]

Another constraint arises from the necessity for qubits to be "entangled", i.e., the state of any qubit must be correlated with that of the others.[11] This comes at the cost of losing some qubits. Both these constraints lead to a loss of qubits. Therefore, building a fully functioning quantum computer will require billions of qubits, since a large percentage of these will be "eaten up" by the system to compensate for entanglement and error correction.

Holevo's theorem states that the amount of data that can be retrieved from n qubits cannot be larger than the amount of data that can be retrieved from n bits.[12] Therefore, most of the data in a collection of qubits cannot be retrieved. Additionally, quantum gates—which are the equivalent of traditional binary logic gates in conventional computing—are very slow and error prone, and they rapidly lose data.[13] This, coupled with the complex measurement process in quantum systems, makes the creation of quantum algorithms tedious and complex.

One solution is noisy intermediate-scale quantum (NISQ) computers,[14] which are gate-based quantum computers with a limited number of decohering or noisy qubits, which may be able to outperform classical computers. However, NISQs are merely a stopgap arrangement until "fully error corrected" quantum computers are realised.

In these contexts, gate model QC holds the greatest promise because it can be applied to solve a variety of problems, whereas other approaches such as AQC can only be used to solve select problems, such as optimisation.

Superconducting Systems and their Physical Implementation

A functional quantum computer requires a physical system that creates qubits and can be manipulated as required. Some ways to achieve this include trapped ions, superconducting qubits, photonic qubits, quantum dots, and topological qubits.[15] Of these, superconducting systems have emerged as one of the most popular. Superconductors are among the few materials that can show macroscopic quantum effects.[16] A unique property of semiconductors, known as the Meissner effect, allows them to become perfect conductors upon reaching a certain "critical temperature", i.e., electrons can flow through them without the dissipation of energy.[17] This property partly addresses the issue of decoherence in quantum processors. Additionally, because a superconductor is an inherently quantum system, it would be ideal for building a quantum computer.

Despite initial hurdles, superconducting quantum computers have come a long way, and the technology continues to evolve. The demonstration of the first functional superconducting qubit came in 1999, in a paper published by a team of Japanese researchers.[18] Consequently, in 2007, the superconducting transmon qubit was invented, which has become the model of choice in the QC industry.[19] However, the critical temperature required to obtain superconducting behaviour poses a hurdle to their practical implementation. This temperature is very close to "absolute zero" (approximately -273°C or 0K).[20] Achieving this condition is physically difficult and the required setup is prohibitive.[21] These problems will only be compounded during commercial production.

These issues have led to a growing interest in developing room-temperature superconductors. In 2023, a team of researchers from South Korea claimed that they had achieved this feat using a material called LK-99, which seemingly behaves like a superconductor at ambient pressure, with a critical temperature of up to 127°C.[22] Subsequent attempts to replicate this behaviour were unsuccessful, and it was later found that the material was likely not superconducting.[23] However, in a January 2024 paper, a group of researchers from institutions in China and Japan claimed to have replicated the experiment.[24] Although the results are unconfirmed, the experiment has already led to increased interest in the field, with the US Office of Naval Research providing US$100,000 in funding for LK-99 research in September 2023 and another US military funded room-temperature superconducting research program reportedly on the way.[25]

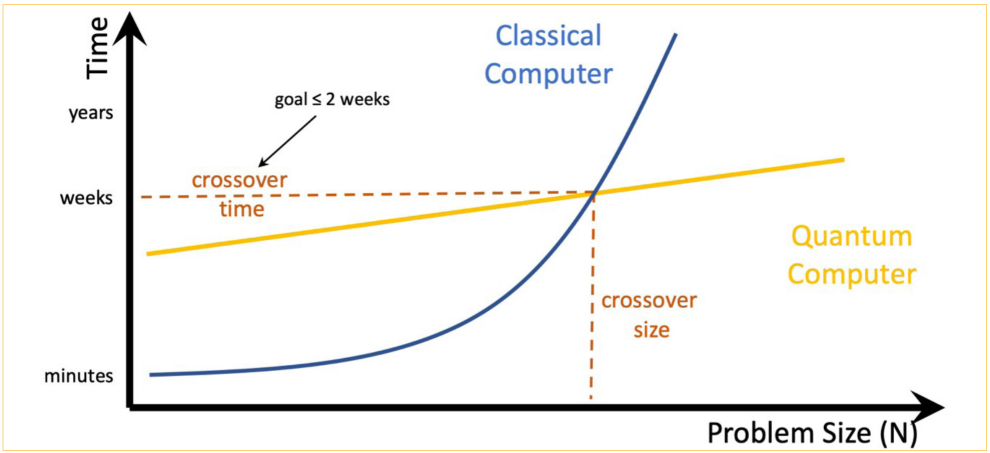
Classical vs. Quantum Computers: The Problem with QC Algorithms

In order for quantum computers to outperform classical computers, it needs to be demonstrated that they can perform computations more efficiently than the latter. This requires a quantum algorithm that has computational advantage over a classical computer for a specific problem. At present, the best understood quantum algorithms are those for quantum chemistry, logistics and finance, binary optimisation, and breaking encryption.[26]

What makes quantum computers faster than classical computers is not the speed of the qubits themselves, which are slower than classical bits, but the different ways in which the qubits can be entangled and correlated with each other. While quantum computers are not faster per operation, they require fewer operations to perform the same task. Therefore, for smaller problems, the classical algorithm will be more efficient since it is faster per operation. However, with increasing complexity, the quantum algorithm becomes the more optimal choice since it would solve the problem in fewer operations. The point at which the quantum algorithm supersedes the classical one is known as the "crossover point".

However, each time a classical computer becomes faster or a more efficient classical algorithm is developed, this point keeps shifting further. This leads to an increase in the number of qubits required for a quantum computer, which may eventually make them impractical and prohibitively expensive. This problem is exacerbated by artificial intelligence, which is making classical algorithms even more efficient. This is one of the central issues that QC has to contend with and makes them less commercially viable. However, irrespective of their advancements, classical computation will remain unable to solve certain complex problem types, and QC will provide the only viable solution.

Figure 1: Solution-Time Scaling Differences between Classical and Quantum Problems



Source: Disentangling Hype from Practicality: On Realistically Achieving Quantum Advantage [27]

Current Global Scenario

Global investment in QC reached US$35.5 billion in 2022, with investments in quantum technology start-ups reaching the highest ever, at US$2.35 billion.[28] Investment is led by China, the European Union (EU), and the United States (US), with Japan, the United Kingdom (UK), Canada, and India emerging as prominent players. By 2022, announced government investments in quantum technology amounted to approximately US$34 billion, with China alone accounting for almost half (US$15.3 billion).[29] The EU was second, at US$8.4 billion, followed by the US, Japan, and the UK.

United States

The US established the National Quantum Initiative Act in 2018 to support the development of quantum technology,[30] which implemented a framework for quantum technology research and development (R&D) and set aside a budget of US$1.2 billion for several initiatives over five years (2019-23). The budget has been allocated to three nodal agencies: the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), and the Department of Energy (DOE), which runs the National Laboratory network.

The private sector is largely responsible for the US's dominance in the QC field, with IBM at the forefront, as was the case in the development of classical computers. In 2021, IBM developed a 127-qubit chip called Eagle,[31] followed by the 433-qubit Osprey in 2022.[32] On 4 December 2023, it unveiled the first quantum computer, consisting of more than 1,000 qubits.[33] The computer is based on a chip called Condor, which has 1,121 superconducting qubits.[34] Evidently, IBM has been doubling the number of qubits yearly, though it has stated its intention to shift focus to error correction. Alongside the computer, it debuted its Heron processor, which has the most efficient error correction till date and serves as the foundation for Quantum System Two, IBM's next-generation QC system architecture.[35] IBM has also highlighted its intention to build large-scale quantum computers by 2033.[36]

China

China makes sizeable investments in QC and has achieved considerable success. Quantum technology R&D has been identified as a strategic industry and area for innovation in China's Five-Year Plans since the 11th plan (2006-10) as well as in 'Made in China 2025'.[37] Its 14th Five-Year Plan (2021-25) announced an investment of US$15.3 billion for the construction and operation of its National Quantum Laboratory (NQL).[38] As of 2023, the country hosted 12 dedicated quantum technology research institutions and had the third largest number of graduates in the QC field.[39]

In 2021, Origin Quantum Computing Technology Co. developed an indigenous quantum computer, making China the third country in the world to do so, after Canada and the US.[40] In May 2023, the Chinese Academy of Sciences (CAS) announced Zuchongzhi, China's largest quantum processor till date, consisting of 176 qubits.[41] In October 2023, a research team led by Pan Jianwei, China's leading quantum physicist, developed the world's largest photon qubit quantum computer, Jiuzhang 3.0, which had 255 photons.[42] Additionally, China is the only country to achieve breakthroughs in both photon and superconducting qubit QC technologies.[43]

Canada

Canada launched its National Quantum Strategy in 2021, backed by a budget of US$360 million.[44] It is driven by three key missions, including one on computing hardware and software.

Canada has remained foremost in terms of the commercialisation of QC. In 2011, D-Wave released the first commercial quantum computer, called the D-Wave One,[45] which was based on QA and consisted of a 128-qubit processor called Rainier. In 2020, D-Wave released Advantage, a 5,000-qubit QA computer, which it also subsequently made commercially available on the cloud via its Leap cloud service.[46] Canada also possesses two universal quantum computers—the IBM Quantum One and MonarQ, which has 24 superconducting qubits and was designed and built by the Montreal-based Anyon Systems.[47]

Patents

R&D is an important factor in the development of any technology, serving as the true indicator of innovation. Patents are often considered to be a useful tool in this regard. According to a McKinsey report, Chinese companies account for more than half (52.8 percent) of the total QC patents filed during 2000-22.[48] Japan is a distant second at 14.1 percent, closely followed by the EU and US.[49] India does not feature in the top ten. According to a 2022 study conducted by the Quantum Economic Development Consortium (QED-C), the US accounted for some 1,838 QC patent applications in 2010-22, which is more than double that of China (908), followed by Japan, the EU, and South Korea.[50] This discrepancy is the result of the nature of the patents that were studied. While the McKinsey report focused on domestic patents, the QED-C report analysed international patents, which are filed in patent offices across multiple countries and are typically reserved for high-quality and high-value patents, making them harder to acquire.[51]

A 2023 study by the European Patents Office revealed that US companies and universities accounted for half of the top 20 entities in international QC patents,[52] followed by Japan, with five patents. There was only Chinese company on the list—Alibaba—and no Indian entity. International patents may be a better metric for R&D since they have more stringent quality standards and are harder to acquire.

Publications and H-Index

The number of research papers published by a country is another prominent indicator of R&D. In 2021, China and the EU led in terms of quantum-relevant publications, with 22.1 percent each.[53] They were followed by the US, UK, and Japan. However, the quality of the papers also needs to be assessed alongside their quantity, which is determined by the Hirsch index (H-index). In terms of the H-index, the US is in the lead, followed by the EU, UK, and China.[54] Therefore, while China leads in terms of volume in 2021, the US emerged the leader in terms of innovation. India does not feature on the list.

The Indian Scenario

On 19 April 2023, India announced its INR 6,003-crore National Quantum Mission (NQM), which lists quantum computation, quantum communication, quantum simulation, and quantum sensing and metrology as its four pillars.[55] To this end, it has mandated setting up four Thematic Hubs (T-Hubs) in academic and national R&D institutes across the country to coordinate each of these verticals.[56] These T-Hubs will be set up as Section 8 companies to provide then with greater freedom and flexibility compared to conventional funding models. The goal of each hub is to coordinate and consolidate all required activities to achieve the targets set out in the Detailed Project Report (DPR) of the mission.

The T-Hub will be awarded to an institute or a consortium based on an open call. Relevant stakeholders are expected to form a cohesive team to bid for the T-Hubs. Additionally, the hubs will carry out translational research, incubate start-ups, create links with industries, foster international collaboration, run an outreach programme, and develop a comprehensive Human Resource Development programme to create the workforce to execute the mission.[57]

Since it is unclear which hardware platform is likely to yield a practical quantum computer, the mission will focus on key hardware platforms like trapped ion, superconducting, semiconducting, photonic, and neutral atom qubits while also being open to any new and emerging platforms. The goal is to develop quantum computers with 50-100 logical qubits within five years and accelerate to 1,000 qubits and beyond within eight years across several hardware platforms.[58] Emphasis will be on the development of quantum error correction and quantum algorithms for practical applications that are relevant to the needs of the country. The mission also aims to create an ecosystem to enable start-ups to develop and provide component technologies for quantum computers and create profitable business cases in the long run.[59]

The Tata Institute of Fundamental Research (TIFR), Mumbai, has developed a 3-qubit quantum computer based on superconducting qubits, and is preparing to develop a computer with 7 qubits in collaboration with DRDO and TCS.[60] IISER Pune's I-HUB Quantum Technology Foundation is working on a 20+ qubit quantum computer based on ion traps and another computer based on neutral atoms along with IIT Roorkee and IIT Guwahati.[61] IIT Bombay and IISER Thiruvananthapuram are working on spin qubits based on semiconductors, while IISc Bangalore is also working on superconducting qubits.[62] The Chatterjee Group Centres for Research and Education in Science and Technology (TCG CREST), is building India's first quantum computer in association with TIFR and IISc Bangalore.[63]

India has established processes to promote quantum education. IIT Madras launched an advanced course in QC technology in 2022 with quantum algorithms and programming of quantum computers.[64] IISc Bangalore launched its Quantum Technology Initiative (IQTI) in 2020 to conduct R&D in quantum technologies and create a framework to encourage collaboration between physicists, material scientists, computer scientists, and engineers.[65] It has also established a quantum computing centre focusing on quantum algorithms, quantum information theory, and quantum error correction.[66] Other institutions, such as IIT Jodhpur; TIFR, Mumbai; IISER Pune; Raman Research Institute, Bengaluru; and the Harish-Chandra Research Institute, Allahabad, have active research programmes in QC.[67] Several QC startups such as Globally Xanadu, Classiq, QRDLab, and QuintessenceLabs.ai are training educational institutes and industries in order to build the quantum workforce in the country.[68]

The Ministry of Electronics and Information Technology (MeitY) has established a Quantum Computing Applications Lab in collaboration with Amazon Web Services (AWS)[69] that aims to accelerate QC-led R&D and enable new scientific discoveries. This is MeitY's first initiative to provide the scientific, academic, and developer communities in the country with access to a QC development environment on the cloud. The lab provides selected applicants with no-cost access to QC hardware, simulators, and programming tools on demand, including access to AWS cloud services, in order to enable them to build algorithms, conduct advanced simulations, and run experiments. This is also the first QC applications lab on the AWS cloud that supports a government's science and technology mission at the country level.[70]

However, there is a shortage of talent and skills in the quantum technology sector, both in India and globally.[71] This could be due to a lack of general awareness about potential career and business opportunities in the field. Many universities lack QC experts, adequate training resources, and cutting-edge laboratories to acquire hands-on learning experience.[72] Few universities—such as IIT Madras and IISc Bangalore—offer courses on quantum technology.

The NQM will create opportunities for quantum education and prepare students and teachers to use and innovate in quantum technology. Universities in countries such as the US and Australia already offer such programmes.[73] This programme also needs to be backed by policies to help build quantum technology, such as by developing novel quantum algorithms, constructing quantum-secure cryptographic methods, and providing training to the staff.

The Importance of QC for India

QC can be tailored to address the unique challenges faced by India across sectors. For instance, in the pharmaceutical industry, quantum computers can be used to revolutionise drug discovery, enabling more accurate simulations of molecular interactions and accelerating the identification of potential drug candidates.[74] This could have profound implications for addressing health challenges specific to the Indian population.

In materials science, QC could aid in the development of new materials with enhanced properties to address critical needs such as efficient energy storage solutions for India's growing energy demands. QC can play a pivotal role in advancing sustainable technologies, from superconductors to advanced batteries, that are aligned with India's focus on renewable energy.[75]

The country's financial sector also stands to benefit from quantum algorithms, which have the potential to optimise financial modelling, risk assessment, and fraud detection, thus contributing to the stability and security of India's financial systems. Additionally, QC can enhance cybersecurity measures to protect financial transactions and data.[76]

In logistics and manufacturing, quantum computers can perform complex optimisation tasks such as storage and determining travel routes faster than classical computers.[77] Quantum annealers are already paying dividends in these fields,[78] which is particularly relevant given India's goals of 'Make in India' and 'Atmanirbhar Bharat' as well as its ambitions of becoming a global manufacturing hub.

QC, supplemented by other quantum technologies like quantum sensors, can enable precision agriculture, which can increase the efficiency of farming operations and improve the livelihood of farmers.[79] QC can also help enhance the prevailing understanding of complex molecular processes, leading to more efficient and less carbon-intensive farming processes such as the production of fertilisers.[80]

Recommendations for India

The NQM needs to address several issues pertaining to QC. Recent developments in the field can serve as important guidelines and pave the way for the future of QC in the country.

- India lags in QC R&D in terms of both the number of patents filed and publications. The NQM needs to address this urgently. The case of China also highlights the importance of innovation in research over volume; of quality over quantity.

- The NQM needs to invest in the development of sophisticated quantum labs and research centres as well as engage in international collaborations. Government policies and investments, as in the case of other emerging technologies such as artificial intelligence, are required to provide a supportive ecosystem for quantum research and development.[81] With the right investments in education, infrastructure, policy, and partnerships, Indian universities can become a global hub for quantum education and research.

- The growing digital education space and the National Programme on Technology Enhanced Learning (NPTEL) provide a foundation for creating a roadmap for quantum education in the country. India must develop a comprehensive curriculum covering a broad range of quantum mechanics and computing topics at the undergraduate, graduate, and doctoral levels. Similar programmes include a bachelor's quantum engineering programme at the University of New South Wales, Sydney, and a master's programme at the University of California, Los Angeles and San Jose State University.[82] Such programmes should be supplemented by hands-on training, internships, and industry collaboration to provide students with practical experience. Free courses such as the ones offered by NPTEL should include quantum education and workforce development.

- The importance of room-temperature superconductors for QC cannot be overstated, especially considering their multiple applications in the material sciences. The developments around LK-99 have led to increased research in the field, and it seems like only a matter of time before they materialise. As such, research on room-temperature superconductors needs to form an integral part of the NQM.

Recommendations for India

- QA is an area where India has made no progress, nor is it part of the NQM. Canada has pioneered the development of annealing quantum computers. Given the potential of QAs for solving complex optimisation problems as well as in implementing encryption-breaking algorithms,[83] it is recommended that India either import the technology or work on building it indigenously.

- The NQM's target to develop intermediate-scale quantum computers up to 1000 logical qubits by 2032[84] is a modest goal that would result in India lagging behind global advances. At present, the country lacks a long-term plan for full-scale quantum computers. IBM has already built a 1,000-qubit (albeit non-logical) processor and set a target to build a large-scale quantum computer by 2033. India needs to accelerate its efforts if it hopes to catch up with the global leaders in QC. The NQM could therefore benefit from a broader and more ambitious vision.

- Presently, India imports the majority of QC components from the US and EU.[85] Promoting the indigenisation of this equipment would enable faster development while cutting down costs and generating employment.

> "India's Quantum Mission needs to invest in the development of labs and research centres, and engage in international collaborations."

Conclusion

The current problems in QC are related to engineering and not physics. In the most optimistic scenario, these problems will be overcome by 2033. However, this is still a long way away. Additionally, while commercial interest in QC is on the rise, the field is much more exciting from a research perspective at present.

Given the recent developments in QC, India's NQM needs to develop a broader strategy. Its current outcomes are shortsighted and need to be updated. QC has the capacity to enable innovation and development in a multitude of fields, and India needs to take advantage of this ripe opportunity.

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