



Quantum Computing-Revolutionising The Era Of Computers

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Abstract. Evolution of computers has seen significant reduction in size and enhancement in computational capabilities. However, these advancements still face limitations in terms of scalability, processing speed, energy consumption, parallel operations and dealing with cryptography. Quantum computing, first proposed in the 1980s, leveraging quantum mechanics is bringing about phenomenal enhancements in computational capabilities. Basic information processing unit in quantum computing i.e. qubit has inherent properties of superposition, entanglement and interference. This allows parallel processing of large and complex datasets. Various techniques for qubit implementation are superconducting qubits, trapped ions, neutral atoms, spin qubits, photonic qubits and topological qubits. However, superconducting qubits, being scalable and fast, are found to be most suitable. Quantum computing has the potential to significantly impact various fields such as cryptography, materials science, drug discovery, engineering, finance, logistics, AI, and climate modelling. Progress in this field is facing challenges of decoherence, requirement of extremely low temperatures and development of appropriate algorithms. In addition, significant enhancement in processing power of quantum computers is raising concerns about cybersecurity threatening classical encryption techniques which safeguard critical sectors. Despite the existing challenges, world renowned companies such as Mercedes Benz, Exxon Mobil, CERN, Mitsubishi, BMW, Hyundai and Rolls Royce are extensively involved in exploring the usage of quantum applications towards designing of batteries, finding fuel efficient routes, study of universe, automation of automobiles and advancement in metallurgy. China has been the leader in both funding and number of patents to its name. Coupled with the potential of AI, quantum computing is going to change the world and bring in a completely new era.

Index Terms - Quantum Computing, Qubits, Superposition, Entanglement.

Introduction

Evolution in the field of computers has been phenomenal. From an apartment-sized machine weighing 30 tons and having a high-speed memory of 80 bytes to tiny wearable computers weighing half a pound and having Random Access Memory (RAM) of one GB. Early mechanical calculators and the first electronic computer were developed in the mid-20th century. The 1960s and 70s brought the development of transistors and integrated circuits, which facilitated miniaturization and increased the power of computers leading to the creation of personal computers in the 1980s. The growth of the internet in the 1990s enabled global connectivity. In recent years, advancements in artificial intelligence, machine learning, and cloud computing have further accelerated developments in this field.

The enhanced capabilities in computers are achieved on the backbone of classical computing technology. However, classical computers face certain significant challenges. These are: -

- **Scaling and Speed.** As the complexity of the problem increases and data sets become large, there is an exponential increase in the number of bits and operations required to be undertaken by each of them. Scaling a classical computer proportionally in an efficient manner becomes impractical. Hence, the processing power gets limited vis a vis the complexity of the task. This compels the researchers and scientists to balance between speed and accuracy in their research.
- **Energy consumption.** With increase in performance enhancement comes the increase in consumption of energy and associated cooling challenges.
- **Parallel operations.** Classical computers struggle with parallel processing, as they typically execute one instruction at a time per core.
- **Cryptography.** Classical computers are vulnerable to certain types of cryptographic attacks, and their ability to break encryption is limited.

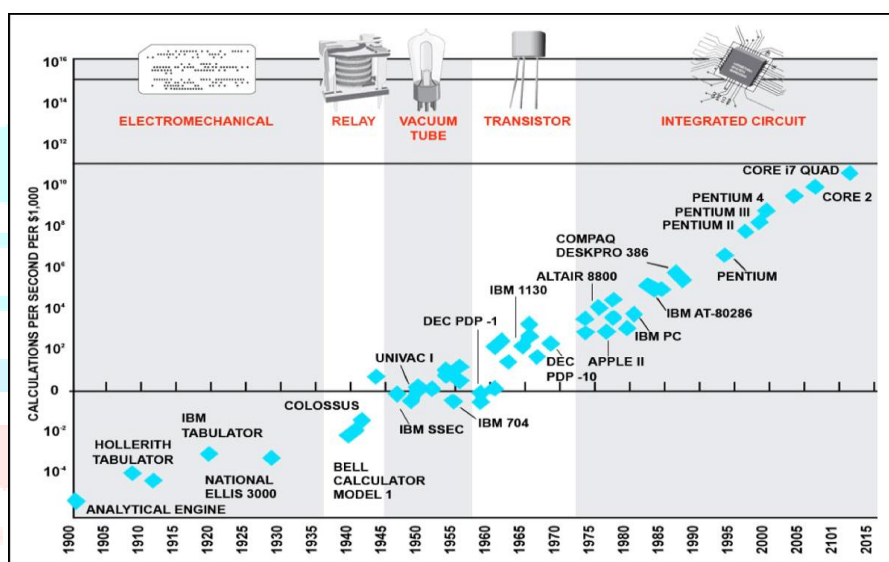


Fig.1. A plot of advances in computer processing (represented as calculations per second per \$1,000) illustrates Moore's law. Credit: Steve Jurvetson/Flickr, CC BY 2.0

Origin of QC. The term 'quantum' is a Latin word meaning 'how much'. It represents the smallest discrete unit possible of any physical property of matter and energy. For instance, a quantum of light is known as a photon, while a quantum of electricity is referred to as an electron.¹ In 1980, physicist Paul Benioff invented a quantum Turing machine. This was a major breakthrough and laid the foundation for quantum computing. In 1982, physicist Richard Feynman created an abstract model to show how quantum computers could solve calculations that are difficult to handle by classical computers. He propagated that classical logic was inadequate to solve problems related to quantum phenomena and would take an exponentially long time to solve certain quantum problems, while quantum computers could solve them phenomenally faster. Interestingly, it took computer scientists nearly fifty years to consider using quantum theory for computing. The major breakthrough came in 1994 when mathematician Peter Shor developed a quantum algorithm to find the prime factors of large numbers. Development in quantum computing has seen significant progress in recent years with number of established company's and new startup working in collaboration with major industries.

¹ Britannica, The Editors of Encyclopaedia. "quantum". Encyclopaedia Britannica, 13 Mar. 2024, <https://www.britannica.com/science/quantum>. Accessed 23 September 2024.

Methodology

The paper is descriptive research based on information processed from secondary sources including academic articles, books, and reliable online resources. The aim is to present a comprehensive understanding of quantum computing, its principles, applications and challenges.

Thesis statement

Quantum computing, based on the principles of quantum mechanics, is resulting in significant enhancements of computational capabilities. This is likely to have unprecedented opportunities and challenges across a spectrum of industries and scientific domains.

Discussion- Quantum Computing-Terminologies and Algorithms

Qubit. As binary bit, the basic unit of information, is to classical (or traditional) computing, a qubit (or quantum bit) is to quantum computing.

Superposition. Superposition is the ability of a quantum system to simultaneously exist in multiple states, until measured or observed. This principle is opposite to that of classical physics, where objects have definite properties and states. For instance, an electron can occupy multiple positions or energies in superposition (Fig.2). When measured, the superposition collapses to a definite state, determining the outcome of the observation. This phenomenon allows quantum bits (qubits) to exist in multiple states at the same time. While classical bits are confined to binary states 0 or 1, a quantum system with two qubits has the probability of these two qubits to be present in four different states at the same time i.e. 2^2 . Thus, a quantum computer with 'n' qubits can exist in a superposition of 2^n states.

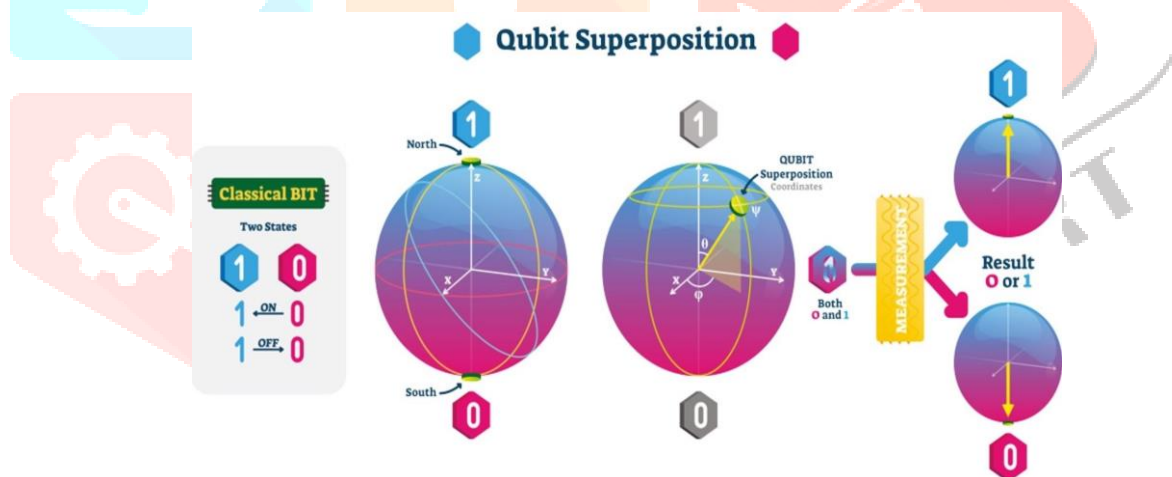
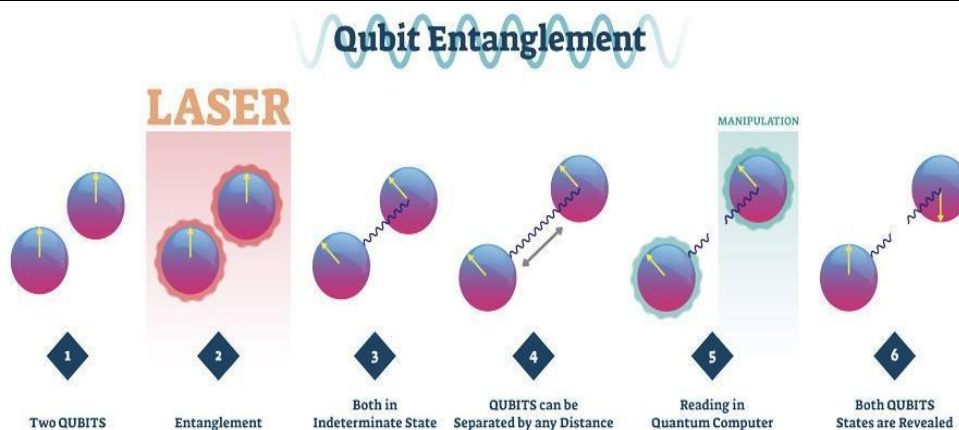


Fig.2. Superposition in Qubits vis a vis Classical bit²

Entanglement. Quantum entanglement is a phenomenon where two or more particles become linked in a way that the state of one particle is dependent on the state of another, regardless of the distance between them or any obstacles in their path (Fig.3). This means that if you measure a particular property of one particle, you can instantly know the corresponding property of the other particle, even if they are light-years away. These particles could be electrons or photons, and the particular property under consideration could be its spinning axis in a particular direction. In relation with quantum computing, it describes a special link where the state of one qubit is dependent on the state of another, no matter how far apart they are.

² [Image of Superposition Explanation Illustrations & Vectors] retrieved from Dreamstime
<https://www.dreamstime.com/qubits-vector-illustration-infographic-superposition-entanglement-states-comparison-classical-one-polarization-bit-image126322079>

Fig.3. Entanglement of Qubits³

Quantum Interference. Quantum interference is a phenomenon where two or more quantum waves interact with each other, resulting in constructive or destructive interference. This is similar to how waves on the water surface can interfere with each other to create patterns of peaks and troughs. When two or more quantum particles interact, their wave functions can interfere with each other, which can either increase the probability of a particular outcome (constructive interference) or decrease it (destructive interference). This characteristic of quantum interference with each other, can be used to amplify the correct answers and cancel out the wrong ones.

Why are Quantum Computers Faster. Quantum computing employs quantum mechanics phenomena of superposition and entanglement, to perform required calculations. It uses qubits to store and process information which is unlike classical computers, which use bits which are binary and can have only two states of 0 and 1. The qubits have the ability to exist in two different quantum-mechanical states, such as the orientation of an electron's spin or the polarisation of a photon of light. Crucially, these qubits can exist in a superposition of both states simultaneously, and can connect to other quantum particles through entanglement. Therefore, the outcome of the whole is no longer simply dependent on the outcome of independent parts but on coupled probabilities.

For instance, a classical two-bit system can exist in one of four states: 00, 01, 10, or 11. Therefore at any given time only two coefficients are required to represent the system. In contrast, a two-qubit quantum entangled system also has four states, but all four states exist simultaneously in a probabilistic manner. This requires four new coefficients to represent the system, rather than just independent coefficients. Extending this concept, for a system with 'n' qubits, it would need 2^n coefficients. Therefore, for quantum processors with even 300 qubits, the entangled qubits would require more coefficients than the number of atoms in the known universe.⁴ This gives quantum computers the capability to process large and complex datasets through parallel operation and thus, making it faster.

Quantum Algorithms. These conditions cannot be managed by conventional algorithms. It opens the field of special quantum algorithms. Two such examples are:

- Lov Grover introduced his algorithm in 1996. Known as Grover's algorithm, it enables searches through unsorted databases at speeds quadratically faster than what could be achieved through classical algorithms. This makes his algorithm suitable for tasks such as database searches, optimisation, and finding solution to combinatorial problems.
- Peter Shor, developed and presented his algorithm, Shor's algorithm in 1994. It enables efficient factorisation of large composite numbers into their prime components - a task that was considered

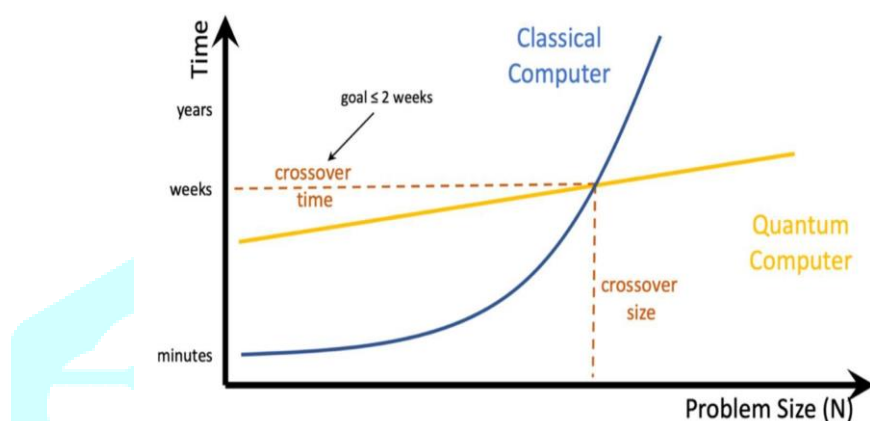
³ [Image of Superposition Explanation Illustrations & Vectors] retrieved from Dreamstime

⁴ Dungey, Triniti, Yousef Abdelgaber, Chase Casto, Josh Mills, and Yousef Fazea. "Quantum Computing: Current Progress and Future Directions." Emerging Technologies and Trends, Monday, July 11, 2022.

computationally extensive for classical machines. Shor's algorithm performed significantly better than the best classical algorithms available for this task, such as the General Number Field Sieve (GNFS).

Crossover Point. Problems that are fundamentally unsolvable or undecidable, as considered by classical algorithms, cannot be solved by quantum algorithms either. Speed and efficiency achieved by quantum computers are not because of any speed advantage of qubits, which are actually slower than classical bits, but because of the properties of superposition and entanglement, displayed in quantum mechanics. For smaller problems, classical algorithms are more efficient as they are faster per operation. However, as problems become more complex, quantum algorithms become better because they require fewer operations to solve the problem. The point where quantum algorithms become better than classical ones is called the “crossover point” or “The Quantum Supremacy Point”.

Fig.4. Solution-Time Scaling Differences between Classical and Quantum Problems



Each time the speed of classical computers is increased or a more efficient classical algorithm is developed, the crossover point keeps shifting further. This shift is further enhanced by artificial intelligence, which is making classical algorithms even more efficient. However, irrespective of their advancements, classical computation will remain unable to solve certain complex problem types, and quantum computing will provide the only viable solution.⁵

Implementation of Qubits

In 1999, Japanese researchers used superconductors to demonstrate one of the most promising types of qubits. These qubits encoded data using a pair of superconducting electrons that can exist in two different states. Switching from one state to the other triggers the superconducting qubit to emit a microwave photon. Since this photon carries information about the qubit's state, it offers a way to send data from one qubit to another.⁶ Currently, various ways in which qubits are being implemented are discussed.

Superconducting Qubits. These use superconducting circuits and are popular in quantum computing due to their easy scalability and faster speeds. Superconductors are among the few materials that can show macroscopic quantum effects.⁷ A unique property of superconductors, known as the Meissner effect, allows them to become perfect conductors upon reaching a certain ‘critical temperature’. At this temperature the

⁵ Torsten Hoefer, Thomas Haner and Matthias Troyer, “Disentangling Hype from Practicality: On Realistically Achieving Quantum Advantage,” Communications of the ACM, May 1, 2023, <https://doi.org/10.48550/arXiv.2307.00523>

⁶ Davis, Robert. "How The First Superconducting Qubit Changed Quantum Computing Forever." Qiskit, September 29, 2022. <https://medium.com/qiskit/how-the-first-superconducting-qubit-changed-quantum-computing-forever-96cf261b8498>. Accessed September 25, 2024.

⁷ H.Y. Yuan and Rembert A. Duine, “Quantum Magnonics,” Encyclopaedia of Condensed Matter Physics, Volume 2 (2024): 147-158. https://www.sciencedirect.com/science/article/abs/pii/B_9780323908009001797

electrons can flow through them without the dissipation of energy.⁸ This property partly addresses the issue of decoherence in quantum processors. Superconducting qubits have shown promising results in terms of coherence and scalability, making them a leading candidate for building large-scale quantum computers. The advancements in quantum technologies have resulted in the creation of powerful quantum processors with over 1,000 qubits. IBM unveiled its 1,121-qubit processor, Condor, in December 2023.⁹ Additionally, Atom Computing is testing a processor with 1,188 qubits.

Trapped Ion Qubits. In these qubits, ions are trapped using electromagnetic fields and manipulated with lasers. They offer high coherence and precise control. In trapped-ion technology, each qubit is encoded in two energy level states of an ion. Two-qubit gates exploit the coupling between the electron and phonon (a quantum of energy associated with a compressional wave, such as a vibration). Trapped ions are found to be most error-resistant and have the least cooling requirements compared to other technologies. Fidelity during scaling is also feasible as the qubits targeted for entanglement can be physically moved and manipulated. However, increasing the number of qubits in trapped-ion systems is the most significant obstacle for the technology. Creating entanglement across more than two qubits in trapped-ion systems has proved difficult. Other difficulties include coherence and limitations of achievable size as fidelity declines with the distance ions must travel.

Neutral Atoms. Neutral atom qubits utilise trapped neutral atoms that are precisely controlled using lasers and optical tweezers. It has advantages in scaling, coherence, and cooling. Scaling up to 1000 qubits of neutral atoms doesn't pose much challenge as their neutrality minimises the interference.¹⁰ The qubits in these systems also have strikingly long coherence times of up to ten minutes in experimental conditions, as compared to other technologies.¹¹ The challenges would be scaling to a million qubits and controlling electronics and error rates. Feasibility of scaling arrays beyond 100,000 neutral atom qubits and employability of control electronics at that scale is still work under progress. Finally, neutral-atom systems' error rates are higher than those of other systems.¹²

Spin qubits. In spin qubit systems, each qubit is encoded with the spin of the electron of a semiconductor quantum dot. Spin qubits benefit from their small size as they revolve around single electron, which creates small quantum systems. However, additional varieties have been developed having multiple spins in multiple quantum dots. They are simple to manufacture based on the knowledge from classical manufacturing methods. They are controlled by microelectronics using magnetic and electronic fields based on their configuration. However, because of the small size, resulting in these qubits being physically closer in space, they require much more precise control electronics. The challenge of cooling at that scale is also intensified because the dissipated heat is localised in a smaller area compared with superconducting circuits. Despite these challenges a large variety of spin qubits have shown error rates that are low enough to be compatible with quantum error correction.¹³

⁸ Yuan and Duine, "Quantum magnonics"

⁹ IBM Quantum Computing Blog. (2023, December 27). The hardware and software for the era of quantum utility is here. <https://www.ibm.com/quantum/blog>

¹⁰ Ballon, Alvaro. "Neutral-Atom Quantum Computers." PennyLane, May 30, 2023. Last updated August 30, 2024. https://pennylane.ai/qml/demos/tutorial_neutral_atoms/. Accessed September 26, 2024.

¹¹ Wang, Ye, Mark Um, Junhua Zhang, Shuoming An, Ming Lyu, Jing-Ning Zhang, L.-M. Duan, Dahyun Yum, and Kihwan Kim. "Single-Qubit Quantum Memory Exceeding Ten-Minute Coherence Time." *Nature Photonics*, vol. 11, no. 10, 2017, pp. 646-650. <https://www.nature.com/naturephotonics>. Accessed September 26, 2024.

¹² Cong, Iris, et al. "Hardware-Efficient, Fault-Tolerant Quantum Computation with Rydberg Atoms." *Phys. Rev. X*, vol. 12, no. 2, 2022, pp. 021049. <https://link.aps.org/doi/10.1103/PhysRevX.12.021049>.

¹³ Harvey, Shannon. "Quantum Dots / Spin Qubits." *Oxford Research Encyclopaedia of Physics*, March 2022. Subjects: Mesoscale and Nanoscale Physics (cond-mat.mes-hall); Quantum Physics (quant-ph). <https://arxiv.org/pdf/2204.0426>

Photonic Qubits. Photonic qubits use photons as the fundamental unit of information. There are two approaches for employing photonic qubits. These are linear optical quantum computing and integrated photonic quantum computing. Linear optical quantum computing uses beam splitters and phase shifters to manipulate the state of photons. Integrated photonic quantum computing is complex and uses a chip specifically designed to perform quantum operations. Photonic qubits can exist at room temperature, enable faster operations, are easy to scale by adding more optical components, and are less susceptible to noise interference. However, they have less fidelity due to photon losses, pose problems in controlling photon behaviour, and require a reliable error correction mechanism.

Topological Qubits. Topological qubits utilise exotic particles called anyons that braid around each other in unique ways. Instead of encoding information in individual particles or atoms, the information is encoded in the arrangement and connectivity of the material, i.e., its topology. Quantum operations are performed by manipulating these braids. They are theorised to have high error resistance, making them easier to scale with fewer error correction requirements. The biggest challenge is to fabricate and manipulate the braiding pattern.¹⁴

Applications of Quantum Computing

Quantum computing holds significant promise across various fields due to its ability to process information in fundamentally different ways compared to classical computers. Some of the significant applications are discussed.

Cryptography. Widely used Elliptic Curve Cryptography (ECC) and Rivest-Shamir-Adleman (RSA) are encryption algorithms employed in the security of critical services like banking, e-commerce, and government communications. These are based on conventional cryptography capabilities provided by classical computers. With the advent of quantum computers, with their ability to perform complex calculations simultaneously in an exponentially faster manner, these algorithms are likely to get compromised. The ability of Shor's algorithm to factor large composite numbers into their prime factors has the potential to break into these cryptographic security systems.¹⁵ Researchers are actively developing cryptographic capabilities based on quantum computing. These quantum-era cryptographies, also termed quantum-proof cryptography, aim to protect critical systems even against the most powerful quantum computers. Even the methodology to exchange keys is undergoing a shift towards quantum key distribution (QKD) techniques. QKD offers a secure alternative by using a series of photons to transmit a random key sequence.

Material Science and Drug Discovery. Creating new useful molecules involves combinatorics due to the numerous possible combinations of atoms and the various ways they can bond. Quantum computers can simulate molecular interactions at the atomic level, enabling researchers to model complex chemical reactions with greater accuracy than classical computers. This advancement in computational chemistry will make R&D significantly more cost-effective compared to traditional trial-and-error methods. Quantum computing has the potential to greatly accelerate the development of new drugs by enhancing target identification, drug design, and toxicity testing. These processes would rely less on trial and error, potentially leading to a faster time to market.¹⁶

Engineering & design. Engineering simulations play a vital role in minimising the efforts required for design and testing by lessening the dependence on physical prototypes and laboratories, such as wind tunnels used in the automotive and aerospace industries. Numerical simulations are essential for modelling intricate processes like aerodynamics, operational strength, structural dynamics, crash safety, and production issues.

¹⁴ Hoogeveen, Martijn. "Quantum Computing Technologies Compared." Icecat catalog, July 5, 2024.

<https://icecatlog.com/quantum-computing-technologies-compared/>

¹⁵ Bova, F., Goldfarb, A. & Melko, R.G. Commercial applications of quantum computing. EPJ Quantum Technol. **8**, 2 (2021). DOI: [10.1140/epjqt/s40507-021-00091-1](https://doi.org/10.1140/epjqt/s40507-021-00091-1)

¹⁶ Bova, F., Goldfarb, A. & Melko, "R.G. Commercial applications of quantum computing".

For instance, AIRBUS is investigating the use of quantum or hybrid quantum-classical methods for computational fluid dynamics to decrease the computational resources needed to study the behaviour of airflow around aircraft.¹⁷

Optimization in Finance, Logistics and Production. Optimization problems are common in production and logistics across all industries. These problems often involve finding the best way to do something, such as planning routes, managing supply chains, scheduling production, or assessing insurance risks. Real-world optimization problems usually have many factors to consider and limitations to follow. Classical computing can often only find an optimum solution in a localised scenario. Same solution is generally found non-optimal when applied at a larger scale. Quantum optimization techniques offer the possibility of solving problems with many factors, finding better solutions, and solving problems faster.

Enhancements in AI and ML Capability. Quantum computing, with its characteristic ability to solve large and complex calculations at an exponential speed, is expected to significantly enhance the capabilities of Artificial Intelligence (AI) and Machine Learning (ML) systems. Accelerated data processing capability and quantum algorithms would enhance the speed in unprecedented manner to carry out critical tasks such as data mining, pattern recognition, and complex simulations which are critical for AI and ML. This would lead to quicker and more accurate decision-making.

Climate Modelling. As scientists strive to improve the accuracy and resolution of their simulations, the computational demands continue to grow. Quantum computers, with their ability to process information exponentially faster than classical computers, could offer a significant advantage in this area. By leveraging quantum algorithms, researchers can potentially tackle fluid dynamics-based simulations more efficiently. These simulations are crucial for understanding the intricate interactions between the atmosphere, oceans, and land, which are essential for accurate climate predictions. With improved computational capabilities, scientists can develop more refined climate models, providing a clearer picture of likely future conditions. This enhanced understanding can inform decision-making regarding mitigation and adaptation strategies to address the challenges posed by climate change.

Climate Modelling. Climatologists and scientists continue to work for improving the accuracy and resolution of their climate models and simulations. However, the need to increase the computational power keeps increasing due to continuously changing climatic conditions and enhanced availability of various sensor data. This gap is likely to be bridged by quantum computers having faster data processing capabilities. Researchers would be able to comprehend the fluid dynamics-based simulations more efficiently using quantum algorithms. Thorough understanding of these simulations model is likely to provide vital insights into the complex relationship that exists between the atmosphere, oceans, and land. This would aid the scientists in providing a more accurate assessment of future climatic conditions which can be used in making informed decisions regarding the mitigation and adaptation strategies required to be adopted.

Challenges in Quantum Computing

Decoherence. The most basic and yet most significant challenge faced by quantum computing is the problem of “noise” or “decoherence”.¹⁸ Quantum systems interact with the external environment via vibrations, temperature fluctuations, and electromagnetic fields. These interactions cause information carried by qubits to decay over time. Individual qubits can retain their quantum state i.e. “coherence”, for only a limited time. To compensate for this, gate operations should occur quickly enough to make complex computations possible before qubits in the system lose coherence. While the complete isolation of any quantum system is impossible, 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 achieved by quantum error correction, which

¹⁷ Quantum Technology and Application Consortium – QUTAC., Bayerstadler, A., Becquin, G. et al. Industry quantum computing applications. EPJ Quantum Technol. 8, 25 (2021). <https://doi.org/10.1140/epjqt/s40507-021-00114-x>

¹⁸ Katherine McCormick,” Decoherence Is a Problem for Quantum Computing But...” ScientiMc American, March 30, 2020. <https://www.scientificamerican.com/blog/observations/decoherence-is-a-problem-for-quantum-computing-but/>

provides greater fidelity from quantum computation. According to estimates, each functional or “logical” qubit requires more than 1,000 physical qubits to perform the desired error correction.¹⁹

Loss of qubits due necessity of entanglement. 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.²⁰ This comes at the cost of losing some qubits.

Scalability: For a quantum computer, the more the number of qubits, the more is the computational power. However, this enhancement of capability or scaling is not straightforward. In quantum computing each qubit must interact with every other qubit in order to harness the advantages of entanglement. This becomes increasingly difficult as the number of qubits increases. Also, as the number of qubits increases so does the scale of errors. Thus, in order to achieve upward scaling of quantum computers there is a requirement of building error resistant qubits and maintaining their quality.

Sensitivity to Temperature. Quantum computing systems face significant challenges due to their sensitivity to temperatures. For optimal performance, these systems are required to operate near temperature of absolute zero i.e. approximately -273°C or 0 Kelvin. Achieving the critical temperature required for superconducting behaviour is essential but complicates practical implementation. Maintaining such extremely low temperatures pose hardware development and infrastructure challenges. These complex and expensive setups, makes the employability of quantum computers a prohibitive option in present scenario.

Programming and Software: Present programming tools and software algorithms would not be able to undertake the operations of quantum computers. Quantum algorithms are required to be developed to exploit the quantum capabilities.

Financial Viability. In the present context, quantum computing is very expensive. A single qubit cost is estimated around \$10000. Considering the number of qubits required for error free reliable operations, hardware and infrastructural requirements, and requirements of dedicated programming and software, quantum computing in the present scenario is financially not viable, especially for commercial usage.

Cyber security Issues. Quantum computers would be able to decrypt the most secure data (e.g., bank records, government secrets, Internet/email passwords and others) that employ present encryption methods. Existing information systems and encryption methodologies would be overwhelmed by the processing power of quantum computers, if used for malicious purposes. This raises serious concerns about cybersecurity. Cryptographic experts around the world are trying to develop encryption techniques that can meet the challenges posed by quantum computers.

Quantum Computing in Practice

Many businesses are already using quantum computing for various kinds of research, development and implementation. Some of the major ongoing developments are: -

Improvements in Batteries and Carbon Neutrality. Mercedes-Benz is exploring quantum computing to develop better batteries for its electric cars. In association with IBM, it works on simulation of complex chemical reactions that take place within the batteries. Mercedes-Benz aims to achieve its twofold aim. One is to create more efficient and long-lasting batteries that would enhance the employability of its EV cars which in turn would aid Mercedes-Benz achieve its goal of becoming carbon neutral by 2039.²¹

¹⁹ Fowler, A. G., Mariantoni, M., Martinis, J. M. & Cleland, A. N. Surface codes: Towards practical large-scale quantum computation. Phys. Rev. A 86, 032324 (2012).

<https://doi.org/10.48550/arXiv.1208.0928>

²⁰ Martin Giles, “Explainer: What Is a Quantum Computer?” MIT Technology Review, January 29, 2019.

<https://doi.org/10.1103/PhysRevA.86.032324>

²¹ "Ambition 2039: Our Path to CO₂-Neutrality," Mercedes-Benz Group

<https://group.mercedes-benz.com/responsibility/sustainability/climate-environment/ambition-2039-our-path-to-co2-neutrality.html>, accessed September 23, 2024

Optimisation. ExxonMobil is one of the largest energy providers and chemical manufacturers in the world. The company faces significant challenges in timely transportation of its Liquefied Natural Gas (LNG). In 2001, around 500 LNG ships made thousands of trips delivering LNG at right time to the power critical infrastructure. For efficient transportation, the position of each ship on each day along with the LNG status of each delivery site, must be assessed. This further gets compounded due to weather and other contingencies. A mathematical estimate puts the number of possible combinations while taking different decisions at $2^{1000000}$. Optimisation of resources in such a scenario using classical computing is not viable. To address such scenarios, ExxonMobil has partnered with IBM for optimisation of resources using quantum computing techniques.²²

Understanding of the Universe. The European Organisation of Nuclear Research, known as CERN is one of the leading physics laboratories of the world. It has many significant discoveries to its credit. Some of these are uncovering the nature of stars, creating the World Wide Web, and discovering the Higgs boson. Higgs boson explains the origin of mass. Analysing raw data to identify Higgs behaviour is a complex challenge, that was extremely difficult for classical computers. However, machine learning and quantum computing offer powerful tools for recognizing patterns in these complex datasets. Through quantum algorithms, CERN can efficiently analyse the massive amounts of data generated by experiments like the Large Hadron Collider. This would be extremely useful in our understanding of the universe.²³

Enhancement of Energy to Weight Ratio of Batteries. Lithium is one of the lightest atoms on the periodic table. Its properties make it great for generating energy when combined with other elements. This mix of light weight and high energy potential makes it one of the most suitable candidates for research in battery chemistry. Today's electric vehicles use lithium-ion batteries, which have been gradually improved over the years. However, these batteries are still the heaviest part of the car, limiting its performance. Researchers at Mitsubishi Chemical and Keio University are studying a key chemical process, lithium superoxide rearrangement, in lithium-oxygen batteries. They use quantum computers to accurately simulate chemical reactions at the molecular level. This could give ways to significantly increase the energy to weight ratio of a battery.²⁴

Automobile Designing. BMW in collaboration with PASQAL, a leading manufacturer of neutral atom processors, is extensively working on improving its cars design and manufacturing processes by utilising quantum computing. The aim is to improve the design, metal forming process, and aerodynamics aspect of its cars.

Enhancing Capabilities of Autonomous Vehicles. In collaboration with IonQ, Hyundai is actively working towards application of quantum machine learning for the task of image processing. This would include image detection, classification and encoding of images such as road signs, lane markings and other infrastructure that enables safe and efficient driving of manned vehicles. Quantum techniques are also used for development of algorithms for utilisation of this database to enhance safety in Hyundai autonomous vehicles.

Aeronautical Engineering. Rolls-Royce, NVIDIA, and Classiq partnered together and designed the world's largest quantum computing circuit for understanding of computational fluid dynamics (CFD). It is achieved using NVIDIA's quantum computing platform. The circuit, using 39 qubits, measures a depth of up to 10 million layers. Rolls-Royce is planning to model the performance of jet engine in simulation, using quantum technology, to enhance the comprehensive performance of its aero engines.

²² "ExxonMobil Strives to Solve Complex Energy Challenges," IBM website <https://www.ibm.com/case-studies/exxonmobil>, accessed on 23 September 2024.

²³ "The Quest to Understand What Sews the Universe Together," IBM case study available at <https://www.ibm.com/case-studies/cern/>, accessed September 23, 2024.

²⁴ "In Quantum Pursuit of Game-Changing Power Sources," IBM case study available at <https://www.ibm.com/case-studies/mitsubishi-chemical>, accessed September 23, 2022

Quantum Computing R&D- Funding and Leaders

By 2022, various government had invested approximately US\$34 billion in quantum technology. China alone accounts for almost half of the total investments (US\$15.3 billion).²⁵ The EU was second at US\$8.4 billion, followed by the US, Japan, and the UK. As per McKinsey reports, in 2022, \$2.35 billion was invested start-ups in the field of quantum computing. Services that got maximum share of these investments are quantum computing, communications, and sensing.

Government of India in 2023, allocated Rs 6,000 crore (approximately US\$720 million), towards The National Quantum Mission. Tata Institute of Fundamental Research (TIFR) in Mumbai, India is on the threshold of developing India's first small scale quantum computer. This is achieved by TIFR in collaboration with the Defence Research and Development Organisation (DRDO), and Tata Consultancy Services (TCS). It plans to develop a 24-qubit computer in three years and a 100-qubit system in five years. Another small scale, 25 qubit computer is being built by a Bengaluru-based startup QpiAI. They expect to offer it via cloud services by the end of the year.²⁶

According to a McKinsey report, Chinese companies account for more than half (52.8 percent) of the total QC patents that are filed between 2000 to 2022. Japan comes at a distant second at 14.1 percent, closely followed by the EU and US. India does not feature in the top ten.²⁷

Conclusion

By harnessing the principles of quantum mechanics, quantum computers have the potential to address complex challenges that would have taken infinitely long time for classical computers. Extensive research is in progress in the field of qubits to make them reliable, scalable, and resistant to decoherence. Quantum algorithms for are also being developed and refined. prominent technologies developed using quantum properties include computing, simulation, sensing, and communication. Although there are other developments, these four cover 80% of the entire technological advancements. As advancements in qubit design and error correction techniques continue to emerge, the potential applications of quantum computing across various fields, including medicine, finance, material science, cryptography, climate modelling, and understanding the universe, become increasingly possible. These positive developments are accompanied by serious concerns regarding unethical use of quantum technology, such as breaking encryption of critical services and unregulated development of AI. Rapid progress is being made to overcome the challenges posed on the technological developmental aspects. Quantum technology is poised to change the world ushering in a new era within the next decade.

²⁵ Masiowski, M., Mohr, N., Soller, H., & Zesko, M. (2022, June 15). Quantum computing funding remains strong, but talent gap raises concern. McKinsey & Company. <https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-computing-funding-remains-strong-but-talent-gap-raises-concern>

²⁶ Swayne, Matt. "India Nears Its Quantum Moment — Completion Of First Quantum Computer Expected Soon." The Quantum Insider, August 21, 2024. <https://thequantuminsider.com/2024/08/21/india-nears-its-quantum-moment-completion-of-first-quantum-computer-expected-soon/>, accessed on September 24, 2024.

²⁷ Masiowski, M., Mohr, N., Soller, H., & Zesko, M. (2022, June 15). "Quantum computing funding remains strong, but talent gap raises concern. McKinsey & Company."