A Detailed Review on Quantum Computing Technologies

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Abstract

Modern computing approaches like quantum computing are based on the remarkable occurrences of quantum mechanics. It is a combination of information theory, computer science, mathematics, and physics. The study of quantum computing includes the design and development of computer-based technologies based on quantum theory, which explains the nature and behaviour of energy and matter at atomic and sub-atomic levels. Sub-atomic particles such as electrons and photons are used in quantum computing. These particles exist in two different states (i.e., 1 and 0) based on quantum bits or qubits. Compared to conventional computers, quantum computing offers higher computing capacity, lower energy utilization, and high speed. This article reviews the state-of-the-art quantum computing technologies and different ways in which the qubits can exponentially increase the efficiency of quantum computers and sort various possibilities and identify potential solutions to different challenges.

Keywords: Quantum mechanics, quantum theory, electrons photons, qubits.

1. Introduction

A novel form of computation called quantum computing, which is based on quantum physics, interacts with the physical world's unpredictable and uncertain nature. Since quantum mechanics is more comprehensive model of mechanics than classical mechanics, quantum computing is a realistic model of processing with greater potential to address issues that classical computing cannot address. The capacity of bits to exist in several states simultaneously provides the quantum computer a large portion of its processing capability. They are capable of carrying out activities using a combination of 1's, 0's, or both at once.

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Quantum Computers are computers that use this sort of computation. Logic gates, transistor circuits, and integrated circuits cannot be used in such tiny computing. As a result, it employs the information about the spins and states of subatomic particles like atom, photons, electrons, and ions as its bits. More combinations are possible when they are superposed. Processors are therefore more efficient since they operate in parallel while utilising memory efficiently [10]. Quantum computing is the manipulation of information using quantum mechanical phenomenon. It is anticipated that quantum computing would help to understand how molecules and chemicals interact, solve challenging optimization issues, and advance artificial intelligence. These could lead the way for cutting-edge medical research, life-saving medications, and advancements in logistics, supply chains, and financial data modelling [11].

1.1 Key specifications of quantum computing

1.1.1 Quantum

The term "quantum" describes a system that computes outputs using quantum mechanics. The lowest discrete unit of every physical attribute is known as a quantum in physics. The most of the time, it refers to the characteristics of atom or subatomic particles like electrons, neutrinos, and photons [5].

1.1.2 Qubit

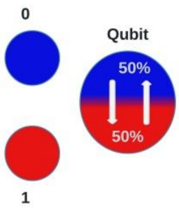
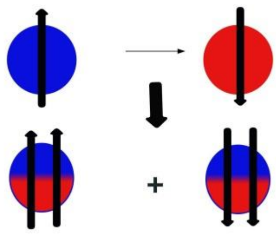
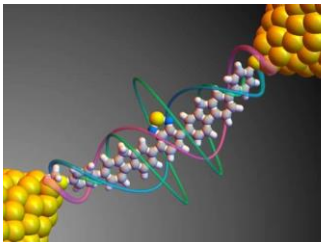
The fundamental data unit in quantum computing is qubit. Although particles function similar to bits in classical computing, qubits exhibit in a completely distinct behaviour. Unlike qubits, which can store a combination of all possible states, traditional bits remain binary and can only result in a value of 0 or 1.

1.1.3 Quantum computing

Figure 1. Q system by IBM [12]

Quantum computing uses the principle of quantum physics to fix problems that are unsolved by classical computers. Quantum computing uses the unique properties of quantum physics, such as superposition, entanglement, and interference [1].

Table 1. Properties of quantum computing

Superposition	Entanglement	Interference
Quantum particles that remain in superposition will combine all conceivable states. Unless they are monitored and measured, they fluctuate. Imagine a coin to help you understand the distinction among binary position and superposition. On "flipping the coin" as well as determining whether it comes up heads or tails, traditional bits are measured. The coin would be situated in superposition, however, when you gaze at it and simultaneously see the heads and tails as well as any other state present in between. 	Quantum particles can correlate its measured values with one another leading to entanglement. Qubits make up a single entity and interact when they are entangled. One qubit's measurements can be used to infer information about the others. Quantum computers will calculate much additional information and tackle more challenging problems by introducing and entangling additional qubits into a system. 	Similarly, as wave interference of classical physics, quantum computers have an interference feature. When two waves contact with one another within the same medium, wave interference results. When waves are aligned in the same direction, it creates a resultant wave known as constructive interference; when waves are aligned in the opposite direction, it creates a resultant wave known as destructive interference. The qubits can intentionally bias with the support of required state based on the concept of interference. 

1.1.4 Decoherence

When the quantum behaviour of qubits decays, decoherence takes place. Vibrations or variations in temperature can abruptly disrupt the quantum state. As a result, Qubits may lose their superposition, which could lead to computational errors. Qubits must be shielded from this influence by utilizing the techniques like supercooled refrigerators, insulators, and vacuum chambers.

2. Quantum computer over classical computer

The early computers were large, expensive, and more power-hungry, whereas the modern computers are less expensive, faster, more intelligent, and even more powerful. The computers are now made feasible by incorporating advancements in architecture, hardware, and software that runs on it. Computer electronic circuits are becoming small and compact every day. Small semiconductor transistors are used to switch and amplify the electrical or electronic signals [4]. Since its development, the number of transistors integrated on a silicon microchip has doubled annually while the prices have decreased by 50%. It leads the concept of creating the tiny computers by reducing the circuit down to the size of a particle. Quantum properties are used to guide the construction of the hardware components. The computers using quantum properties are known as ‘Quantum Computers’. The below table 2 lists the comparison between quantum computing and classical computing.

Table 2. Comparison of Quantum computing over classical computing

Quantum computing	**Classical computing**
Utilizes qubits, which can have values of 0 or 1 or both	Computes using transistors
Error rates in quantum computing are high.	The error rate in classical computing is lower.
Operates at zero temperature	Operates at room temperature
Provides high security	Provides low security

Suitable for complex task	Suitable for processing daily task
Increases exponentially with number of qubits	Increases linearly with number of transistors
Speed:To perform n=2000 RSA 21.3 days	73000years

2.1 Working of Quantum computer

A quantum computer has three primary parts

- An area where the qubits are housed
- A procedure for transmitting data to the qubits
- Using a traditional computer to execute a programme and communicate commands

In order to maximize the coherence and minimize interference of qubits, certain qubit storage techniques maintain the unit housing the qubits at a temperature a little above absolute zero [3]. Other qubit housing designs employ a vacuum chamber to lessen vibrations and keep the qubits stable. Microwaves, lasers, and voltage are just a few of the different ways in which signals can be transmitted to the qubits.

3. Benefits of quantum computing

1) Information sharing could be made **more secure** with the help of quantum computers or to enhance radars' capacity to find missiles and aircraft.
2) Quantum computing is anticipated to be beneficial for the environment and for using chemical sensors to keep **water pure**.
3) The areas of security, finances, military and intelligence affairs, drug development, aircraft design, utility (nuclear fusion), machine learning, polymer design, artificial intelligence (AI), digital manufacturing and big data search, and could all benefit substantially from quantum computing [2].

3.1 Quantum computing language

In order to simulate a quantum computing environment, we can build an actual quantum computer using quantum languages and libraries. These language and libraries are not compatible with the quantum computing paradigm. The smallest number of outside interferences is necessary for a quantum computing environment to operate effectively. As each interaction has an impact on other parts of the system, the system shouldn't be constantly disturbed. If the following requirements are met, we will be able to find a solution to all of these issues.

A functional programming framework should be used in the programming language. We can calculate the process as a full entity with a suitable limited structure by using a functional programming structure. Using this type of programming, the numerous mathematical operations required by a quantum computer will be carried out according to a clearly defined mathematical framework.

The quantum environment must operate without interference inside the case of a programming language technique, and the outcome is produced once all computations have been completed. By using this approach, we don't worry about the details; only appropriate execution and accurate output are necessary. Such a strategy will guarantee that the simulation corresponds to the fundamentals of quantum computing. A quantum computer requires a constantly changing environment, which a digital computer can only simulate.[4]

3.2 Quantum algorithm

It is highly important to note that the quantum algorithms address issues that a classical computer is capable of resolving. However, it can complete tasks like integer factorization, search algorithms, etc. considerably more quickly than a traditional computer.

This basic principle, known as extended Church-Turing thesis, asserts that there are three ways to resolve computational problem more quickly:

(1) By performing many steps in parallel,

(2) By reducing the time taken to implement a single step, or

(3) By reducing the total number of steps required to complete the problem.

3.3 Applications of Quantum computing:

3.3.1 Computational Chemistry

It is believed that even the smallest molecules have a massive amount of quantum states, making it challenging for traditional computational memory to store all of them. In order for the machine to correctly **map the molecules**, quantum computers may need to be able to concentrate on the presence including both 1 and 0 simultaneously. This might give rise to new chances for pharmaceutical research. Developing a room-temperature superconductor, eliminating carbon dioxide for a better environment, making solid-state batteries, and enhancing the nitrogen-fixation method for the manufacture of ammonia-based fertiliser are some of the pressing issues that could be resolved with quantum computing.

3.3.2 Cryptography and Cyber security

The current state of online security is rather precarious because of the daily rise in the number of **cyber-attacks** that take place all around the world. Although organisations are setting up the necessary security architecture, traditional digital computers find the procedure overwhelming and unworkable. Therefore, cyber security has remained a crucial worry for people all over the world. We are particularly vulnerable to these risks because of our growing reliance on technology. Machine learning and quantum computing can aid in the development of numerous strategies to counter these **cybersecurity risks**. Quantum cryptography, another name for encryption, can also be developed with the aid of quantum computing.

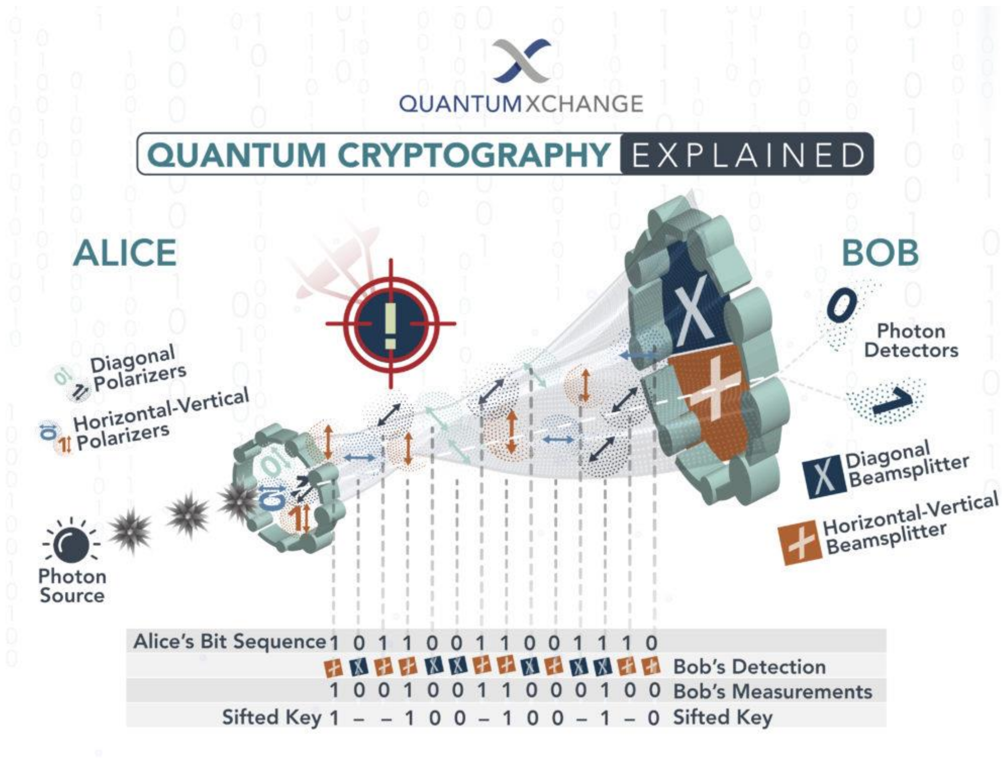


Figure 2. Quantum cryptography [7]

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3.3.3 Weather Forecasting

Accurate weather forecasting is challenging since there are so many factors to consider, including air pressure, temperature, and air density. The use of quantum machine learning can assist in enhancing the process of pattern identification by making it simpler for researchers to predict severe weather conditions and save human lives. Meteorologists will be able to create and analyse more intricate climate models with quantum computers, which will enable a better understanding on the climate change. [6]

3.3.4 Quantum computing and artificial intelligence

The combination of Artificial Intelligence [AI] and quantum computing can handle more challenging issues. The application of quantum computing in the calculation of machine learning algorithms is known as quantum AI. With the computational advantages of quantum computing, Quantum AI can assist in achieving optimal results that are not attainable with classical computers.

Solar Capture

Quantum dots are semiconductor nanoparticles with special electrical and optical properties that emerge as a result of quantum mechanics, which remain as the effective **solar energy** converters. This will assist in lowering the carbon emissions while enhancing current energy-generation technology. The University of Queensland in Australia has already created a flexible and printable quantum dots with a power conversion efficiency more than 16%.[8]

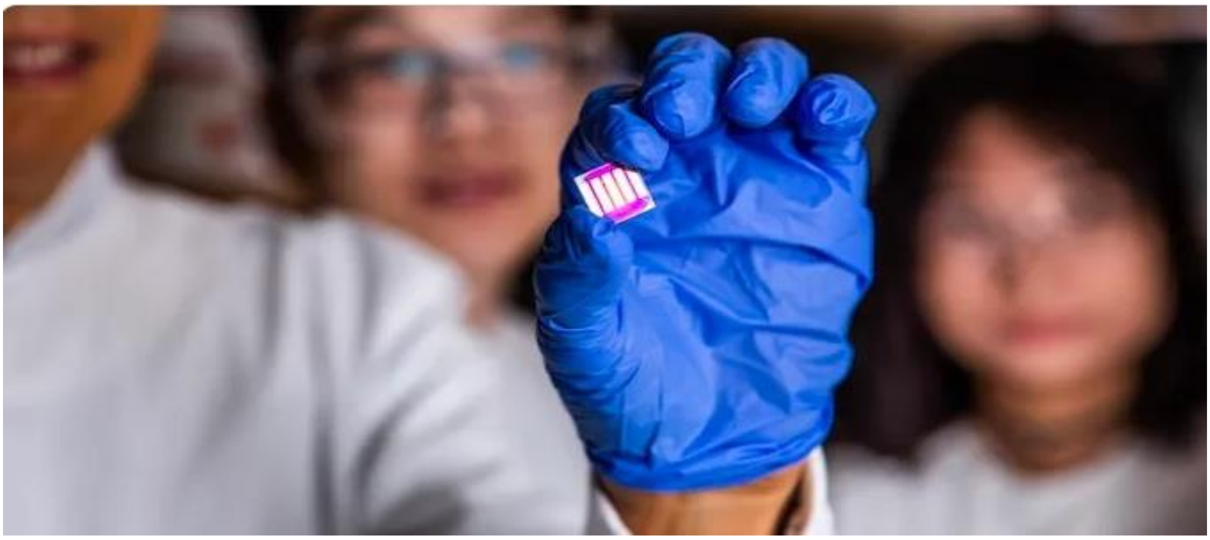

Figure 3. The quantum dot solar cell-University of Queensland

3.3.5 Traffic Optimization

Traffic congestion can be avoided, and waiting times can be reduced, using quantum technology. This prevents long wait times for cabs and reduces the need for buses and taxis to make long trips without paying customers. Volkswagen has already shown how quantum computing may be used in real-world traffic optimization. Its quantum routing technique determines the fastest individual travel routes in real time using the D-Wave quantum computer. There are other businesses engaged in "quantum traffic optimization" than Volkswagen. Nearly all automakers, like Toyota, BMW and Ford, are making investments in quantum science.

Figure 4. Quantum traffic optimization by Volkswagen

3.3.6 Quantum computing in India

According to an IBM study, there is a rising interest on quantum computing in India, with participation from academia, developers, and students. As a result, the nation is becoming into a talent hotspot for quantum computing [5].

3.3.7 Quantum Computing Initiatives by IBM India

- IBM created the **open-source software** development toolkit known as Qiskit for the community of quantum programmers.
- IBM frequently hosts events with an India focus, like the over 300 students who attended the Qiskit India Week of Quantum, who recognised **women in quantum** to help them begin their careers in the field.

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- With the help of IBM Quantum Educators Program, IBM is working with some of India's top educational institutions.
- For educational reasons, the teachers and institutions students of these will have access to IBM Quantum systems, quantum learning materials and quantum tools via IBM Cloud.

3.3.8 Quantum Computing Initiatives by Infosys Quantum Living Labs

Quantum computing is progressing rapidly with millions of dollars in funding from across the world. As per leading analysts, quantum optimization applications in finance, logistics, and aerospace alone could potentially cross over approximately $200 billion in annual revenues. At this stage in the quantum technology progression, experimenting with industry-relevant quantum use cases today will help prevent higher costs and inefficient processes in the future.

Infosys Quantum Living Labs (QLL) investigates the numerous opportunities and transformations for the client's needs through the super-effective quantum computing technology. Through professional advice, assistance with POC implementation, application of prospective use cases, access to quantum infrastructure and advancements from our partner ecosystems, clients of the "Early Access Program" can be quantum-ready to address business problems [9].

3.3.9 Indian Government's initiatives

1. National Mission on Quantum Technologies and Applications, which aims to advance quantum computing, cyber security, communications, and material science, received INR 8000 Crore from the government in its 2021 budget.
2. In October 2021, the Centre for Development of Telematics (C-DOT) opened a quantum communication lab. More than 100 kilometres of common optical fibre can be supported by it.
3. The Indian Army established a quantum computing facility as well as an AI centre at a military engineering institute in Mhow, Madhya Pradesh, in December 2021. The National Security Council Secretariat also supports it (NSCS).

4. Limitations of quantum computing

- It is extremely vulnerable to error. Atoms and electrons are subatomic particles that are affected by all types of vibrations. Therefore, it is possible for noise, malfunctions, and even failures. It results in "Decoherence”, which is a disadvantage of quantum coherence.
- The significant challenge is to truly build a personal computer while considering the consumer budgets. Large-scale industries will have an initial access to them before they reach retail markets.
- They are extremely unstable and challenging to test quantum processors.
- It is not yet fully invented because only a portion of it is being used, and people are still are imagining what it would look like.

5. Conclusion

Quantum computers, like the earliest digital computers hold the promise of providing a considerably more powerful technology than what is currently available. By resolving challenges that currently appear impossible, they have the potential to transform businesses, industries, and the entire world. According to a recent Gartner report, 20% of firms have budgets set out for quantum computing initiatives by 2023. Organizations will require more quantum computing expertise as this new technology emerge in the near future.

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