



An extensive review on quantum computers

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ABSTRACT

Quantum Computing is a rapidly arising innovation that tackles the laws of quantum mechanics to take care of issues excessively complex for already available classical computers. The development of quantum computers is the most remarkable achievement in the field and legacy of quantum computers. For instance, an already available classical computer can represent any number between 0 and 255 using just eight bits. However, a quantum computer can simultaneously represent all 256 numbers between 0 and 255 with just eight qubits. More numbers could be represented by a few hundred entangled qubits than there are atoms in the universe. There are many quantum computers available such as quantum circuit models, quantum Turing machine, adiabatic quantum computer, one-way quantum computers, and various quantum cellular automata. D-wave quantum computers have been available for more than eight years which use a process called quantum annealing to search for solutions to a problem. IBM, Microsoft, Google, Intel, and NASA and various universities around the globe have engaged themselves in the development of quantum computers and their applications. This paper presents the fundamental ideas of quantum computing and portrays notable quantum applications for non-physicists. The ongoing status of the improvements in quantum computers is likewise introduced.

1. Introduction

As science and technology have developed around the years, chips, transistors and various other components have changed drastically in their shapes, sizes and complexity. Altogether, computers have also become compact and their performance and efficiency have also achieved a great speed and quality, still their main job focuses over controlling and interpreting an encoding of binary bits into a helpful computational outcome. Moore's law is the observation that the number of transistors in a dense integrated circuit (IC) doubles about every two years which means that the representing atoms for a bit of memory are also being decreased exponentially yearly. Contrary to classical physics and its rules, quantum mechanics is the master for future technology as matter obeys its rules. A lot more is pending to explore in the field of quantum mechanics and so it has a lot more to offer rather than our current understanding for it to just pack as many bits to silicon or to just proliferate the clock speed of microprocessors. Components and so computers can also gain their reduced size in the near future as we explore our quantum mechanics field. Studies by researchers and scientists have shown that a computer whose components are meant to

behave and function in a quantum way, have defeated their counterparts which follow a classical approach in terms of power. To concise the discussion till now, "a computer whose memory is exponentially larger than its apparent physical size, a computer that can manipulate an exponential set of inputs simultaneously – a whole new concept in parallelism; a computer that computes in the twilight (space like) zone of Hilbert Space (or possibly a higher space – Grassman Space & so on), is a quantum computer" [1].

This paper includes the study of various topics related with quantum computing as well as quantum computers and technologies. This paper has been ordered in such a manner that a reader gets to know regarding quantum computing from the basics and then the paper covers vast and proposed models for quantum computers. It also includes the future scope and developments of how much potential the field of quantum computing holds and current developments have been discussed throughout.

The structure of the paper includes the following:

- 1 Introduction
- 2 A brief about nuclear shell model

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- 3 Bit and qubit
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2. A brief about nuclear shell model

The nuclear shell model is partly similar to the model of an atomic shell where a filled shell leads to greater stability. Protons or Neutrons/ Nucleons when added to a nucleus, certain places or points are there where binding energy is less of the next nucleon. The shell model’s historical context is the observation of magic numbers of nucleons which are firmly bound more closely than their higher number. Many shell model codes are available for extensive calculations such as NuShellX. Computation of this kind in a classical computer is convenient as only valence shells are taken into account and the inner cells are treated as frozen. This leads to the calculation of light nuclei only. For example, NuShellX code can compute the matrix order of 1×10^8 . Higher calculations are not possible. A quantum computer only consumes $O(\text{poly}(N))$ resources, while a classical computer has to use $O(2^N)$ resources. The development in the field of quantum computers has made us capable of using quantum computers (rudimentary) with 100 qubits. To find the eigenvalues and eigenstates of a molecule in chemistry, variational quantum eigensolver (VQE) and the full quantum solver (FQE) are being used. Nuclear physics has also taken the advantage of VQE to compute the binding energy of the deuteron nucleus [2].

3. Bit and qubit

The fundamental unit of information is a bit, and in classical computers, a binary digit is described by the values 0 or 1. While shifting or switching from one of the two levels of a processed bit, in classical computer technology of low DC Voltage, two logic levels are required. In the case of qubit, there are two possible outcomes. As the state of a bit can only be either “0” or “1”, coherent superpositions of both can be the general state of a qubit. Quantum superposition states that any two or more quantum states can be superposed and the resultant state will be valid. As it can be realized that there would be no disturbance during measurement of a classical bit but on the other hand, while measuring and analyzing a qubit, it can eradicate its nature of coherence and therefore, its state of superposition can be disturbed. In classical physics, the state may be described for a system with h components using only h bits, while in quantum physics, 2^h complex numbers are required [3].

The two possible states of occurrence of a qubit include (i) The pure state, and (ii) The superposition state. The behavior of a qubit in its pure state is exactly similar to that of a classical bit. When the qubit exists in the state of superposition, it is more appropriate to represent its state of occurrence in terms of a function.

Mathematical function representing qubit in superposition state [4]: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where ‘ α ’ and ‘ β ’ are the amplitudes of the occurrence of the 0 and 1 states respectively ($\alpha, \beta \in \text{Complex numbers}$).

Let ‘ p ’ be the probability of occurrence of the state ‘0’, thus making ‘ $1 - p$ ’ as the probability of occurrence of the state ‘1’ when the qubit is in superposition. So,

$$\begin{aligned} \text{Probability of occurrence of the state 0: } p &= (|\alpha|)^2 \\ \text{Probability of occurrence of the state 1: } 1 - p &= (|\beta|)^2 \end{aligned}$$

We know that the sum of probabilities is always equal to 1, which leads us to the normalization constraint:

$$(|\alpha|)^2 + (|\beta|)^2 = 1.$$

With respect to the mathematical function representing the qubit in its superposition state, $|0\rangle$ can be represented as a vector that has its zeroth element to be 1 and all other elements to be 0: $[1, 0]$. Similarly, $|1\rangle$ can be represented as a vector whose 1st element is 1 and all other elements are 0: $[0, 1]$.

Hence, the function $|\psi\rangle$ can be represented as: $|\psi\rangle = \alpha[1, 0] + \beta[0, 1] = [\alpha, \beta]$.

Taking note of the normalization constraint, we can conclude that $(|\psi|)^2 = 1$.

4. Quantum gates

Quantum gates operate in a manner similar to logical gates in classical computers and operations on quantum bits are done to change the state of these qubits to either remain in the same state or alter them to a different state.

The most frequently used quantum gates include:

- (i) NOT GATE: This gate is widely known as X-Pauli Gate, as this particular quantum gate transforms the existing state of the qubit to be rotated around the X-axis. As the name suggests, the NOT gate would convert a qubit from its initial state to its complement state.

$$|0\rangle \rightarrow (\text{NOT GATE}) : |1\rangle$$

$$|1\rangle \rightarrow (\text{NOT GATE}) : |0\rangle$$

The matrix representation of the NOT Gate is: $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$

- (ii) PHASE GATE: On passing a quantum bit to a phase gate, in general, the phase gate would transform the qubit into a state by transforming it on a scalar factor of $e^{i\theta}$. Phase gate would provide a selective phase when the input is $|1\rangle$.

$$|0\rangle \rightarrow (\text{PHASE GATE}) : |0\rangle$$

$$|1\rangle \rightarrow (\text{PHASE GATE}) : e^{i\theta} |1\rangle$$

The PHASE GATE matrix is represented as $\begin{bmatrix} 1 & 0 \\ 0 & e^{i\theta} \end{bmatrix}$.

- (iii) T GATE: A specific case of a phase gate is the T GATE, where the phase of the input quantum bit is altered by a factor of $e^{i\pi/4}$.

$$|0\rangle \rightarrow (\text{T GATE}) : |0\rangle$$

$$|1\rangle \rightarrow (\text{T GATE}) : e^{i\pi/4} |1\rangle$$

T GATE’s matrix representation is $\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$. [5 and 6].

- (iv) HADAMARD GATE: The transformation of the qubit through the Hadamard gate is as follows:

$$|0\rangle \rightarrow (\text{HADAMARD GATE}) : (|0\rangle + |1\rangle)/\sqrt{2}$$

$$|1\rangle \rightarrow (\text{HADAMARD GATE}) : (|0\rangle - |1\rangle)/\sqrt{2}$$

The matrix representation of HADAMARD GATE is: $(1/\sqrt{2})^*[[1, 1], [1, -1]]$.

- (v) Y-PAULI GATE: The Y-PAULI gates are capable of rotating the input qubit around the Y-axis. We have already seen above the implementation of X-PAULI GATE which works as a NOT GATE. The Z-PAULI GATE is again a special case of the PHASE GATE.

The matrix representation of Y-PAULI GATE is: $[[0, -i], [i, 0]]$.

- (vi) CONTROLLED NOT GATE (CNOT GATE): Unlike all the previous gates mentioned, the CNOT gate takes two quantities as inputs and results in two output values too. The following operation is performed by the controlled NOT gate [5,6]:

Let 'a', and 'b' be the two inputs, then if $a = 0$, then, the quantum bit 'b' remains as it is, while if $a = 1$, then, the quantum bit 'b' outputs its conjugate [7].

The Truth Chart of the CNOT GATE can be given as:

a	b	b'
0	0	0
0	1	1
1	0	1
1	1	0

The following is CNOT GATE's matrix representation: $[[1, 0, 0, 0], [0, 1, 0, 0], [0, 0, 0, 1], [0, 0, 1, 0]]$.

5. Quantum computations

As discussed earlier also, 2^n states are possible in a memory of n bits. Classical computers involved bits cannot be in superposition, so one of the values should have a hundred percent probability in the state and be having value 1 which leads all other values to 0. A universal quantum computer is a computer which can run such circuits. It can be explained that n qubits if utilized as a quantum circuit's input as being allowed via the universal quantum gates as the choice can be any arbitrary quantum circuit. Four classical values {1, 2, 3, 4} can be stored in two qubits simultaneously. If a function is $f(x) = x + 3$, a circuit can be designed to calculate it, due to the placement of qubits in superposition state, only one step is required to solve it and thus the output is {4, 5, 6, 7}, four possible outputs. So, there is a requirement of a quantum circuit which can manipulate over the probability amplitudes as the probability is $1/2^n$ whereas measurement result is one of the 2^n possible outputs [8].

6. Quantum computers and technologies

a. Superconducting quantum computing

Robust capability of representing information is required to achieve a new-aged and advanced quantum computer. Every research organization is busy exploring the field of quantum computing to build advanced quantum computers but practically if we try to observe in everyday life, quantum phenomena is difficult to observe and this makes physical implementation of quantum gates and qubits hard. For making the quantum effects macroscopic, one way is to implement this by using superconductors where operating temperatures must be low. The use of a quantum computer in superconducting electronic circuits is known as superconducting quantum computing. An electron pair that is linked together at low temperatures is known as a Cooper pair. So, charge carriers in a superconductor are these pairs of electrons. Cooper pairs are bosons because their total spin is an integer and they can only occupy one quantum energy level when they are cooled. This effect is known as a Bose-Einstein condensate. With the use of shadow evaporation technique, a thin layer of insulation is implemented which is a weak

connection between two leads of a superconducting wire and the superconducting quantum circuits use Josephson junction which is an electrical element. Many qubit machines using this superconducting technology have been produced by Google, IBM, Intel and Rigetti. Machines in the 50-qubit range have been announced by IBM and Intel and Google has announced for 70-qubit range but currently, machines are available in the eight to twenty-two qubit range. Additionally, Fermilab is concentrating on quantum networking, quantum computing and quantum technologies for high energy physics. Fermilab is investigating superconducting RF technology to build improved qubits and with the usage of innovative cold instruments for data capture in quantum information systems. Research is being done in the area of quantum machine learning, which has applications in the areas of astrophysical picture processing and detector reconstruction [9].

b. Trapped ion quantum computer

It is a suggested method for building a substantial quantum computer. With the use of electromagnetic fields, ions can be suspended in free space. It is possible to transport quantum information across the aggregate quantized movement of the particles (or ions) in a shared or joint trap where interaction is due to Coulomb force and qubits in a stable state are kept in each ion's electronic state. Coupling is induced by applying lasers between the qubit states. Moving particles to spatially distinct particular areas in a variety of particle traps, fabricating huge entangled states through photonically associated Ion/particle chain networks with remote entanglements, as well as combinations of these two concepts. The trapped ion quantum computer architecture is thus one of the most promising topologies for a versatile, universal quantum computer.

As can be explained through an example of a linear optics quantum computer, a proposed quantum computer. The states of qubits for computations can be controlled by the placement and use of phase shifters and beam splitters between the paths of photons [10].

c. Nuclear magnetic resonance quantum computer

Nuclear magnetic resonance quantum computer, or NMR quantum computer, is a proposed quantum computer that uses the spin states of molecular nuclei as qubits. The framework can be used as a variation of nuclear magnetic resonance spectroscopy because the quantum states are investigated by nuclear magnetic resonances. It uses a group of systems rather than a single pure state, which sets it apart from other types of quantum computers. One significant strand of exploration is, obviously, the endeavor to assemble bigger NMR quantum computers. In spite of the fact that there are significant challenges in the approach to building NMR devices sufficiently enormous to be truly fascinating by their own doing, it is positively conceivable to gain huge headway past the ongoing point as currently the record is seven qubit system and it is possible to achieve a ten qubit system in upcoming years. Due to the reason for low state polarization it gets limited by spin polarization, with the number of qubits, signal strength also reduces exponentially and the low state polarization makes one ponder over whether NMR quantum computing is real or not. All this makes large systems impractical completely. Optical pumping can be one solution but it also has its own issues [10,11].

d. Quantum computing with defects

Additionally, defect-based quantum computing must be mentioned. A defect in diamond known as the nitrogen-vacancy (NV-1) center stands out among the possible outcomes in the solid state for its robustness; at room temperature, its quantum state can be established, controlled, and estimated with high accuracy. Following research over the previous two decades on how to implement qubits in a variety of materials, including semiconductors, liquids, superconductors,

insulators, and ion-doped insulators, diamond nitrogen-vacancy (NV-1) centers attracted attention. Diamond NV-1 is excellent when looking for deep cores that behave like the valuable gem for a variety of reasons. From a design perspective, it is currently very difficult to create and produce items out of diamond. The discovery of a similar flaw in a host material with more advanced technology may lead to more advanced single- and multi qubit device implementations [12].

e. Linear optical quantum computing

Linear optical quantum computing or LOQC uses photons as the carrier of information and to process quantum information by mainly using linear optical elements like reciprocal mirror and waveplates, photon detectors are also used to detect quantum information and so storing quantum data in quantum memory. Representation, encryption, transmission and detection using photons can be easily achieved by superposition of quantum states. Information light operations using direct linear optical components (in this case, beam splitters, mirrors, and phase shifters) spare the photon measurements. For instance, coherent (classical) light is produced when a superposition of quantum states is applied as an input. In order to investigate the effects of administrators and straight optical components, people frequently select a single photon source situation. A few measured changes can be used to theorize multi-photon instances. A characteristic issue in involving photons as data transporters is that photons scarcely connect or interact with one another. Since nonlinear operations are challenging to carry out, the complexity of operators might increase and the assets required to understand a particular computational function can therefore increase, thus posing a problem for LOQC's ability to scale. Carrying nonlinear devices into the quantum network is one way to address this problem. One operation that the Kerr effect can perform in LOQC is to make a single photon controlled-NOT [13,14].

7. Quantum Cryptography

Quantum cryptography is the study of using quantum mechanical concepts in cryptographic procedures. Quantum key distribution or QKD the most widely used example of quantum cryptography, gives a solution to the main trade problem that is information theoretically secure. The benefit comes from the fact that the tasks which are practically impossible by classical communication, quantum cryptography allows those smoothly also quantum state data encoding is not replicable practically. The chain of data science has cryptography as its strongest link. In the past, governments and military were able to keep the data secret over the time period of 60 years due to quantum cryptography. Quantum no-cloning theorem and Heisenberg's uncertainty principle guarantee the security of communication. The no-cloning theorem, which has important ramifications for the study of quantum computing among other areas, argues that it is impossible to make an independent and identical duplicate of any given unknown quantum state. The primary tenet of the uncertainty principle is that it is impossible to determine a particle's position in the micro universe since it always exists in several locations with varying probabilities. An oblivious transfer (OT) protocol is a type of cryptographic protocol where a sender sends one of potentially many bits of information to a recipient while being unaware of which piece, if any, has been sent. A method for transferring quantum data or information from a sender in one location to a beneficiary some distance away is known as quantum teleportation. Quantum teleportation only exchanges quantum data, as opposed to instant transportation, which is typically portrayed in science fiction as a method of moving actual objects from one location to another. It is not necessary for the sender to be aware of the precise quantum state being moved. Additionally, the beneficiary's location may be unknown, but conventional data must still be transferred from the source to the receiver to complete the teleportation [15].

The method of using quantum communication to lay out a shared key

between two groups (such as Alice and Bob) without a third party (Eve) finding out about it is QKD, and it is the most widely used and developed application of quantum cryptography. This is true even if Eve can eavesdrop on all communication between Alice and Bob. Contradictions will become obvious if Eve takes an effort to examine the specifics of the key that is being laid out, catching Alice and Bob's attention. After it has been laid out, the key is often used for encrypted communication via standard methods. For instance, the key exchanged might be used for symmetric cryptography (for example One-time pad). QKD is safe, but there are certain issues with its practical application. There are restrictions on the key generation rate as transmission distances increase. Significant advancements have been made in this fashion thanks to ongoing studies. Recently, the twin-field QKD protocol was put forth as a way to get around or past the limitations of lossy communication. Beyond key distribution, research on quantum cryptography focuses on quantum message authentication, entity authentication and quantum fingerprinting as well as public-key encryption and quantum digital signatures [16]. An example can be given as while using a mobile phone to make a payment, the mobile device sends a secret key to the payment terminals. Therefore, in order to prevent misuse, these secret keys must be encrypted. Instead of using secret keys, we can employ quantum keys to send data from mobile devices to payment terminals. Millions of tiny particles found in light are used by quantum technology to transmit their encrypted keys. This process can stop hacking as well as identify eavesdropping. Hackers have a hard time obtaining information if we send signals using light. The only way to protect data is to make sure it goes directly from source to receiver [17,18].

8. Quantum error correction

In quantum computing, quantum data is protected from errors due to decoherence and other quantum noise using quantum error correction (QEC). According to theory, quantum error correction is necessary to provide fault-tolerant quantum computing, which can lessen the effects of noise on quantum information that has been stored, as well as errors in quantum gates, quantum preparation, and measurements. Traditional error correction employs overt repetition. The repetition code is the simplest but most inefficient way. The idea is to store the information multiple times and take a larger vote in the event that these copies are later found to differ. For example, let's say we copy a piece of information in one state three times. Assume additionally that the three-bit state is corrupted by noisy error, resulting in one of the copied bits being equivalent to zero while the other two being identical to one. It is almost certain that the error is a single bit error and that the message being transmitted is three ones on the supposition that noisy errors are uncharged and happen with a sufficiently low probability, p [19]. Although it is technically possible for a double-bit error to occur, resulting in the sent message being equivalent to three zeros, this result is much more ludicrous than the one previously discussed. In this paradigm, the physical information is represented by the three copied bits, while the logical and sensible information is represented by a single bit in a single state. The process of determining which logical state is stored in the physical state is known as decoding. The no-cloning theorem makes it absurd to copy quantum data. This theorem seems to act as a barrier to the development of a quantum error correcting theorem. Nevertheless, it is conceivable to transfer the (logical) information of a single qubit to a highly entangled state of several (physical) qubits [20].

9. Conclusion and future scope

In this paper, we began with the fundamentals before moving on to cover quantum computing and related technology. Through the use of cloud computing, businesses have already begun providing access to quantum devices for use in academic and industrial research. Access to a single company's array of quantum devices is made possible by cloud services. The IBM Quantum Qiskit cloud services are the most well-

known. multi-platform services that act as middlemen and provide customers access to quantum devices from various suppliers. Amazon Bracket, a service provided by Amazon Web Services, is a famous illustration of this type of service [10]. The ability to simulate the behavior of matter at the molecular level with quantum computers is one of their most exciting uses. Quantum computers are being used by automakers like Volkswagen and Daimler to replicate the chemical make-up of electrical vehicle batteries in an effort to discover new ways to enhance their performance. And pharmaceutical firms are using them to compare and study chemicals that might result in the development of new medicines. A revolutionary technology, quantum computing has the potential to transform society. The machines are also excellent at solving optimization problems because they can quickly evaluate a huge number of alternative solutions. For example, Airbus uses them to determine the ascent and descent trajectories for its aircraft that use the least amount of fuel. Additionally, Volkswagen has unveiled a tool that determines the best bus and taxi routes in cities to reduce traffic. Some scientists believe that the devices could speed up artificial intelligence. The full potential of quantum computers might not be realized for many years. Universities and companies working on them are struggling to find qualified researchers in the subject, as well as suppliers of some essential parts. Until post-quantum cryptography, or cryptographic algorithms that are secure against attacks by quantum computers, is developed, quantum computing can pose a cybersecurity threat. Post-quantum cryptography can be defined as cryptographic algorithms that are secure against the attacks by quantum computers, and it significantly improves and enhances database search and solves many optimization problems used in business such as data analytics, for example big data, logistics, and medical research [8]. According to one idea, if one had access to a quantum computer with on the order of 10-100 physical qubits, one could mimic physical systems that are beyond large for current conventional computers to handle. Assume that adding active error correction would not be a smart idea if we limited the size of our quantum array to 100 qubits. To lower effective error rates below those required to run a few qubit applications, approaches for error avoidance—which use substantially fewer resources than error correction—and better quality fabrication and control would be used [19].

Author response

As per your reviewer comments the paper is rewritten.

Declaration of Competing Interest

None.

Data Availability

No data was used for the research described in the article.

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