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Challenges and Opportunities: Quantum Computing in Machine Learning

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ABSTRACT: Many computing applications are being developed and applied in almost every aspect of life and in every discipline. With increasing number of problems and complexities, there is requirement for more computational power, faster speed and better results. To overcome these computational barriers, quantum computers, which are based on principles of quantum mechanics were introduced. Faster computation is the main reason behind the evolution of quantum computers which is achieved by using quantum bits instead of bits as quantum bits store both the values 1 and 0 together in superposition. The article focuses on basics of quantum computing in brief and the underlying phenomenon behind quantum computers. Also this article exposes recent trends and the problems that are being faced in this quantum technology. The major impact of quantum machine learning is also discussed. The quantum machine learning is providing better application in this modern field. This article analyses the different research gaps and possible solutions in quantum computing. Recent days quantum computing is implemented in different applications which is also described.

Index Terms – Machine Learning, Computing, Quantum Computing, Data Analyzes, Classical Computing.

I. INTRODUCTION

Quantum computing is a principle of different quantum mechanics as basis of computation. A proper working model will be able to overthrow the conventional computing methodologies. Quantum Computing is a phenomenon of using superposition and entanglement to demonstrate a working model 100 million times [1]. It is faster than a conventional computer. Instead of binary digits, a quantum computer has quantum bits. The use of quantum bits is one of the main reasons why quantum computers are so fast. Quantum computers use D-wave system which basically searches for an optimum solution to a problem [2]. Quantum computers use less amount of energy to store more information and works on completely different principles. It is very difficult to make a fully functional quantum computer in present scenario but within a couple of years we will be able to witness the benefits and advantages of quantum computers. Then it'll be very easy to model complex processes with it, especially those containing prime numbers used for cryptography. Cryptography is used to keep our online information secured, but with more computational power greater risks like quantum hacking is involved [3]. Hence due to this risk, scientists are trying to develop such a technology which will not be prone to quantum hacking but in fact be the most secured technology of all time.

The calculations performed by a classical computer are slow as it uses transistors that take input as bits that is 0 (for off) and 1 (for on). While on the other hand, a quantum computer is based upon certain laws of physics. Though even a quantum computer has a concept of 0's and 1's, qubits are used in it instead of bits [4]. A bit is either 1 or 0 but a qubit's value can be a superposition of 1 and 0 that is a particle can be in multiple states simultaneously. In Classical mechanics the behaviour of particles and elements are predictable and continuous in nature whereas in quantum mechanics it's totally unpredictable. It cannot be prejudice about the behaviour of particles in quantum state, as the sub-atomic particles in quantum realm can have multiple states, position, energies at the same time. Thus, classical mechanics fails to explain these properties at such levels; hence we go for quantum mechanics. The particles can be moving with different speeds that make it completely strenuous to predict the particle. There are multiple sub atoms in an atom with different masses, moment of inertia and they can be interacting with each other by different laws of forces, this various motion is referred as states. These atomic states can also be considered as waves. The phenomenon of superposition in quantum mechanics refers to the convergence or overlapping of two or more quantum states into a single quantum state or we can say that a single stable quantum state is the combination of two or more different quantum states [5]. These new states have properties of all the states it's comprised off, or we can say these states have vague properties between the actual states. In reality, we don't observe superposition what is noticed is the consequences. This is referred as de-coherence, a situation in which particles interact with its surrounding and the result is the loss of quantum behaviour, which apparently destroys the ability of individual states to interfere and form superposition. If we talk in context of quantum computing, the superposition in terms

of qubits (quantum bits) will be the presence of the bits in both the states at once (0 & 1) in contrast with classical computers where it can be either 0 or 1

II. RELATED WORK

In quantum mechanics the property of entanglement explains the correlation between quantum states of two or more elements which form groups or pairs. The pair has the fundamental properties of the elements and these pairs are formed by direct interactions of those particles through various methods like entangle swap where two systems that never interact directly are entangled. There is reaction of each other and how one element is described in reference to another element. For example, measurements taken on one particle have immediate influence on other. Two or more particles undergoing entanglement shows same physical properties like spin momentum. The entangled system is inseparable and interrelated. Whenever these entangled pairs or groups interact with the environment, they lose their entanglement properties known as entanglement broke by means of coherence. Decay of a single particle can also lead to the formation of entangle pair. Bell states represent maximum entanglement state of 2 qubits, where each qubit has two characteristics value and phase, which changes according to the scenario. Mostly the spin states of the coupled particle in quantum entanglement are opposite [6]. Quantum computing can resolve the problem of speed and limitations of classical computers moreover provide more security in communication. Logic gates perform major operations on qubits. Although photons play a major role but a non-linear coupling is required for performing operations. Quantum cryptography is one of major issues faced; scientists are still working on solutions. China developed a quantum computing satellite which is claimed un-hackable. Data paths are still unknown to the developers. Quantum simulators are used to develop real time applications to process information [7]. Quantum computing has many advantages like the quantum states helps in secure transmission, entanglement helps in reliable transmission moreover we can test these properties on small scale devices. Sometimes it's often misunderstood that quantum computers may replace classical computers but that's not true at all. Quantum computing just gives new ways to understand and implement laws of physics in a different way, which is not covered by classical physics [8]. For instance, take example of quantum gate, which gives us an insight of quantum state manipulation, which is very difficult to imagine if we go by normal logical gates. However there's still a big question about the nature of quantum computing algorithms and their class, which may take some more years to be properly understood. To build more complex algorithms for quantum computers, it requires open source software for designing these algorithms and then testing it. Many tools are available for these purposes. Through which we can design and implement quantum hardware interfaces, compilers for implementing algorithms [9]. There are many open source projects which help us to better understand, create, execute these models and algorithms and dive into depths of quantum computing. This will help new comers of the field and provide support to them with better open source frameworks. After the release of IBM's 5 qubit quantum computer the "IBM quantum experience" is widely used by researchers and scientists [10]. Many researches have been done and analyzed. Quintuple which is one of the open source modules which provides you with all the functions and operations of IBM quantum experience and deploy algorithms on IBM quantum experience?. Quintuple provides you with advantages of studying and analyzing 5 qubit system and the applications of 5 qubit systems, helping students to go on hand with the concepts of quantum computing in classroom. The Quintuple algorithm can be programmed in various languages including python. The quintuple is made flexible enough to expand in functionality that makes it an ideal simulator for quantum computing.

Entanglement is considered to be a very important part in quantum computing ever since the term quantum computing first came up. No one would have ever thought that quantum computing could be possible without entanglement too [11]. Usually, for quantum computing pure and noise free qubits are used which entangle to produce a powerful computing. A group of scientists used one pure qubit along with a noisy qubit (which is called a DQC1 scheme) to check quantum computing without entanglement. They checked it using phase-estimation algorithm and realized there was no entanglement involved. They came onto a conclusion that there are algorithms which can work efficiently without entanglement i.e. no need to use pure qubits but then there are some algorithms which need pure qubits and entanglement for them to work efficiently. Decoherence is the major problem which stands in the way of quantum computing. Different qubits interact with each other in different environments which change or dismiss their quantum behavior. A group of scientists assumed the qubits to interact in the same environment. This led to less decoherence in the memory. Before putting away a state into the memory, we change it into a coherence preserving state. The changed state experiences no decoherence in the memory and after a while, it can be changed again into the first state. This is how decoherence can be reduced. Quantum dots are semiconducting nanoparticles which differ in optical and electrical properties from the larger particles due to quantum mechanics. A method of computing where quantum dots interact with each other is described. We can use quantum dot arrays for computations. Quantum-dot Cellular Automata (QCA) circuits are flexible because of adiabatic switching and pipelining [12]. QCA circuits can be very powerful when used in parallel with large arrays. Fabrication of QCA is very tough but once done, it is very useful as it provides a clear goal to the architecture. Existing ideas alongside the development of new approaches for quantum machine learning are being developed by two main approaches, first is finding new quantum algorithms that can be used instead of the classical ones to solve a problem. This is how the complexity of the computation can be reduced. Another process that can be used to depict a stochastic process is probabilistic description. Bayesian algorithm is used for

tasks related to quantum state discrimination. There are still a lot of machine learning processes and algorithms which when mixed with quantum mechanics can do wonders. We can't tell about the strength of such a system right now because even scientists don't know about it and it's hard to compute.

III. APPLICATIONS OF QUANTUM COMPUTING

This section is discussed about different application of quantum computing. Machine learning and artificial intelligence (AI) are some of the most trending and in demand topics and a lot of research has been going on, especially in the field of quantum machine learning [13]. Quantum machine learning is a field integrated of machine learning and quantum computing. The data generated by quantum computers is analyzed by machine learning algorithms. These algorithms can help to analyses quantum states and other quantum properties, thus increasing the efficiency. The classic data is coded into the quantum computer to perform processing and quantum information processing routines. Amplitude encoding, which is based on connecting amplitudes with the input and output of computation gives total number of quantum algorithms required. Quantum machine is also associated with the field of neural networks that deals in finding similarities between physical and learning systems. Figure 1 is elaborating the different application of quantum computing. Cryptography is another field where the use of quantum computing is much appreciated [14]. Encoding and decoding sensitive information is a crucial task in cryptography. Classical computers provide these functionalities but they face trouble in factoring huge numbers into primes. Though this is also possible through classical computers but "deciphering the code" is costly and impractical. Quantum computers have new methods to solve such complex problems which make it very fast and easy to use. Quantum computers also have the power to decrypt the encoding techniques used by classical computers, so it becomes necessary to make quantum resistant cryptography techniques. One of the most common quantum cryptographies is quantum key distribution [15]. The models of particle physics are very complex and cannot be solved using pen-paper or classical computers as it takes a lot of time. With the evolution of quantum computing, particle physics will end up having even more characteristics and uses [16]. Many scientists have already started using quantum systems for their projects and are getting a better result. Weather forecasting sounds like a small application but it is the most important one [17]. Quantum computers can make weather forecasting so fast that we can get to know about the change in climate actually many days before so that precautions can be taken [18]. The global weather data generated by a large number of satellites and systems are too big for any classical computer to handle and the processing can take a lot of time [19]. But quantum computers can do that computation instantly. A UK based weather service has started using this application to predict the change in climatic conditions. Markets nowadays are really very random and it cannot be controlled. To overcome this, quantum computing can be used to predict the randomness of the markets by creating large number of random scenarios. A lot of people are investing on financial modelling due to the promising behavior of quantum computers [20]. It can be very useful in market predictions, analyzing the risks and processing huge amount of data that is generated [21]. These processed data can help to generate patterns and thus predict future outcomes [22].

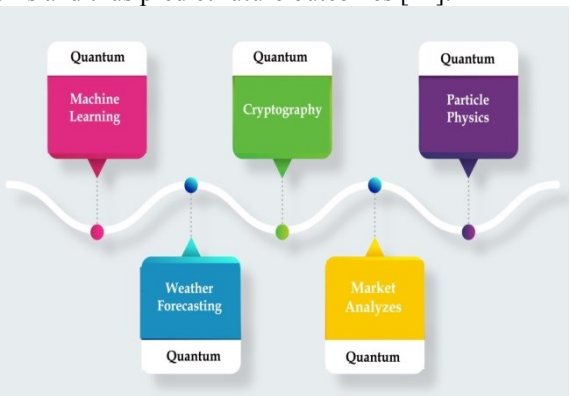

Figure 1: Quantum Computing Application

IV. TRENDS AND RESEARCH PROBLEMS IN QUANTUM COMPUTING

Quantum computing has been a trending topic in the past decade, due to its capabilities of solving complex problems and a promising nature of exploring new field and paths in science. With recent developments quantum computers has been used in a wide range of fields and many new emerging technologies has been discovered and are in development phase. Some of those are discussed below. Quantum simulators are used to simulate workings of engineering components and designs. Though classical computers are used for this process, they have a limited prediction of the designs. They are unable to predict the behavior of particles, there chemical and electrical properties at subatomic levels. Quantum computers can be useful to vanquish this problem, by using quantum physics to simulate these particles. Quantum computers are a low-level quantum computer, which are easy to build and are useful to depict behavior of particles at very low temperatures and in quantum states. One of the major benefits is that they don't require complete control of particles. The field has an enormous scope and is developing very fast. Many models like array of quantum dots, trapped ions are under development. Quantum communication security is always a major concern for the researchers, business clients and consumers. Classical computers provide communication security via various encryption methods and algorithms. Quantum computers has the ability to break these algorithms and encryption techniques, hence there is a need for a safer technique that is not vulnerable to these attacks. Many methods of quantum cryptography, one of which known as QKD quantum key distribution is widely used. In the approach two parties known as Alice and Bob with single photons, are used both these photons are polarized into 0 or 1 state. Then a random series of numbers is generated by these photons, which is used as a key in the communication. Both

parties are connected by classical and quantum channel. First Alice sends generated qubits through quantum channel, upon receiving both parties crosscheck eavesdropping by third parties by performing classical operations on classical channel. If there is any mismatch correlation between the two strings of bits after transmission of qubits the presence is detected. Adiabatic Quantum computing is a subclass of quantum computing that performs calculations based on adiabatic principles. At an initial stage a Hamiltonian is found whose ground state depicts the solution of problem. Then a framework of simple Hamiltonian is made and initialized at ground state. Ultimately the simple Hamiltonian gets transformed to the desired Hamiltonian. In this method the system stays in ground state, and the solution to the problem is found at the end state of system.

Although quantum computing is noticing a remarkable growth in the era, it still faces a lot of issues in its full-fledged development. Some of the major issues are been covered in the article. One of the major issues faced in the development of quantum computers is decoherence. Decoherence happens when there is an interaction with the surrounding environment, which in turn leads to change in the state function. As we increase the number of qubits to enhance the performance to perform many operations in parallel, the isolation of these particles becomes difficult, hence there is entanglement with the environment and the qubits lose their ability to remain in superposition. This can happen due to various reasons like vibrations, sound and light. The qubits can retain any information for only a certain period of time, which is known as coherence length, henceforth there is information loss which leads to the occurrence of fault. Once decoherence has occurred it destroys the quantum information processing which in turn creates problem for the user to read the data. Error correction is also a hurdle in development of large scale and stable quantum computers. Errors on even a single qubit can have a large impact on the quantum data and information. As quantum bits are totally different from classical bits, they are way more complex. In a classical bit, error can be just a state change from 0 to 1, but in quantum computers the qubits have a continuous state of freedom hence there can be continuous errors. Quantum bits can also have phase errors as a single qubit holds both states in its superposition. Another major difficulty with quantum computer is their fabrication. The components are small and need to be precisely at the right place and with right alignment, with minimal variations. The system temperature should be absolute zero or less than that, so that the qubits remain stable and hold information for a long period of time. The quantum performance is measured based on system speed and task quality. The indirect way should analyze the task quality that means the comparison should happen with and without quantum machine.

V. QUANTUM MACHINE LEARNING

The term machine learning is used to predict the future result based on existing data. This data is gathered from the previous data set. This machine learning is dealing with larger data set to find the reliable solution. These kind of situation they need more computational power, this quantum computing is providing better solution for this problem. The combination of this quantum computing with machine learning is named as quantum enhanced machine learning that means advanced machine learning. This quantum computing algorithm is implemented with this machine learning. The figure 2 is proving latest trends details that means machine learning is a vast and emerging research area in modern computing platform. This figure is showing google search terms, the quantum computing is searched in and average 6%. At the same time 81% people searched in machine learning related to quantum. It is showing that quantum machine learning importance.

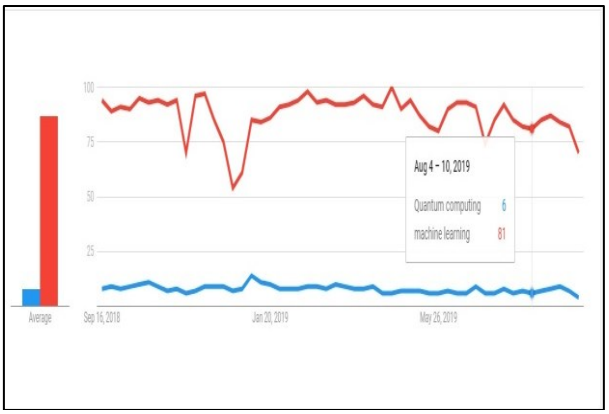

Figure 2: Trends in Quantum Computing Vs Machine Learning

VI. CONCLUSION

Quantum computers exploit the principles of quantum mechanics. These principles are stated for quantum particles, the quantum particles are very small in size and their behavior is very difficult to predict, thus making it more complex and tedious task to control and manipulate them to get desired results. Quantum computers still have a lot of flaws and the path to create fully functional and operative quantum computers is long. Though recent advancements in the field are astounding but the relative speed of development is slow. Regardless of the ideas and concepts known in the field, it is still hard to implement it and produce the desired results. Superposition is the mixing of two or more states to combine and form a single state. These superimposed states are capable of storing qubits values of 0 and 1 both at the same time, thus increasing the potential of calculations. Entanglement explains the correlation between quantum states. These two properties are the basis of quantum computing. The working of a quantum computer is more complex than a classical one. With time, scientists got too realize that entanglement is not important in quantum computing. There are ways in which we can do it without entanglement. Many developments are still in process; the ones which are in concern are the development

of a smaller and more compact systems which would be capable of holding more qubits. The modern quantum machine learning is also used in big data, cryptography and cyber security. This method is also used to solve the atomic clock problems and provide the better solution for NP complete problems.

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