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An Insight Into Quantum Computing Applications

ABSTRACT

Newtonian physics has provided an explanation for the interactions occurring in the everyday world while encouraging the development of technology, such as computers, that utilize our understanding of physics. However, classical computers based on Newtonian physics fail to operate on an advanced level necessary in the growing fields of dark matter or machine learning. As an alternative, quantum mechanics provide the potential for an improved computing system. The nonlinearity and superposition properties of quantum computing ensure that quantum computers will be better suited in certain matters, such as simulating quantum systems or factoring insurmountable numbers, when compared to classical computers. Advances in machine learning and dark matter detection with the use of quantum technology exemplify the true potential of quantum computing. While quantum computing has the capability to advance the world, the realistic means of creating a quantum computer is hindered by the difficulties of quantum mechanics. For example, measuring qubits through entanglement and isolating a quantum computer are both tasks posing as barriers in the …path of quantum computing. Nevertheless, experiments overcoming these obstacles demonstrate a means to achieve the implementation of quantum computers to solve scientific mysteries. This paper will review the potential applications of quantum computing while also considering the problems it faces. It will stress the importance of research in quantum mechanics and a future focused on improving quantum technology.

Introduction

Regular computers have utilized the mechanics of classical physics to revolutionize the technological world to a considerable extent. For instance, transistors, a fundamental building block of computers, work as an amplifier or switch, turning the current on or off to indicate a binary code of 0 or 1. The physics of the current flowing from negative to positive is being taken advantage of in the form of transistors, thus demonstrating the importance of classical physics in modern computers. Over years of technological development, transistors and other components have improved to create computers used on a daily basis. However, when dealing with advanced computations or algorithms, classical computers are either too slow or insufficient, prompting the need for quantum computers. Quantum computers, unlike classical computers, operate based on quantum mechanics which describes the behavior of particles at the atomic level. Rather than having binary bits, only occurring in the states of 0 or 1, quantum computers have qubits that can be in a superposition state of 0 and 1. Having more qubits increases the power of a quantum computer exponentially compared to an increase of transistors in a classical computer only increasing its power linearly. For instance, the most powerful classical supercomputers can peak at 200 trillion calculations per second while a quantum computer could perform calculations at a rate a billion times more than that (Rangaswamy, 2020). The significant difference in processing ability between a classical computer and a quantum computer evokes investigation into the practicality and implementation of quantum technology into modern scientific research.

Quantum Computing

Background of Quantum Computing

Blackbody radiation was one of the first instances where the quantization of energy was introduced. At that time, the accepted theory was a continuous flow of energy; however, the blackbody radiation curve did not match such theory, prompting the idea of quantized energy. Planck, not believing the plausibility of packets of energy, proposed quantized energy mainly for mathematical purposes. $E = hf$ became the equation put forth by Planck, translated into $E = \frac{hc}{\lambda}$, meant to explain the curve of the blackbody radiation.

$$E = \frac{hc}{\lambda}$$

Even more catastrophic to the previously held theories, Albert Einstein brought up the notion that particles can behave like waves, proven through the photoelectric effect, thus, bringing photons into the picture. After Louis de Broglie proposed that electrons could behave as waves in 1924, Erwin Schrodinger constructed a theory in which a mathematical equation would be able to describe the position and behavior of a particle through the means of its wavefunction (Clegg & Ball, 2017). Providing a mathematical basis to help describe the behavior of atomic particles, Schrodinger's equation gave a way for scientists to calculate the probability of the location of a particle or the wavefunction of a quantum system, allowing the application of quantum mechanics to rise (Clegg & Ball, 2017). Eventually, quantum mechanics would reach a stage where applications in computing were the next step, thus, allowing quantum computing to take the main stage. Richard Feynman would eventually be the first to theorize a completely quantum computer meant to simulate quantum physics; he wanted to create a *universal quantum simulator* (Demmer, 2004). In 1998, UC Berkeley was able to develop the first two qubit magnetic resonance computer which slowly improved over time (Demmer, 2004). Quantum computing has reached a time where the greatest issues lie in its application and realistic configurations rather than simply theorizations.

Comparison with Conventional Computing

Regular computers, using binary bits, work in a similar fashion to quantum computers. They consist of transistors and switches and many other electrical components such as logic gates that work to amplify or switch on and off a current in order to simulate binary bits. The binary bits of 1 and 0 can be combined into binary code where numbers and eventually letters can be formed. Binary bits are very capable in a regular computer meant for simple processing but lack the capability in areas of extreme data analysis or artificial intelligence, both rising fields in STEM. On the other hand, quantum computers, using the principles of quantum mechanics, are able to solve problems too complex for classical computers in a shorter amount of time. In quantum computers, qubits can be 0 or 1 or in a superposition of both states, allowing for exponential results, therefore, exceeding classical computers. The two states of a qubit are represented using amplitude to allow for them to be put in a linear combination of both states.

$$\alpha_0: amplitude\ for\ 0$$
$$\alpha_1: amplitude\ for\ 1$$

Qubits prompt computations to occur at a rate simply not possible with the use of binary bits. The very idea that quantum computing could complete calculations at an exceedingly faster rate gives possibilities to the potential of quantum computing. The implementation of those possibilities, however, is where many of the issues in quantum computing lie.

Superposition in Qubits

The concept of superposition is a foundational element of quantum mechanics and can be easily explained by Schrodinger's cat. Schrodinger proposed that the state of a cat being dead or alive in a box was dependent on a quantum event such as the decay of an atom (Clegg & Ball, 2017). The decaying atom, although, could be in superposition of the state of the cat being dead and alive, meaning it was simultaneously occupying both states. Unfortunately, the superposition state would be reduced to either the cat being alive or dead once the box was opened, as the observation or measurement of the state ruins the very act of quantum superposition. The simple idea of a cat helps to explain the complicated abstract of superposition, an essential quantum property in the field of quantum computing.

Quantum computing has utilized the superposition principle in the form of qubits; a qubit's advantage is that it is in a superposition of two states. The main obstacle, as seen with Schrodinger's cat, is measuring the state of an atomic particle without disrupting its superposition state. Nevertheless, a team of scientists has discovered a way to measure the oscillation of a qubit, a characteristic of a qubit, in its state of superposition. By using a superconducting qubit and a microwave cavity, researchers made weak measurements of the qubit's oscillation without destroying the state of superposition (Vijay et al, 2012). The measurements made a small change in the system so they injected an opposite charge into the system to allow it to keep its superposition oscillation (Vijay et al, 2012). By prohibiting the decay of the Rabi oscillations, researchers showcased a means of quantum feedback control to exemplify advances in quantum computing regarding superposition (Vijay et al, 2012). The preservation of a qubit in its superposition state would allow the applications of quantum computing to become more realistic, making it essential to the future development of quantum computing.

Quantum Computing Applications

The unique properties of quantum computers make them an ideal alternative in situations where classical computers simply lack the capability to work efficiently enough. Superposition is a key quantum property utilized by quantum computers, setting them apart from current technology. In this modern age, physicists are realizing the true extent of the universe, searching for a way to understand the mysterious behavior of atomic particles different from the ones on Earth, many of which require the capabilities that quantum computers offer. Numerous scientific fields are slowly comprehending the potential of quantum computers, looking for a way to incorporate them into modern research.

Factoring Numbers

A seemingly simple concept, the factoring of numbers is an area in which quantum computing can provide an edge. The implementation of a prime factoring algorithm on a quantum computer can provide aid in factoring large numbers, something a classical computer would take ages to do. A team of researchers from UCSB were able to use Peter Shor's algorithm to factor the number 15 into its prime factors 3 and 5 (Lucero et al., 2012). By using four superconducting bits and five superconducting co-planar waveguide resonators for a total of nine elements in their quantum system, the scientists achieved the desired result approximately 50% of the time (Lucero et al., 2012). They were able to implement their quantum algorithms, utilizing entanglement by using high-fidelity single-qubit gates along with swap and controlled-phase gates (Lucero et al., 2012). In order to achieve the high goal of factoring a 600 digit number, improving the superconducting qubit coherence times and creating more complex circuits would be necessary (Lucero et al., 2012). However, this experiment demonstrates a pathway for quantum computing to solve a problem not even imaginable on a classical computer. Cyber security relies on the fact that no computer can factor 600 digit numbers, proving that quantum computing could revolutionize the cyber security system as a need for quantum cryptography would arise. Regardless, quantum innovations create a new pathway for technology, therefore, exemplifying the potential quantum computing assures.

Detecting Dark Matter

One of the greatest fascinations of recent physics is dark matter, or matter that is not able to be seen through electromagnetic radiation but still affects particles around it. Technological innovation involving quantum physics has the potential to detect dark matter and allow further research to be conducted. Researchers have recently used quantum mechanics to double the speed at which the axion particle could be searched for. Using the classical version of the axion detector HAYSTAC, one could only detect the axion wave, if it even exists, in a small bandwidth of frequency (Backes et al., 2021). Since the axion wave could exist at a frequency from 300 hertz to 300 billion hertz, blindly searching for the hypothetically correct frequency could take 10,000 years (Backes et al., 2021). The noise encountered by these detectors is also hindered by the noise interfering with the detection of two quadratures since the Heisenberg uncertainty principle prevents one from knowing two certain pairs of properties regarding a particle at the same time. The noise can be manipulated, however, to allow one property to be more precise while the other retains more of the noise. Through the method of quantum squeezing, researchers have doubled the bandwidth of the HAYSTAC detector with the use of a superconducting circuit to allow for the search for the axion to continue at twice the speed (Backes et al., 2021). In areas where classical computers come short, quantum computers provide the technology necessary to work with quantum theory based techniques often required for the detection of hypothetical particles. While unobtrusive in the classical world, at an atomic level, many laws, such as the Heisenberg uncertainty principle, and forces are rather significant in causing noise when dealing with dark matter. Nevertheless, quantum computing provides the potential to aid the problems concerning modern research in dark matter and theoretical physics.

Quantum Machine Learning

Machine learning, through classical computers, is meant to recognize patterns from large data sets through supervised or unsupervised learning. For instance, through supervised learning, one could have an input and output pair *(x, t)* in which one would want to predict the output *t(x)* for any input *x* by deducing a relationship between the input and output (Kanamori et al., 2020). Additionally, to understand the quality of a prediction, a loss function is used to determine the accuracy of the prediction when compared to the actual outcome; to create effective predictions, a reduction of the loss function would be ideal (Kanamori et al., 2020). Unsupervised learning aims to target a similar process but without the use of labeled data points (Kanamori et al., 2020). However, with such large amounts of data being introduced to machine learning, quantum computing offers a solution meant to aid in organizing and processing new large data sets. Quantum algorithms provide a better option for machine learning due to the ability to have a superposition state of qubits, prompting them to be implemented into unsupervised and supervised methods of machine learning. Quantum Neural Networks, for instance, puts multiple single neural networks together in superposition instead of opting for the classical neural networks that work through the classical methods of gradient descent and backpropagation (Mishra et al., 2019). In the widely developing field of machine learning, applicable in areas such as artificial intelligence, quantum computing can offer the technology to advance the modern world even further.

Quantum Blockchain

Blockchains are an ingenious method of encryption used to provide high level security for important technological information such as cryptocurrency. Classical blockchains aim to stray from a centralized management node by operating using a database consisting of a network of nodes in which all nodes are in agreement (Rajan & Visser, 2019). Cryptographic hash functions allow blocks of time-stamped data to be linked together while also invalidating all future blocks in the case that one is tampered with. Through this method of constructing a blockchain, the encrypted information becomes sensitive to tampering as any inconsistency would render the entire chain invalid (Rajan & Visser, 2019).

Quantum blockchains, on the other hand, provide a way to strengthen security and resist tampering without the immediate invalidation of the chain of data (Rajan & Visser, 2019). Essentially, one would code information into a quantum particle before entangling it with a second particle at the onset of new data and discarding the initial particle. Through this method, a chain of entangled particles could be created and hackers would have no way to reach previously entangled particles as they would be nonexistent. In cases of high importance such as health records or voting, quantum blockchains can provide foolproof security. The implementation of the quantum phenomenon in encryption illustrates another growing path for the field of quantum computing.

Challenges in Quantum Computing

The desire to implement quantum computers in various fields prompts the question as to why they are not being widely developed and used. They likely would be if not for the difficulties that lie in creating and maintaining the environment in which a quantum computer can function. Unlike Newtonian physics, quantum physics properties are rather fragile and difficult to utilize because of factors such as the Heisenberg Uncertainty Principle. While quantum computing is being theorized in a variety of situations, the actual building of a practical quantum computer with a high number of qubits still stands to be an issue.

Difficulties of Measuring a Qubit

During early hypothesizations of quantum computing, qubits were assumed to be stable and thought to be easily interfered with while maintaining their own state. Peter Shor, who introduced the idea that a quantum machine could hypothetically factor large numbers, was a driving force in quantum computing that failed to account for the true nature of qubits (Cho, 2022). Attempting to measure a qubit would prompt it to default to a state of 0 or 1, essentially reducing it to a classical bit. The method used in classical computers of copying one qubit onto another would change the original identity of the qubit, making it impractical in a quantum computer. Maintaining the integrity of the system whilst also measuring it is the main issue that quantum physicists often struggle with. Entanglement, however, provides a potential way of measuring qubits in which two or more qubits interact with the intent of measuring the original state of a qubit. The "controlled not" operation (CNOT) can entangle qubits to create a state of superposition in which a qubit is both 0 and 1. Most methods of quantum entanglement are initially clouded with noise and interference, so error correction is necessary to produce accurate results. The development of technology to efficiently enact error correction is a barrier to the applications of quantum computing.

Nevertheless, correction through ancillary bits after the error is a method in which a qubit could be measured with accuracy. Publishing their research in Nature Physics on 08 June 2020, a group of scientists including Andreas Wallraff was able to use seven superconducting bits to detect an error in a qubit, finding that qubits without error had a preserved logical quantum state (Andersen et al, 2020). They used high-fidelity ancilla-based stabilizer measurements before attempting error detection multiple times. Methods of error correction can help counteract the difficulties of measuring qubit states. Maintaining a qubit still stands as an obstacle in creating a truly efficient quantum computer; however, advances are being made in order to create the most precise manner of error correction possible.

The Practicality of Quantum Computing

Quantum computers require complete isolation from the macroworld and a lack of observers in order to fully function. The noise and decoherence in a quantum system pose as insurmountable challenges to overcome in the field of quantum computing. Not only that, the workings of probabilities necessary to predict events in the quantum world leave quite a few uncertainties. However, due to the limitless potential of the infinite quantum world, one may be satisfied with the rather small probability of all predicted events actually occurring (Al Adeh, 2017). But in order for a quantum computer to truly function by the operations of quantum physics, total isolation is a requirement. The isolation necessary to create such a complete form of a quantum computer appears to create difficulties for quantum scientists hoping to implement quantum mechanics widely. Quantum computers that currently exist still face the problem of noise and decoherence, often eased by extremely low temperatures; unfortunately, this also creates an impractical environment for research that hinders the potential applications of quantum computers. All hope is not lost, though, since scientists have recently measured the axial Higgs mode, a quantum characteristic, at room temperature, providing a pathway toward quantum experiments in realistic conditions (Wang et al., 2022). The introduction of practical quantum computing experiments could allow for quantum computers to operate in more reasonable conditions; nevertheless, the limited practicality of quantum computers still hinders the extent of their capabilities.

Recent Advances in Quantum Computing

Quantum computers have entered numerous labs around the globe, prompting a continuity of experiments involving quantum technology. As discussed previously, the challenge of building a quantum computer allows for the limited applicability of quantum computing. Despite this, physicists continue to address this challenge, utilizing creative technology to take a step towards a future encompassed by quantum computers. A recent landmark achievement, the Max Planck Institute of Quantum Optics credits itself for being the first to entangle 14 photons, creating a quantum computer with increased efficiency (Thomas et al., 2022). The researchers used a single atom as a photon source, differing from previous methods of entanglement with this one allowing for determined properties to apply to each photon (Thomas et al., 2022). Philip Thomas, one of the physicists involved, explains the potential this new basis for quantum computing brings to the table, including advancements in quantum communication and a scalable quantum computer (Thomas et al., 2022).

However, improving the stability of quantum properties is not the only manner in which quantum computing is progressing. As quantum physics begins to define the world around us, physicists are seeking ways to investigate the fragile quantum world, often turning to quantum computers for help. Nearing the end of 2021, scientists at Cambridge were able to recognize a rare state of matter known as a quantum spin liquid, furthering a previous theory regarding the existence of such a state (Semeghini et al., 2021). The researchers at Cambridge used a 219 atom quantum simulator in which the atoms were arranged in links of a kagome lattice to create a quantum spin liquid state (Semeghini et al., 2021). Then, they detected it by the means of a topological string operator, furthering the capability of researchers to examine topological matter (Semeghini et al., 2021). This recent instance of applying quantum computing to the advancement of science exemplifies the potential of the quantum computing field.

Conclusion

After examining both sides of the quantum computing revolution, one can assume that quantum computing will be a significant aspect of technology in the future. Classical computers have been maximized to an extraordinary level of efficiency. A transition to quantum computers for advanced scientific problems is the most logical way for technology to evolve. Even with current quantum computers, applicability to once impossible problems, including factoring numbers, appears to be plausible due to the unique nature of superposition. However, problems such as practicality, qubit error, and entanglement prove to hinder the evolution of quantum technology. Yet scientists are still innovating ways to solve such difficulties. The overcoming of practicalities would allow quantum computers to provide a technological upgrade to encryption, machine learning, and even dark matter. With a vast amount of unknowns in the universe, quantum physics provides the fundamental means by which atomic particles interact, encouraging the introduction of quantum computers to better simulate a quantum environment. Due to the insurmountable number of researchers working towards solving the issues facing quantum computing, it seems reasonable to assume the eventual development of a practical and effective quantum computer.

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