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Quantum Computing: A New Era for Computers

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ABSTRACT

Using the principles of quantum mechanics, computing can be thought in a different way, one which transcends the boundaries of imagination creating multidimensional computing spaces to solve complex problems. In this paper I will explore the quantum mechanics underlying quantum computing briefly and explain the process of computing within a quantum computer. I will highlight the key differences between classical and quantum computer using a well elaborated example, and then soon delve into the architecture of quantum computers. The last part of the paper will be mostly about how we determine or measure the progress of its performance and capabilities. I will then conclude it by claiming its potential to revolutionize industries.

KEYWORDS: *Quantum Computing, Quantum Mechanics, Qubits, Classical vs. Quantum, Sycamore Processor, Richard Feynman, Quantum Supremacy, Performance, Architecture, Industry Revolution, Problem Solving*

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INTRODUCTION

Richard Feynman introduced the concept of quantum computing in 1981 during a keynote lecture at a conference titled *The Physics of Computation* at MIT. Feynman argued that a computer based on quantum mechanics—using quantum bits (qubits)—could simulate quantum phenomena inherently, making it an ideal tool for studying quantum systems. 38 years later, in 2019 Google achieved "Quantum Supremacy", Demonstrating a quantum processor (Sycamore) performing a specific task faster than the best classical supercomputers. A huge part of my motivation in exploring quantum computing is to simulate real world phenomenon at a scale that is almost as accurate as the real world itself. By doing so, I believe we could unlock new insights into complex systems, optimize processes across industries, and develop innovative solutions to challenges in all different fields, making it easier to connect theoretical models into practical ones.

Understanding Quantum Computing

In order to explore quantum computing, there are four very important principles of quantum mechanics that must be understood properly first. Quantum particles exist in a state of superposition where they exhibit multiple possible states at the same time, rather than being confined to one single state. In quantum computing, qubits (which are quantum particles) take advantage of this property to represent and process information, enabling an exponential increase in computational potential compared to classical bits for specific tasks. Entanglement is another property where qubits that are entangled, become correlated to each other and thus manipulation on one influences the others even when they are distant from each other. Qubits are very sensitive to external disturbances which can lead to decoherence, which is a process where they transform into singular measurable classical states. That’s why quantum systems are maintained at temperatures close to absolute zero.

When the Quantum circuit runs its algorithm, interference between quantum states is made to cancel out some possibilities while amplifying others. Interference is the phenomenon where quantum states interact, leading to constructive interference (increasing certain amplitudes) and destructive interference (canceling others).This ensures that the end results displays the outcome with the highest probability of being correct.

Now that we have understood these concepts, it will be easier to understand how quantum computers are made. The quantum particles that constitute the quantum system are called qubits as in quantum bits. Unlike classical computers which can store information in bits representing either 0 or 1, qubits can exist in a superposition of 0 and 1, representing a combination of both states probabilistically. This property of superposition allows quantum systems to create multidimensional computational spaces that are beyond the reach of classical computers.

Quantum processors made out of quantum chips which hold qubits are structured specifically along with control electronics to form the basic hardware of the quantum computer. As noted earlier, quantum systems are required to be kept at incredibly low temperatures, which is achieved using supercooled systems such as dilution refrigerators. At these temperatures, certain materials exhibit superconducting properties, where electrons pair up to form Cooper pairs. These pairs can carry a charge across barriers, or insulators, through a process known as quantum tunneling. Two superconductors placed on either side of an insulator form a Josephson junction, a crucial piece of quantum computing hardware.

Computation in a quantum computer begins by preparing a superposition of all the computational states. The circuit then implements an algorithm that manipulates these states, generating entanglement within these states and causing interference which cancels out some of the outcomes and amplifies other ones. Finally, measurement collapses the quantum state, revealing the amplified solution as the result of the computation.

These computations are done in a quantum software which designs and executes quantum algorithms to manipulate quantum states. Developers use programming languages such as Qiskit which is in the process of evolving to a full stack software for quantum computing enabling tasks such as circuit design, algorithm implementation, simulation, and execution on quantum hardware. This will ease the development process and make quantum programming more accessible to researchers and developers around the world.

Differences between classical and quantum computing

Classical and quantum physics are fundamentally very different from each other. We are more acquainted with the classical world that phenomenon in the quantum world is counterintuitive to our perception. For example, electrons can pass through barriers in the quantum world, even when their wavefunction extends beyond the size of the barrier, a phenomenon known as quantum tunneling.

All classical computers including supercomputers which have evolved from encoding data in punch card holders to solving complex problems using parallel computing and interconnected processors are fundamentally dependent on their basic information holder bit.

In order to better understand how much increase in computational power a quantum computer holds over any modern supercomputers, we can analyze the maze solving strategy by each of them. A classical computer will test each path of a maze step by step and will retreat once it meets a dead end. It then stores that information in the bit and then follows on until it discovers the correct path. A quantum computer tests multiple paths simultaneously, using quantum interference to reveal the correct solution.

However, qubits don't test multiple paths at once; instead, quantum computers measure the probability amplitudes of qubits to determine an outcome. These amplitudes function like waves, overlapping and interfering with each other. Incorrect paths cancel out and the correct solution is amplified. This enables the quantum computer to solve the maze exponentially faster for certain types of problems compared to classical methods. Even supercomputers with parallel solving techniques are no match for this method.

The State of Quantum Computing

With the clear understanding of the fundamentals, we can now explore where the progress of its developments stands today. Benchmarks in Quantum Computing allows us to measure the capabilities and performance of quantum systems while also identify areas of improvement. Classical computer uses benchmarks like processing speed and memory, but quantum computer has special benchmarks such as Quantum Volume (QV) which measures the largest quantum circuit that can pass a quantum volume test (successfully perform a random quantum circuit of a given depth). Layer fidelity is another valuable benchmark which provides a way to encapsulate entire quantum computers processing ability. By running this protocol, scientists can gain access to granular performance and error information about individual components. Error rates in quantum gates and measurement, helps in determining its reliability as lower rates relate to higher quality of computation. Execution of algorithms in their system is another practical test that can prove the efficiency of the quantum computer. Progress can also be seen in the advancement of developing more stable qubits technology (such as superconducting qubits and trapped ions).

Although very useful, these metrics have not scaled to a level where developments can be directly judged through any one of these, as seen in classical computers. There is no standard metric for determining quantum computers performance. They are just road signs indicating that researchers are going in the right direction. Nonetheless, the integration of quantum and classical computing in hybrid systems and the application of quantum algorithms to real-world scenarios are emerging as promising indicators of progress.

It is important to distinguish between the key milestones in the journey of quantum computing: Quantum Advantage and Quantum Utility. Quantum advantage is the stage when Quantum computers will be able to outperform classical computers in specific tasks, even if they are not yet practically useful. Quantum Utility on the other hand represents the stage where quantum computers provide accurate and tangible solutions to real-world problems that are beyond the reach of classical computers. And although immense progress has been made, we are still yet to navigate through its errors and challenges to release its potential.

Conclusion

Quantum computing is a huge shift from our previous ways of approaching complex problems using classical computers. By using the principles of quantum mechanics the level of exponential computational capability is truly beyond the imagination of someone who has been working with classical computers for a long time. By further allowing programmers and researchers worldwide to use quantum programming tools like Qiskit to make discoveries and enhancements in its algorithm, the field of quantum computing only leaps forward. Also the benchmarks ensure that progress is being made in the right direction and feedbacks on errors helps in building these system to be more reliable and stable. There is no doubt that quantum computing will revolutionize industries from development of life saving drugs in pharmaceuticals to advancing cryptography and offering novel methods in looking at data sets of machine learning. With continued research and innovation, we will bring the once thought to be impossible power of quantum mechanics to life, heralding a new era of computing.

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