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Quantum Computation

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ABSTRACT

A quantum computer is a device that makes use of quantum-mechanical phenomena to process data. It would enable more effective algorithms by introducing operations that are not possible in classical machines. Quantum computation is a cutting-edge area of study that combines principles from computer science and quantum mechanics to revolutionize the way data is processed. The power of quantum computation lies in its ability to exploit quantum phenomena like superposition and entanglement, enabling it to solve complex problems such as factoring large numbers and searching databases more efficiently. We have not yet reached the advent of useful quantum computation, but when we do, it will affect nearly all scientific disciplines. In this paper, our aim is to provide the necessary insights for an understanding of the field of quantum computation.

KEYWORDS: *technology, quantum computing, quantum computation.*

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INTRODUCTION

Quantum computers process information stored within quantum mechanical systems. Unlike traditional computers, which encode the information using bits that are either 0 or 1, quantum computers utilize qubits—quantum bits, that can exist in superpositions of states, which can represent multiple states simultaneously, enabling them to perform complex calculations much faster than classical computers. Due to the fact that atomic systems are not in a definite state until measured, quantum computers can perform certain functions in fewer operations than would be needed to perform the computation on a classical digital computer. Quantum algorithms have been shown to provide computational speed ups over some of our best-known classical algorithms. An increasing number of researchers with a whole spectrum of different backgrounds, ranging from physics, via computing sciences and information theory to mathematics and philosophy, are involved in researching properties of quantum-based computation [1].

QUANTUM COMPUTERS

A quantum computer (QC) behaves according to the laws of quantum mechanics. Thus, quantum computers are different from binary digital electronic computers based on transistors. A major difference between classical and quantum computing lies in the way they encode data. While a digital computer requires that the data be encoded into binary digits (0 or 1), quantum computers use quantum bits, which can be in superpositions of states [2]. In other words, instead of storing information in bits as conventional digital computers do, quantum computers use quantum bits, or qubits, to encode information. (Qubits are the basic units of quantum information.) In addition to ones and zeros, qubits have a third state called "superposition" that allows them to represent a one or a zero at the same time. Figure 1 shows the comparison between the bit and qubit [3]. The computing power of a QC grows exponentially with the number of qubits it uses.

Quantum computers have the potential to perform certain calculations significantly faster than any digital computers. QC consists of a quantum processor which operates at a very low temperature (a few tens of mK) and an electronic controller which reads out and controls the quantum processors, as shown in Figure 2 [4]. Several forms of physical media (optical fibers and free space) can be used to deliver quantum information. Figure 3 shows a representation of quantum computing [5].

In quantum system, the computational space increases with the size of the system. This enables exponential parallelism which leads to faster quantum algorithms. Unlike classical computer, QC offers massive parallelism within a single piece of hardware.

A typical quantum computer is shown in Figure 4 [6]. The basic building blocks of quantum computers include quantum gates, quantum memories, quantum CPUs, quantum languages, and quantum languages [7,8]:

- *Quantum Gates:* Quantum computers require quantum gates, which are basically different from classical Boolean gates seen in a conventional computer (AND, XOR and so on). A quantum gate acts on superpositions of different basis states of qubits. The quantum gates perform unitary operations on quantum states and lead to quantum circuits. They are particularly important for quantum error correction and experimental quantum information processing. They can be realized by superconductors, linear optic tools, or quantum dots**.** Common quantum gates are CNOT and SWAP.
- *Quantum Memories:* Quantum memories store the quantum systems in a quantum register for information processing. Quantum memories are formulated by n stationary quantum states. Quantum computers are expected to have limited memory.
- *Quantum CPUs:* These use a quantum bus for the communication between the functional elements of a quantum computer. From a computing perspective, quantum CPUs can be approached through quantum adders.
- *Quantum Languages:* These enable us to create an artificial quantum computer to simulate a quantum computing environment. The programming language should follow a functional programming structure, which can compute the process as a whole entity with a proper bounded structure.
- *Quantum Algorithms:* Quantum algorithms are significantly faster than any classical algorithm in solving some problem. Most of the successful quantum algorithms use quantum Fourier transforms in them because they require less hardware. Popular quantum algorithms include Shor's algorithm (since integer factorization is faster) and Grover's search algorithm.

In ambitious attempts to realize practical quantum computers, enormous efforts are still being expended both in designing software (quantum algorithms) and hardware development (physical implementation).

QUANTUM COMPUTATION

Quantum computation leverages quantum-mechanical phenomena, such as superposition and entanglement, to solve complex problems exponentially faster than classical computers. It is an interdisciplinary study that merges the fields of computer science, experimental particle physics, and theoretical physics. At any given stage in the computation, the computer may be in a mixture of states. The quantum-computational revolution of the mid-1980s, led by David Deutsch and Richard P. Feynman, was inspired by the idea of the supercomputer to look at the quantum effects on small components in a radical new way. The first results in quantum computation, produced by David Deutsch, showed that a quantum computer could not solve any problems that could not be solved by a classical Turing machine.

Perhaps the simplest computation imaginable is adding one and one to make two. This can be implemented by two bits and an AND gate. The gate produces a 1 if both inputs are 1; if they are not, it produces a 0. This gate is a universal set of logic gates, adequate to do any computation that is Turing computable. The classical computation is based on Boolean logic. The basis of modern computers rests on semiconductor technology. Quantum computers require quantum logic, something fundamentally different to classical Boolean logic. There are no quantum circuits; no electrical pulse is moving from place to place. The final output value depends not only on a single sequence of calculations but also on all possible steps. The output of a quantum computer's qubits is a randomly assigned state from a series of possible answers [9]. That is where the computational power of quantum computers comes from.

Quantum computation can be summarized as the mapping of an -qubit state into the new state for the purpose of doing some desired computation. The complexity of a quantum algorithm can be characterized in three main ways: the number of one-qubit gates, the number of two-qubit gates and the depth of the quantum circuit [10]. The amalgamation of these quantum properties enables a universal quantum computer to conduct a vast number of computations simultaneously.

APPLICATIONS OF QUANTUM COMPUTATION

Quantum computers can in principle solve certain problems exponentially more quickly than their classical counterparts. Most quantum algorithms have assumed access to a quantum random access memory (QRAM), which is a black-box device able to construct superposition. This advanced approach has potential applications in fields like cryptography, climate modeling, computational biology, medicine, and pharmaceutical industry. Common applications of quantum computation include the following [11,12]:

- *Computational Biology*: Quantum computing has the potential to change the way we do biology much as classical computing did. Since the advent of modern computing, algorithms and mathematical models have been used to help solve biological problems. Computational methods are now routinely used to inform and extract information from biological experiments, as well as predict the behavior of biological entities and systems. Despite such progress, many challenges in biology remain computationally infeasible. The best algorithms for problems like predicting the folding of a protein, calculating the binding affinity of a ligand for a macromolecule, or finding optimal large-scale genomic alignments require computational resources that are beyond even the most powerful supercomputers of our time. There are three main areas of computational biology where quantum computing has already shown promising algorithmic developments: statistical methods, electronic structure calculations, and optimization.
- *Drug Discovery*: Quantum computers could revolutionize many industries, from developing new drugs and materials by simulating their behaviors at a quantum level, and even transforming the field of cryptography. Simulating chemistry is about electrons and protons that influence each other instantaneously. Simulating big quantum systems as a whole is difficult for classical computers, since the requirements scale exponentially in the size of the system. If we have a quantum computer with enough qubits, problems like this are a natural fit to solve with this technology since the available resources per additional qubit scale in the same way as the size of the quantum system to simulate. Protein folding could be sped up by quantum computing.
- *Quantum Fourier Transform*: The quantum Fourier transform is a critical algorithm underpinning the speedups from many quantum algorithms. Requiring a polynomial number of operations to complete, the quantum Fourier transform provides an exponential speedup over the classical Fourier transform when performing operations in superpositions. There are some cases when the quantum Fourier transform and its variants can be efficiently simulated classically. A quantum algorithm which harnesses the quantum Fourier transform was proposed by Kitaev to estimate the phase of a quantum state and is widely utilized as a quantum subroutine.
- *Prime Factoring:* Peter Shor, a computer scientist, looked at the problem of finding prime factors in a new way. A quantum algorithm for factoring integers was formulated by Shor, providing an exponential speedup compared to the most efficient known classical algorithm. This algorithm relies on speedups from the quantum Fourier transform and modular exponentiation. It has implications for classical encryption methods that rely on a public-key encryption scheme, whereby security is derived from the classical complexity of prime number factoring.
- *Cryptography:* One potential application of quantum computers is the sending and decryption of secret messages. A popular form of sending information is public-key cryptography, in which the recipient of the message discloses a public key to anyone who wants to send a message. This key is mathematically related to a private key, which the recipient keeps. Anyone may use the public key to encode a message, but the recipient is the only one who can decode it.
- *Quantum Parallelism:* Quantum computers achieve parallelism in computation through the principles of quantum mechanics, specifically superposition and entanglement. The obvious way to apply quantum parallelism to factoring some large number with N digits would be to try in parallel to divide it by all numbers less than the square root of N. A quantum computer could be programmed to do this, and some of the superposition paths that evolved from the application of gates would indicate solutions to the problem.

BENEFITS

Quantum simulation is one of the first useful applications of practical quantum computing. There are certain problems that would be intrinsically faster on a quantum computer. The total number of steps needed to solve the problem, the computational complexity, would be smaller than the number of steps required for the classical computer. Other benefits include the following [13]:

- *Computational Power*: Classical computers are extremely proficient at handling everyday tasks, like browsing the Internet, word processing, or running business software. They do so at a fraction of the cost and complexity of quantum computers. It is accurate to view quantum computers as a powerful complement to classical computers, rather than a replacement. They will co-exist, each playing to their strengths, providing us with a comprehensive tool set for tackling the computational challenges of the future. Supercomputers, including their modular versions, harness their immense computational power and parallelism to cover large territories swiftly.

- *Quantum Advantage*: Quantum computing holds enormous potential, and its advantages could revolutionize various fields. Some people even believe that this technology will be capable of solving humanity's big problems, from climate change to the battle against various diseases. Researchers have used quantum computers to solve difficult physics problems. Quantum computers have plenty of potential as tools for carrying out complex calculations.

CHALLENGES

The implementation of quantum computation faces significant challenges, notably the decoherence problem, where qubits lose their quantum state due to external interactions. There are some disadvantages in quantum simulation of quantum systems. For example, it is very difficult to extract information from a quantum computer. Quantum computing is difficult to comprehend for most people. There is still a long way to go before quantum computing will be ready for prime-time. Other challenges of quantum computation include the following [14]:

- *Decoherence:* The main challenge to effective quantum computation is called the decoherence problem. Any interaction with a qubit at all will cause it to take a certain definite state. If a qubit takes a definite state, then the superposed coherence of the calculation is lost.
- *Noise:* Quantum systems are highly susceptible to environmental noise, leading to errors in computation. Putting too many computer components too close together or running the processor too fast generate so much heat that errors would result. Quantum computers are highly susceptible to noise, meaning qubits need protection against errors. The laws of quantum mechanics prevent the use of classical error correction protocols, requiring quantum compatible protocols.
- *Limitation:* The fact that the quantum state space becomes exponentially large in the number of qubits explains why quantum simulators (e.g. supercomputers using classical bits) have trouble to simulate quantum systems. From the moment you have around 50 qubits in a random state, no current supercomputer is sufficient to fit the state in memory and simulate its dynamics. At some point, classical computers will hit a complexity wall, and we will need quantum computers to break through it.
- *Scalability:* Building a large-scale quantum computer is a formidable challenge due to the delicate nature of maintaining quantum states.
- *Cooling Requirements:* Quantum computers need to be cooled to near absolute zero temperatures to minimize environmental noise, making them expensive and difficult to maintain.
- *Programming Complexity:* Quantum algorithms fundamentally differ from classical ones, requiring a new approach to programming and problem-solving.

CONCLUSION

The advent of quantum computers sets forth a new computing paradigm that can potentially result in game-changing efficiencies and computational performance. It harnesses the unique laws of quantum physics, such as superposition, entanglement and interference, which allow for information processing capabilities beyond those of classical devices. It promises to solve problems far beyond the capabilities of classical computers.

As quantum computing develops, scientists are working to identify tasks for which quantum computers have a clear advantage over classical computers. So far, researchers have only pinpointed a handful of these problems [15]. However, the recent claims of quantum supremacy by Google indicate that the era of quantum computing will soon be with us. Early processors leveraging quantum effects to perform classically impossible calculations are expected within the next decade. More information about quantum computation can be obtained from the books in [16-29].

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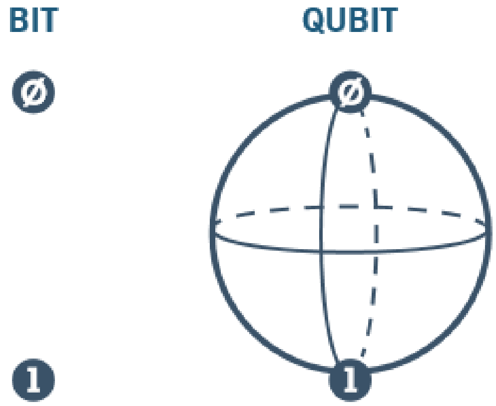

Figure 1 The bit and the qubit [3].

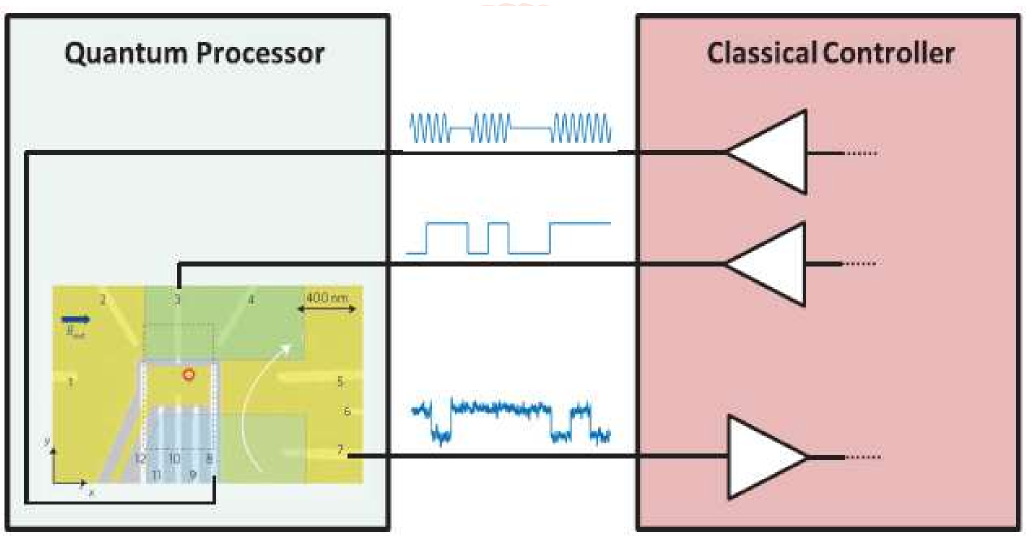

Figure 2 Quantum processor and classical electronic controller [4].

Figure 3 A representation of quantum computing [5].

Figure 4 A typical quantum computer [6].