THE VALUE OF QUANTUM

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ABSTRACT: This research paper, intended to be an introduction to the subject, discusses the field of quantum computing, describing its historical evolution and its properties that separate it from normal (classical) computing. While being able to potentially exponentially increase the speed of many computational tasks, practical quantum computing faces many challenges. Chief among these are the issues of coherence and error correction. Quantum systems are inherently unpredictable and susceptible to environmental interference, posing difficulties in maintaining the stability of quantum states (coherence). Furthermore, error correction in quantum computing remains an unresolved challenge, especially in the context of scalable solutions. This paper discusses these challenges in the context of today's cutting-edge quantum technology, including Google's Sycamore quantum processor. This exemplifies the current state of quantum computing while underscoring the current efforts being made to make today's computer processors practical.

Introduction

A quantum computer is a computer that uses **quantum mechanics** in order to make calculations. Unlike typical computers (hereafter referred to as "classical" computers), quantum computers do not use binary bits—sometimes referred to as **classical bits** in the context of the quantum computing field—to represent and manipulate data. Quantum computers instead use what is known as quantum bits, or **qubits** [6].

When a classical computer needs to make a computation, it does so by manipulating the states of the billions of **transistors** on its **central processing unit chip**, or CPU. A transistor is essentially a light switch inside a computer's CPU chip that can be in either an "on" state or "off" state. The computer can then read these real-world states as a binary value of either 0 (off) or 1 (on) and can execute commands based on them using the computational power of the CPU.

In contrast, a qubit also exists on a quantum computer's processor, except it can exist in many more states than just 0 or 1. The **wave-particle duality** theory of quantum physics states that many subatomic particles can be considered as both waves and particles; they neither fit the criteria as being fully a wave nor fully a particle [1]. A qubit, represented in the real world as a subatomic particle on a quantum processor, exhibits a similar property; it exists in many more states than a classical bit can, and thus, cannot be represented as a conventional bit [6].

Due to this property, quantum computers can make calculations at a much faster rate than classical computers. If properly developed and released to the public, quantum computers could have many massive, unprecedented effects on the way we use computers. In fact, a properly developed advanced quantum computer could easily solve some of the most difficult problems in computational science. This report will delve into the history of quantum computers, how they work on a technical level, and the impacts quantum computing technology may have in the future using real quantum hardware developed by Google as a case study.

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History

In 1959, the concept of the quantum computer was first theorized by famous American physicist Richard Feynman [7]. He saw the phenomenon of **Moore's Law -** the observation that the computer chips tend to double in density approximately every two years [9] and theorized that if transistor sizes ever reached atomic scales, computer scientists could take advantage of the laws of quantum physics to build more powerful computers. He thought that quantum researchers could utilize a phenomenon known as **quantum superposition**: the idea that a quantum particle can be in multiple states at once. In the same way that a photon can be considered both a particle and a wave, scientists could possibly manufacture a computer that could process bit input as both a 0 and a 1 at the same time. Later on, researchers also believed that the efficiency of quantum computers could be improved due to a phenomenon known as **quantum entanglement.** Quantum entanglement prevents particles under certain conditions from acting independently. This means that, for example, changing the spin of an electron could automatically change the spin of another electron that it is entangled with, no matter how far apart in space those two electrons are [1]. A quantum computer could take advantage of this property by using it to process multiple qubits of data at a time, amplifying the efficiency of its processor. This is similar to how a classical computer typically groups its bit data into bytes to better improve its efficiency when making calculations.

In 1998, the concept of a quantum computer was realized for the first time. Researchers from MIT and Berkeley developed one of the first quantum computers: a rudimentary, 2-qubit system that relied on oscillating magnetic fields to operate. [5]. This computer, while unable to make any meaningful calculations, was the first physical proof-of-concept of decades of scientific theory about the use of quantum physics applied to computer processing.

Quantum Hardware

Quantum computers, like classical computers, are based on groups of information that are processed by a computer's central processing unit [11]. Whether quantum or classical, almost everything a modern computer does comes down to information in either its short term or long-term storage, which is ultimately stored as bit information. The main difference between a quantum computer and a classical computer is the fundamental way in which these bits function.

Components of a Qubit

The qubit, like the classical bit, is the most basic aspect of the quantum computer's hardware. In a classical computer, the bit is stored in the computer's memory as a stored charge in memory cells built from electrical transistors. In contrast, qubits are stored as physical photons or electrons on a silicon chip, often at extremely cold temperatures [11]. Photons and electrons are small enough particles for the laws of quantum mechanics to apply, so when one is in superposition, a scientist can direct the processor to manipulate its spin using magnets and radio waves to produce different quantum states.

Quantum Computing Efficiency

The main reason quantum computers will be so efficient is due to two laws of quantum mechanics, already described above: superposition and entanglement. When a qubit is in superposition, it is in a special state where it can be considered as both a 0 and a 1 at the same time, and therefore, it is a bit that can be processed as two bits at once. If one bit in a classical computer can perform one calculation, then one qubit in a quantum computer can perform two. Therefore, when a qubit is entangled with another qubit, it can perform 2^2 (or four) calculations. When three qubits are entangled, they can perform 2^3 (or eight) calculations. Four entangled qubits can perform 2^4 calculations, and so on [11].

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In contrast, two classical bits can perform only two calculations. Three classical bits can perform only three calculations, four can only perform four, and so on. Thus, it is easy to see how quantum computing systems are theoretically able to outperform classical computers by many orders of magnitude. Of course, the speed of some classical computer processing can be improved by clever hardware and operating system design choices, but none of those designs change the fundamental truth that one classical bit can only ever be processed as one bit.

Challenges in Quantum Computing

The field of quantum computing is still highly experimental and likely won't be available for widespread commercial or academic use in the near future. There are many reasons for why this is so, but it comes down to two main problems, described in detail below: lack of coherence and lack of error correction.

Coherence

Coherence is the ability for the quantum computer to maintain its state long enough to make a meaningful calculation [11]. Quantum particles are inherently unpredictable and very sensitive to the environment around them. Even stray specks of light can cause interference within a quantum computer system. Therefore, it is very difficult for scientists to maintain control over them long enough to make meaningful calculations. When a quantum computer loses coherence, the electrons in its processor lose superposition and start to behave more according to the laws of classical physics [11]. Many of today's quantum computers do not have coherence times long enough to make very many calculations. This is why the first quantum computer was not able to make any useful calculations; it was only able to maintain coherence for a few nanoseconds before its qubits lost their state of superposition [11].

Error Correction

In both quantum and classical computing, error correction is the ability for the computer to ensure the reliability of the data that it receives across communication lines, such as emails and file downloads through the Internet. Classical computers utilize error detection and correction using various schemes to make sure the data it receives is reliable [3]. Quantum computers, on the other hand, are especially prone to errors, as the particles that make up a quantum processor are highly unpredictable. Thus, even when making internal calculations, quantum processors will need to have error correction schemes in order to make sure their calculations are correct [3]. This issue has scaling problems as well, since as the number of qubits in a processor increases, the number of errors made during calculations increases as well. So, it is therefore important to build an error correction scheme that can scale up with bigger quantum computers. However, no scalable quantum error correction schemes exist yet. Several proposals have been made but none have been proven to be scalable at the level that is needed for a truly practical quantum computer [11].

Case Study: Google's Quantum Processor

Introduced in 2018, Sycamore is the name of Google's newest experimental quantum processing unit, or QPU. A QPU fulfills many of the same tasks as a classical computer's central processing unit by carrying out the complex calculations and information processing tasks essential for various computational operations. However, Sycamore of course, distinguishes itself by making its calculations using quantum mechanics.

It has many experimental features that other quantum systems developed by competing companies currently do not, and so, makes an excellent case study for this research paper. Exploring the attributes of Sycamore provides insight to some of the most cutting-edge technology within the quantum field and the limits of the current capabilities of quantum computing. It also is a great showcase of the current problems the field is facing and what quantum researchers are doing to solve them.

Sycamore

The advancement of quantum computing has advanced significantly since the first quantum computer in 1998. Sycamore, with its 53 qubits, is at the forefront of Google's current quantum computing research. It is the company's latest foray into the field and runs on Weber, its quantum computer [8]. Like with all current quantum processors, lack of coherence time is an issue with Sycamore. However, its system is able to remain coherent for a long enough time to make complex, real-world calculations. For example, in 2022, it simulated traversable wormhole dynamics [8], an advanced topic in theoretical physics.

Google's current objective with this processor is to implement an effective quantum error correction algorithm. The way they are attempting to implement this error correction is by a process that groups some of the existing qubits on the system together as one "logical qubit." When the qubits in the system are grouped this way, the error rate goes down. Recently, Google announced that when they applied this algorithm to the Sycamore processor, the error rate actually decreased when applied to a greater number of qubits [8]. This is an exciting early indicator of how the scalability of quantum computing could be viable.

Quantum Supremacy

In 2019, Google claimed that the Sycamore processor had completed a task in 200 seconds that would take a state-of-the-art classical supercomputer 10,000 years to finish [10]. Thus, Google claimed the Sycamore processor had achieved **quantum supremacy.** Quantum supremacy, also known as quantum advantage, is the goal of having a quantum computer that can make calculations that no classical computer could make in a reasonable amount of time [4].

However, IBM, a company that also pioneers quantum computing research, dismissed Google's claim of quantum supremacy, stating that their calculations would only take about 2.5 days on the fastest supercomputer hardware at the time [10]. In response to IBM's critique, Google researchers argued that the classical supercomputer's estimated simulation time provided by IBM was based on specific assumptions and optimizations that may not accurately represent a practical scenario [10]. The disagreement between the two corporations was never concretely resolved, but the very fact that what exactly constitutes "quantum supremacy" is still debated within the field shows how new it is. It also underscores our ever-evolving understanding of quantum computers and how they may be used as tools to aid human progress in the future.

Quantum Computing as a Social Good

There are currently many barriers to making quantum computing practical, even for specialized scientific uses. However, if it were ever made practical for mass production and home use, it has the potential to revolutionize the way we use computers. A practical quantum computer would not only be able to greatly enhance the computing tasks we all do at home every day, but would also lead to critical advancement in the fields of chemical engineering, biological engineering, cybersecurity, and of course, artificial intelligence [2]. It could lead us to make better, more accurate models of viruses and disease pathogens, deepening our understanding of them and ultimately speeding up the time it takes to develop vaccines to protect people from getting sick. It would mean stronger cybersecurity measures being implemented on our country's critical infrastructure, better protecting ourselves against hackers and cybercriminals. Cancer biopsies could be evaluated much quicker if the biological material is fed through quantum systems, diagnosing people much faster and potentially saving lives.

Even though the technology sounds lofty and far-off, or even something out of science fiction, quantum computing research is an incredible investment in the future of humanity. Every field from manufacturing to space travel stands to benefit from a world where quantum computing is freely available to all. Given how revolutionary it will be, it stands to reason that it is something that everyone should benefit from in order to make a better world possible

Glossary of Terms

Central Processing Unit: Often abbreviated as CPU. It is the primary component of a classical computer and is responsible for carrying out many of the basic computational tasks a computer needs to function, such as arithmetic logic operation and data storage-related tasks.

Classical Bit: The most basic unit of information that a classical computer can process, determined by the states of a computer's transistor. Read by the computer as either a 0 or 1 and used in conjunction with millions of other bits to execute instructions.

Classical Computer: A traditional computer that processes information according to the classical laws of physics, as opposed to quantum physics. Its main processor contains transistors that can be read as either 0 or 1.

Coherence: The ability of a quantum computing system to maintain a synchronized quantum state over a given period of time, often due to interference within its immediate environment. When a quantum processor loses coherence, its qubits lose their state of superposition, and the processor is no longer able to process information on a quantum level.

Error Correction: A computer's process of detecting and rectifying errors during data transmission or storage. Since quantum computers are much more prone to errors, figuring out schemes to efficiently correct errors in quantum computers without introducing more of them is an ongoing challenge in the field.

Moore's Law: An observation by Gordon Moore, co-founder of the technology corporation Intel. In 1965, he predicted that due to technological advancements in the field, the number of transistors on an average computer's processing unit would approximately double every two years. This observation has remained generally true in the decades since he made this prediction.

Transistor: A microscopic semiconductor device that exists on the processing units of all modern classical computers, functioning as an electronic switch that can represent the binary bits 0 and 1. Modern computers contain tens of millions of these transistors in order to make complex calculations.

Qubit: Also known as quantum bit, it is the most basic unit of information that a quantum computer can process. Unlike classical bits, qubits do not exist in a strictly binary state, and therefore, they can be read by the computer as many different states and not just as a 0 or 1.

Quantum Entanglement: Also referred to as simply entanglement, it is a phenomenon in which two or more quantum particles in superposition can influence each other, no matter how far apart they are. This property of quantum particles is what makes quantum computing on large scales feasible.

Quantum Mechanics: Also referred to as simply quantum physics. It is the branch of physics that describes the special behavior of matter and energy at the smallest scales, typically at the level of subatomic particles. Distinct from classical physics, which describes the behavior of matter and energy at larger scales.

Quantum Processing Unit: Often abbreviated as QPU. Similar to a classical computer's CPU, it is the primary component of a quantum computer responsible for carrying out many of its

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basic computational tasks. A QPU is required to manipulate its quantum bits to make these computations.

Quantum Superposition: Also referred to as simply superposition, it is a state of a quantum particle wherein it can be said to be in multiple states simultaneously until it is observed by a third party.

Quantum Supremacy: Also referred to as quantum advantage, it is a term in the quantum computing field which refers to a point in which a given quantum computer can perform a specific computational task more efficiently than the fastest classical computer currently available.

Wave-particle Duality: The concept in quantum physics that a subatomic particle can exhibit both wave-like and particle-like properties under different circumstances. This observation is the basis for many concepts in the field of quantum physics.

References

[1] Ananthaswamy, Anil. "Particle, Wave, Both or Neither? The Experiment That Challenges All We Know about Reality." Nature News, N*ature Publishing Group*, 13 June 2023, www.nature.com/articles/d41586-023-01938-6. Accessed 26 Dec. 2023.

[2] Bova, F., Goldfarb, A., and Melko, R.. "Quantum Computing Is Coming. What Can It Do?". *Harvard Business Review,* 2021, https://hbr.org/2021/07/quantum-computing-is-coming-what-can-it-do. Accessed 7 Mar 2023.

[3] Cai, W., Ma, Y., Wang, W., Zou, C. and Sun, L. "Bosonic Quantum Error Correction Codes In Superconducting Quantum Circuits". *Fundamental Research,* vol 1, no. 1, 2021, pp. 50-67. Elsevier BV, doi:10.1016/j.fmre.2020.12.006. Accessed 7 Mar 2023.

[4] Choi, Charles Q. "How Many Qubits Are Needed for Quantum Supremacy?" IEEE Spectrum, *IEEE Spectrum,* 24 June 2021, https://spectrum.ieee.org/qubit-supremacy.

[5] Gershenfeld, Neil, and Kubinec, Mark. "Experimental Implementation of Fast Quantum Searching." *Physical Review Letters,* vol. 80, no. 15, 1998, pp. 3408-3411.

[6] IBM. "What Is Quantum Computing?" IBM. www.ibm.com/topics/quantum-computing. Accessed 26 Dec 2023.

[7] Press, Gil. "27 Milestones In The History Of Quantum Computing." Forbes, *Forbes Magazine*, 18 May 2021, www.forbes.com/sites/gilpress/2021/05/18/27-milestones-in-the-history-of-quantum-computing/?sh=654be4817b23. Accessed 26 Dec. 2023.

[8] Quantumai.Google, 2023, https://quantumai.google/hardware/datasheet/weber.pdf. Accessed 7 Mar 2023.

[9] Roser, Max. "What Is Moore's Law?" *Our World in Data*, 28 Mar. 2023, ourworldindata.org/moores-law. Accessed 26 Dec. 2023.

[10] Roush, Wade. "The Google-IBM 'Quantum Supremacy' Feud." *MIT Technology Review,* 13 July 2020, www.technologyreview.com/2020/02/26/905777/google-ibm-quantum-supremacy-computing-feud. Accessed 26 Dec. 2023.

[11] Shea, Shannon Brescher. "Creating The Heart Of A Quantum Computer: Developing Qubits". *Energy.Gov*, 2023, https://www.energy.gov//creating-heart-quantum-computer-developing-qubits. Accessed 7 Mar 2023.

N065175.01F
N65175_2024 CROW Journal-Draft 6_.pdf
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