IMPACT OF QUANTUM COMPUTING ON THE COMPUTING INDUSTRY

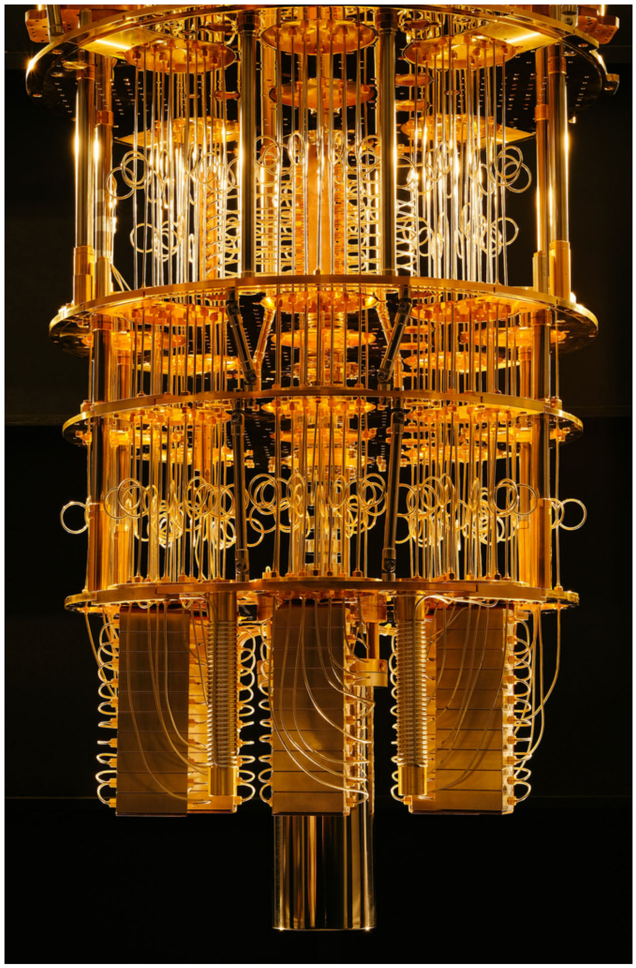

Figure: A Quantum Computer

Image From: [6]

Prepared by: Ridham Zalawadia

May 22, 2020

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Introduction

Computer Engineers try to find methods of improving the complexity of a program. Complexity is the amount of time taken by a program to solve a given problem. These methods can be aimed at either the hardware level or the software level. A Hardware Level improvement describes a change in the underlying physical structures that perform the computation. A Software Level improvement means an improvement in the algorithm (a series of discrete steps.)

"A new type of computing is needed, one that can take advantage of the very complexity that computers are trying to penetrate" [2]. Quantum Computing is an improved method of computing that results from a hardware level change in a computer. Through this fundamentally new method of computation, problems that could take trillions of years to solve could be compute within hours.

Background

Moore's law- the number of transistors per square millimeter of area on a microprocessor doubles every two years- is failing [7]. To speed up computations, scientists have been trying to decrease the size of transistors on microprocessors. However, they have reached a roadblock, clearly visible in figure 1**.** Classical computers solve problems by exploring every possibility. For example, given the problem of solving a maze, a classical computer explores every single pathway to find a solution. This approach is extremely time consuming. Quantum Computers bypass this roadblock.

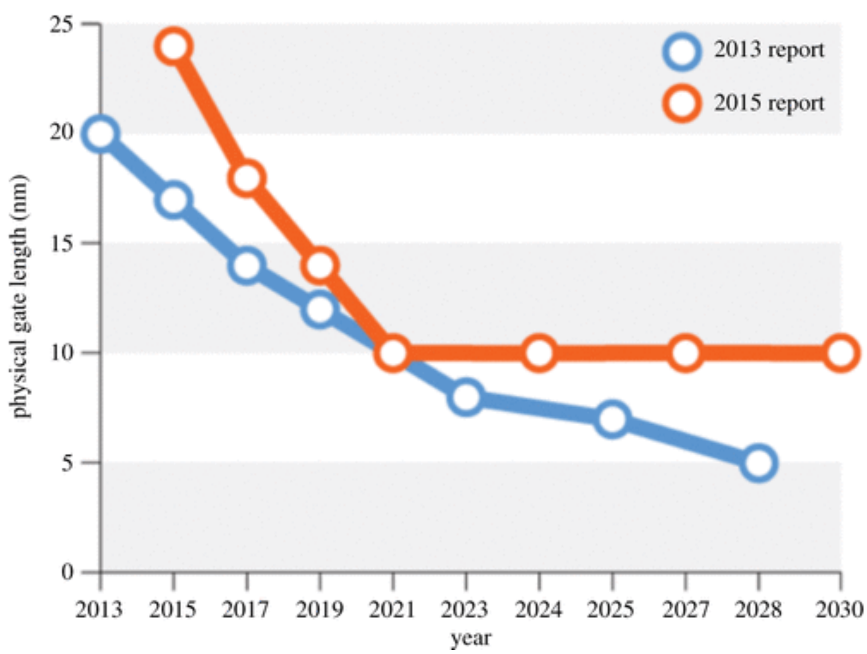

Figure 1: Depiction of the End of Decreases in Transistor Size

Data From: [7]

Design of a Classical Computer

Classical Computers all around the world follow the Von Neumann Architecture [8]. This architecture consists of, as shown in figure 2, an input device, an arithmetic logic unit (ALU), a control unit, a memory, and an output device. The ALU performs various operations such as the addition, multiplication, subtraction, or negation of two numbers. The control unit interprets instructions and directions numbers to the ALU for computation.

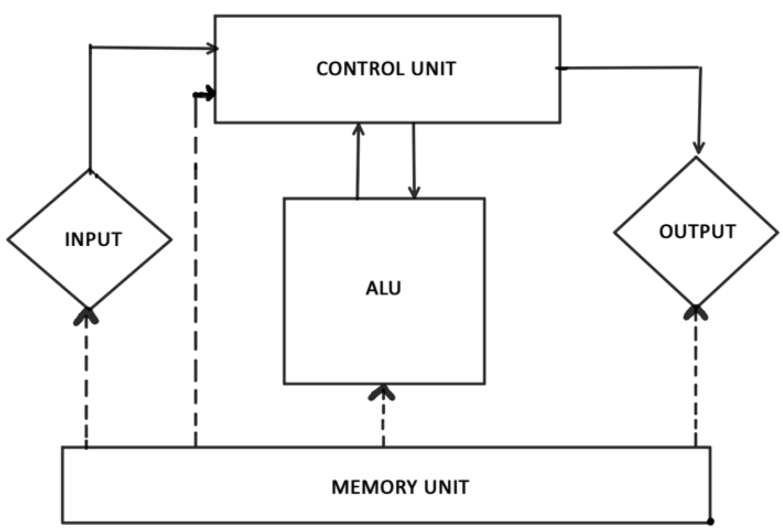

Figure 2: Architecture of a Classical Computer

Figure Adapted From: [8]

Data, such as which numbers to compute, and instructions, such as what operations to perform, are both contained in memory. This data is stored in the form of 1's and 0's. For example, number 2 is represented as a 10, number 3 as a 11, number 4 as a 100, and so on. All data- including images, text, and animations- are stored as binary numbers. When a program is run, instructions are fetched by the control unit from the memory and sent to the ALU for computation. All computers follow this architecture. Improvements in classical computing have been made by increasing the number of basic components, such as memory or transistors, in this architecture.

Limitations of a Classical Computer

In a classical computer, only a singular instruction can be received from the memory segment and only a singular operation can be performed by the ALU. This reveals a drastic inefficiency of the classical computer: its inability to perform multiple tasks at the same time. Although performance improvements help us mimic multiprocessing, the execution method is still the same. By changing this structure of singular computation, quantum computers are able to achieve its rapid speed.

Superposition

The concept of superposition is essential to understand the difference between a classical computer and a quantum computer. To understand superposition, we image electrons to have two properties: color (green or black) and shape (square or circle.) Furthermore, as shown in figure 3, we assume the existence of boxes that expel the electrons from their respective exits based on their property. If millions of random electrons are passed first through the color box, 50% output green and 50% output black (figure 3, color box). The result is the same for the shape box.

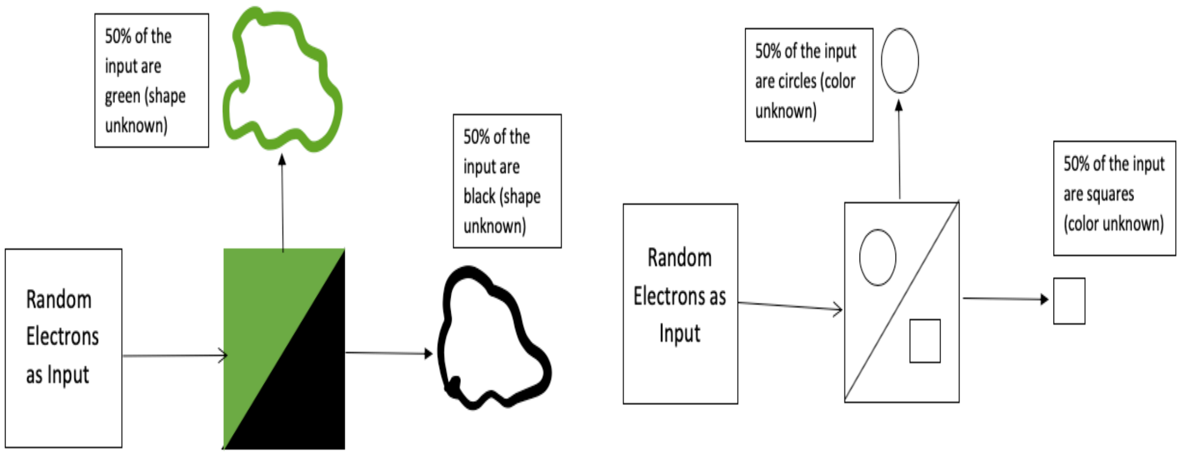

Figure 3: Color and Shape Box Behaviour

Adapted From: [1]

As shown in Fig 4, if random electrons are passed through the color box, and the resulting 50% green electrons are inputted into the shape box, with the resulting square passed through the color box, it is observed that 50% turn out black and 50% green. Furthermore, if the setup is as shown in Appendix 1, the resulting electrons out of the color box are 100% green. In the setup 1 figure 3**,** the shape property was known but the color property wasn't. In the setup 2 (Appendix 1), the color property was known but the shape wasn't, because the shapes were combined. It is observed that humans can only know one property, either shape or color. It is impossible to know both. This concept of being both square and circle or being both black and green is called superposition. The property of color and shape can be replaced with spin and position; the behavior remains the same.

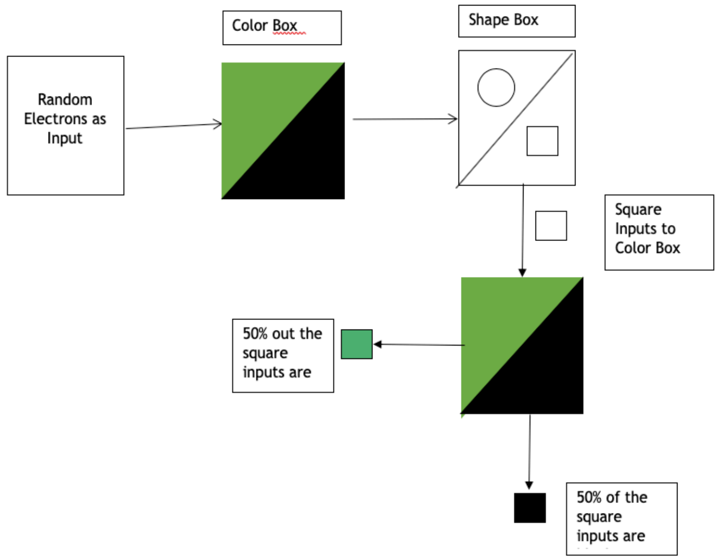

Figure 4: Quantum Behavior Example

Adapted From: [1]

Information Encoding in a Quantum Computer

In a quantum computer, quantum bits (q-bits) can be created with electrons, neutrons, semi-conductors, and any other materials that have quantum properties. Q-bits exist in both spin-up (1 in binary) and spin-down (0 in binary) states. This property enables us to encode 2 numbers in a bit. With 1 q-bit, two numbers can be stored as information. With 2 q-bits, 4 numbers can be stored as information. With 3 q-bits, 8 numbers can be stored as information. With n q-bits, 2^n numbers can be stored as information. With only 300 q-bits, a quantum computer could simulate the entire observable universe (2^300 atoms in the observable universe.) Through this method of information encoding, quantum computers are able to achieve its incredible speed.

Application: Molecular Simulations

A single caffeine molecule is extremely complex. Simulating a caffeine molecule in a computer would require enormous amounts of memory, something that hasn't been achieved yet. The complexity is due to the various spin states of electrons. Q-bits can simulate spin states due to its capability of storing enormous amounts of information. In fact, researchers are currently working on creating a quantum espresso computer library for users to use in simulations [9]. Being able to perform operations on molecules can help us discover new elements, thus advancing our understanding of the nature of the universe. Discovering new chemicals will also help humans create new technologies that could advance agriculture. These discoveries could solve global warming and world hunger.

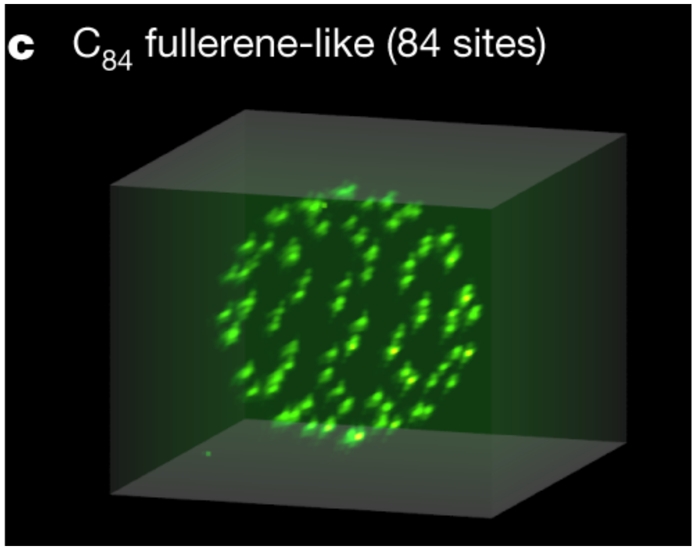

Figure 5: C-84 Simulation

Adapted From: [4]

Researchers have been successful at simulating basic three-dimensional atomic structures [4]. These atomic simulations, shown in Fig 5, could be used in various complex 3D structures such as Chern insulators- insulators used in quantum computers for maintaining temperature. The advantages of simulations to the humankind are enormous.

Economic Benefits

Governments and Banks are heavily invested in quantum computing research. The primary driver for the validity of these investments is economic growth. Machine Learning- training machines to make decisions by themselves- applied to quantum computing has massive benefits. Currently, machine learning models are used by massive banks to predict market demand and supply based on historical data. Investment in quantum computing can help banks reduce the computer decision error bounds (the percentage time they are wrong.) Not only could banks better detect fraudulent transactions, but they could also prevent hacks by establishing quantum encryption [5]. The current encryption algorithm, although unbreakable with current technology, is easily breakable with a quantum computer. The efficiency can be seen in the Fig. 6. Benefits of Quantum Computing can be traced to virtually every sector.

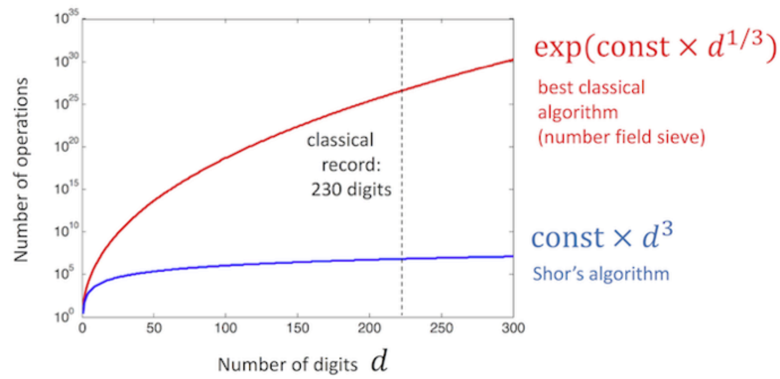

Figure 6: Efficiency of Shor's encryption breaking algorithm.

Adapted From: [10]

Conclusion

Quantum Computing has the power to directly affect our lives, not only by increasing a person's standard of living, but also by increasing human's potential. Investment and research in this field will most likely lead to advances in technology that will solve problems that may have otherwise seemed unsolvable. It has the potential to simulate universes and answer the question: "Are we living in a simulation?" These answers are only achievable if the human society pays particular attention to it. To push the boundaries of our understanding, we should consider pursuing quantum computing.

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Appendix 1

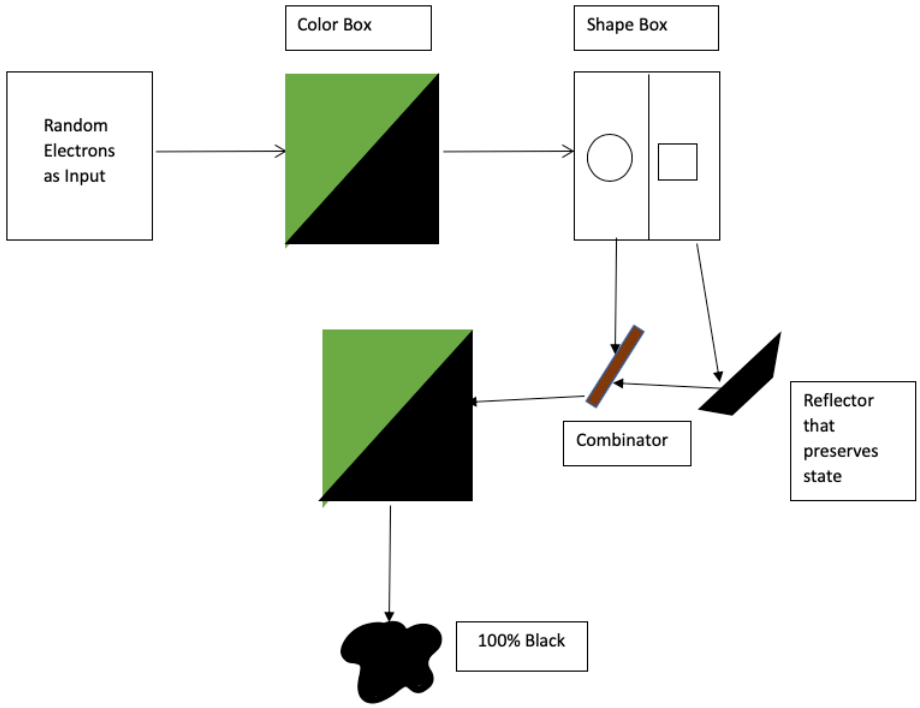

Figure 6: Quantum Behaviour Example

Adapted From: [1]