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THE POWER OF QUANTUM COMPUTER AND ITS LIMITATIONS

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ABSTRACT

Quantum computers have grown as an essential study in the field of physics and computer science throughout the country since 20 years ago although at the time, the existence of quantum computers is still a mystery. However, studies on quantum computers have successfully provided a new breath in the development of the latest technology. Thus, the brief descriptions in this paper are aimed to guide computer science experts to fully understand how the quantum computer differs from the current computer. Next, this study will explain the basic concepts of quantum mechanics that make quantum computers more powerful than other computers today. Then, two algorithms that apply the concepts in quantum computers will also be explained in details. Finally, this paper will describes the constraints faced when developing quantum computers in reality.

KEYWORDS: Quantum computer, quantum bit, entanglement, quantum cryptography, image processing, artificial intelligence, quantum algorithm.

I. INTRODUCTION

The field of computer science was explored around 1936 by a mathematician named Alan Turing [10]. Turing had built a computer model known as a programmable Turing machine for calculating mathematical calculations. This study was continued by Von Neumann when he successfully created a computer using electrical components. The computer created by Von Neumann was based on a simple computer model theory that included all important components which are similar to the computer model built by Alan Turing. The evolution of micro and optoelectronic devices had led to the rapid development in the field of computers. Previously large components of computers have been converted to smaller sizes. By reducing the size, it allows computer components to be loaded into a small-sized computer chip capable of storing and processing data with a large capacity.

From this evolution, Gordon Moore, co-founder of the Intel Company [10] introduced Moore's law in 1965 after realizing that the number of transistors loaded in the computer chip will double exponentially every two years. This had caused the transistor’s size to shrink. His prediction was proven to be precise because some of these laws are being used in the semiconductor industry to expect long-term output as well as set targets for research and development purposes. However, most researchers during that time assumed that Moore's law faced constraints in transistor storage at a later time when the size of the computer chip becomes too small; down to atomic size. Intel companies reported that the use of the latest chip technology requires more power over faster execution for processing as well as assuming the end of Moore's law [31]. Thus, a shift was done by switching to a quantum computer to replace the current computer because only a quantum computer can process data in atomic size. Accordingly, the time taken to process data can be accelerated exponentially using the quantum parallelism concept, which is a method in quantum computers that is capable of performing two simultaneous processing. Therefore, the field of quantum computers is an option because of its ability to process data faster than the current computer.

In 1985, David Deutsch [10] considered the law of physics to simulate the universal computer quantum problem more accurately. He attempted to define computer tools that were capable to simulate precisely in any physical system. Hence, he was the first person to consider quantum-based computer tools as well as to introduce the modern concept of Church-Turing machine known as the Universal Quantum Computers. However, Deutsch cannot determine whether this conjecture is sufficient or not to simulate any physical system. He assumed that the quantum computer has the power of compute data that exceeds the current computer.

Additionally, Richard Feynman [4,10] a physicist has put forward in 1982, the idea of using a quantum computer that uses the concept of quantum mechanical phenomenon. He also noted that there is a constraint in simulating quantum mechanics in the current computer. Therefore, Feynman proposed the development of a quantum mechanics-based computer to overcome the problem. Furthermore, quantum computers have the advantages with the existence of new concepts of quantum bit (qubit), superposition and entanglement that are capable of processing more data faster than the current computers.

Today, there are many recent achievements made by scientists in the field of quantum computers. One of them is the creation of D-Wave by Eric Ladizinsky, the head of science experts with his colleagues at the D-Wave manufacturing company. D-Wave is said to be the first quantum computer to be built theoretically by using nitrogen fluid to cool the hardware. It is also known as a quantum computer simulator based on some of the predicted benchmark results [3,15,17]. D-Wave has succeeded in producing 439 qubits that could satisfy standard qualification. In line with D-Wave construction, the company has partnered with Google companies to test the types of solutions generated by quantum computers and compare these solutions to the current CPU. As a result, Hartmurt Neven, Google's Engineering Director has successfully proven a solution with this quantum simulator, which is capable of processing at 108 times faster than the current computer. Neven has stated in his blog that the D-Wave is able to counter the current computer for a huge optimization problem at 100 million speeds [16].

Additionally, the development of quantum computer technology has attracted Intel computer companies to study deeper. Intel chief executive officer Brian Krzanich issued a promissory note to allocate 50 million US dollars and provided an independent source of information and expertise in this study for the long term. The study was conducted in collaboration between CPU giant and QuTech, a quantum study institute at TU Delft, the largest and oldest technical university. This research was conducted at a laboratory at College Park, Maryland with a focus on quantum cryptography [29]. The United Kingdom (UK) has allocated 270 million pounds Sterling for this quantum technology research [19].

This paper is divided into four main sections. Section 2, describes the basic concepts of quantum mechanics used in quantum computers. This section aims to explain the mathematical formulas and notations used with the basic concepts of quantum mechanics in quantum computers. This section also describes the concept of quantum bits (qubits) that represent the data during the calculation. Section 3 briefly explains two well-known algorithms, i.e., the Shor algorithm and the Grover algorithm. The Shor algorithm is also known as a polynomial time-factoring algorithm. This algorithm utilizes the quantum parity advantage by using the Fourier analog quantum transformation [25] exponentially. Meanwhile, the Grover algorithm [7] is used in data searching that is not sequenced in steps on quantum computers. Computer capabilities are now only limited using polynomial steps. The current computer cannot exceed the speed of Grover's algorithm, which is able to complete the search for a short period of time exponentially. Applications of quantum computer are described in Section 4 including quantum cryptography, image processing and artificial intelligence. Section 5 explains the advantages of quantum computers and constraints faced to build a quantum computer.

II. BASIC CONCEPTS OF QUANTUM MECHANICS

Quantum mechanics, or also known as quantum physics is one of the branches of knowledge in physics theory which describes physical phenomena of nature in the form of atoms or sub-atoms. The quantum mechanical phenomenon is difficult to understand because the description is about the behavior of photons, electrons and other atoms of very small sizes that cannot be seen with the naked eye. However, these quantum mechanics applications can be seen through superconducting, LED, laser, transistor, and semiconductor magnetics such as imaging and electron microscopy.

This section is divided into two subsections. First, the notation used to measure the quantum state. The second subsection explains the concept of quantum bit (qubit) used to represent data during information processing.

Space of State and Ket / Bra Notation

Quantum state in Hilbert space represents the space of state in quantum system, which includes position, polarity and spin of elements. For quantum computers, the system used is a finite quantum system that uses vector space for complex vector dimensions inner product of a vector.

The quantum state and the transformation of the state are represented by vector and matrix or in bra / ket notation created by Dirac [25]. The ket notation, $|x\rangle$ represents the column vector and is used to describe the state of quantum. The bra notation, $\langle x|$ is complement for ket notation to represent the conjugate transpose. As an example, two bases $|0\rangle$ and $|1\rangle$ in the ket notation in Equation (1):

$$|1\rangle = \begin{pmatrix}0\\1\end{pmatrix}, |0\rangle = \begin{pmatrix}1\\0\end{pmatrix} \tag{1}$$

while the conjugate is as follows:

$$\langle 1| = (0 \quad 1), \langle x| = (1 \quad 0) \tag{2}$$

The inner product of the two vectors is a combination of $\langle x|$ and $|y\rangle$ simplified as $\langle x|y\rangle$. For example, vector $|0\rangle$ is a unit vector, hence, the inner product is $\langle 0|0\rangle = 1$. Since $|0\rangle$ and $|1\rangle$ are orthogonal, then$\langle 0|1\rangle = 0$. The outer product is represented with the notation $|x\rangle\langle x|$. For Example,

$$\begin{aligned}|0\rangle\langle 1| &= \begin{pmatrix}1\\0\end{pmatrix} \otimes (0 \quad 1)\\ &= \begin{pmatrix}1(0 & 1)\\0(0 & 1)\end{pmatrix}\\ &= \begin{pmatrix}0 & 1\\0 & 0\end{pmatrix}\end{aligned} \tag{3}$$

Quantum bit (Qubit)

Quantum bit or qubit [12] is a unit vector for two dimension complex vector space that is represented with standard bases $\{|0\rangle, |1\rangle\}$. Orthonormal bases $|0\rangle$ can be represented as $|\uparrow\rangle$ or $|\nearrow\rangle$ for photon polarization and spin up or spin left for electron. $|1\rangle$ can be represented as $|\rightarrow\rangle$ or $|\nwarrow\rangle$ for photon polarization and spin down or spin right for electron. Qubit is used to represent the element in computing data and information storage in quantum computer. Qubit in quantum is equivalent to bit 0 or 1 in the current computer [24]. Qubit can be represented by the state of unit vector $|0\rangle = \begin{pmatrix}1\\0\end{pmatrix}$ and $|1\rangle = \begin{pmatrix}0\\1\end{pmatrix}$.

Figure 1 illustrates the qubit representation in geometry using the Bloch sphere. The bits can only be represented at the North pole position, $|0\rangle$, and the South pole, $|1\rangle$. Qubit can be described at any point on the surface of the sphere. The surface of this sphere is a 2-dimensional space representing the state of the space for a pure state.

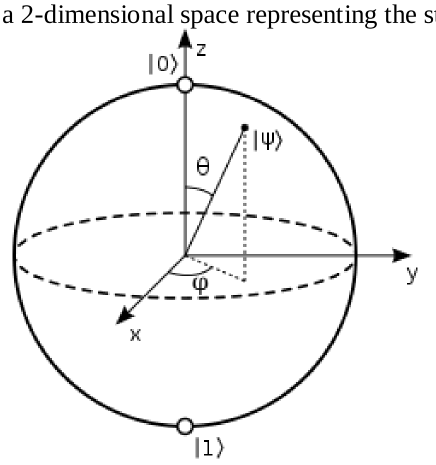

Figure 1. Qubit representation based on Bloch sphere

III. QUANTUM ALGORITHM

This section discusses the two famous algorithms, namely the Shor algorithm and the Grover algorithm.

The Shor Algorithm

The Shor algorithm is an extension of Simon's algorithm. In 1994 [14], Peter Shor had published his algorithm and is one of the most important algorithms in the world representing quantum computers. This algorithm is a modification of Simon's algorithm to a periodic function $f(x) = f(x + a)$ with the addition of two modulo bits. In 1993, Shor had shown that the quantum computer must be in the form of a major factor principal of the combined integer in polynomial time. He used factoring problems to be applied in finding periods in a function. In detail, it includes the process of finding two prime numbers of factors p and q for $N = pq$ and the duration of function $f_{a,N}(x) = a^x \text{mod } N$, with a as the arbitrary number, smaller than N and the prime number that has no common factor with N. This function is periodically with period r and dependent on values a and N [20].

Shor's algorithm is also able to factor the number exponentially faster than the current computer because the it is dependent on the capability of a quantum computer being available in many states simultaneously. The Shor algorithm will assay the number to prime factor as polynomial at one time, which equals as the input size that has been calculated. On the other hand, the current computer can takes a long time to do the same task, even though it has been done exponentially. This causes difficulty in the field of cryptography because the system uses public keys (represented in prime numbers) during communication. For example, many RSA security systems use this in electronic financing, such as credit card transitions, using a key that is made from the product of two major prime numbers. Shor's algorithm will easily break the key to counter the problem of RSA systems and other cryptographic systems [18].

The Grover's Algorithm

The Grover's algorithm differs from the Shor's algorithm because this algorithm is a search algorithm used to search certain values in an unorganized database. In 1996, Grover considered a problem in databases and introduced a more meaningful and efficient algorithm than an existing algorithm that was not an exponent form [20]. In the current computer, the fastest solution that can be done is a simple search conducted by checking for each item looking one-by-one. This means that on average, current computers have to search nearly half the data in order to find the right value. On the other hand, Grover's algorithm is able to solve this problem by a square root faster than the current computer. This is because in a quantum system, the situation can be in a superposition state and simultaneously determines the multiple solutions for each item searched [18].

IV. QUANTUM COMPUTER APPLICATION

This section describes the quantum computer applications, which include three fields, i.e., quantum cryptography, image processing, and artificial intelligent.

Quantum cryptography

Quantum cryptography describes the effects of quantum mechanics on quantum communication to destroy the security of cryptographic security systems. Quantum cryptography measures the state to detect the eavesdropper in quantum system immediately. This concept involves the production of a pair of photons that are constantly entangled. Two parties who want to communicate will measure every photon used. The eavesdropper would try to detect the photon used and retransmit photons in the system for not being detected by the party during the communication held. However, the detection of photons by the eavesdropper will destroy the entanglement between the photon, which can be easily detected by the party. Thus, the system will be safe without any eavesdroppers [18].

An example that is always associated with this cryptography system is the process of sending a security key through quantum communication without any eavesdroppers. This can be seen in the importance of quantum cryptography not only to allow security protocols, such as BB84 [5] and B92 [6] to be used. This can be seen during the transmission of information between Alice and Bob during communication, Alice creates a random bit from random base to send one photon, either 1 or 0 to Bob. Bob will receive this photon without knowing the basis used by Alice. Bob measures this photon randomly for both bases. Next, Alice and Bob will determine the chosen base to be measured through the public channels and throw any bits not measured by Bob on the same basis as Alice. This process allows the transmission of information in a secure channel because the eavesdropper needs to guess the basis used by Alice and Bob in this channel. If Alice and Bob chose the same base, but the eavesdropper chose a different bases, then the opportunity for Bob to measure the bit value differently from what

Alice sends is 50-50. With that, Alice and Bob can detect eavesdropper by comparing and removing certain numbers of bits other than the bases they have chosen.

Image Processing

Image processing is one of the important areas in the current computer field because of the need to extract vital information from the three-dimensional world. Among the frequent studies are the complexity algorithm, 3D image representation to 2D, and visual information. In the sequence of the development of quantum computers, the image of processing field has become influenced when the image processing field is able to extend using a quantum computer. Quantum image processing uses quantum computer technology to capture, manipulate, and refine images obtained in quantum format for specific purposes. In general, the image retrieval requires a representation to encode the image based on mechanical quantum. Many studies related to quantum computers include qubit representation to encode quantum images, quantum image characterization using Lattore's real ket and flexible representation of quantum images from 2003 to 2011. Now, researches are more focused on the development of basic equipments needed to process images in quantum computers. Therefore, in order to make it a success, computer scientists must determine and implement "disruptive algorithms" and "killer apps" (high impact apps) to demonstrate the power and advantages of quantum image processing compared to existing [32, 33].

Artificial Intelligence

The main contribution of quantum computers in the field of artificial intelligence is the creation of real random numbers. Actual random causes increased performance on genetic programming and other automated induction programming methods. Thus, Monte-Carlo, simulated annealing, random coating and other analogy search methods are expected to benefit. Two researches related to quantum artificial intelligence are the quantum games theory and quantum evolution programming. Artificial intelligence techniques that have been built and quantum computer features that can reduce the time complexity to the polynomial range are applied in NP-issues [26].

The lab, known as Quantum Artificial Intelligence Lab (QuAIL) has been established in collaboration with NASA, Universities Space Research Association, and Google (Google Research). This lab was built to research how computer quantum can help with machine learning and other computer science problems. The main goal of QuAIL is to show in the future those quantum computers and quantum algorithms are able to increase agency capabilities to solve optimization problem in aeronautics, as well as earth and space exploration. Their researchers also hope to discover new findings in solving real world problems with the use of sophisticated technology. Their aim in the next five years is to develop quantum artificial intelligence algorithms, decomposition problems, application software techniques and classic quantum hybrid algorithms [22].

V. ADVANTAGES AND LIMITATIONS OF THE QUANTUM COMPUTER

In this section, the advantages of a quantum computer, compared to the current computer, and the limitations and challenges to build quantum computer are explained.

Advantages of Quantum Computer

Quantum computers have special features, known as quantum superposition and entanglement that make them more powerful than the current computers.

Quantum superposition

The current computer processes data stored in bits that only represent two values of either 0 or 1. The current computer also performs calculation on the string bits. Thus, the string of n bits only represents one of the 2^n different values. Compared to quantum computers, the current computer uses qubits to store data and can exist in superposition state, as shown in Equation (4) [10,25]:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{4}$$

where $\alpha, \beta \in \mathbb{C}$ are complex dimensions and $|\alpha|^2 + |\beta|^2 = 1$. For example, in the case of polarization, if the superposition state is measured based on the orthonormal bases $\{|0\rangle, |1\rangle\}$, the probability of measuring $|0\rangle$ is $|\alpha|^2$ and the probability of measuring $|1\rangle$ is $|\beta|^2$.

If the bit is manipulated using logic gate, the superposition state can also be manipulated by using quantum logic gate. The quantum register contains n qubits that can exist in 2^n different superposition conditions at one time. It shows the ability of a quantum computer, which can perform simultaneously for all qubit conditions that cannot

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be performed on the current computer. This feature is called quantum parallelism, which is one of the advantages of quantum computers.

Figure 2 [8] illustrates a vector that shows the direction of the value between 0 and 1, which is known as superposition.

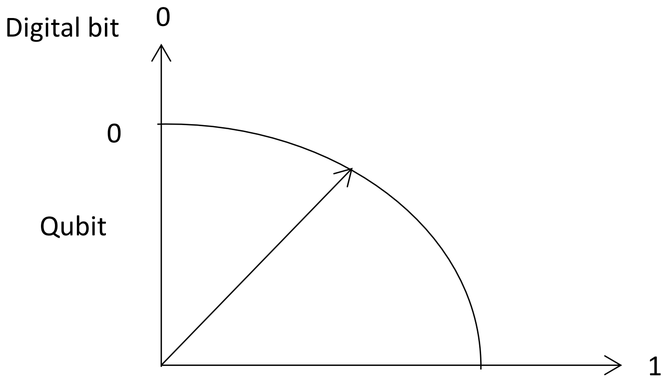

Figure 2. Superposition state

Table 1 summarizes the differences between the current computer and the quantum computer in some of the major parts related to the computing and communication mechanisms [8].

Table 1. The different between current computer and quantum computer

CURRENT COMPUTER	**ITEMS**	**QUANTUM COMPUTER**
Bit: 0 or 1	**DATA REPRESENTATION**	Qubit: 0, 1 and superposition
1 in one time	**NUMBER OF SIMULTANEOUS CALCULATION**	More than 1 in one time
Bit movement in logic gate	**CALCULATION METHOD**	Change of atom state
Data can be copied without interruption	**DATA TRANSMISSION**	Data cannot be copied or read even without interruption
One direction	**DATA NATURE**	Many direction simultaneously like overlapping of waves
Low: Communication channel easily can be interrupt.	**SAFETY**	High: Noisy in communication channel can be detect easily

Entanglement

Entanglement or quantum correlation is the immediate relationship between two or more particles without considering the distance between them [27]. Since the 1990s, a lot of researches have been ongoing since the current computer does not have this feature, including qubit and superposition [21]. Entanglement makes the quantum computer more powerful because the transmission of information can be done simultaneously. Measuring the condition of one of the qubits of an entangled pair of qubit will immediately determine the condition of the other qubits. For example, Figure 3 shows a pair of entangled photons separated at a long distances. Photon A represents the upper spin, while photon B is entangled with photon A, representing the lower spin automatically [30].

Figure 3. Entangled photons separated at long distances

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The latest study involving entanglement in the journal "The Optical Society's (OSA)" [27] describes a microscopic study that can match the large-scale optoelectronic components by using photons that are entangled with one another. Spanish scientists have acknowledged the advantages of quantum computer production using faster processing. They have successfully acquired 103 dimensions through two entangled particles [28]. Physicists from the Massachusetts Institute of Technology (MIT), Cambridge and the University of Belgrade have also developed new techniques that allow 3,000 atoms to be entangled using a very weak single photon [9].

Systems that use the concept of entanglement can be divided into two types, namely two qubit systems and multiqubit system. The difference between the two qubit entangled and the multiqubit entangled is quite large in terms of the determination of the degree of entanglement and classification of entanglement classes. This is because multiqubit system structure is more complicated and some problems could occur [2].

Limitations of the Quantum Computer

The qubit used to represent the data is able to store data in large quantities at a time. For example, 100 qubits can store 1,267,650,600,228,229,401,496,703,205,375 different numbers. This amount is a trillion times more storage capacity than the current computer. This shows how powerful quantum computers are able to process information faster than the current computers. However, in an experiment, creating that much data is harder [11,23]. Even though the process of making quantum computers can be said to be well-established, the manufacturing of qubits in quantum computers is much harder than the existing bits. Accordingly, no one is able to prove the best way to build a quantum computer.

To date, several techniques have been implemented, such as ion, electron, or other particles being trapped, using superconductors to create microscopic quantum circuits, and the use of complex photons and optical equipment. All these techniques have been successful, but on a small scale as they are difficult to realize on a larger scale. This is because the existence of decoherence would be trying to be eliminated during the process. Hence, quantum systems that want to be built should be without external interference because it can turn a quantum computer quantum into current computer [11,13]. Additionally, quantum computers use the principles in quantum mechanics to retrieve information and this is impossible to build on current computer. Computational problem solving for certain problems, such as integer factorization, can be done faster than the current computer, but previous analysis has concluded that quantum computers can only solve minimal problems [1].

VI. CONCLUSION

Quantum computers are able to solve problems that current computers cannot because of the special features that exist in them. However, to build quantum computers is more challenging when trying to be applied in the real world. It would require more experimental studies to be done to make sure that the quantum computers can be used in real the world the same way as the current computers.

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