An Introduction to Quantum Computers Architecture

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***Abstract*—Since 1982 that Richard Feynman proposed the idea of quantum computing for the first time, it has become a new field of interest for many physics and computer scientists. Although it's more than 30 years that this concept has been presented but it's still considered as unknown and several subjects are open for research. Accordingly, concepts and theoretical reviews may always be useful. In this paper, a brief history and fundamental ideas of quantum computers are introduced with focus on architecture part.**

Keywords— Quantum, Computer, Hardware, Qubit, Gate

I. INTRODUCTION

Concept of quantum computation was firstly introduced by famous physicist, Richard Feynman in 1982. He believed that quantum phenomenon cannot be simulated by universal computers. In his opinion, nature of classical computers is not capable of describing quantum mechanics problems, so designing a computer with quantum logic and structure seems inevitable [1].

At the beginning, quantum computer should be defined clearly. A quantum computer is a machine, which obeys quantum mechanics rules and utilizes quantum states or superposition of them for benefiting from their advantages in computation and simulation. Some of these advantages can be considered as factoring big numbers and finding marked items in very large databases using Shor's and Grover's quantum algorithms respectively [2]. But quantum computing is not limited to just these problems and as time passes, complexity, type and size of problems are changing.

Many of current works are focused on quantum error correction or related algorithms. Nevertheless, because of the importance of quantum computers structure, this paper will concentrate on architecture and its purpose is to provide a better outlook.

In the first section, a brief history of classical and quantum mechanics and the reasons of classical mechanic's breakdown is discussed. Then basic concepts of quantum mechanics including wave function is considered. Third section will cover definition of quantum bit (qubit), its structure and basic gates. Finally, in the fourth section, basic ideas of quantum computers architecture will be proposed.

II. QUANTUM MECHANICS

A. The beginning of qunatum mechanics

In order to better understand that what quantum mechanics is, first we should know its origins. Simply it can be said that some failures of classical mechanics lead to creation of quantum mechanics.

In the seventeenth century, Isaac Newton initially described classical problems like motion of rigid bodies modeling and formulation. It was working very well for those kind of problems and accordingly it was thought it's also true for explaining atomic phenomenon but it failed.

Classical mechanics was no longer capable of describing modern physics experiments. One of the most important of those experiments was black body radiation. Black body (Fig. 1) is something like a cavity with a hole which can absorbs and emits all spectrum of frequencies radiation uniformly [3].

According to classical Rayleigh-Jeans law, it was supposed that by increasing temperature (T), the intensity would increase by proportion of T^4 but related experiments showed that it is not true. In this case, Planck's formula, which was independent of temperature, worked properly and it was first origination point of quantum mechanics.

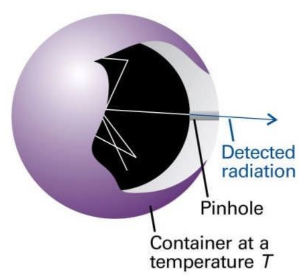

Fig. 1. Black body is a physical object which can absorbs all electromagnetic radiation independent of frequencies [3].

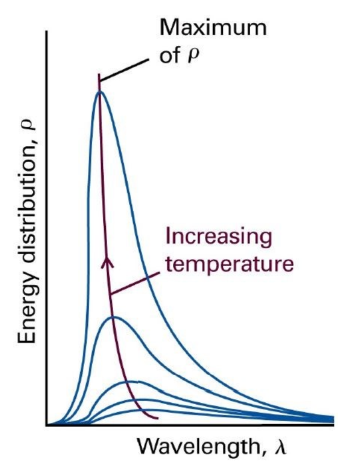

Fig. 2. Comparison of black body energy distribution predicted by Rayleigh-Jeans and Plancks model [3].

Another significant examination that confirmed defeat of classical mechanic was photoelectric effect which investigated by Albert Einstein in 1905.

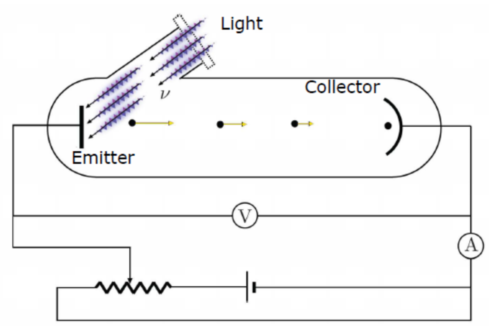

Fig. 3. Typical Photoelectric expriment setup which consists of a photocell, collector and voltmeter [4].

In this trial, electromagnetic waves in form of light is emitted on a surface of metal and in consequence, some electrons will be released. With this experiment, Albert Einstein offered that light consists of discrete quantum of energy called photons with energy equals to $\hbar\,\upsilon$, which $\hbar$ is Planck's constant and υ is the emitted photon frequency [4].

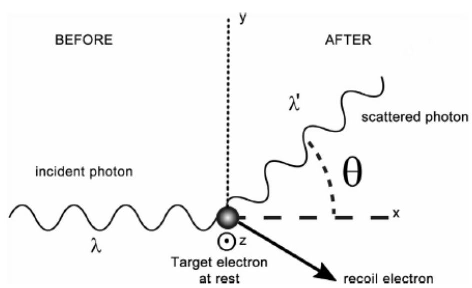

Fig. 4. Arthur Holly Compton in 1923 launched an exam that showed particle charachteristic of a wave [5].

Compton effect was one of the most important works which empowered initial thoughts about particle characteristic of waves. In this experiment, X-Ray photon is scattered to collide with an electron. After collision, energy of the photon is decreased and will scattered by another wavelength that is increased. The reason of energy decrement is that a part of scattered photon's energy is transferred to the electron, so the electron is recoiled and photon scattered again in another angle [5].

Compton effect and photoelectric experiment together presented particle-wave duality concept. In other word, scientists came to this point that both wave and particle has common characteristics in different situation.

B. Wave function

After clarifying wave properties of atomic particles like electron, it seemed necessary to define a wave function for describing their behavior. Erwin Schrodinger in 1925 proposed a mathematical equation for describing quantum systems over the time. It has offered in two form, time-dependent and time independent as it is shown in (1) and (2) respectively [6].

$$i\hbar\frac{\partial}{\partial t}\psi(r.t) = \left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(r.t)\right]\psi(r.t) \quad (1)$$

Where ψ presents the wave funcation, μ is reduced mass and V is the potential energy.

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(r)\right]\psi(r) = E\psi(r) \quad (2)$$

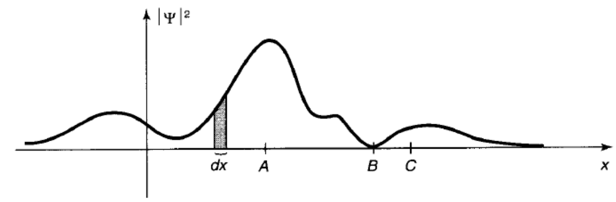

Fig. 5. Wave function diagram of an atomic particle. Since the exact position of a particle is not clear, the probanility function is measured [6].

In Fig. 5. A typical wave function is shown. The square of wave function $|\psi|^2$ represents probability of particle presence within position of x+dx. According to this definition, presence probability of the particle in A is more than B and C [6].

III. QUANTUM BIT (QUBIT)

Bit is the most fundamental concept in computer science. There are two state for the bits in classical computation, which are 0 and 1. Nevertheless, the subjects are completely different in quantum space. There isn't limited state for the electrons. As mentioned in previous section, atomic particles behave like a wave and they do not have deterministic position. As a result, quantum information and computation benefited from in many aspects such as its foundation, which is quantum bit or qubit [7].

A qubit has a state as well and it might be whether $|0\rangle$ or $|1\rangle$ but unlike classical computation, it also can be in unlimited states (Fig. 6) which are superposition of these two basic state which is a mixture of two arbitrary states and described by the wave function shown in equation (3).

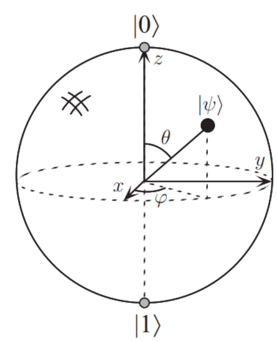

Fig. 6. Quantum bit (qubit) reprsented by an sphere called bloch. It's an infinite space where the probability of the qubit presence is measured by the square of its wave function which would be $|\psi|^2$ [8].

$$\psi = \alpha|0\rangle + \beta|1\rangle \quad (3)$$

$$|\alpha|^2 + |\beta|^2 = 1 \quad (4)$$

Where $|\alpha|^2$ offers probability of measuring the qubit in state $|1\rangle$ and $|\beta|^2$ for the state $|0\rangle$ as well. As mentioned this qubit might be in a superposition of these two known states like what has shown in (4) which make this space infinite. This is the most significant different of bits and qubits.

This infinite space brought many advantages for quantum computers that are like a dream in classical computers world and as a result, many complex problems are now solved by quantum computers in much shorter times and less complexity like Shor's algorithm for factoring large numbers and Grover's for finding marked items in huge databases.

Before focusing on quantum computers architecture, it's appropriate to have a brief review on basic quantum gates. Classical computers consist of circuits and wires and bit streams which forms data units. Suppose that there's one single bit, in this case the only gate that can work on it is NOT gate. But for single qubit systems, there are more than one gate that can operate on them. Some of the most well-known of these single qubit gates are shown here [8].

$$\text{Pauli I (Identity)} \equiv \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{5}$$

$$\text{Pauli X (NOT)} \equiv \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \tag{6}$$

$$\text{Pauli Y} \equiv \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \tag{7}$$

$$\text{Pauli Z (Phase Flip)} \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{8}$$

$$\text{Hadamard} \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \tag{9}$$

$$\text{Phase} \equiv \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \tag{10}$$

If the supposed single qubit is $|0\rangle$, then the result of Pauli X (NOT) gate on that, $X|0\rangle$ would be $|1\rangle$. In this case, output of Hadamard gate is not a pure state, but it's a superposition of state. In other words, the result of $H|0\rangle$ would be $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ that is shown in Fig. 7.

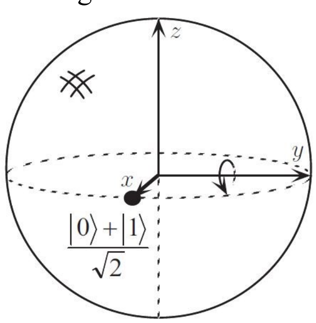

Fig. 7. Output of Hadamard gate (H) on single qubit $|0\rangle$ [8].

There are also many gates developed for multiple qubits that are complex and is not considered here.

IV. QUANTUM COMPUTERS ARCHITECTURE

Quantum computer can be referred to a machine that consists of a many-particle quantum system for solving complex computational problems.

Possibly the most important issue in quantum computers fabrication is making a closed box. In other words, since quantum systems are very fragile, the probability of decoherence and dephasing is very high.

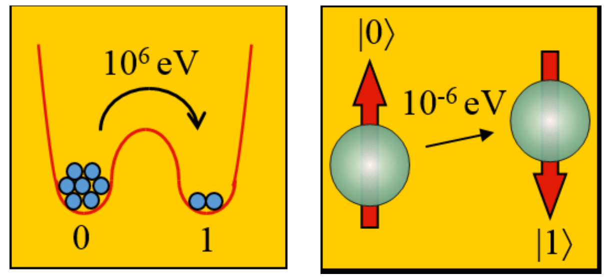

Fig. 8. Quantum systems (right) are very fragile in comparison of classical systems and just a little bit of energy can change the current state and cause system error.

The main challenges for scientists and engineers in making quantum computers are controlling, measuring, conserving and isolating quantum elements and their interaction from uncontrolled environment. Some techniques have been selected and developed for overcoming these barriers that can be classified in 6 categories [9].

- Photons. Polarization of photons can be considered as qubits and since they're almost free of decoherence, they are good candidate for using but their interaction with other photons still is a challenge.
- Trapped atoms. Based on T.D. Ladd et al [9]. trapped ions are the best option in the case of decoherence and dephasing time. They have relatively higher decoherence time (in order of seconds) in comparison with others (~milliseconds) as shown in Table I. Atomic ions can be trapped within nanometer space with electromagnetic fields.
- Nuclear magnetic resonance. Liquid state of NMR [1] provides the possibility of handling many of qubits, related quantum algorithm and also quantum error correction (QEC).
- Quantum dots. Quantum communication depends on single photons with very low probability of being two or more. One of the way to produce such of these single photons is stimulating quantum dots [10]. Quantum dots (QD) or sometimes called artificial atoms are very small semiconductors in nanometer size which can play several rules according to their usage. According to their properties, they can emit different wavelengths. However, despite their advantages, the short time of their decoherence is a problem which should be considered.

[1] NMR: Nuclear Magnetic Resonance

- Superconductors. They are some materials that can conduct electricity from one atom to another atom without resistance. There are three types of superconductors which are charge, flux and phase. Short time of decoherence and very low temperature of maintenance are the challenges that are under development and investigation.
- Other technologies. There are still several materials, methods and techniques which are being considered by scientists for improving quantum computers architecture and increasing their reliability.

TABLE I. MEASURED DECOHERENCE TIME FOR VARIOUS QUBITS [9].

No.	Decoherence time (T_2) comparison for various qubits	
	Qubit type	T_2
1	Infrared photon	0.1 ms
2	Trapped ion	15 s
3	Trapped neural atom	3 s
4	Liquid moldecule nuclear spins	2 s
5	e^- spin in GaAs quantum dot	3 µs
6	e^- spin bound to ^{31}P:^{28}Si	0.6 s
7	^{29}Si nuclear spins in ^{28}Si	25 s
8	NV centre in diamond	2 ms
9	Superconducting circuit	4 µs

V. RELATED WORKS

This section presents a brief review of related significant work on this topic since 2010 through some prestigious journals and conferences such as Nature, Physical Review, ACM, Elsevier, IEEE and Quantum Science and Technology. A distribution of these works based on the year and related journal is shown in Table. II and Fig. 9.

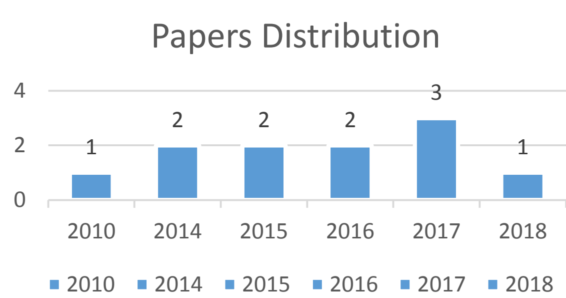

Fig. 9. Papers distribution on the topic of quantum computers architecture between 2010-2018 among prestigous publishers in the world.

TABLE II. CLASSIFICATION OF ARTICLES ON QUANTUM COMPUTERS ARCHITECTURE BETWEEN 2010-2018 AMONG WELL-KNOWN PUBLISHERS.

No.	Year	Paper	Main Idea	Publisher
1	2010	P1	2D quantum architecture	Quantum Information and Computation
2	2014	P2	Molecular ion-trap architecture	Physical Review A
3		P3	Hybrid Architecture	IJSR
4	2015	P4	Topological quantum computer	arXiv
5		P5	Optimization of quantum computer	IEEE
6	2016	P6	Heterogonous Architecture	ACM
7		P7	Quantum perceptron	Neural Networks
8	2017	P8	Silicon based quantum computer	NATURE COMMUNICATIONS
9		P9	Classical vs quantum structure	IEEE
10		P10	NN evaluation in quantum computer	IEEE
11	2018	P11	Network architecture of QC	Quantum Science and Technology

P1: Byung-Soo Choi and Rodney Van Meter [11] depicted a 2D quantum architecture as an adder with $\Theta(\sqrt{n})$ depth complexity and $O(\sqrt{n})$ qubits for the first time. The authors proved that the described architecture is faster than 1D architecture if the length of input registers n is greater than 58. Choi and Meter claimed that this architecture is the most stable architecture in case of performance and overhead.

P2: C. Monroe et al. [12] offered MUSIQC model, which is a hierarchical molecular ion trap architecture for quantum computers. In the proposed architecture, the processor is capable of having more than 10^6 qubits with two major attributes: stable qubits and ascendible photonic interconnections. The main specification of this work is its fault-tolerant property. Also modular elementary logic unit (ELU) is introduced which make the computation very fast and deterministic. ELU consists of a solitary crystal with N trapped atomic ion and a source of laser that is used to impact on quantum gates. Scalability in all aspects of the system is the most significant part of this work.

P3: E. M. Ameen et al. [13] proposed a hybrid architecture for typical computers with co-quantum processor. The aim is enhancing the performance with collaboration of both classical and quantum processors. Classical processors are used for conventional procedures and network communications and co-quantum processors are responsible for handling complicated algorithms and computations. The described architecture is capable of processing any given classical or quantum computation.

P4: Maissam Barkeshli et al. [14] depicted a physical architecture for topological quantum computers (TQC). Generally, qubits are fragile in the environment affecting from other systems and interactions. Topological qubits have higher stability and more resistance against interference, which results in fault-tolerant capability and performance improvement of quantum computers.

P5: Muhammad Ahsan and Jungsang Kim [15] worked on optimization of quantum computers utilizing simulation on resource performance. Device parameters (DP) that defines hardware architecture can be used for architecture optimization. The authors used a resource performance simulation tools and showed that the execution latency of adder circuit for qubit interactions can be defaced and also failure probability of the system is eventually specified by qubits decoherence time.

P6: X. Fu et al. [16] offered a heterogeneous architecture for quantum computers. The proposed model is a multi-layer structure, combined of classical, and quantum part. Since quantum states and systems are fragile and unstable against undesirable interactions, quantum error correction (QEC) is a challenging issue. As a result, the authors of this work suggested that classical part of computer handles the error correction role. Moreover, control unit is based on quantum architecture. X. Fu et al. in this research showed that the required instruction for the offered hardware architecture is considerably reduced.

P7: Adenilton Jose da Silva et al. [17] described quantum perceptron on a neural and field network in quantum computer. Quantum perceptron over field (QPF) is a development of classical perceptron with some improvements and solved defeats. The authors also presented a new learning algorithm which is based on quantum states superposition and named superposition based architecture learning algorithm (SAL). This algorithm optimizes weight and architecture of neural network and it's the first learning algorithm that specify neural network in polynomial time order.

P8: M. Veldhorst et al. [18] explained an architecture for a silicon-based quantum computer processor in accordance with CMOS technology. In the proposed architecture, CMOS transistors are working with qubits in a two dimensional quantum system properly. In other words, control part is handled by classical CMOS transistors and on the other side, qubits are defined by the spin state of electrons bounded in quantum dots. This compatibility between classical and quantum systems brings the chance of scalability for thousands or millions of qubits to work with standard transistors.

P9: Kuntam Babu Rao [19] compared classical and quantum computer architectures. Firstly, an overview, history and structure of classical computer is depicted. In the following, architecture and implementation techniques of quantum computers is discussed. The evaluation results showed that for the given algorithm in the research, the speed of quantum computer is 100 times more than a general computer.

P10: Adenilton et al. [20] discussed evaluation of neural network architecture in a quantum computer. A quantum algorithm is proposed for evaluation of neural networks architecture which named QNNAE. The offered algorithm unlike similar algorithms is independent of initial weights. The proposed algorithm can be applied for other machine learning purposes but is burdensome for classical computers.

P11: Brandon Buonacorsi et al. [21] investigated network architecture for topological quantum computers. For achieving fault-tolerant quantum computers, quantum error correction should be considered and this brings an overhead for the system. Topological stabilizers operating on two dimensional quantum surface codes can tolerate fairly high level of errors making them more reliable. As a result, these types of stabilizers are the best choice for the system future scale up. The authors introduced QMOS which is qubits in CMOS device architecture at very low temperature. QMOS can gain from several advancements in CMOS technologies. The authors suggested a novel QMOS architecture that is found on network/node method.

At the end, it is appropriate to mention that for making quantum computers still there are many challenges that needs more research, work and concentration which some of them is mentioned here.

- Lower dephasing and decoherence times
- More qubit systems: 64, 128, 192, 256.
- Non-cryogenic temperature
- Much greater connectivity
- Much lower error rate
- True fault tolerance
- Much lower cost

VI. CONCLUSION

In this paper, at first a brief history of classical mechanics presented. Then its failures, which led to origination of quantum mechanics discussed. In the following, basic concepts and rules of quantum mechanics is mentioned. After that, primary foundation of quantum computers, which are qubits, has been presented. Basic quantum gates and their functions are presented. Some methods of qubits fabrication and their related challenge is then investigated. Finally, some basic concepts of quantum computers architecture, related and future works is reviewed.

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