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Quantum Computing

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Abstract– Quantum computing is a new development in the field of information processing as it performs complex calculations and solve mathematical problems and equations. Quantum bit (qubit), a two-state quantum mechanical system, is the basic unit in quantum computing. The nature of superposition principle allows the qubit to be in superposition of states at same time. Superposition of qubits causes quantum computing to inherent parallelism and thus quantum computers can perform calculations faster and more accurate compared to classical computers. Since qubits are understood as quantum mechanical systems, this paper reviews the concepts of quantum computing, then qubits and some operators are explained in two- and N-dimensions in different spaces, and finally, some quantum gates are expanded.

Keyword: Quantum computing; quantum computers; quantum bit; quantum gate**.**

1. Introduction

Quantum computing is a breakthrough in the field of information processing because quantum algorithms cloud solves some mathematical tasks presently considered as intractable, such as the factorization of large numbers, exponentially faster than classical algorithms operated on sequential Von Neumann computer [1]. Richard Feynman [2] proposed the idea that certain calculations cloud be computed much efficiently with quantum mechanical rather than with classical computers; however, creating quantum computer is not an easy task. He proposed the concept of simulating physics with a quantum computer and postulated that by manipulating the properties of quantum mechanics and quantum particles one could develop and entirely new kind of computer [1]. In quantum computing at one particular time the state can be 0 or 1 or both at the same time keep on switching to either 0 or 1. In classical computer, calculation can be performed one at a time but in quantum computer it can perform multiple calculations at once and makes it much faster. Because quantum computers can contain multiple states at the same time, they have the potential to be much more times powerful than the classical supercomputers. In quantum computers, inherent parallelism is due to superposition of qubits and this parallelism causes that quantum computers perform millions of calculations at once. of superposition of qubits.

2. Quantum Computers

Using concept of the superposition, entanglement and interference in quantum computing, quantum computers can solve some complex problems faster and more accurate than classical computers. There are set of criterion put forward by Vincenzo [3], which tries to summarize the basic structure and needs of an ideal quantum computer, as follows: (i) a quantum physical system must have orthogonal quantum states, (ii) it should be possible to prepare the system in one of the orthogonal states, (iii) There should be a macroscopic procedure for measuring distinguishably, (iv) one can create a universal set of quantum logic elements to act upon it, (v) coherence time (time to remain in superposition upon action of external disturbances) should be larger than the decoherence time, and (vi) scalability: should be able to create a huge number of qubit and is enabled to control each qubit separately such that all are safe from decoherence.

a quantum computer provides a speed up over some classical algorithms, as well as, for some complex calculations e.g., Shor's algorithm [4]. Other task can be realized only using a quantum computer, that is the case for complicated simulations, such as many body systems or biological processes [5]. Quantum computers have much advantage and more applications in different fields than classical computers. A few applications are as following:

Machine learning: machine learning is a treading area now a day because we can now significant deployment at the consumer level of many different platforms. we are now seeing aspect of every day in voice, image and handwriting

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recognition, to name just a few examples. But it is also difficult and computationally expensive task in term of data and processing, where here the quantum bits help a lot.

Weather forecasting: the weather forecasting needs fast computation of huge data and if classical computer is used to perform such analysis might take longer than it takes the actual weather to evolve.

Cryptography: quantum cryptography is a latest and advanced branch of cryptography, where its basis lays in the two beliefs of quantum techniques: Heisenberg's uncertainly principle and principle of photon polarization [6]. As we know the quantum computer are very powerful machine for computation of any equation. It will be so easy to decrypt any data encrypted by the classical computers. Encryption and decryption will be too powerful and easy for quantum computer.

Molecular modeling: today the quantum chemistry is too complex that only the simplest molecules can be analyzed by today's classic computers. Chemical reactions are quantum in nature as they form highly entangled quantum superposition states.

Drug design: drug design is a promising are of application that will find a number of uses for these new machines. As a prominent example, quantum simulation will enable faster and more accurate characterizations of molecular systems than existing quantum chemistry methods.

Data storage: since the quantum computer uses qubits and increases exponentially (2^x), therefore, each time a qubit is added, the amount of numbers that can be stored on the device becomes double. For example, two qubits can store four numbers and five qubits can store for thirty-two numbers.

3. Qubits

A bit is the basic unit of information in classical computing. Analogously the qubit is the basic unit in quantum computing(qubit). A qubit is a 2 - state quantum mechanical system, which in fact is an abstract entity that can be physically realized in different ways. The main difference between a bit and qubit is that whereas in a classical computer a bit of information will encode either a 0 or 1, the nature of the principle of superposition in quantum mechanics allows the qubit to be in superposition of both states at same time. This means that a quantum computer could perform many calculations at the same time: A system with N qubits could execute 2^N calculation in parallel.

The certain period of time that the qubits are able to store quantum information is called coherence time. This time is necessary for correlation of qubits and parallelism processing. Due to out of control or non-desired interactions of systems with environment, the quantum systems have tendency to lose quantum properties through a process which called decoherence [7] Another important feature is that multiple qubits can exhibit quantum entanglement, allowing a set of qubits to express higher correlation than in classical system. In the entangled state, a system cannot be described by meanings of a local state. A qubit is a two-dimensional system; likewise, a qubit is a d-dimensional system. Unfortunately, some difficulties are generated when we try to operate mathematically [8]. Qubits could simplify some simulations of quantum mechanical systems and improve quantum cryptography [9]. A quantum bit can exist in superposition, which means that it can exist in multiple states at once. Compared to a regular bit, which can exist in one of two states, 1 or 0, the quantum bit can exist as a 1,0 or superposition of them at the same time. This allows for fast computing and the ability to do multitudes of calculations at once, theoretically. The basic element in the classical computing model is the bit variable, which can only accept two value 1 and 0 which, in the mathematical description in the context of Boolean algebra are called truth and false. Theoretical bits are implemented as transistor devices that can be localized in two stable states, by which Boolean operation And, Or and Not can be expressed. Physical and technological limitations have led to the creation of quantum information, the basic concept of which is a quantum bit a qubit, which is understood as a quantum mechanical system that can be in two states [1]. In a two-dimensional Hilbert space, the qubit state is described by the vector; which in Dirac's notation is called a ket vector [10] given in equation 1.

$$|\psi\rangle = \begin{pmatrix} a \\ b \end{pmatrix} = a|0\rangle + b|1\rangle \quad (1)$$

Where $|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ are the orthogonal base vectors, and in the general case the complex number a and b, called probability amplitudes, satisfy the condition as given in equation (2).

$$a^2 + b^2 = 1 \quad (2)$$

Equation 1 shows that unlike the classical bit, which may be in the state zero or in the state one, the qubit exist in a superposition state -the understanding of which is possible only from the point of quantum mechanics [9,10]. Classical bits can be operated on independently of each other changing 0 to 1 or 1 to 0 but a bit in one location has no effect on bits in other locations. Qubits can be set up using a quantum mechanical property called entanglement so that they are dependent on each other [1]. Qubit can also be defined as a two-state quantum-mechanical system. In the language of mathematics, it can be called a two-dimensional vector in Hilbert space [11] As given in equation 3.

$$|\psi\rangle = \begin{bmatrix} a \\ b \end{bmatrix} = a|0\rangle + b|1\rangle \text{ , } |0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} |1\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (3)$$

a^2 (in Eq.(2)) gives the probability of getting |0> state and similarly. b^2 (in Eq.(2)) gives the probability of getting |1> upon measuring the qubit. Length of the state vector should be unit as given Eq2. Using the above reasons, qubit |ψ> can be writing as a reduce form.

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi} \sin\frac{\varphi}{2} b|1\rangle \quad (4)$$

Where, θ and φ are polar and azimuthal angels, respectively. Such representation of a single qubit can be visualized through the Bloch sphere as shown in Fig. 1 [12].

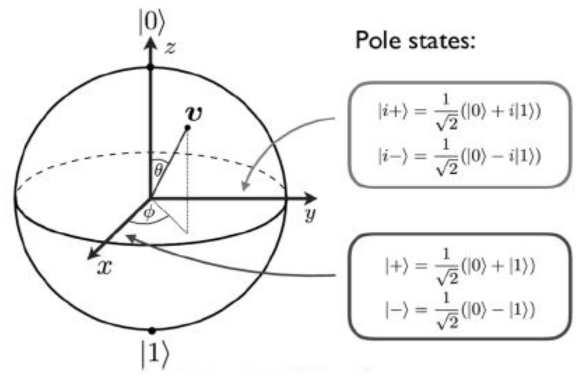

Fig. 1. A Bloch sphere.

Fig. 1 is a Bloch sphere representing the state of a qubit.

In a Bloch sphere, qubit is an arrow residing on the surface of the sphere corresponding to the pure states of the system, whereas the interior points correspond to the mixed states tip on a unit radius sphere in R*3 space [13]. Any two-level quantum mechanical system can be used as a qubit. The following is an incomplete list of physical implementations of qubits and the choices of basis are by convention only.

Table 1. Two-level quantum mechanical system.

Physical support	Name	Information support	|0>	|1>
Photon	Polarization encoding	Polarization of light	Horizontal	Vertical
Photon	Number of photon	Foke state	Vacuum	Single photon state
Photon	Time Bin encoding	Time of arrival	Early	Late
Electrons	Electronic spin	Spin	Up	Down
Electrons	Electron number	Charge	No electron	One electron
Nucleus	Nuclear spin addressed through NMR	Spin	Up	Down
Optical lattices	Atomic spin	Spin	Up	Down

4. Masny Qubits' System

Usually, we have a system with more than one qubit, which means that we have to form tensor products. For a system with two qubits the underlying ordered basis is [9]:

$$\left(\begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix}, \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix}, \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix}, \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix}\right) \quad (5)$$

This can be written as follows:

$$(|0> \otimes |0>, |0> \otimes |1>, |1> \otimes |0>, |1> \otimes |1>) \quad (6)$$

Finally, we make the convention that we let |ab> denote |a>|b>, giving the representation (|00>,|01>,|10>,|11>) that is short and easy to read. According to procedure, $2^2=4$, basis vectors for the two-qubits system appear to be as follows:

$$|0>|0>=|00>=\begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}1\\0\\0\\0\end{pmatrix} \quad (7)$$

$$|0>|1>=|01>=\begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}0\\1\\0\\0\end{pmatrix} \quad (8)$$

$$|1>|0>=|10>=\begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}0\\0\\1\\0\end{pmatrix} \quad (9)$$

$$|1>|1>=|11>=\begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}0\\0\\0\\1\end{pmatrix} \quad (10)$$

They form an orthogonal basis, the state vector |ψ> in this basis recorded as:

$$|\psi>= a_{00}\,|00> + a_{01}|01> + a_{10}\,|10> + a_{11}|11> \quad (11)$$

Where, probability amplitudes satisfy the condition:

$$a_{00}^2 + a_{01}^2 + a_{10}^2 + a_{11}^2 = 1 \quad (12)$$

In general case, the state vector for the n qubits system is a schedule based on the2^n basis state of the system.

$$|i_1 \cdots i_n>, i_1 \cdot\cdot i_n = \{0,1\} \quad (13)$$

$$|\psi>= \sum_{i_1 \cdots i_n} a_{i_1 \cdots i_n} |i_1 \cdots a_n> \quad (14)$$

In other words, the base state $|i_1 \cdots i_n>$ in equation 4 is a n dimensional binary number $|x>$. In these notations, the state of vector is recorded in the form of:

$$|\psi>= \sum_{x=0}^{2^{x-1}} a_x\,|x> \quad (15)$$

In a system of several qubits, a super positional state is formed for the whole system. The basis for such a system is formed as a tensor product of the state of each qubit. In general case, the tensor product of the matrices A, with dimension M×N and B with dimension R×S, their tensor product is called the matrix with dimensionality MR×NS that is obtained according to equation (16) [9,10].

$$A \times B = \begin{pmatrix} a_{11}\,B & a_{12}\,B & . & . & . & . & . & . & a_{1n}\,B \\ a_{21}\,B & a_{22}\,B & . & . & . & . & . & . & a_{2n}\,B \\ . & . & . & . & . & . & . & . & . \\ a_{m1}\,B & a_{m2}\,B & . & . & . & . & . & . & a_{mn}\,B \end{pmatrix} \quad (16)$$

5. Quantum Gates

In classical computers, the computational process can be described by the formalism of Boolean algebra: $f: \{0,1\}^n \rightarrow \{0,1\}^m$; which transforms the state of the n bits in the state of the m bits. Such functions are constructed from certain blocks, using schematic approaches, and they are called logical elements. In a quantum computation, model the state of a qubit $|\psi>$ under the action of a certain physical variable is changing. It is known that quantum mechanics physical quantities are assigned to the matching Hermitian operator, to which in turn, matrix is matched in Hilbert space. Within this formalism, for example, the qubit rotation can be described by changing the basis, which provides the method for finding the matrices of corresponding rotation as a product of the ket-vector on the bra-vector: $|i><j|$. For example, if the operator carries out the following transformation of the basis: $|0>\to |0>; |1>\to |1>$, then the Matrix of such an operator will be unitary [9,10]:

$$I = |0><0| + |1><1| = \begin{pmatrix}1\\0\end{pmatrix}(1 \quad 0) + \begin{pmatrix}0\\1\end{pmatrix}(0 \quad 1) = \begin{pmatrix}1&0\\0&0\end{pmatrix} + \begin{pmatrix}0&0\\0&1\end{pmatrix} = \begin{pmatrix}1&0\\0&1\end{pmatrix} \quad (17)$$

The operator X which carriers out the following transformation of the basis $|0>\to |1>; |1>\to |0>$ have the matrix:

$$X = |0><1| + |1><0| = \begin{pmatrix}1\\0\end{pmatrix}(0 \quad 1) + \begin{pmatrix}0\\1\end{pmatrix}(1 \quad 0) = \begin{pmatrix}0&1\\0&0\end{pmatrix} + \begin{pmatrix}0&0\\1&0\end{pmatrix} = \begin{pmatrix}0&1\\1&0\end{pmatrix} \quad (18)$$

Where, X is Pauli matrix.

This unitary operator is an analogue of the classical NOT, because it rearranges the coefficients a and b.

$$X|>= X(a|>+b|>) = \begin{pmatrix}0&1\\1&0\end{pmatrix}\begin{pmatrix}a\\b\end{pmatrix} = \begin{pmatrix}b\\a\end{pmatrix} \quad (19)$$

Other important standard are single-qubit elements, the Y and Z elements, whose matrices are Pauli matrices [9,10]:

$$Y = i|0><1| - i|1><0| = -i\begin{pmatrix}1\\0\end{pmatrix}(0 \quad 1) + i\begin{pmatrix}0\\1\end{pmatrix}(1 \quad 0) = \begin{pmatrix}0&-i\\0&0\end{pmatrix} + \begin{pmatrix}0&0\\i&0\end{pmatrix} = \begin{pmatrix}0&-i\\i&0\end{pmatrix} \quad (20)$$

$$Z = |0><0| - |1><1| = \begin{pmatrix}1\\0\end{pmatrix}(1 \quad 0) - \begin{pmatrix}0\\1\end{pmatrix}(0 \quad 1) = \begin{pmatrix}1&0\\0&0\end{pmatrix} - \begin{pmatrix}0&0\\0&1\end{pmatrix} = \begin{pmatrix}1&0\\0&-1\end{pmatrix} \quad (21)$$

Of great importance, single qubit elements is transformation of Hadamard, H, which carries out such a transformation of the basis.

$$|0>\to \frac{1}{\sqrt{2}}(|0>+|1>)\ ;\ |1>\to \frac{1}{\sqrt{2}}(|0>-|1>) \quad (22)$$

Where, it's Matrix looks like:

$$U_H = \frac{1}{\sqrt{2}}(|0><0| + |0><1|) + \frac{1}{\sqrt{2}}(|1><0| - |1><1|) = \frac{1}{\sqrt{2}}\left[\begin{pmatrix}1\\0\end{pmatrix}(1 \quad 0) + \begin{pmatrix}1\\0\end{pmatrix}(0 \quad 1) + \begin{pmatrix}0\\1\end{pmatrix}(1 \quad 0) - \begin{pmatrix}0\\1\end{pmatrix}(1 \quad 0)\right] = \frac{1}{\sqrt{2}}\left[\begin{pmatrix}1&0\\0&0\end{pmatrix}\right] + \begin{pmatrix}0&1\\0&0\end{pmatrix} + \begin{pmatrix}0&0\\1&0\end{pmatrix} - \begin{pmatrix}0&0\\1&0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}1&1\\1&-1\end{pmatrix} \quad (23)$$

This operator is often used in quantum algorithms. Some of the o quantum gates are as following:

NOT gate in classical: $a \to \overline{a} \equiv a + 1;\ 0 \to \overline{0} \equiv 0 + 1 = 1$: $1 \to \overline{1} \equiv 1 + 1 = 0$

Quantum NOT: $X|a>=|\overline{a}>\equiv |a \oplus 1>$; $X|0>=|\overline{0}> \equiv |0 \oplus 1>=|1>$;

$X|1>=|\overline{1}>\equiv |1 \oplus 1>=|0>$, Where $\oplus$ is the summation operator that sums two kets.

Controlled-U gate: $|a>\to |a>, |b>\to u^a|b>$. U can be an arbitrary single-qubit gate, where U works only if a=1.

CNOT gate i: $|a>\to |a>, |b>\to X^a|b>=|b \oplus a>$, when $|0 \oplus 0 \geqslant = |0>, |1 \oplus 1>=|0 \geqslant$

$c_{12}|00>=|0>|0 \oplus 0>=|00>$, $c_{12}|01>=|0>|0 \oplus 1>=|01>$

$c_{12}|10>=|1>|1 \oplus 0>=|11>$, $c_{12}|11>=|1>|1 \oplus 1>=|10>$

Using equations 7 to 10 as following

$$|00>=\begin{pmatrix}1\\0\\0\\0\end{pmatrix}, |01>=\begin{pmatrix}0\\1\\0\\0\end{pmatrix}, |10>=\begin{pmatrix}0\\0\\1\\0\end{pmatrix}, |11>=\begin{pmatrix}0\\0\\0\\1\end{pmatrix}$$

then matrix exhibition of CNOT gate is as following:

$$c_{12} = \begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{pmatrix}$$

CNOT gate п: $|a>\to |\overline{a}>=|a \oplus b>, |b>\to\ |b>=|b>$ when $|0 \oplus 0>=|0>, |1 \oplus 1>=|0>$

$c_{21}|00>=|00>$, $c_{21}|01>=|11>$, $c_{21}|10>=|10>$, $c_{21}|11>=|01>$ then matrix exhibition of CNOT gate as following:

$$c_{21} = \begin{pmatrix}1&0&0&0\\0&0&0&0\\0&0&1&0\\0&1&0&1\end{pmatrix}$$

SWAP gate: $|a>\to |b>$, $|b>\to |a>$; $|a>|b> \xrightarrow{c_{12}} |a>|b \oplus a> \xrightarrow{c_{21}} |a \oplus b \oplus a>|b \oplus a>=|b>|b \oplus a> \xrightarrow{c_{12}} |b>|b \oplus a \oplus b>=|b>|a>$

To implement SWAP gate, we need to take the following steps: (i) encode the information on $|a>$ in to 2nd qubit, (ii) erase the information on $|b>$ from 1nd qubit, (iii) encode the information on $|b>$ in to 1nd qubit, and (iv) erase the information on $|b>$ from 2nd qubit. Therefore, we can obtain the following example from above mentioned

$$c_{12}|00>=|00>$$

$$c_{12}|01>=|10>$$

$$c_{12}|10>=|01>$$

$$c_{12}|11>=|11>$$

Then, matrix exhibition of SWAP is as follows:

$$SWAP = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Controlled-Z gate: $|a> \to |a>, |b> \to (-1)^{a\times b}|b>$;$|a>|b> \xrightarrow{cz} (-1)^{a\times b}|a>|b>$. In this gate, |a> does not change but sign of |b> changes if a×b not zero.

$$|00> \to |00>$$

$$|01> \to |01>$$

$$|10> \to |10>$$

$$|11> \to -|11>$$

Then, matrix exhibition of CZ is as follows:

$$cz = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

6. Conclusion

Quantum computing has helped to the information processing by introduce quantum computers which can solve some specific types of problems many time faster and more accurate than classical computers by using the concepts of quantum mechanics. They can perform complicated simulations such as; many body systems or biological processes. But classical computer cannot replace, soon, with quantum computers because classical computers are better at some tasks, such as email, spreadsheet and desktop publishing, than quantum computers.

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