New age for quantum computing with dynamic platforms

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Abstract

Quantum computers are information processing devices which rely on quantum parallelism. Various physical systems such as NMR and ion traps are employed for realizing this parallelism. Specific algorithms which utilize this parallelism are in place. These algorithms make quantum computers outperform their classical counterparts in computational performance for certain class of problems. As and when efficient quantum algorithms are developed, and with a reliable physical system in place, quantum computer are destined to become universal computing platforms in decades to come. This review sheds light on some of the fundamental aspects of quantum computing along with the physical systems which implement them in an unambiguous way.

Keywords: quantum computing, qubit, NMR, ion trap

1. Introduction

As transistor based digital logic gates reach their ultimate limit in miniaturization, new technologies are sought to take forward the computing performance to the next level. The most promising technologies in this race are quantum computing and optical computing [1, 2]. Optical computing makes use of light for computing, and is gradually transforming into a reliable platform with the introduction of logic gates based on photonic technologies [3, 4]. Quantum computing on the other hand has many competing platforms which vary in their computational performance and reliability. Some of the platforms which are commonly employed

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for quantum computing include NMR, ion trap, superconducting circuits, semiconductor quantum dots, and so on [5]. When compared to current generation of semiconductor microprocessors, quantum computers are at their nascent stage of evolution. Albeit, for complex problems, there is an upper hand for quantum computers over their classical counterparts in computational performance. This is referred to as quantum supremacy [6]. Quantum computing technologies are coming of age, and many of the systems are at the verge of commercialization [7]. An energy efficient, compact, and scalable platform is the ultimate aim of research in this area. This review sheds light on the basics of quantum computing in an unambiguous way. Some of the physical systems which are used for quantum computing are also considered.

2. Theoretical framework

When size of the structure (integrated circuit components) is reduced to the size of atoms, quantum effects creeps in, and it would be difficult to explain the observed physical phenomenon based on classical laws of physics [8]. This was conveyed by Feynman by mentioning that nature is not classical. Feynman also proposed a computing scheme based on laws of quantum mechanics, today known as quantum computing. Taking into account the quantum nature of these quantum computing platforms, novel algorithms were proposed for these systems [9]. These algorithms which can run only on a quantum computing platform can execute codes at a fraction of time than their classical counterparts. This was one of the motivation factors for venturing into the realm of quantum computing in the first place. Current generation of quantum computers are prone to errors because of external disturbances (surroundings), and are known as Noisy Intermediate Scale Quantum (NISQ) computing. A robust quantum computing platform which can withstand interference from surrounding medium is the focus of research in this area.

2.1. Quantum bit

In conventional digital computer, information is stored as a series of bits, either 0 or 1. Electronically, logical states, 1 and 0, are represented by high voltage and low voltage respectively. In a quantum computer, the logical state is represented by a quantum bit (qubit). The platform which is commonly employed for quantum computing is a two-level system. A qubit represents and takes the value which is a superposition (linear combination) of these two logical states. Mathematically,

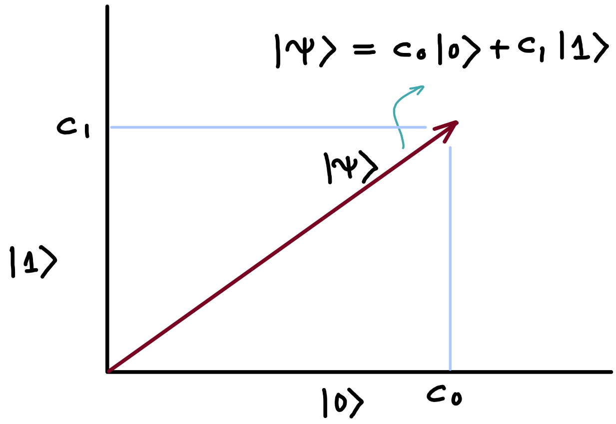


Figure 1: Representation of qubit $|\psi\rangle$ as superposition (linear combination) of two orthogonal basis states, $|0\rangle$ and $|1\rangle$.

this is represented by

$$|\psi\rangle = c_0 |0\rangle + c_1 |1\rangle \tag{1}$$

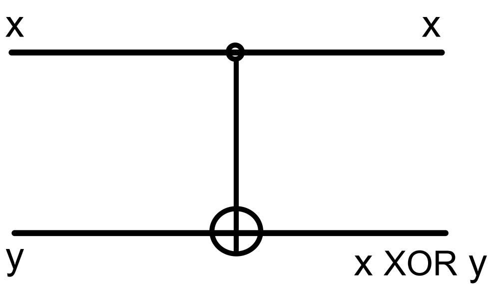
where $|0\rangle$, $|1\rangle$, are the two logical states and $|\psi\rangle$ represents the state of the qubit. Here, c_0 and c_1 represents the probability amplitudes along $|0\rangle$ and $|1\rangle$. This is better illustrated in Figure 1. Equation 1 is the case of a single qubit. A quantum computer can have N number of qubits. If all these qubits are entangled, the state of the system can be represented by a superposition (linear combination) of 2^N mutually orthogonal basis states. Logical operations done on this superposition state is equivalent to doing 2^N operations in parallel. The computing power of a quantum computer stems from this parallelism that is inherent to a quantum computing system. Specifically written quantum algorithms exploit this parallelism and put it to good use, and thereby enable quantum computers to outperform supercomputers.

2.2. Quantum register

Quantum register consists of an array of qubits which stores information in the form of logical states, viz. $|0\rangle$ and $|1\rangle$, for a two-level system. Quantum state of the register is represented mathematically by

$$|\psi\rangle^{reg} = c_0 |0, 0, 0..0\rangle + c_1 |0, 0, 0..1\rangle + c_2 |0, 0, 0..1, 0\rangle + \cdots \tag{2}$$

Just like a register in a classical computer, quantum register also need to be initialized to zero before starting computation. Usually, initialization is done to the



x	y	x	x XOR y
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

Figure 2: Circuit and truth table of CNOT gate.

quantum mechanical ground state, viz. $\mid 0, 0, ...0\rangle$. Logical operations are done on a quantum register by quantum gates. A quantum algorithm makes use of a series of quantum gates to implement a logical operation on the quantum register. Once all the instructions on the algorithm are implemented, the resulting state of the quantum register denotes the output of the quantum computer.

2.3. Quantum gates

Quantum computers use reversible logic gates. Some of the commonly employed quantum gates include CNOT gate, Toffoli gate, and Fredkin gate. Functioning of CNOT gate is given below.

2.3.1. CNOT gate

Controlled NOT or CNOT is also known as ”reversible XOR”. It has two inputs and two outputs. Its function can be represented as

$$(x, y) \rightarrow (x, x \text{ XOR } y) \tag{3}$$

where x is the control bit and y is the target bit. Circuit and truth table of CNOT gate is shown in Figure 2 As shown in Figure 2, if the control bit is zero, CNOT passes both bits to the output. If the control bit is one, it passes the control bit unchanged, but inverts the target bit. In other words, the target bit y is flipped if and only if the control bit x=1. (In the circuit, symbol $\oplus$ denotes XOR. Output of XOR is 1 only when both inputs are different.)

3. Quantum computing platforms

Quantum computers can be used as universal computers, to execute either classical or quantum algorithms. When a classical algorithm is executed, the performance of quantum computer will be at par with a classical computer. But, when

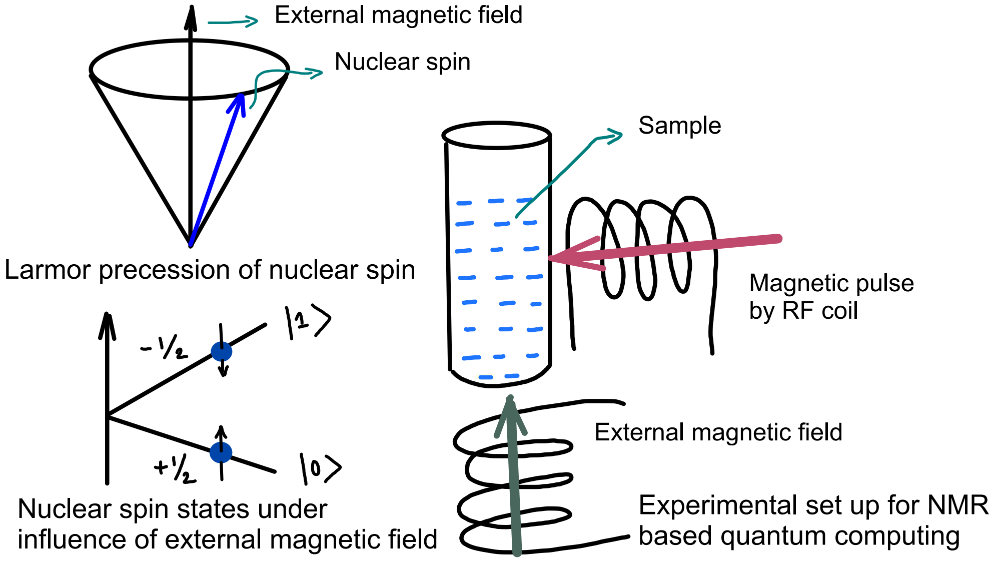


Figure 3: NMR based quantum computing.

a quantum algorithm is executed, it outperforms a classical computer. Quantum algorithms can be executed only on hardware (platform) designed for quantum computing. For any physical system to be suitable for quantum computing, it has to satisfy certain requirements. Firstly, the ability to represent information as qubits in a quantum register. Secondly, the ability to perform logical operations on quantum register. Thirdly, the ability to read out the result from a quantum register. Some of the physical systems used for quantum computing are described below.

3.1. NMR system

Nuclear magnetic resonance (NMR) is a technique used to visualize nuclear spin states of a given sample. When an external magentic field is applied to a given sample, nuclear spin degeneracy is broken, and the splitting of nuclear spin states occurs, known as nuclear Zeeman splitting [10, 11]. Spectrum of nuclear Zeeman sublevels is called NMR spectrum. For a spin 1/2 system, two nuclear Zeeman sublevels (+1/2 and -1/2) are formed on application of an external magnetic field, as shown in Figure 3. When an external magnetic field in applied, the nuclear magnetic moment tries to align parallel to this field in order to minimize magnetic energy. Moreover, the nuclear magnetic moment precess about the external magnetic field with Larmor frequency. For a spin 1/2 system, this precessional motion which is aligned with the external magnetic field corresponds to the lower nuclear spin state. It is possible to flip the nucleus to higher nuclear spin state by applying an energy equivalent to difference in energy between nuclear spin states. Interestingly, Larmor frequency corresponds to this energy difference. In this way, flipping between nuclear spin states is possible by applying energy equivalent to Larmor frequency. This is a resonant phenomenon wherein the flipping occurs only at Larmor frequency, and hence the name nuclear magnetic resonance.

Magnetic pulses are applied to flip the nuclear spin states. These magnetic pulses are generated from a RF (radio frequency) coil kept perpendicular to the external magnetic field. Incoming magnetic pulse rotates the precession angle by 90°, and makes the nuclei orient towards the coil. This precession of nuclear magnetic moments against the axis of the coil induces an electric signal in the coil. This is the NMR signal. This signal which is in the time domain is converted into frequency domain using Fourier transform, and the NMR spectrum is obtained. When the magnetic pulse is withdrawn, the NMR signal starts decaying. Gradually, realignment of nuclear magnetic moment occurs towards the initial angle of precession, under the influence of external magnetic field. Succeeding magnetic pulses can again rotate the precession angle and make the nuclear moments orient towards the axis of coil, and the process is repeated. It is possible to make use of NMR as a platform for quantum computing. Here, the spin states of nuclei in the sample act as the qubits. Logical operations are done on the NMR qubits by applying magnetic pulses from the RF coil. The read out of data from the qubits are possible from the collected NMR signal.

3.2. Trapped-ion system

Electrostatic potential does not have a minimum in the free space, and cannot be used for trapping ions (Earnshaws theorem) [12]. Due to this, ion trapping is usually done by suitable designed time varying quadrupole potentials [13, 14]. Commonly, quadrupole traps such as linear Paul trap is used for trapping ions for quantum computing (see Figure 4). Linear Paul trap consists of a set of parallel electrodes with AC voltage and end cap electrodes with DC voltage. Ions are produced by knocking our electrons from neutral atoms. Once ions enter the linear Paul trap, because of switching of polarity of AC voltage continuously, ions are are confined between the parallel rods, along their length. End cap electrodes prevents the leakage of ions along the longitudinal direction. Since evenly charged ions repel each other, there is good spacing between ions, and a linear chain of ions in formed in the trap.

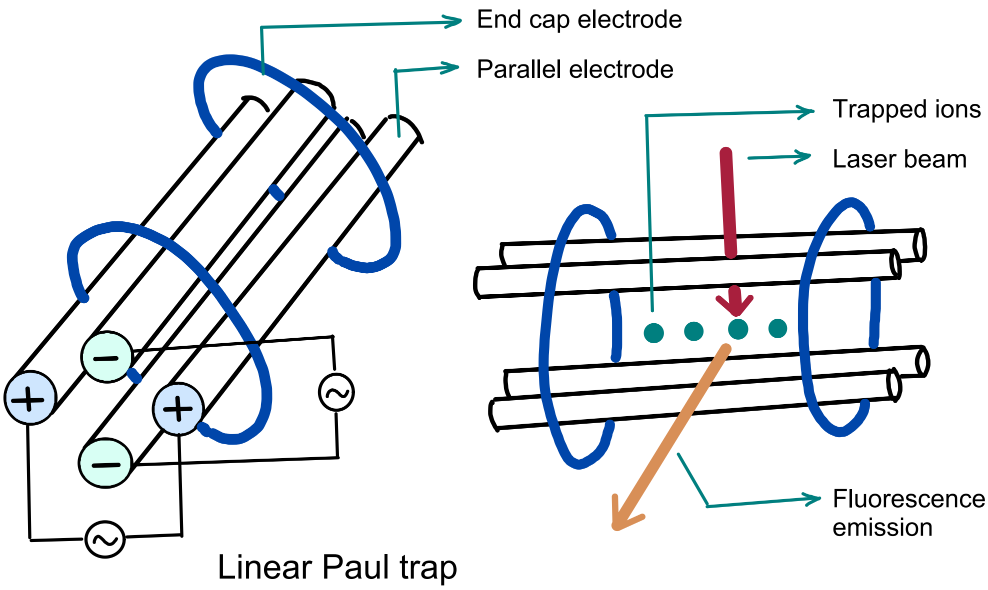


Figure 4: Ion trap based quantum computing.

Qubits are represented by electronic ground state and excited states of ions, for $|0\rangle$ and $|1\rangle$ respectively. For proper working, motion of ions need to be reduced, and this is done by laser cooling. Quantum register is initialization to the ground state by optical pumping. Logical operations are done on qubits by illuminating laser pulse on ions. Read out is possible by tuning the laser for a particular state which in turn emits fluorescence photon which is detected by a photo detector.

4. DiVincenzo criteria

DiVincenzo listed out a set of criteria to be satisfied by every physical system to be useful as a quantum computer. They are: (1) The physical system should be scalable with well-defined qubits. This criterion insists that the physical system should be able to represent large number of qubits with well-defined quantum states. (2) Ability to initialize quantum register. This criterion insists that there should be a mechanism to initialize qubits to their ground state. (3) Ability to read out from quantum register. This criterion insists that there should be a mechanism to read out data stored in the quantum register after completion of logical operations on the qubits. (4) Ability to implement quantum gates. This criterion insists that there should be a mechanism for implementing logical operations on the qubits by a set of quantum gates. (5) Long qubit life time. This criterion insists that the decoherence time for the physical system be longer enough for the gate operations to be completed.

In addition to these five criteria, DiVincenzo introduced two more criteria if quantum communication is involved. They are: (1) Ability to interconvert stationary and flying qubits. Qubits of stationary quantum computers are called stationary qubits, and those qubits which connect these quantum computers are called flying qubits. This criterion insists that there should be a mechanism for implementing interconversion between stationary and flying qubits. This is analogous to conversion from electronic signal to optical signal for transfer of data between computers through an optical fiber. (2) Ability to faithfully transmit flying qubits between specified locations. This criterion insists that there should be a mechanism to insist the reliability of flying qubits that are transferred.

5. Conclusion

Quantum computer is an information processing device which makes use of the principles of quantum mechanics. Information is stored in a quantum computer as qubits. In contrast with classical computer where a bit can take only one logical state, qubits in quantum computers can represent superposition (linear combination) of 0 and 1. Large number of qubits in a quantum register can form a superposition state. Logical operations done on this superposition state is equivalent to doing operations in parallel. The computing power of a quantum computer stems from this parallelism. A reliable and scalable physical system that can implement this parallelism is required to make quantum computer a universal computing platform.

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