International Journal of Information Science and System, 2018, 6(1): 21-27

Modern Scientific Press

International Journal of Information Science and System

Journal homepage: www.ModernScientificPress.com/Journals/IJINFOSCI.aspx

ISSN: 2168-5754

Florida, USA

Article

Quantum Computing

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Article history: Received 26 September 2018, Revised 2 November 2018, Accepted 10 November 2018, Published 21 November 2018

Abstract: Quantum Computing employs quantum phenomenon such as superposition and entanglement for computing. A quantum computer is a device that physically realizes such computing technique. They are different from ordinary digital electronic computers based on transistors that are vastly used today in a sense that common digital computing requires the data to be encoded into binary digits (bits), each of which is always in one of two definite states (0 or 1), whereas quantum computation uses quantum bits, which can be in superposition of states. The field of quantum computing was initiated by the work of Paul Benioff and Yuri Manin in 1980, Richard Feynman in 1982, and David Deutsch in 1985. Quantum computers are incredibly powerful machines that take this new approach to processing information. As such they exploit complex and fascinating laws of nature that are always there, but usually remain hidden from view. By harnessing such natural behavior (of qubits), quantum computing can run new, complex algorithms to process information more holistically. They may one day lead to revolutionary breakthroughs in materials and drug discovery, the optimization of complex manmade systems, and artificial intelligence.

Keywords: Superposition, Entanglement, Quantum Bits.

1. Introduction

Quantum Physics describes the way our world works at the most fundamental level. **Quantum Computing** has become one of the most leading applications of Quantum Physics. Quantum Computers have the potential to solve the world's most complex problems that are beyond the reach of even today's most powerful supercomputers.

Quantum computing takes advantage of the ability of subatomic particles to exist simultaneously in more than one state. Due to this natural behaviour of subatomic particles, operations can be done much more quickly and use less energy than classical computers.

In classical computing, a bit is a single piece of information that can exist in either of the two states – 1 or 0 at a given time. Quantum computing uses quantum bits, or 'qubits' instead. These are quantum systems with two states. However, unlike a usual bit (0 or 1), they can store much more information because they can exist in any superposition of these values. A qubit can be thought of like an imaginary sphere – a qubit can be any point on the sphere, whereas a classical bit can be represented at either of the two poles of the sphere. This means a computer using these bits can store a huge amount more information using less energy than a classical computer[2,].

2. Qubits – The Building Blocks of Quantum Computers

Classical computers encode information in bits. As already mentioned each bit can take the value of 1 or 0. These 1s and 0s physically act as on/off switches for various logical devices and transistor circuits that ultimately drive computer functions. To perform a simple calculation like solving a maze, a classical computer would test each possible route one at a time to find the correct one.

Quantum computers, on the other hand, are based on qubits or quantum bits which is a unit of quantum information—the quantum analogue of the classical binary bit. A single qubit can represent a one, a zero, or any quantum superposition of those two qubit states; a pair of qubits can be in any quantum superposition of 4 states, and three qubits in any superposition of 8 states. In general, a quantum computer with n qubits can be in an arbitrary superposition of up to 2^n different time (a classical computer can only be in any one of these 2^n states).

A qubit operates according to two key principles of Quantum Physics:

I. Superposition
II. Entanglement

Quantum superposition is a fundamental principle of quantum mechanics. It states that any two (or more) quantum states can be added together ("superposed") and the result will be another valid quantum state; and conversely, that every quantum state can be represented as a sum of two or more other distinct states. In case of Quantum Computing, superposition means that each qubit can represent both a 1 and a 0 at the same time.

Quantum entanglement is a physical phenomenon which occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle depends on the state of the other(s), even when the particles are separated by a large distance. In case of Quantum computing, Entanglement means that qubits in a superposition can be correlated with each other; that is, the state of one (whether it is a 1 or a 0) can depend on the state of another.

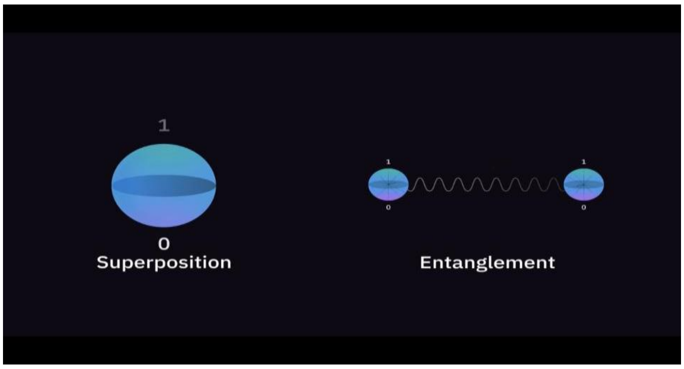

Figure 1: Entanglement

Using these two principles, qubits can act as more sophisticated switches, enabling quantum computers to function in ways that allow them to solve difficult problems that are intractable using today's computers[2]. As a result, a quantum computer can do parallel operation on all the eigenstates simultaneously and reach the solution (say for a maze) a lot quicker.

3. Physical Realization of Qubits

In classical computer technologies, a processed bit is physically implemented by applying a low DC voltage, and whilst switching from its low level to high level, a so-called forbidden zone must be passed as fast as possible, as electrical voltage cannot change from one level to another instantaneously.

In quantum computing, to make a qubit, we need an object that can attain a state of quantum superposition between two states. An atom can be considered as a kind of qubit. The direction of its magnetic moment (it's "spin") can point in different directions, say up or down with respect to a magnetic field and it is this spin which is manipulated to read and write the information off of a qubit. The challenge is in placing and then addressing that single atom.

An Australian team led by Michelle Simmons at the University of New South Wales, has made atomic qubits by placing a single Phosphorus atom at a known position inside a Silicon crystal [6, 7]. The outermost electron of this Phosphorous atom is associated with an intrinsic spin (angular momentum) which has two orientations: Up or Down — which are like the classical 1 and 0. To differentiate the energy state of the electron when it's in spin up or spin down state we need to apply a strong magnetic field. This field is produced be a superconducting magnet which is a large solenoid of superconducting coil.

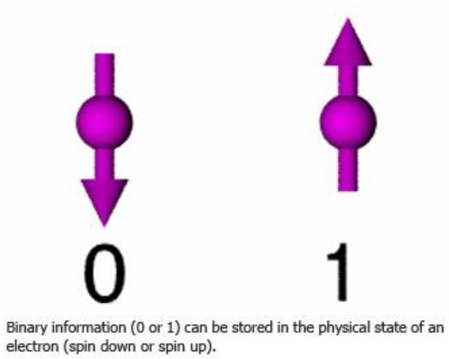

Figure 2: Binary information can be stored in physical state of an electron

At room temperature, the electron will have so much energy that it would be bouncing around spin up and spin down states so the whole apparatus has to be cooled down to a very low temperature. That way we know that electron will be in spin down state because there won't be enough thermal energy to alter its state. Now the information is "written" onto the qubit by flipping the electron into the spin up state by hitting it with a pulse of microwaves, whose frequency depends upon the strength magnetic field the electron is sitting in. This information is then read by the transistor that is in close vicinity. This whole operation depends so sensitively on strength of magnetic fields that all residual and unwanted magnetic fields must be eliminated. For this, a Silicon isotope – Si^{28} is used which has no nuclear spin and is completely non-magnetic.

Another idea of physical realization of a qubit is to strip an electron off the atom and turn it into an ion. Then we can use electromagnetic fields to suspend the ion in free space, firing lasers at it to change its state.

A viable qubit technology, however, will need a number of other characteristics as well. Some system requirements include:

I. The quantum state of interest must be stable. That is, it must be possible to preserve it long enough to actually manipulate it for computation;
II. The qubit technology being used must be scalable. It must be possible to create large numbers of identical qubits, and to propagate information between them. In particular, qubits must be able to interact over distances while preserving their superposition of quantum states;
III. To make a qubit stable, it is important to isolate it from outside influences that can disrupt the quantum state. Thermal vibrations also affect qubit stability, and for this reason many proposed designs operate at cryogenic temperatures.

4. Obstacles

There are a number of technical challenges in building a large-scale quantum computer, and thus far quantum computers have yet to solve a problem faster than a classical computer. One of the biggest obstacles in path to achieve quantum supremacy is Quantum Decoherence.

Quantum decoherence is simply the loss of quantum coherence. In quantum mechanics, subatomic particles are described by a wavefunction, a mathematical description of the quantum state of a system having probabilistic nature and consequently giving rise to various quantum effects. As long as there exists a definite phase relation between different states, the system is said to be coherent. This fundamental property of quantum mechanics is necessary for the functioning of quantum computers. However, when a quantum system is not perfectly isolated, coherence decays with time, a process called quantum decoherence. As a result of this process, the relevant quantum behavior is lost.

Decoherence represents a technical obstacle for the practical realization of quantum computers, since such machines are expected to rely heavily on the undisturbed evolution of quantum coherences. Simply stated, they require that coherent states be preserved in order to actually manipulate quantum states of qubits and perform quantum computation. Currently, some quantum computers require their qubits to be cooled to 20 millikelvins in order to prevent significant decoherence. As a result, time consuming tasks may render some quantum algorithms inoperable, as maintaining the state of qubits for a long enough duration will eventually corrupt the superpositions.

5. Applications & Potential

• **Artificial Intelligence:**

A primary application for quantum computing is artificial intelligence (AI). AI is based on the principle of learning from experience, becoming more accurate as feedback is given, until the computer program appears to exhibit "intelligence."

This feedback is based on calculating the probabilities for many possible choices, and so AI is an ideal candidate for quantum computation. For example, Lockheed Martin plans to use its D-Wave quantum computer to test autopilot software that is currently too complex for classical computers, and Google is using a quantum computer to design software that can distinguish cars from landmarks.

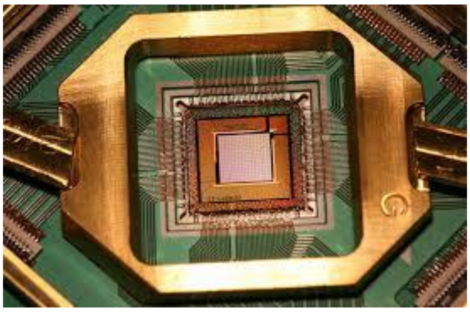

Figure 3: Chip designed by D-Wave Systems that is used in the aircraft control

• **Molecular Modelling:**

Another example is precision modelling of molecular interactions, finding the optimum configurations for chemical reactions. Such "quantum chemistry" is so complex that only the simplest molecules can be analysed by today's digital computers. But quantum computers, operating at full potential would not have any difficulty evaluating even the most complex processes [1].

• **Supply Chain & Logistics:**

Finding the best solutions for ultra-efficient logistics and global supply chains, such as optimizing fleet operations for deliveries during the holiday season could be achieved efficiently.

• **Cryptanalysis:**

Integer factorization, over which public key cryptographic systems are based, is believed to be computationally infeasible with an ordinary computer for large integers. By comparison, using Shor's algorithm a quantum computer could efficiently solve this problem and find the required factors. This ability would enable a quantum computer to de-crypt many of the cryptographic systems in use today.

6. Conclusion

In quantum computing, a qubit (short for "quantum bit") is a means to transmit and process quantum information—the quantum analogue to a classical bit. Qubits have certain special properties that help them solve complex problems at a rate much faster than classical bits. One of these properties is superposition, which states that instead of holding one binary value ("0" or "1") like a classical bit, a qubit can hold a 'superposition' of "0" and "1" simultaneously. As such when multiple qubits interact coherently, they can explore numerous options and process information in a fraction of the time as compared to even the fastest non-quantum systems.

However, quantum computers aren't going to replace the classical computers as quantum computers in a sense they will benefit us for some very specific problems—important problems, but not problems most people deal with. Their primary benefit would be to researchers, particularly physicists, chemists, material scientists, and medical & pharmaceutical researchers. Each of these areas would gain a lot from being able to simulate quantum systems to better explore how matter behaves in larger conglomerates (even just hundreds of particles).

Acknowledgement

The authors would like to acknowledge their parents, for their unrelenting support, blessings and faith which helped us to sail our ship of ambition and anchor it in a harbour of success. We extend our sincere gratitude to the Department of Electrical Engineering, SSM College of Engineering and Technology; for their meticulous suggestions and constructive criticism, throughout the academic pursuit.

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