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Quantum Computing

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Abstract

Today's computers work on bits that exist as either 0 or 1. Quantum computers aren't limited to two states; they encode information as quantum bits, or qubits, which can exist in superposition. Qubits represent atoms, ions, photons or electrons and their respective control devices that are working together to act as computer memory and a processor. Because a quantum computer can contain these multiple states simultaneously, it has the potential to be millions of times more powerful than today's most powerful supercomputers. A processor that can use registers of qubits will be able to perform calculations using all the possible values of the input registers simultaneously. This superposition causes a phenomenon called quantum parallelism, and is the motivating force behind the research being carried out in quantum computing. Due to technical obstacles, till date, a quantum computer has not yet been realized. But the concepts and ideas of quantum computing has been demonstrated using various methods like NMR, Ion Trap, Quantum Dot, Optical Methods, etc. A quantum computer manipulates qubits by executing a series of quantum gates, each a unitary transformation acting on a single qubit or pair of qubits. In applying these gates in succession, a quantum computer can perform a complicated unitary transformation to a set of qubits in some initial state. The qubits can then be measured, with this measurement serving as the final computational result. Research must devise a way to maintain decoherence and other potential sources of error at an acceptable level. Probably the most important idea in this field is the application of error correction in phase coherence as a means to extract information and reduce error in a quantum system without actually measuring that system. Thereby, quantum computers will emerge as the superior computational devices and perhaps one day make today's modern computer obsolete.

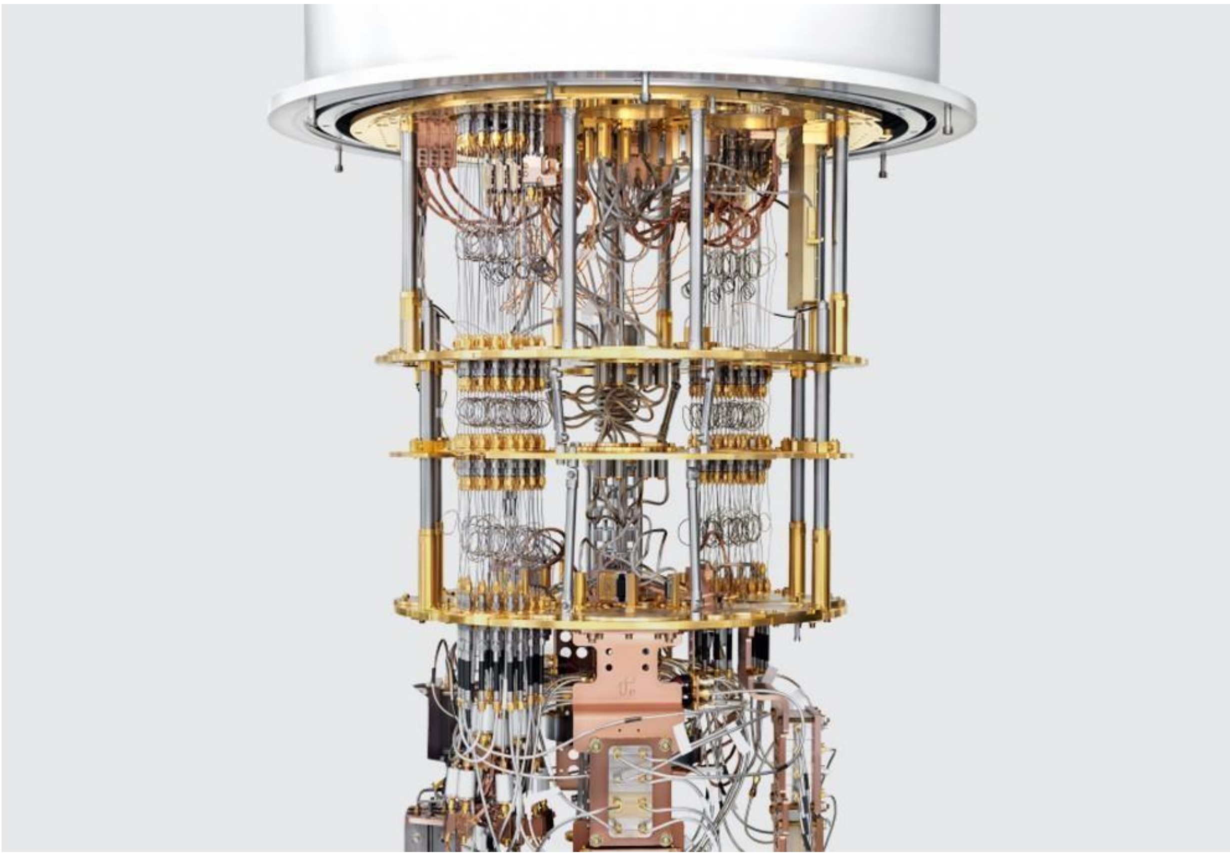
Keywords

Qubits, Superposition, Parallelism, Coherence, Entanglement, Quantum gates, Decoherence, NMR, Quantum dots.

1. Introduction

Quantum Computing is a new and exciting field at the intersection of mathematics, computer science and physics. It concerns a utilization of quantum mechanics to improve the efficiency of computation. Here we present a gentle introduction to some of the ideas in quantum computing. The paper begins by motivating the central ideas of quantum mechanics and quantum computation with simple toy models. From there we move on to a formal presentation of the small fraction of (finite dimensional) quantum mechanics that we will need for basic quantum computation. Central notions of quantum architecture (qubits and quantum gates) are described. The paper ends with a presentation of one of the simplest quantum algorithms: Deutsch's algorithm. Our presentation demands neither advanced mathematics nor advanced physics.

The focus of the course will be on the practical aspects of quantum computing and on the implementation of algorithms in quantum simulators and actual quantum computers (as the ones available on the IBM Quantum Experience and D-Wave Leap). No previous knowledge of quantum physics is required and, from the mathematical point of view, only a good command of basic linear algebra is assumed. Some familiarity with the python programming language would be helpful, butis not required either.



Quantum computing promises to solve problems which are intractable on digital computers. Highly parallel quantum algorithms can decrease the computational time for some problems by many orders of magnitude. This important book explains how quantum computers can do these amazing things. Several algorithms are illustrated: the discrete Fourier transform, Shor's algorithm for prime factorization; algorithms for quantum logic gates; physical implementations of quantum logic gatesin ion traps and in spin chains; the simplest schemes for quantum error correction; correction of errors caused by imperfect resonant pulses; correction of errors caused by the nonresonant actions of a pulse; and numerical simulations of dynamical behavior of the quantum Control -Not gate. An overview of some basic elements of computer science is presented, including the Turing machine, Boolean algebra, and logic gates. The required quantum ideas are explained.

There are problems that even the most powerful classical computers are unable to solve becauseof their scale or complexity. Quantum computers may be uniquely suited to solve some of these problems because of their inherently quantum properties. This curated set of videos is intended to introduce the field of quantum computing with increasing complexity from one video to the next.

While the curated learning resources compiled by EPiQC serve to inform the general public aboutthe topic of quantum computing, they are also designed to invite college and graduate students, as well as practicing professionals, to learn more about the field.

Get started by reading out EPiQC zines about the History of Quantum Computing and Quantum Computing - its current state and promise for the future!

Start with the facts! The Quantum Computing Fact Sheet is a quick source for up-to-date information about quantum computing - designed to help readers separate fact from fiction as quantum computers gain more news coverage.

2. Quantum Bits

Quantum bit is a quantum mechanical property having charge, magnetic dipole and spin. Charge and Spin is influenced by angular momentum and orientation in space whereas dipole is associated with spin. The concept of Quantum Bit was introduced by Stephen Wiesner. Benjamin Schumacher in his acknowledgment of his paper described a way of compressing states emitted by a quantum source of information so that they require fewer physical resources to store. The bits operate in parallel having simultaneous states ‘0’and ‘1’.

3. Quantum Parallelism

This makes it possible to perform a large number of operations in parallel, which represents a key difference from classical computing. Namely, in classical computing it is possible to know the internal status of the computer. On the other hand, because of the no-cloning theorem, it is not possible to know the current state of a quantum computer. This property has led to the development of the Shor factorization algorithm, which can be used to crack the Rivest–Shamir–Adleman (RSA) encryption protocol. Some other important quantum algorithms include: the Grover search algorithm, which is used to perform a search for an entry in an unstructured database; the quantum Fourier transform, which is the basis for a number of different algorithms; and Simon’s algorithm. These algorithms are the subject of Chapter 5. A quantum computer is able to encode all input strings of length *N* simultaneously into a single computational step. In other words, the quantum computer is able simultaneously to pursue 2*N* classical paths, indicating that a quantum computeris significantly more powerful than a classical one.

4. Quantum Coherence

Quantum physics has come a long way since its theoretical beginnings in the early twentieth century. Techniques to manipulate light and matter have become increasingly sophisticated, facilitating fundamental studies of quantum effects and inspiring new technologies. From atomic networks to semiconductor 'spintronics', seemingly disparate areas of research are being driven by a shared goal — to harness and exploit quantum coherence and entanglement. Inevitably, these laboratory endeavours have necessitated a new theoretical toolbox. The image of a pair of photons zooming off in opposite directions, each sensitive to the other through their quantum entanglement, is conceptually tidy. But what happens when describing the quantum properties of more complex systems? This Insight on quantum coherence and entanglement starts with a Progress article that addresses the problem of 'thinking big': how can entanglement be quantified or measured in a system that comprises many particles and degrees of freedom? The reviews in this Insight highlight the exciting experimental progress in such systems, covering a wide range of physical settings. They describe both bottom-up approaches, in which researchers strive to achieve increasingly complex systems starting from a very small number of particles and degrees of freedom, and top-down approaches, in which the individual and collective degrees of freedom in larger systems are controlled. Ultimately, the goal is to control many-particle systems at the quantum limit, an attractive prospect for quantum simulation and information applications. As such, this Insight brings together varied research. We trust, however, that you will find coherence in this diversity.

5. Quantum Entanglement

It is a physical phenomena where quantum state of each particle can’t be described independently rather they are described for system as whole and as an event. According to Albert Einstein:”An event at one point in a universe can spontaneously affect event arbitrarily far away.” Accordin g to Quantum Mechanics, particles don’t have well defined spin, they are in fact entangled i.e. spin is completely opposite to that of particle.

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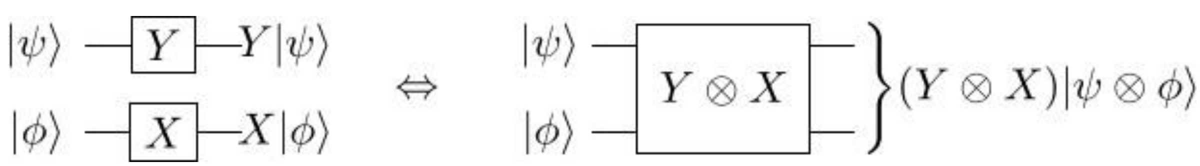
6. Quantum gates

Currently, the circuit model of a computer is the most useful abstraction of the computing process and is widely used in the computer industry in the design and construction of practical computing hardware. In the circuit model, computer scientists regard any computation as being equivalent to the action of a circuit built out of a handful of different types of Boolean logic gates acting on some binary (i.e., bit string) input. Each logic gate transforms its input bits into one or more output bits in some deterministic fashion according to the definition of the gate. By composing the gates in a graph such that the outputs from earlier gates feed into the inputs of later gates, computer scientists can prove that any feasible computation can be performed.

Traditional computers are like microscopic cities. The roads of these cities are wires with electricity coursing through them. These roads have lots of gates, known as logic gates, which enable computers to do their job. Like physical gates that allow or block cars, logic gates allow or block electricity. Electricity that goes through the gates represents a “1” of digital data, and blocked electricity is a “0.”



Logic gates are building blocks for processing information. One kind of logic gate, known as the AND gate, could, for example, quickly determine whether two people agree to a business deal. It takes in two bits of information, and generates a 1 if both incoming bits are 1s. So, if both business people say “yes” (1) to the deal, the AND gate will output 1. If one or both say “no” (0), the AND gate generates a 0 or a no.

By arranging gates in a circuit, engineers can create something akin to a flowchart that enables computers to carry out many kinds of logical operations, such as mathematical calculations —and perform the kinds of tasks that computers can do.

In their quantum logic gate, Monroe, Wineland and colleagues controlled the energy levels in an individual ion so that a lower-energy state represented a 0 and a higher-energy state represented a 1. The ion's internal energy was the first qubit. They created a second quantum bit with the atom's external motion: 0 represented less motion and 1 represented a greater amount of motion.

The group entangled the ion's internal energy state with its overall motion. In the process, they made a quantum version of a CONTROLLED NOT gate. In their gate, the ion's energy of motion serves the "control" bit. If it is a 1, then it causes the ion's internal energy state to flip.

7. Decoherence

Quantum decoherence is the loss of quantum coherence. In quantum mechanics, particles such as electrons are described by a wave function, a mathematical representation of the quantum state of a system; a probabilistic interpretation of the wave function is used to explain various quantum effects. As long as there exists a definite phase relation between different states, the system is said to be coherent. A definite phase relationship is necessary to perform quantum computing on quantum information encoded in quantum states. Coherence is preserved under the laws of quantum physics.

If a quantum system were perfectly isolated, it would maintain coherence indefinitely, but it would be impossible to manipulate or investigate it. If it is not perfectly isolated, for example during a measurement, coherence is shared with the environment and appears to be lost with time; a process called quantum decoherence. As a result of this process, quantum behavior is apparently lost, just as energy appears to be lost by friction in classical mechanics.

Decoherence was first introduced in 1970 by the German physicist H. Dieter Zeh and has been a subject of active research since the 1980s. Decoherence has been developed into a complete framework, but it does not solve the measurement problem, as the founders of decoherence theory admit in their seminal papers.

Decoherence can be viewed as the loss of information from a system into the environment (often modeled as a heat bath), since every system is loosely coupled with the energetic state of its surroundings. Viewed in isolation, the system's dynamics are non-unitary (although the combined system plus environment evolves in a unitary fashion). Thus the dynamics of the system alone are irreversible. As with any coupling, entanglements are generated between the system and environment. These have the effect of sharing quantum information with—or transferring it to—the surroundings.

Decoherence has been used to understand the possibility of the collapse of the wave function in quantum mechanics. Decoherence does not generate actual wave-function collapse. It only provides a framework for apparent wave-function collapse, as the quantum nature of the system "leaks" into the environment. That is, components of the wave function are decoupled from a coherent system and acquire phases from their immediate surroundings. A total superposition of the global or universal wavefunction still exists (and remains coherent at the global level), but its ultimate fate remains an interpretational issue. Specifically, decoherence does not attempt to explain the measurement problem. Rather, decoherence provides an explanation for the transition of the system to a mixture of states that seem to correspond to those states observers perceive. Moreover, our observation tells us that this mixture looks like a proper quantum ensemble in a measurement situation, as we observe that measurements lead to the "realization" of precisely one state in the "ensemble".

Decoherence represents a challenge for the practical realization of quantum computers, since such machines are expected to rely heavily on the undisturbed evolution of quantum coherences. Simply put, they require that the coherence of states be preserved and that decoherence is managed, in order to actually perform quantum computation. The preservation of coherence, and mitigation of decoherence effects, are thus related to the concept of quantum error correction.

8. NMR

Nuclear magnetic resonance quantum computing (NMRQC) is one of the several proposed approaches for constructing a quantum computer, that uses the spin states of nuclei within molecules as qubits. The quantum states are probed through the nuclear magnetic resonances, allowing the system to be implemented as a variation of nuclear magnetic resonance spectroscopy. NMR differs from other implementations of quantum computers in that it uses an ensemble of systems, in this case molecules, rather than a single pure state.

Initially the approach was to use the spin properties of atoms of particular molecules in a liquid sample as qubits - this is known as liquid state NMR (LSNMR). This approach has since been superseded by solid state NMR (SSNMR) as a means of quantum computation.

8.1. Liquid State NMR

The ideal picture of liquid state NMR (LSNMR) quantum information processing (QIP) is based on a molecule in which some of its atom's nuclei behave as spin-½ systems. Depending on which nuclei we are considering they will have different energy levels and different interaction with its neighbours and so we can treat them as distinguishable qubits. In this system we tend to considerthe inter-atomic bonds as the source of interactions between qubits and exploit these spin-spin interactions to perform 2-qubit gates such as CNOTs that are necessary for universal quantum computation. In addition to the spin-spin interactions native to the molecule an external magnetic field can be applied (in NMR laboratories) and these impose single qubit gates. By exploiting the fact that different spins will experience different local fields we have control over the individual spins.

The picture described above is far from realistic since we are treating a single molecule. NMR is performed on an ensemble of molecules, usually with as many as 10^15 molecules. This introduces complications to the model, one of which is introduction of decoherence. In particular we have the problem of an open quantum system interacting with a macroscopic number of particles near thermal equilibrium (~mK to ~300 K). This has led the development of decoherence suppression techniques that have spread to other disciplines such as trapped ions. The other significant issue with regards to working close to thermal equilibrium is the mixedness of the state. This required the introduction of ensemble quantum processing, whose principal limitation is that as we introduce more logical qubits into our system we require larger samples in order to attain discernable signals during measurement.

8.2. Solid State NMR

Solid state NMR (SSNMR) differs from LSNMR in that we have a solid state sample, for example a nitrogen vacancy diamond lattice rather than a liquid sample. This has many advantages such aslack of molecular diffusion decoherence, lower temperatures can be achieved to the point of suppressing phonon decoherence and a greater variety of control operations that allow us to overcome one of the major problems of LSNMR that is initialisation. Moreover, as in a crystal structure we can localize precisely the qubits, we can measure each qubit individually, instead of having an ensemble measurement as in LSNMR.

9. Quantum State

It refers to the state of an isolated quantum system. A quantum state provides the value of the outcome of each possible measurement on the system. It predicts the system behaviour.

In quantum physics, a quantum state is a mathematical entity that provides a probability distribution for the outcomes of each possible measurement on a system. Knowledge of the quantum state together with the rules for the system's evolution in time exhausts all that can be predicted about the system's behavior. A mixture of quantum states is again a quantum state. Quantum states that cannot be written as a mixture of other states are called pure quantum states, while all other states are called mixed quantum states. A pure quantum state can be represented by a ray in a Hilbert space over the complex numbers, while mixed states are represented by density matrices, which are positive semidefinite operators that act on Hilbert spaces.

Pure states are also known as state vectors or wave functions, the latter term applying particularly when they are represented as functions of position or momentum. For example, when dealing with the energy spectrum of the electron in a hydrogen atom, the relevant state vectors are identified by the principal quantum number n, the angular momentum quantum number l, the magnetic quantum number m, and the spin z-component sz. For another example, if the spin of an electron is measured in any direction, e.g. with a Stern–Gerlach experiment, there are two possible results: up or down. The Hilbert space for the electron's spin is therefore two-dimensional, with a length of one; that is, with

$$|\alpha|^2 + |\beta|^2 = 1,$$

where |α| and |β| are the absolute values of α and β. A mixed state, in this case, has the structure of a **2 × 2** matrix that is Hermitian and positive semi-definite, and has trace 1. A more complicated case is given (in

$$|\psi\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\big),$$

bra–ket notation) by the singlet state, which exemplifies quantum entanglement:

which involves superposition of joint spin states for two particles with spin 1/2. The singlet state satisfies the property that if the particles' spins are measured along the same direction then either the spin of the first particle is observed up and the spin of the second particle is observed down, or the first one is observed down and the second one is observed up, both possibilities occurring with equal probability.

A mixed quantum state corresponds to a probabilistic mixture of pure states; however, different distributions of pure states can generate equivalent (i.e., physically indistinguishable) mixed states. The Schrödinger–HJW theorem classifies the multitude of ways to write a given mixed state as a convex combination of pure states. Before a particular measurement is performed ona quantum system, the theory gives only a probability distribution for the outcome, and the form that this distribution takes is completely determined by the quantum state and the linear operators describing the measurement. Probability distributions for different measurements exhibit tradeoffs exemplified by the uncertainty principle: a state that implies a narrow spreadof possible outcomes for one experiment necessarily implies a wide spread of possible outcomes for another.

10. Quantum Superposition

Quantum Superposition refers to atom that can be at two positions at same time. The superpositionof state is applied to any quantum particle in the universe. In fact quantum superposition is responsible for the exchange of information in quantum bit. Let's focus on atom. Its excitation can be visualized with energy levels but when one measures it, only one of the two states is observed randomly. If we send an electromagnetic wave on quantum object with proper frequency, the atom alternates progressively between a non-excited and excited state. If the state of the atom is measured many times and averaged, we can find some oscillation explained by Sine wave. In real life, the quantum object is never completely isolated as an atom collides with other atom and quantum object and they are compelled to electromagnetic field or to a thermal bath. Hence the superposition of states stop after a while and the oscillation disappears. At start, the atom can really be in two states at a time but in the end the atom can be only in one state at a time randomly chosen. The time it takes for the superposition to disappear is called the decohorence time which gives valuable information about the interactions between the quantum object and its environment andalso determines error probability per operation.

11. Quantum Dots

Quantum dots (QDs) are man-made nanoscale crystals that that can transport electrons. When UV light hits these semiconducting nanoparticles, they can emit light of various colors. These artificial semiconductor nanoparticles that have found applications in composites, solar cells and fluorescent biological labels.

Nanoparticles of semiconductors — quantum dots — were theorized in the 1970s and initially created in

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the early 1980s. If semiconductor particles are made small enough, quantum effects come into play, which limit the energies at which electrons and holes (the absence of an electron) can exist in the particles. As energy is related to wavelength (or color), this means that the optical properties of the particle can be finely tuned depending on its size. Thus, particles can be made toemit or absorb specific wavelengths (colors) of light, merely by controlling their size.

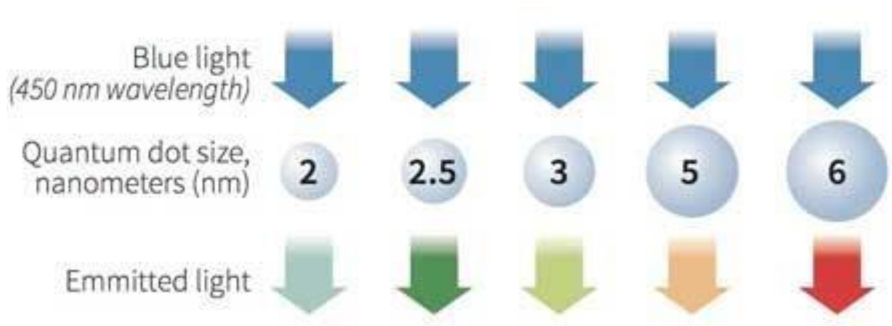

Fig1.1: Quantum dots are nanoscale man-made crystals that have the ability to convert a spectrum of light into different colors. Each dot emits a different color depending on its size. (Image: RNGS Reuters/Nanosys)

Quantum dots are artificial nanostructures that can possess many varied properties, depending on their material and shape. For instance, due to their particular electronic properties they can be used as active materials in single-electron transistors.

The properties of a quantum dot are not only determined by its size but also by its shape, composition, and structure, for instance if it's solid or hollow. A reliable manufacturing technology that makes use of quantum dots' properties — for a wide-ranging number of applications in such areas as catalysis, electronics, photonics, information storage, imaging, medicine, or sensing — needs to be capable of churning out large quantities of nanocrystals where each batch is produced according to the exactly same parameters.

Because certain biological molecules are capable of molecular recognition and self-assembly, nanocrystals could also become an important building block for self-assembled functional nanodevices.

The atom-like energy states of QDs furthermore contribute to special optical properties, such as a particle-size dependent wavelength of fluorescence; an effect which is used in fabricating optical probes for biological and medical imaging.

So far, the use in bioanalytics and biolabeling has found the widest range of applications for colloidal QDs. Though the first generation of quantum dots already pointed out their potential, it took a lot of effort to improve basic properties, in particular colloidal stability in salt -containing solution. Initially, quantum dots have been used in very artificial environments, and these particles would have simply precipitated in 'real' samples, such as blood. These problems have been solved and QDs have found numerous use in real applications.

12. Working

Unlike conventional electronics where bits propagate through wires and exchanged between memory and processor, Qubits typically stay in a place. Instead, control signals which are translation of machine language instruction are brought to the qubits and the quantum logical gates are implemented. The translated machine language instruction is voltage pulses sent to qubits. Qubits contain information which is processed in quantum processor and the output is in the form of binary bits separated.

13. ADVANTAGE AND APPLICATION

Let’s consider ‘2’ bit system whose possible combination of ‘2’ bit data system{ (00)(01)(10)(11)} contain ‘4’ possible states. Here, a ‘2’ bit classic computer can at most simultaneously perform ‘1’ of these ‘4’ possible function. In order to check all of them, the computer would need to repeat function separately. Whereas due to phenomenon of superposition a ‘2’ quantum bit quantum computer is able to analyze all of the operation at a time.‘2’ quantum bit system contains information about 4 states. Then a machine with ‘n’ quantum bit system contains information about 2n states simultaneously. Hence, the storage, computation and analysis increase with increase in data. Quantum Computing entirely depends upon the rule and property of quantum mechanics to solvethe problem. Since quantum processor is million times faster than the conventi onal system, Tech Giants like Google and NASA uses it to store data and solve complex problem. Its application iswide in research of NASA. It can be useful in learning more about universe as it can accumulate and process large chunk of data efficiently in less time. Medical research require efficient processing and storage system to learn about molecules, DNA, RNA and various other metabolic activities like protein sequencing which can be useful in design of drugs to cure various disease. Meteorological department can find its use in predicting weather condition. It can be used in study of forensic, financial and stock market and Information security as well. Graphics visualization can be enhanced resulting in high definition video effect. Network and routing system can be optimized thereby allowing the systems to communicate quickly and efficiently.

14. OBSTACLE IN QUANTUM SYSTEM

Our surrounding is full of elementary particle and it's not cold enough which only serve to destroy the Processing. Such uncontrolled entanglement of quantum bit with the surrounding outside leadto leakage of information. This effect is called decohorence which determines error probability per operation which is responsible for leakage. Apart from this, the control signal generated by machine language needs to be propagated through system immune to environmental phenomena. Hence it is necessary to isolate and cool the quantum processor as it removes wiggling of atom to just calm down and when it can be done then these powerful magical property that exist in quantum mechanics will blossom out. However, efforts are being made at various levels to minimize error probability per operation. The target is to bring it below fault tolerance threshold. A very important development in recent year was to bring down this threshold from 10-4 to about 1%, a number thatis either achieved or in reach with current technology. Today, no more than a dozen qubits havebeen integrated and operated on a chip. Control and read-out signal rely on bulky and expensive equipment. Currently built every quit has different behaviour which can be compensated by calibration and tweaking which is time consuming. In addition, Interconnects between the qubits and the control and read-out electronics present an important challenge.

15. CONCLUSION

Hence if quantum algorithm can be enhanced with the lower error probability per operation at the minimum tolerance threshold, the powerful magical property of quantum computing will blossom and next big transformation in the technology and life of people can be witnessed. It can be blessing in disguise for mankind as the planet is being digitized.

Quantum computing will give rise to a wave of technological applications, creating new business opportunities and helping solve some of today's most pressing global challenges. Previously untapped effects of quantum theory can now be used as a resource in technologies with far-reaching applications: secure communication networks, ultra precise sensors, study of chemical reactions for pharmacology, novel materials and fundamentally new paradigms of computation. In the last few years, governments and companies around the world, including Google, Microsoft, Intel, Toshiba and IBM, are considerably investing to unleash this potential. Although there has been significant progress in quantum computing, the field faces a number of challenges including the difficulty of building a large-scale quantum computer; designing new quantum algorithms and building expenses.

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