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Quantum Computing

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Abstract: After some remarks on the fundamental physical nature of information, Bennett and Fredkin's ideas reversible computation are introduced. This leads to the suggestions of Benioff and Feynman as to the possibility of a new type of essentially 'quantum computer'. If we happen to build such devices, Deutsch scientists showed that'quantum parallelism' leads to new algorithms and new complexity classes. This is dramatically illustrated by Shor's quantum algorithm for factorization which is polynomial in time in contrast to algorithms for factorization on a classical Turing computer. This discovery has potentially important implications for the security of many modern cryptographic systems. The fundamentals of quantum computing are then introduced - reversible logic gates, qubits and quantum registers. The key quantum property of 'entanglement' is described, with due homage to Einstein and Bell. As an illustration of a quantum program, Grover's database search algorithm is described in some detail. After all this theory, the status of experimental attempts to build a quantum computer is reviewed: it will become evident that we have a long way to go before we can factorize even small numbers. Finally, we end with some thoughts about the process of 'quantum compilation' - translating a quantum algorithm into actual physical operations on a quantum system - and some comments on prospects for future progress.

Keywords: Quantum Computing, Quantum Mechanics, High Performance Computing, Secure Computing.

INTRODUCTION

Quantum computation is an extremely exciting and rapidly growing field of investigation. An increasing number of researchers with a whole spectrum of different backgrounds, ranging from physics, via computing sciences and information theory to mathematics and philosophy, are involved in researching properties of quantum–based computation. Interplay between mathematics and physics of course has always been beneficial to both types of human activities. The story of quantum computation started as early as 1982, when the physicist Richard Feynman considered simulation of quantum-mechanical objects by other quantum systems. Whatever be the reason but the unique power of quantum processing wasn't actually predicted until in 1985 when David Deutsch belonging from University of Oxford published a crucial breakthrough in a form of theoretical paper in which he gave an explanation about the universal quantum computer. At the time of inspection things they found were a few rather spontaneous mathematical complex problems and the whole issue of quantum computation seemed little more than an academic curiosity. There was a sudden change in 1994 when Peter Shor from AT&T's Bell Laboratories represented the first quantum algorithm that can actually perform highly efficient factorization. This became a `killer application' as it was found that something very useful that only a quantum computer could do. Difficulty of factorization supports security concerned too many common methods of encryption; as an example, RSA --- one of the most popular public key cryptosystem which happens to be used for protecting electronic bank accounts actually gets its security from the difficult complexity of factoring large numbers. Potential use of quantum computation for ethical code-breaking purposes has now definitely raised an obvious question --- what about building a quantum computer.

Today's computers are classical, a fact which is actually not entirely obvious. A basis of modern computers rests on semiconductor technology. Transistors, which are the "neurons" of all computers,

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work by exploiting properties of semiconductors. However, the explanation of how semiconductors function is entirely quantum mechanical in nature: it simply cannot be understood classically. Are we thus to conclude that classical physics cannot explain how classical computers work?! Or are we to say that classical computers are, in fact, quantum computers! Surprisingly both questions result to a yes and a no. Yes, classical computers are in a certain, restricted, sense quantum mechanical, because, as far as we understand today, everything is quantum mechanical. However the classical computers, nevertheless based upon quantum physics, aren't quite quantum as they do not imply quantumness of matter at the information-theoretical degree, where it actually matters.

THE FUTURE OF COMPUTING: CLASSICAL OR QUANTUM

Computers increasingly pervade our society. This increasing influence is enabled by their ever increasing power, which has roughly doubled every 18 months for the last half-century. The continuing miniaturization of the elements of which computers are made, increases the power resulting in more and more elementary gates slammed with higher and higher clock pulse per unit, accompanied by energy efficient dissipation per elementary computing event. Roughly, a linear increase in clock speed is accompanied by square increase in elements per silicon unit--so if all elements compute all of the time, then the dissipated energy per time unit rises cubically (linear times square) in absence of energy decrease per elementary event.

This continuous decrease in dissipated energy per elementary eventually has made Moore's law possible. But there is a foreseeable end to this. It has been found that a little quantum of energy dissipation associated with elementary incidents. This puts an obvious basic limit on how far we can go with abatement, or does it?

It turns out that only irreversible elementary events (like erasing information) by the laws of thermodynamics necessarily dissipate energy; there is no physics law that requires reversible events (like negation) to dissipate energy. However the development of computation machinery is highly dependent on the classical physics principles and irreversible elements. However at the basic level, where matter is ruled by quantum mechanics, we acknowledge it is reversible. Further miniaturization will very soon reach scales where quantum mechanical effects take over and classical laws cease to apply accurately. The mismatch of computing organization and reality will express itself in friction. Computers will generate gigantic (megawatts) of energy unless their mode of operation becomes quantum mechanical (and thus reversible). That is, harnessing quantum mechanical effects is essential for further miniaturization and hence acceleration of classical computing methods.

QUANTUM MECHANICS

Quantum mechanics is considerably taken as the ideal behaviour of minute things. At this scale matter becomes quantized, this means that it can be subdivided no more. Quantum mechanics be in the fundamental concept of quanta has never been wrong, it explains why we have shining stars, how matter is has its definite shape, the periodic table, and numerous other phenomena. One day scientists hope to use quantum mechanics to explain everything, but at present the theory remains incomplete as it has not been successfully combined with classical theories of gravity. Some strange effects happen at the quantum scale. The following are main parts of quantum mechanics that are important for quantum computing:

- Superposition and interference
- Uncertainty
- Entanglement
- Linear algebra
- Dirac notation
- Representing information

Superposition

Superposition explains that a system can be found existing in two or even more of its states simultaneously. For example a single particle can be traveling along two different paths at once. It simply means that the particle possesses wave-like properties, implying that the waves from different paths can interfere with each other. Interference can cause the particle to act in ways that are impossible to explain without these wave-like properties. Particle's ability of being in a superposition tells us about the parallel nature of quantum computing: If each of the states corresponds to a different value then, if we have a superposition of such states and act on the system, we effectively act on all the states simultaneously.

Uncertainty

The quantum world is irreducibly small so it's impossible to measure a quantum system without having an effect on that system as our measurement device is also quantum mechanical. Resultantly there isn't any way to precisely predict all characteristics of a particle. There is a trade off - the properties occur in complementary pairs (like position and momentum, or vertical spin and horizontal spin) and if we know one property with a high degree of certainty then we must know almost nothing about the other property.

That unknown property's behaviour is essentially random. An example of this is a particle's position and velocity: if we know exactly where it is then we know nothing about how fast it is going. This indeterminacy is exploited in quantum cryptography. Estimations (that are currently accepted) reveal that particles actually DON'T have defined magnitudes for undefined characteristics until they are calculated. This is like saying that something does not exist until it is looked at.

Entanglement

In 1935 Einstein (along with colleagues Podolski and Rosen) demonstrated a paradox (named EPR after them) in an attempt to refute the undefined nature of quantum systems. Their experiment seemed to show results that implied quantum systems were uniquely defined and they have local state BEFORE the measurement. However this hypothesis was declared wrong (as it was evident that quantum systems do not actually have any local state before proper measurement). Eventually the effect even being into controversy was still equally important, and hence became known as entanglement later.

Entanglement is taken as the tendency where pairs of particles tend to interact over any distance instantaneously. Particles don't exactly communicate, but there is a statistical correlation between results of measurements on each particle that is hard to understand using classical physics. To become entangled, two particles are allowed to interact; they then separate and, on measuring say, the velocity of one of them (regardless of the distance between them), we can be sure of the value of velocity of the other one (before it is measured). The reason we say that they communicate instantaneously is because they store no local state and only have well defined state once they are measured. Therefore this limitation has restricted the particles to be used for transmitting classical messages faster than the speed of light. Entanglement is chiefly utilized in applications for a wide variety of complex quantum algorithms and machinery.

Dirac Notation

Dirac notation is used for quantum computing. We can represent the states of a quantum system as kets. For example, an electron's spin can be represented as |0> spin up and |1> as spin down. The electron can be taken as a small magnet and the effect would be of a charged particle spinning on its axis. When we pass a horizontally traveling electron through an inhomogeneous magnetic field, in say, the vertical direction, the electron either goes up or down. Then if we repeat this again but with the up electron it will rise up, with the down electron it will fall down. We say the up electron after the first measurement is in the state |0> and the down electron is in state |1>.

But, if we take the up electron and pass it through a horizontal field it comes out on one side 50% of the time and on the other side 50% of the time.

Representing Information

Quantum mechanical information are subject to physical realisations in numerous ways. To have something not following a binary to a level of classical bit we eventually need quantum mechanical systems pertaining two states only, when measured. Methods for representing binary information in a way that is capable of exhibiting quantum effects (e.g. entanglement and superposition) are: electron spin, photon direction, polarisation of photons and nuclear spins.

ELEMENTS OF QUANTUM COMPUTING

In general terms we use to think of a quantum computer as a classical computer with a quantum integrated circuit attached with some discrete interface between conventional and the unique quantum logic. But as we know that there are quite a little list of things a quantum computer in comparison to the classical computer, it somehow makes some sense to do the loads of processing on the classical machine.

Bits and Qubits

These are the "nuts and bolts" of quantum computing. It describes qubits, gates, and circuits. Quantum computers perform operations on qubits which are analogous to conventional bits but they have an additional property in that they can be in a superposition. A quantized register having 3 qubits has the potential of storing 8 numbers all in superposition accordingly, likewise a 250 qubit register holds more superposed numbers than there are atoms in this whole universe. The amount of information stored during the "computational phase" is essentially infinite - it's just that we can't get at it. The unfeasibility of the data is associated to quantum calculations: An attempt made to visualise the measurement of a superposition state storing many values, the state eventually collapses and thus we are left with only one value and the rest gets lost. It seems encouraging but, in some eventual cases, it can be made possible to have it work in our computational advantage.

ENTANGLED STATES

Subatomic particles can be entangled; this means that they are connected, regardless of distance.

Their effect on each other upon measurement is instantaneous. This can be useful for computational purposes.

Consider the following state (which is not entangled):

$$\frac{1}{\sqrt{2}}(|00\rangle + |01\rangle)$$

It can be expanded to:

$$\frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|01\rangle + 0|10\rangle + 0|11\rangle.$$

Upon measuring the first qubit (a partial measurement) we get 0 100% of the

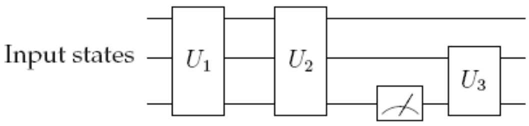
Time and the state of the second qubit becomes:

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

QUANTUM CIRCUITS

If we take a quantum state, representing one or more qubits, and apply a sequence of unitary operators (quantum gates), the result is a quantum circuit.

We now take a register and let gates act on qubits, in analogy to a conventional Circuit



This gives us a simple form of quantum circuit (above) which is a series of operations and measurements on the state of n-qubits. Each operation is unitary and can be described by a 2^n X 2^n matrix. Each of the lines is an abstract wire, the boxes containing Un are quantum logic gates (or a series of gates) and the meter symbol is a measurement. Altogether these gates, wires, input, and output mechanisms eventually follow quantum algorithms.

Unlike classical circuits which can contain loops, quantum circuits are "one shot circuits" that just run once from left to right (and are special purpose: i.e. we have a different circuit for each algorithm). It is always possible to rearrange quantum circuits so that all the measurements are done at the end of the circuit.

QUANTUM COMPUTER

Quantum computers are different from binary digital electronic computers based on transistors. Whereas common digital computing requires that the data be encoded into binary digits (bits), each of which is always in one of two definite states (0 or 1), quantum computation uses quantum bits, which can be in superposition of states. A quantum Turing machine supposedly is a theoretical model of such a computer, also called by the name 'universal quantum computer'. 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. A quantum computer having quantum bits like spin was also crafted in a formula to be used as quantum space–time in 1968.

As of 2017, the development of actual quantum computers is still in its infancy, but experiments have been carried out in which quantum computational operations were executed on a very small number of quantum bits. Both practical and theoretical research continues, and many national governments and military agencies are funding quantum computing research in an effort to develop quantum computers for civilian, business, trade, environmental and national security purposes, such as cryptanalysis.

What Quantum Computers can do?

The biggest success so far -- and the event which ignited the current explosive growth of the field of quantum computing -- was Peter Shor's 1994 discovery of an efficient quantum algorithm for finding the prime factors (factoring) of large integers.

By making clever use of superposition's, interference, quantum parallelism, and some classical number theory, Shor's algorithm finds a factor of a number N in time roughly the square of the length of the input (which is log N bits). In contrast, every known classical algorithm requires exponential time to factor. Since factoring is one of the most elementary aspects of number theory, the oldest mathematical discipline, and centuries of efforts by the greatest mathematicians have not yielded better methods, it is widely believed that such better methods either do not exist or are prohibitively difficult to find.

In fact, this belief underlies most of current public-key cryptography, notably the RSA system, ubiquitously used on the Internet and in the financial world. Such crypto-systems can be broken if one can factor large numbers fast. Accordingly, the advent of quantum computing compromises all such systems: if a quantum computer can be built, then most of current cryptography becomes totally insecure, and, for example, electronic money can be forged.

CONCLUSIONS

There are many exciting avenues to be explored involving computer scientists, quantum physicists and electronic and photonic engineers. One example has been provided by Butler and Hartel at Southampton. They have shown how Grover's search algorithm can be expressed in terms of a probabilistic version of Djikstra's wp calculus and derived closed forms for its convergence. Another example is the new field of 'quantum compilers'! Quantum compilation is the business of translating an abstract quantum algorithm down to operations in a given implementation technology. For NMR, for example, a Hadamard transformation must be translated into a specific set of NMR magnetic field pulses. It is now evident that multi particle entangled states have actually given quantum algorithms an ultimate power. This is where the peculiar non-local behaviour of quantum mechanics enters the game. It is extremely necessary to address the error correction in order to have quantum computer survive interactions with slightly inaccurate quantum gate operations and the environment as well. Surprisingly, Shor and Steane have independently proposed schemes that show that quantum error correction is indeed possible in principle - something that had hitherto been doubted. Again, entanglement is at the heart of these error correction schemes. In his 1981 talk in which he first proposed the idea of a quantum computer, Feynman confessed that he was "not sure if there is a real problem with quantum mechanics." He was also not clear whether quantum computers could be made or would ever do anything useful. But he thought that quantum computation was a wonderful problem to "squeeze the difficulty of quantum mechanics into a smaller and smaller place." Since quantum computation relies so heavily on the non-local aspect of quantum theory we can extend and stress the theory in new and exciting ways. We may have the foundations of a new multibillion industry or we may find the first clues towards a theory that may eventually supplant quantum mechanics! Both possibilities are exciting.

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