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Quantum Computing: Future Directions

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ABSTRACT

Quantum theory is one of the most successful theories that have influenced the course of scientific progress during the twentieth century. It has presented a new line of scientific thought, predicted entirely inconceivable situations and influenced several domains of modern technologies. There are many different ways for expressing laws of science in general and laws of physics in particular. Similar to physical laws of nature, information can also be expressed in different ways. The fact that information can be expressed in different ways without losing its essential nature, leads for the possibility of the automatic manipulation of information. All ways of expressing information use physical system, spoken words are conveyed by air pressure fluctuations: "No information without physical representation". The fact that information is insensitive to exactly how it is expressed and can be freely translated from one form to another, makes it an obvious candidate for fundamentally important role in physics, like interaction, energy, momentum and other such abstractors. This is a project report on the general attributes of Quantum Computing and Information Processing from a layman's point of view.

***Keywords* —** computation, EPR, quantum mechanics, superposition, unitary transformation, decoherence.

I. INTRODUCTION

With the development of science and technology, leading to the advancement of civilization, new ways were discovered exploiting various physical resources such as materials, forces and energies. The history of computer development represents the culmination of years of technological advancements beginning with the early ideas of Charles Babbage and eventual creation of the first computer by German engineer Konard Zeise in 1941 [1]. The whole process involved a sequence of changes from one type of physical realization to another from gears to relays to valves to transistors to integrated circuits to chip and so on. Surprisingly however, the high speed modern computer is fundamentally no different from its gargantuan 30 ton ancestors which were equipped with some 18000 vacuum tubes and 500 miles of wiring. Although computers have become more compact and considerably faster in performing their task, the task remains the same: to manipulate and interpret an encoding of binary bits into a useful computational result [2].

The number of atoms needed to represent a bit of memory has been decreasing exponentially since 1950. An observation by Gordon Moore in 1965 laid the foundations for what came to be known as "Moore's Law" – that computer processing power doubles every eighteen months. If Moore's Law is extrapolated naively to the future, it is learnt that sooner or later, each bit of information should be encoded by a physical system of subatomic size. As a matter of fact this point is substantiated by the survey made by Keyes in 1988 [3]. This plot shows the number of electrons required to store a single bit of information. An extrapolation of the plot suggests that we might be within the reach of atomic scale computations with in a decade or so at the atomic scale however.

With the size of components in classical computers shrinking to where the behaviour of the components, is practically dominated by quantum theory than classical theory, researchers have begun investigating the potential of these quantum behaviours for computation. Surprisingly it seems that a computer whose components are all to function in a quantum way are more powerful than any classical computer can be [4]. It is the physical limitations of the classical computer and the possibilities for the quantum computer to perform certain useful tasks more rapidly than any classical computer, which drive the study of quantum computing.

A computer whose memory is exponentially larger than its apparent physical size, a computer that can manipulate an exponential set of inputs simultaneously – a whole new concept in parallelism [5]; a computer that computes in the twilight (space like) zone of Hilbert Space (or possibly a higher space – Grassman Space & so on), is a quantum computer. Relatively few and simple concepts from quantum mechanics are needed to make quantum computers a possibility. The subtlety has been in learning to manipulate these concepts. If such a computer is inevitability or will it be too difficult to build on, is a million dollars question.

II. QUANTUM ENTANGLEMENT

The observation of correlation among various events is day to day phenomena. These correlations are well described with the help of laws of classical physics [6]. Let us consider the following example: Imagine a scene of bank robbery is picturised. The bank robber is pointing a gun at the terrified teller. By looking at the teller one can tell whether the gun has gone off or not if the teller is alive and unharmed, one can be sure the gun has not been fired. If the teller is lying dead of a gunshot wound on the floor, one knows the gun has been fired. This is a simple detective case. Thus there is a direct correlation between the state of gun and the state of the teller 'gun fired' means "teller alive" [7]. In the event it is presumed the robber only shots to kill and he never misses.

In the world of microscopic objects described by quantum mechanics, correlation among the events is not so simple. Consider a nucleus which might undergo a radioactive decay in a certain time or it might not [8]. Thus with respect to decay the nucleus exist in two possible states only: 'decayed' and 'not decayed', just as we had two states, 'fired' and 'not fired' for the gun or 'alive' and 'dead' for the teller. However, in the quantum mechanical world, it is also possible for the atom to be in a combined state decayed-not decayed in which it is neither one nor the other but somewhere in between. This is due to the principle of linear superposition of two quantum mechanical states of the atom, and is not something we normally expect of classical objects like guns or tellers. Further let us consider a system consisting of two nuclei. Two nuclei may be correlated so that if one has decayed, the other will also have decayed [9]. And if one has not decayed, neither has the other. This is 100% correlation. However, the nuclei may also be correlated so that if one is in the superposition state, 'decayed-not decayed', the other will also be. Thus quantum mechanically, then one more correlation between nuclei than we would expect classically. This kind of quantum 'super correlation' is called 'Entanglement' [10].

Entanglement was in fact originally named German, 'Verschrankung', by Erwin Schrodinger, a Nobel laureate in physics, for his basic contribution in quantum mechanics. Schrodinger was the first to realize the strange character of entanglement. Imagine it is not the robber but the nucleus, which determines whether the gun fires. If the nucleus decays, it sets off a hair trigger, which fires the gun. If it does not decay, the gun does not fire [11]. But if the nucleus is in the superposition it can be correlated to the gun in a superposition state fired-not fired. However such a correlation leads to a catastrophic situation. In the present case teller is dead or alive at the same time! Schrodinger was worried about the similar situation where the victim of the quantum entanglement was a cat in a box (Schrodinger cat: A paradox) [12]. For Schrodinger cat in a box decay nucleus could trigger the release of lethal chemical. The basic problem is that in the everyday world we are not used to see anything like dead-alive cat or dead-alive teller. However, in principle, if quantum mechanics is to be a complete theory describing every level of our experience, such strange states should be possible [13]. Where does the quantum world stop and the classical world begins? Do we really have an interface separating quantum phenomenon from the classical one? And so on. These and allied problems have been described since long and in the process a number of different interpretations of quantum theory have been suggested [14].

The problem was brought into focus by a famous paper in 1935 by Einstein, Podolsky and Rosen, who argued that the strange behaviour of entanglement that quantum mechanics is an incomplete theory not wrong [15]. This is widely known as EPR paradox. The concept of EPR paradox can be understood with the help of following example: consider a Helium atom in the ground state. It has two electrons having following quantum numbers: n=1, l=0, s=1/2, s_z = +1/2 for one and s_z = -1/2 for another. Thus we have j = 0 & 1. But $j_z = (s_z)_1 + (s_z)_2 = 0$. Hence only j=0 state is allowed. Thus in a Helium atom, two electrons are antiparallel to each other and hence form entangled pair of system. The atom is provided sufficient energy (equal to the binding energy of the atom). So that it disintegrates at rest. Consequently two electrons fly away in opposite direction [16].

Two electrons are taken apart. With the application of magnetic field when the spin of one electron is flipped, the spin of other electron is also flipped instantaneously (communication with speed faster than speed of light). This is a real phenomenon Einstein called it spooky action at a distance; the mechanism of which cannot, as yet be explained by any theory- it simply must be taken as given and this was Einstein's objection about the completeness of quantum theory. However we know that further developments (Bell inequality and its experimental verification) proved that quantum considerations are correct even if it means communication between space like events [17]. Even more amazing is the knowledge about the state of spin of another electron without making a measurement on it.

Quantum Entanglement allows qubits that are separated by incredible distances to interact with each other instantaneously (not limited to the speed of light) [18]. No matter how large the distance between the correlated particles, they will remain entangled as long as they are isolated. Taken together, quantum superposition and entanglement creates an enormously enhanced computing power.

III. BERTLEMAN'S SOCKS

In the first instant one may be inclined to ask: What is so special about quantum entanglement? [19] One does encounter similar situations (phenomenon of correlation between two events) in areas other that quantum world. Let us consider the case of Mr. Bertleman who has the peculiar habit of wearing socks of different colours in left and right foot. If he wears red coloured sock in one foot, it should be green in the other, or if it is yellow in one then it should be blue in the other [20]. Presumably Mr. Bertleman never breaks the rule. Therefore looking at the colour of one sock one can tell the colour of the other sock which he is wearing. However on deeper scrutiny, the kind of objection raised above, does not stand. As a matter of fact in quantum entanglement the choice of measurement also plays a crucial role. One may decide to measure x-component of spin, or its y-component or a compound along s direction inclined at an arbitrary angle to x-axis. The other particle arranges its spin accordingly. In case of Bertleman's example the onlooker has a role to play. The onlooker once decides to see the yellow-blue combination of colours for Bertleman socks, looks at accordingly the intention of onlooker in deciding the colour is interesting and equally interesting is the instant communication of this intention.

IV. EPR SITUATION, HIDDEN VARIABLES AND BELL THEOREM

The critical examination of the paper "Is Quantum Mechanics Complete?" by Einstein, Podolsky and Rosen (EPR) carried by John Bell lead to following contradictory conclusion:

1. EPR correlations (usually referred as quantum entanglement) predicted by quantum mechanics are so strong that one can hardly avoid the conclusion that quantum mechanics should be completed by some supplementary parameters (those so called hidden variables.)
2. The elaboration of the above result, demonstrates that the hidden variables description in fact contradicts some predictions of quantum mechanics.

In the face of these two perfectly convincing and contradictory results, there is only one way out: ask Nature how it works [21]. Till the end of 1970 there was no experimental result to answer this question. The contradiction discovered by Bell in EPR paper, is so subtle that it appears only in a very peculiar situations that had not been investigated. And require design and build specific experiments.

Thus the two situations the case of correlation between the polarized states of two photons and the case of twin brothers (a number of such situations can be exemplified) are exactly analogous. It seems therefore, natural to link this correlation between the pairs of photons to some common property analogous to the common genome of the two twin brothers. This common property changes form pair to pair, which accounts for the random character of the single event. This is the basic conclusion drawn by John Bell regarding EPR states. A natural generalization of the EPR reasoning leads to the conclusion that quantum mechanics is not a complete description of physical reality [22]. As a matter of fact, introduction of "some common property" which changes from pair to pair, invokes the idea that complete description of a pair must include "something" in addition to the state vector, which is the same for all pairs. This "something" can be called supplementary parameter or hidden variables. Inclusion of hidden variables sends an account of the polarized states of two photons, for any set (**a**, **b**) of orientations.

V. BELL INEQUALITIES

Bell examined critically the requirement for hidden variables to explain the expected correlation between the two polarized states of photons. It was shown that the expected correlations, for the joint measurements of polarized states of photons as mentioned above, cannot take any set of values, but they are subjected to certain constraints. More precisely, if we consider four possible sets of orientations [(**a.b**), (**a.b'**), (**a'.b**), (**a'.b'**)], the corresponding correlation coefficients (which measure the amount of correlation) are restricted by Bell inequalities which states that a given combination of these four coefficients 's' is between –2 and +2 for any reasonable hidden variable theory. Thus Bell inequalities prescribe a test for the validity of hidden variable theory. However, quantum mechanics predicts the value of s as 2.8 i.e., it violates Bell inequalities, and the same is tested by experiments. Thus the hidden variable theories envisaged above are unable to send an account of the EPR correlation (quantum entanglement) predicted by quantum mechanics. As a matter of fact quantum mechanical correlations are more intricate to understand as compared to mutual correlations between twin brothers [23].

Bell inequality is based on the assumption of local hidden variable models. The assumption of locality states that the result of a measurement by a polariser cannot be directly influenced by the choice of the orientation of the other remotely located polariser. Actually this is nothing but the consequence of Einstein causality (No signal can move with a speed greater than speed of light in vacuum). Nevertheless, Bell inequalities apply to wide class of theories than local hidden variable theories. Any theory, in which each photon has a "physical reality" localized in space-time, determining the outcome of the corresponding measurement, will lead to inequalities that (sometimes) conflict with quantum mechanics. Bell's theorem can thus be phrased in the following way: some quantum mechanical predictions (EPR correlations-quantum entanglement) cannot be mimicked by any local realistic model in the spirit of Einstein ideas of theory of hidden variables.

VI. CONCLUSION

The foundation of the subject of quantum computation has become well established, but everything else required for its future growth is under exploration. That covers quantum algorithms, understanding dynamics and control of decoherence, atomic scale technology and worthwhile applications. Reversibility of quantum computation may help in solving NP problems, which are easy in one direction but hard in the opposite sense. Global minimization problems may benefit from interference (as seen in Fermat's principle in wave mechanics). Simulated annealing methods may improve due to quantum tunneling through barriers. Powerful properties of complex numbers(analytic functions, conformal mappings) may provide new algorithms.

Quantum field theory can extend quantum computation to allow for creation and destruction of quanta. The natural setting for such operations is in quantum optics. For example, the traditional double slit experiment (or beam splitter) can be viewed as the copy operation. It is permitted in quantum theory because the intensity of the two copies is half the previous value. Theoretical tools for handling many-body quantum entanglement are not well developed. Its improved characterization may produce better implementation of quantum logic gates and possibilities to correct correlated errors.

Though decoherence can be described as an effective process, its dynamics is not understood. To be able to control decoherence, one should be able to figure out the eigen states favored by the environment in a given setup. The dynamics of measurement process is not understood either, even after several decades of quantum mechanics. Measurement is just described as a non-unitary projection operator in an otherwise unitary quantum theory. Ultimately both the system and the observer are made up of quantum building blocks, and a unified quantum description of both measurement and decoherence must be developed. Apart from theoretical gain, it would help in improving the detectors that operate close to the quantum limit of observation. For physicist, it is of great interest to study the transition from classical to quantum regime. Enlargement of the system from microscopic to mesoscopic levels, and reduction of the environment from macroscopic to mesoscopic levels, can take us there. If there is something beyond quantum theory lurking there, it would be noticed in the struggle for making quantum devices. We may discover new limitations of quantum theory in trying to conquer decoherence.

Theoretical developments alone will be no good without a matching technology. Nowadays, the race for miniaturization of electronic circuits is not far away from the quantum reality of nature. To devise new types of instruments we must change our view- point from scientific to technological-quantum effects are not for only observation, we should learn to control them from practical use. The future is not foreseen yet, but it is definitely promising.

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