Quantum computing a new paradigm in science and technology

Part Ib: Quantum computing. General documentary. A stroll in an incompletely explored and known world.[1]

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3. Quantum Computer and its Architecture

A quantum computer is a machine conceived to use quantum mechanics effects to perform computation and simulation of behavior of matter, in the context of natural or man-made interactions. The drive of the quantum computers are the implemented quantum algorithms. Although large scale general-purpose quantum computers do not exist in a sense of classical digital electronic computers, the theory of quantum computers and associated algorithms has been studied intensely in the last three decades.

The basic logic unit in contemporary computers is a *bit*. It is the fundamental unit of information, quantified, digitally, by the numbers 0 or 1. In this format bits are implemented in computers (hardware), by a physic effect generated by a macroscopic physical system. Usually, it consists in the magnetization imprinted on a "hard" disk. Other physical effects can be taken into consideration such as the charge on a capacitor. In quantum computing the fundamental unit of information is referred to as quantum bit or *qubit*. The properties of qubits follow directly from the laws of quantum mechanics. Specifically, the effect of quantum superposition is, conceptually, at the core of quantum computing.

Qubits are made up of controlled particles and the means of control (e.g. devices that trap particles and switch them from one state to another. As is the tradition with any sort of quantum states, they are represented by Dirac—or "bra–ket"—notation. The | 0 ⟩ {\displaystyle |0\rangle }, and | 1 ⟩ {\displaystyle |1\rangle }, are the conventional writing forms of the two computational basis states, and are pronounced „ket 0" and „ket 1" respectively.

Qubit base states can also be combined. For example, a pair of qubits would have the following base states:|00⟩=[1000]{\displaystyle|00\rangle={\biggl….

A qubit can exist unequivocally, at quantum level, not only in classical logic state 0 or 1, as is the case of the classical bit, but also in a hybrid state consisting of a superposition of classical states. In other words, a qubit can assume 0 or 1, as a classical bit, but also can be in a state corresponding to an intermingling classic states, i.e. as zero, one or simultaneously both 0 and 1. In the latter case, it is associated with a probability measure for each state (for disambiguation, see further, theabout this conjecture). As concerns the probability of observing a quantum configuration of two entangled qubits, as outlined above, it is impossible to assess the probability of observing one configuration without considering the other and, it is true even if they are separated considerably in the space.

It is fair to assert that the exact mechanism of quantum entanglement is, nowadays explained on the base of elusive conjectures, already evoked in the previous sections, but this state-of- art it has not impeded to illuminate ideas and imaginative experiments in quantum information theory. On this line, is worth to mention the teleportation concept/effect, deeply involved in modern cryptography, prone to transmit quantum information, accurately, in principle, over very large distances.

Summarizing, quantum effects, like interference and entanglement, obviously involve three states, assessable by zero, one and both indices, similarly like a numerical base two (see, e.g. West Jacob (2003). These features, at quantum, level prompted the basic idea underlying the hole quantum computation paradigm.

At quantum level, experimentally evinced, physical properties of particles, such as, position, momentum, spin or polarization, display correlations. For instance, if a pair of particles are generated in such a way that their total spin is demonstrated to be zero and one particle is found/observed to have the spin orientation, referred to a reference axis, oriented clockwise, the correlated particle has the spin orientation counter-clockwise, along the same axis. Most of physicists accept that this appearance owes to quantum entanglement phenomenology. This effect follows when particles such as electrons or photons, interact intimately, in such a way, that a specific kind of change in the state of one particle is reflected, instantly, in a one-to-one correspondence, to similar particles, remaining, "entangled", at future times, irrespective of the distance between particles.

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 cannot be described independently of the state of the other(s), even when the particles are separated by a large distance—instead, a quantum state must be described for the system as a whole.

Measurements of physical properties such as position, momentum, spin, and polarization, performed on entangled particles are found to be correlated. For example, if a pair of particles is generated in such a way that their total spin is known to be zero, and one particle is found to have clockwise spin on a certain axis, the spin of the other particle, measured on the same axis, will be found to be counterclockwise, as to be expected due to their entanglement. However, this behavior gives rise to paradoxical effects: any measurement of a property of a particle can be seen as acting on that particle (e.g., by collapsing a number of superposed states) and will change the original quantum property by some

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[1] the continuation of the article appeared in issue 1/2018 of the magazine

unknown amount; and in the case of entangled particles, such a measurement will be on the entangled system as a whole. Thus It appears that one particle of an entangled pair „knows" what measurement has been performed on the other, and with what outcome, even though there is no known means for such information to be communicated between the particles, which at the time of measurement may be separated by arbitrarily large distances.

Such phenomena were the subject of a 1935 paper by Albert Einstein, Boris Podolsky, and Nathan Rosen, and, concurrently, by several papers by Erwin Schrödinger, shortly thereafter, describing what came, posteriorly, to be known as the EPR paradox. Einstein and others considered such behavior to be impossible, as it violated the local realist view of causality (Einstein referring to it as „spooky action at a distance") and argued that the accepted formulation of quantum mechanics – in Copehagen's interpretation – must, therefore, be incomplete. Later, however, the counterintuitive predictions of quantum mechanics were verified experimentally in tests where the polarization or spin of entangled particles were measured at separate locations, proving, statistically, as violating Bell's inequality, indicating that the classical conception of „local realism" cannot be correct. In earlier tests it couldn't be absolutely ruled out that the test result at one point (or at location where test has being performed) could have subtly transmitted information to remote points, affecting the outcome at a second location. However so-called „loophole-free" Bell tests have been performed in locations that were separated, such that communications at the speed of light would have taken longer - in one case 10,000 times longer - than the interval between the measurements. Since faster-than-light signaling is impossible according to the special theory of relativity, any doubts about entanglement due to such a loophole have thereby been suppressed.

According to some interpretations of quantum mechanics, the effect of one measurement occurs instantly. Other interpretations which don't recognize wavefunction collapse, dispute that there is any „effect" at all. After all, if the separation between two events is spacelike, then observers in different inertial frames will disagree about the order of events. John will see that the detection at point A occurred first, and could not have been caused by the measurement at point B, while Mary (moving at a different velocity) will be certain that the measurement at point B occurred first and could not have been caused by the A measurement. Of course both John and Mary are correct: there is no demonstrable cause and effect involved. However, all interpretations agree that entanglement produces correlation between the measurements, and that the mutual information between the entangled particles can be exploited, but that any transmission of information at faster-than-light speeds is impossible and this conclusions closes the matter.

In May 2018, researchers performed Bell test experiments in which further „loopholes" were closed.

Entanglement is considered fundamental to quantum mechanics, implicitly in Quantum Computing, even though it wasn't recognized in the first instance. Quantum entanglement has been demonstrated experimentally with photons, neutrinos, electrons, molecules, as large as buckyballs (see Cioclov, 2013) and even small diamonds. The utilization of entanglement in communication and computation is a very active area of research.

In May 4, 1935 New York Times article headline about an imminent paper, which remained in the scientific community consciousness under name of the EPR paper.

The article tackled the counterintuitive predictions of quantum mechanics about strongly correlated systems an issue first discussed by Albert Einstein in 1935, in a joint paper with Boris Podolsky and Nathan Rosen (EPR). In this study, the three scientists formulated what is nowadays referred as the EPR paradox, a thought experiment that attempted to show that quantum mechanical theory was at that time incomplete. They wrote: „We are, thus, forced to conclude that the quantum-mechanical description of physical reality given by Schrödinger wave functions is not complete."

However, the three scientists did not coin the word entanglement, nor entered generalize the special properties of the quantum state they considered. Following the EPR paper, Erwin Schrödinger wrote a letter to Einstein in German language in which he used the word Verschränkung (translated by himself as entanglement, though according to German language semantics it means, literally, to hug oneself to keep warm) „to describe the correlations between two particles that interact and then separate, as in the EPR experiment.

Schrödinger shortly thereafter published a seminal paper defining and discussing the notion of „entanglement." In the paper he recognized the importance of the concept, and stated: I would not call [entanglement] one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought."

Like Einstein, Schrödinger was dissatisfied with the concept of entanglement, because it seemed to violate the speed limit on the transmission of information implicit in the theory of relativity. Einstein later famously derided entanglement as „spukhafte Fernwirkung. or „spooky action at a distance."

The EPR paper generated significant interest among physicists and inspired much discussion about the foundations of quantum mechanics (perhaps most famously Bohm's interpretation of quantum mechanics), but produced relatively little other published work. So, despite the interest, the weak point in EPR's argument was not discovered until 1964, when John Stewart Bell proved that one of their key assumptions, the principle of locality, which underlies the kind of hidden variables interpretation hoped for by EPR, was mathematically inconsistent with the predictions of quantum theory.

Specifically, Bell demonstrated an upper limit, seen in Bell's inequality, regarding the strength of correlations that can be produced in any theory obeying local realism, and he showed that quantum theory predicts violations of this limit for certain entangled systems. His inequality is experimentally testable, and there have been numerous relevant experiments, starting with the pioneering work of Stuart Freedman and John Clauser in 1972[28] and Alain Aspect's experiments in 1982,all of which have shown agreement with quantum mechanics rather than the principle of local realism.

Until recently each had left open at least one loophole by which it was possible to question the validity of the results. However, in 2015 an experiment was performed that simultaneously closed both the detection and locality loopholes, and was heralded as „loophole-free"; this experiment ruled out a large class of local realism theories with certainty. Alain Aspect notes that the setting-independence loophole, which he refers to as „far-fetched" yet a „residual loophole" that „cannot be ignored" has yet to be closed, and the free-will, or superdeterminism, loophole is unclosable, saying „no experiment, as ideal as it is, can be said to be totally loophole-free."

A minority opinion holds that although quantum mechanics is correct, there is no superluminal instantaneous action-at-a-distance between entangled particles once the particles are separated.

Bell's work raised the possibility of using these super-strong correlations as a resource for communication. It led to the discovery of quantum key distribution protocols, most famously BB84 by Charles H. Bennett and Gilles Brassard and E91 by Artur EkertAlthough. Worth to mention that BB84 protocol does not use the entanglement quantum effect, while Ekert's protocol tolerates the violation of Bell's inequality, which is a proof of security.

a) More on the meaning of the concept of entanglement

An entangled system is defined to be one whose quantum state cannot be factored as a product of states of its local constituents; that is to say, they are not individual particles but are an inseparable whole. In entanglement, one constituent cannot be fully described without considering the other(s). Note that the state of a composite system is always expressible as a sum, or superposition, of products of states of local constituents; it is entangled if this sum necessarily has more than one term.

Quantum systems can become entangled through various types of interactions. For some ways in which entanglement may be achieved for experimental purposes, see the section below on methods. Entanglement is broken when the entangled particles decohere through interaction with the environment; for example, when a measurement is made.

As an example of entanglement: a subatomic particle decays into an entangled pair of other particles. The decay events obey the various conservation laws, and as a result, the measurement outcomes of one daughter particle must be highly correlated with the measurement outcomes of the other daughter particle (so that the total momenta, angular momenta, energy, and so forth remains roughly the same before and after this process). For instance, a spin-zero particle could decay into a pair of spin-½ particles. Since the total spin before and after this decay must be zero (conservation of angular momentum), whenever the first particle is measured to be spin up on some axis, the other, when measured on the same axis, is always found to be spin down. (This is called the spin anti-correlated case; and if the prior probabilities for measuring each spin are equal, the pair is said to be in the singlet state.)

The special property of entanglement can be better observed if we separate the said two particles. Let's put one of them in the White House in Washington and the other in Buckingham Palace (think about this as a thought experiment, not an actual one). Now, if we measure a particular characteristic of one of these particles (say, for example, spin), get a result, and then measure the other particle using the same criterion (spin along the same axis), we find that the result of the measurement of the second particle will match (in a complementary sense) the result of the measurement of the first particle, in that they will be opposite in their values.

The above result may or may not be perceived as surprising. A classical system would display the same property, and a hidden variable theory (see below) would certainly be required to do so, based on conservation of angular momentum in classical and quantum mechanics alike. The difference is that a classical system has definite values for all the observables all along, while the quantum system does not. In a sense to be discussed below, the quantum system considered here seems to acquire a probability distribution for the outcome of a measurement of the spin along any axis of the other particle upon measurement of the first particle. This probability distribution is in general different from what it would be without measurement of the first particle. This may certainly be perceived as surprising in the case of spatially separated entangled particles.

The encountered paradox is that a measurement made on either of the particles apparently collapses the state of the entire entangled system—and does so instantaneously, before any information about the measurement result could have been communicated to the other particle (assuming that information cannot travel faster than light) and hence assured the "proper" outcome of the measurement of the other part of the entangled pair. In the Copenhagen interpretation, the result of a spin measurement on one of the particles is a collapse into a state in which each particle has a definite spin (either up or down) along the axis of measurement. The outcome is taken to be random, with each possibility having a probability of 50%. However, if both spins are measured along the same axis, they are found to be anti-correlated. This means that the random outcome of the measurement made on one particle seems to have been transmitted to the other, so that it can make the "right choice" when it too is measured.

The distance and timing of the measurements can be chosen so as to make the interval between the two measurements spacelike, hence, any causal effect connecting the events would have to travel faster than light. According to the principles of special relativity, it is not possible for any information to travel between two such measuring events. It is not even possible to say which of the measurements came first. For two spacelike separated events x and x there are inertial frames in which x is first and others in which x is first. Therefore, the correlation between the two measurements cannot be explained as one measurement determining the other: different observers would disagree about the role of cause and effect.

b) Hidden variables theory

A possible resolution to the paradox is to assume that quantum theory is incomplete, and the result of measurements depends on predetermined "hidden variables".[40] The state of the particles being measured contains some hidden variables, whose values effectively determine, right from the moment of separation, what the outcomes of the spin measurements are going to be. This would mean that each particle carries all the required information with it, and nothing needs to be transmitted from one particle to the other at the time of measurement. Einstein and others (see the previous section) originally believed this was the only way out of the paradox, and the accepted quantum mechanical description (with a random measurement outcome) must be incomplete. (In fact similar paradoxes can arise even without entanglement: the position of a single particle is spread out over space, and two widely separated detectors attempting to detect the particle in two different places must instantaneously attain appropriate correlation, so that they do not both detect the particle.)

c) Violations of Bell's inequality

The hidden variables theory fails, however, when we consider measurements of the spin of entangled particles along different axes (for example, along any of three axes that make angles of 120 degrees). If a large number of pairs of such measurements are made (on a large number of pairs of entangled particles), then statistically, if the local realist or hidden variables view were correct, the results would always satisfy Bell's inequality. A number of experiments have shown in practice that Bell's inequality is not satisfied. However, prior to 2015, all of these had loophole problems that were considered the most important by the community of physicists. When measurements of the entangled particles are made in moving relativistic reference frames, in which each measurement (in its own relativistic time frame) occurs before the other, the measurement results remain correlated.

The fundamental issue about measuring spin along different axes is that these measurements cannot have definite values at the same time—they are incompatible in the sense that these measurements' maximum simultaneous precision is constrained by the uncertainty principle. This is contrary to what is found in classical physics, where any number of properties can be measured simultaneously with arbitrary accuracy. It has been proven mathematically that compatible measurements cannot show Bell-inequality-violating correlations, and thus entanglement is a fundamentally non-classical phenomenon.

d) Other types of experiments

In experiments in 2012 and 2013, polarization correlation was created between photons that never coexisted in time. The authors claimed that this result was achieved by entanglement swapping between two pairs of entangled photons after measuring the polarization of one photon of the early pair, and that it proves that quantum non-locality applies not only to space but also to time.

In three independent experiments in 2013 it was shown that classically-communicated separable quantum states can be used to carry entangled states.[48] The first loophole-free Bell test was held in TU Delft in 2015 confirming the violation of Bell inequality.

In August 2014, Brazilian researcher Gabriela Barreto Lemos and team were able to "take pictures" of objects using photons that had not interacted with the subjects, but were entangled with photons that did interact with such objects. Lemos, from the University of Vienna, is confident that this new quantum imaging technique could find application where low light imaging is imperative, in fields like biological or medical imaging.

e) Time Mystery

There have been suggestions to look at the concept of time as an emergent phenomenon that is a side effect of quantum entanglement. In other words, time is an entanglement phenomenon, which places all equal clock readings (of correctly prepared clocks, or of any objects usable as clocks) into the same history. This was first fully theorized by Don Page and William Wootters in 1983. The Wheeler–DeWitt equation that combines general relativity and quantum mechanics – by leaving out the time altogether – was introduced in the 1960s and it was taken up again in 1983, when the theorists Don Page and William Wootters proposed a solution based on the quantum phenomenon of entanglement. Page and Wootters argued that entanglement can be also used to measure the time.

In 2013, at the Istituto Nazionale di Ricerca Metrologica (INRIM) in Turin, Italy, researchers performed the first experimental test of Page and Wootters' ideas. Their result has been interpreted to confirm that time is an emergent phenomenon for internal observers but absent for external observers of the universe, just as the Wheeler-DeWitt equation[1] predicts.

f) Source for the arrow of time

The Arrow of Time, or Time's Arrow, is a concept developed in 1927 by the British astronomer Arthur Eddington involving the "one-way direction" of the time flow , or other way stated, "asymmetry" of time. This direction, according to Eddington, can be determined by studying the organization of atoms, molecules, and bodies, might be drawn upon a four-dimensional relativistic map of the world

Physicist Seth Lloyd asserts that quantum uncertainty gives rise to entanglement, the supposed source of the arrow of time. According to Lloyd; "The arrow of time is an arrow of increasing correlations. The approach to entanglement would be from the perspective of the causal arrow of time, with the assumption that the cause of the measurement of one particle determines the effect of the result of the other particle's measurement.

g) Non-locality and entanglement

In the media and popular science, quantum non-locality is often portrayed as being equivalent to entanglement. While it is true that a pure bipartite quantum state must be entangled in order to produce non-local correlations, there exist entangled states that do not produce such correlations, and there exist non-entangled (separable) quantum states that present some non-local behavior. This paradox have explanations but this matter is beyond this presentation remining the subterfuge of using the description in terms of local hidden variables. In short, entanglement of a two-party state is necessary but not sufficient for that state to be non-local. Moreover, it was shown that, for arbitrary number of party, there exist states that are genuinely entangled but admits a fully local strategy. It is important to recognize that entanglement is more commonly viewed as an algebraic concept, noted for being a precedent to non-locality as well as to quantum teleportation and combined with super-dense coding, whereas non-locality is defined according to experimental statistics and is involved in the foundations and interpretations of quantum mechanics.

h) Testing a system for entanglement

To refresh the meaning, of the entanglement this concept, being already approached in the aboves, let's assert in repetition that: *quantum entanglement* is a physical phenomenon that occurs when pairs or groups of particles are generated or interact, in a way a that the quantum state of each particle cannot be described independently — instead, a quantum state must be described like a system, as a whole.

However, for the general case, the criterion is merely a sufficient one, for separability purpose, otherwise, the problem

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[1] The Wheeler–DeWitt equation is an attempt to combine, mathematically, the ideas of quantum mechanics and general relativity, a step towards a theory of quantum gravity. In this approach, time plays no role in the equation, leading only to the problem of time. More specifically, the equation describes the quantum version of the Hamiltonian constraint using only metric variables.

becomes, computationally, NP-hard. A numerical approach to the problem was suggested by Jon Magne Leinaas, Jan Myrheim and Eirik Ovrum in their paper "*Geometrical aspects of entanglement*". Leinaas et al. offer a numerical approach, iteratively refining an estimated separable state towards the target state to be tested, and checking if the target state can indeed be reached. An implementation of the algorithm (including a built-in Peres-Horodecki criterion testing) is brought in the "StateSeparator" web-app.

In 2016 China launched the world's first quantum communications satellite. The $100m Quantum Experiments at Space Scale (QUESS) mission was launched on Aug 16, 2016, from the Jiuquan Satellite Launch Center in northern China at 01:40 local time.

For the next two years, the craft – nicknamed "Micius" after the ancient Chinese philosopher – will demonstrate the feasibility of quantum communication between Earth and space, and test quantum entanglement over unprecedented distances.

In the June 16, 2017, issue of Science, Yin et al. report setting a new quantum entanglement distance record of 1203 km, demonstrating the survival of a 2-photon pair and a violation of a Bell inequality, reaching a CHSH valuation of 2.37 ± 0.09, under strict Einstein locality conditions, from the Micius satellite to bases in Lijian, Yunnan and Delingha, Quinhai, China, increasing the efficiency of transmission over prior fiberoptic experiments by an order of magnitude.

i) Testing a system for entanglement; Naturally entangled systems

The electron shell of multi-electron atoms always consists of entangled electrons. The correct ionization energy can be calculated only by consideration of electron entanglement.

j) Photosynthesis

It has been suggested that in the process of photosynthesis, entanglement is involved in the transfer of energy between light-harvesting complexes and photosynthetic reaction centers where the kinetic energy is harvested in the form of chemical energy. Without such a process, the efficient conversion of optical energy into chemical energy cannot be explained. Using femtosecond spectroscopy, the coherence of entanglement in the Fenna-Matthews-Olson complex was measured over hundreds of femtoseconds (a relatively long time in this regard) providing support to this theory.

k) More on Quantum Effects and associated concept - see also Cpt-1 of this essay and Wikipedia or Cortana Windows searching machine using following key words:

- CNOT gate
- Concurrence (quantum computing)
- Einstein's thought experiments
- Entanglement distillation
- Entanglement witness
- Faster-than-light communication
- Ghirardi–Rimini–Weber theory
- Multipartite entanglement
- Observer effect (physics)
- Quantum coherence
- Quantum discord, see also this essay
- Quantum phase transition
- Quantum computing
- Quantum pseudo-telepathy
- Quantum teleportation
- Retrocausality
- Separable state
- Squashed entanglement
- Ward's probability amplitude
- Wheeler–Feynman absorber theory

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Physicist John Bell depicts the Einstein camp in this debate in his article entitled "Bertlmann's socks and the nature of reality", p. 143 of Speakable and unspeakable in quantum mechanics: "For EPR that would be an unthinkable 'spooky action at a distance'. To avoid such action at a distance they have to attribute, to the space-time regions in question, real properties in advance of observation, correlated properties, which predetermine the outcomes of these particular observations. Since these real properties, fixed in advance of observation, are not contained in quantum formalism, that formalism for EPR is incomplete. It may be correct, as far as it goes, but the usual quantum formalism cannot be the whole story." And again on p. 144 Bell says: "Einstein had no difficulty accepting that affairs in different places could be correlated. What he could not accept was that an intervention at one place could influence, immediately, affairs at the other." Downloaded 5 July 2011 from Bell, J. S. (1987). Speakable and Unspeakable in Quantum Mechanics (PDF). CERN. ISBN 0521334950. Archived from the original (PDF) on 12 April 2015. Retrieved 14 June 2014.

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More specifically, the quantum state of each particle cannot be characterized independently of the other corresponding particle, but only in the context, as a whole. If an individual measurement is tempted, as outlined above, then entanglement "collapses".

In this stage of exposure it is not superfluously to advice the reader to manipulate with care quantum computing concepts and reasoning and observe accurate definitions since in the literature there are many semantic blurs even in the language of quantum mechanics founders and philosophers (see, e.g. Daintith 2009).

p) quantum computing and errors correction*

A key problem in quantum computing is errors correction. De-coherence and those imbued in hardware architecture (e.g. in quantum gates) seems most redoubtable (e.g. West 2003, Shore 1985, Shore and DiVincenzo 1996). Other sources cannot be overlooked, as well, such as those originated in the crystalline lattice vibration, natural randomness of the nuclear spin of the system used to implement qubits. A robust hint was formulated at Los Alamos National Laboratory and MIT by a group under the lead of Laflamme (see Chuang, Laflamme and Yamamoto 1995) launching the hint that error correction should be applied in the coherence phase of existence of the quantum state, in order to extract information before the system is de-cohered, as result of any direct measurement procedure, that inevitably destroys the superposition of states, forcing them to assume value of either 0 or 1. It permitted that though it was not performed a direct measurements, but only to compare the spins for perceiving if any difference arose between them. By this way it was circumvented the acquiring of any information by measurements per se. This technique enabled to detect and fix errors in the phase of coherence of quantum states thus stabilizing the coherence in the quantum system. Worth to say that this maneuver it was accomplished by the technique of magnetic nuclear resonance.

It should mention, additionally, that de-coherence is irreversible and post-factum measures are illusive. De-coherence time for quantum computing entities (de-phasing time) ranges between nano-seconds and seconds at low temperature. In the present state-of-art, quantum computers require their qubits to be cooled to 20 mili-K in order to avoid de-coherence (Jones 2013). It follows that any quantum manipulation must be accomplished much more quickly than de-coherence time. If the error rate is sufficiently low, it is possible to introduce quantum error corrections, mainly targeting quantum gates. It is presumed that the error rate per gate should be of the order of 10-4.

Large-scale quantum computers, theoretically, have the potential to solve some intricate problems much more quickly and accurately, than classical electronic digital computers even with best known numeric algorithms.

For quantum computers, the structure and machine operation systems are already known, even it is in rudimentary format. Concomitantly, there are devised quantum computing algorithms, as Simon's algorithm, that run faster than any mathematic algorithm conceived for the most performant electronic digital computer or systems of digital computers in operation nowadays, and in foreseeable future. Worth to mention that quantum computers do comply with Church-Turing digital electronic computer model which confer a certain flexibility in applications. Concurrently, by using quantum computing in the realm of cryptography, new possibilities arise. Similarly, potential is created to undertake, with powerful computing means, the breaking of sophisticated codes or, conversely, to devise unbreakable codes and also, speed up, otherwise unmanageable, computations.

Quantum computation hardware technology is, nowadays, in its infancy but workable devices are under scrutiny and development. It is only a matter of time before we will have at disposal hardware facilities large enough to test advanced quantum algorithms already developed in practicable format and buildup a computation power, not surprisingly, unconceivable, in our times.

4. On Quantum Simulation

In order to be able to give a compact presentation of quantum mechanics concepts, beyond the engineering mathematical formalism, touch of algebraic standard formalism common in quantum physics, will be tempted in the followings.

The early applications of quantum computing have been envisaged for simulation of quantum systems themselves (Feynman 1982, Brown et al. 2010), Georgescu et al. 2014. The concept of quantum simulation emerged from the possibilities offered by the stand of development of quantum mechanics theory. Generally, the task of computer simulation is to assess the dynamic state of a system. Specifically, when referred to quantum simulation it means that given a Hamiltonian, H, which describes a physical system, in the initial state of the system, characterized by the initial state Schrödinger's wave function, Iψ, the output as result of some property, after the time, t, assumes the wave function, Iψt =e-iHtIψ, corresponding to the evolving of quantum system according to the Hamiltonian at time, t . The formalist use above -“bra-ket”- notation was introduced by Dirac abd is standard notation for describing quantum states).

It should be stressed that following this path the complexity of assessment, develops in time, exponentially, and the achieving the task, it is much over the capacity of classical digital computers. Both as concerns the hardware and algorithms dedicated to quantum simulation. This situation, as suggested Feynmann (1982), oriented the efforts towards quantum computing which, in principle, has the potential to cover, accurately in reasonable time, the solving of this problem. (Montanaro 2016).

5. Quantum computing algorithms

Quantum mechanics algorithms ought, in first instance, to comply with quantum mechanics theory and overall governing, principles such as superposition principle. A quantum system can exist, simultaneously, in any permitted quantum states. This means that a quantum register of the computer contains, in superposition of all its possible configuration of 0’s and 1’s, at the same time. It is unlike as in classical electronic computers, in which, a register contains, exclusively, only one value.

The simultaneous superposition of states holds until the system is subjected to observation, when it collapses in an observable state, i.e., a well-defined classical state.

There is, however, a possibility to circumvent this circumstance resorting to the description of quantum states in probability terms. Accordingly, one apportions to each of the possible quantum states in the system, the likelihood that this specific state will be observed. If measurements are pursued to get knowledge of this assessment then, according to Feynman conjecture and Bell’s theorem, the quantum system is perceived as collapsed, annulling any assessment, thus impeding the use the state for further manipulations. Without introducing any “magic”, quantum computation it is still performable by increasing the probability of observing the correct state until the attainment of a sufficient high value so that the correct answer attains a reasonable level of certainty.

There are, broadly speaking, three classes of quantum algorithms which provide advantage over classical algorithms. First class identifies with the quantum version of the Fourier transform, as is Deutsch-Jozsa (1992) algorithm and Shor’s (1994) algorithm for factoring discrete algorithms. The second class of algorithms covers quantum search algorithms discovered by Grover (1996), whereas the third class encompasses quantum simulation algorithms.

Quantum computing algorithms has become, nowadays, a vigorous field of theoretical field of research, the same as the complementary activity of devising hardware structures able to run such algorithms. A detailed presentation of this matter is much beyond the area covered by this Essay, but the interested reader, apart the references cited above, can also consult the following sources: Stanford Encyclopedia of Philosophy; Bacon and Dam 2010, Ladd, T. et al. 2010, Montanaro 2016, and Penrose 2004.

6. On the state-of-art in quantum computing

Despite quantum mechanics and, more generally, quantum physic, in the contemporary state of development, has passed successfully all challenges in describing phenomena and effects occurring at sub-atomistic size level, the basic foundational principles of quantum physics contain many contra-intuitive, strange, conjectures which are at stake in the debate on the possibility to devise and construct universal quantum computers. This matter is, nowadays, not unambiguously settled in the perspective to construct viable quantum computers. The need for superfast computers, built on revolutionary new principles, as quantum physics, aims to trespass the limitation of digital-logic computers, despite their success in nowadays science and technology. Necessity for faster computers arises from the fact that in the mathematicas field, powerful algorithms has been already developed to solve problems, intractable on the base of digital logic computing technology. However, physical systems are known which can provide entities enabling to implement quantum algorithms on quantum computers. Moreover, the handling of unavoidable errors that plague quantum computers remain to be deciphered and mastered in computation practice.

As result of experiments with candidate quantum effects that can underlay quantum computing, nuclear magnetic resonance (NMR) has been found to be one of most promising. In the line of urgency, is to find methods for combatting the myriad of redoubtable challenges in quantum computing, mostly, the controlling and removing quantum de-coherence (Preskill (1999). In de-coherence, information about the state of the computational sub-system is lost in the environment.

This type of error is major, since the environment is beyond the overall computational control. There is, nevertheless, at hand the operator “sum decomposition” that describes the effect on the computational sub-system of an interaction with another sub-systems, restraining only to operations on the computational sub-system alone. A tolerant error model presupposes that the environment interacts independently, vis-à-vis, with constitutive parts of the computational sub-system. This implies the enabling of the isolation of quantum system from its environment, since interactions with the external world, as already suggested, cause the system to de-cohere (“collapse”).

As concerns error-tolerant quantum computing architecture, making realistic assumptions about the underlying hardware, reveals that a 2,000-bit number could be factorized by a quantum computer using, approximately 3×1011 quantum gates and approximately 109 qubits, running for a day at a clock rate of 10 MHz (see Fowler et al. 2012).

More recent information on quantum computing, algorithms, achievements as well as deceptions can be found in the works of: Bacon and Dam 2010, Chuang et al., 1995, Fowler et al., 2012, Mika 2001,) Mosca 1912, Nielsen and Chuang (2010), Rieffel and Polack (2011), Severini et al., 2011, Shor 2004), Stanford Enc. 2011, Strubell 2011, West 2003.

General References

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