NANOSTRUCTURE QUANTUM COMPUTATION OR CELLULAR AUTOMATA?

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In this presentation, an attempt is made to assess the possibilities of nanostructure science and engineering to build either a quantum computer or alternatively a computational engine based on Cellular-Automata architectures. The assessment is based on both theoretical and experimental considerations and it is concluded that the Cellular Automata approach is the more promising.

From a theoretical point of view, quantum computation derives its special advantages over the classical von Neumann type computer from the involvement of entanglement. It is crucial for all claims of intrinsic novelty of quantum computation that entanglement has a non-local character. Entangled pairs, for example, are assumed to have the property that a measurement of one entity of the pair leads to an influence on the second entity that is instantaneous and reaches over arbitrary distances. It is this "magic" property that distinguishes quantum computing from any classical computer or nearest neighbour Cellular Automata architectures. Without this property it is possible, at least in principle, to replace the preparation and manipulation of the entangled pair by some combination of classical digital- plus analog-computation.

The possibility of quantum non-locality was already a major topic of dissent between Einstein and Bohr and has led to publications counting in the millions. There are currently two major schools of thought related to quantum non-locality. A large number of scientists particularly in the area of quantum optics [1] but also in the area of nano-structure research embraces quantum non-locality as an absolute necessity to explain the experiments. Not surprisingly, the proponents of quantum computation take sides with this group. The "proofs" of quantum non-locality are never experimentally direct. A detailed investigation has brought this author to the conviction that all such proofs are based on experiments of the Einstein-Podolsky-Rosen type and involve invariably a theoretical component: the Theorem of Bell [2].

The second school of thought is less homogeneous. A large number of probabilists and mathematically oriented physicists deny that the Theorem of Bell is general enough to apply to EPR experiments and are therefore sure that the proofs of quantum non-locality are incorrect and unconvincing [3]. In addition to this group there are other groups in physics that refuse to believe in quantum non-locality because of physical reasons that mostly are based on Einsteins relativity in connection with modern views. The statement of Kerson Huang that "Local gauge invariance frees us from the last vestige of action at a distance" is typical for the conviction of a large number of superb physicists. In the opinion of this author, quantum non-locality "influencing", as described, quantum states over arbitrary distances and instantaneously is a dubious concept for the reason that it is based on Bell's Theorem and that this theorem is not applicable to complex experimental situations [3]. Nevertheless, judging by the current number of papers on "quantum weirdness" the scale is bent very heavily toward the side of influences at a distance.

Cellular Automata architectures, that have been proposed and have been realised by nano-engineering, are not based on influences at a distance but on the contrary on nearest neighbour interactions as shown in the figure below that illustrates the well known "domino" like interactions of electrons in quantum dots (shaded circles in Fig. 1) that are mainly governed by electrostatic forces.

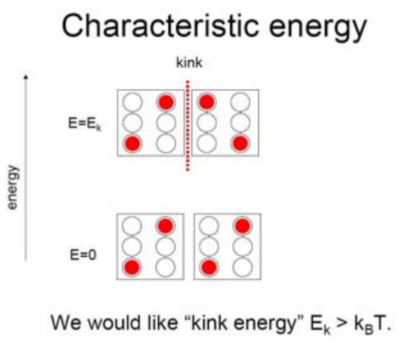

Fig. 1 Domino-like arrangement of quantum dots with characteristic energies based on electron-electron interaction (after Lent et al., see [5]).

The experimental features of quantum computing and Cellular Automata arrangements weigh also on the side of the Cellular Automata.

The results of quantum experiments are often cited for their incredible accuracy. Energy levels and their splitting (as in the Lamb shift) are measured and predicted with the accuracy of a large number of digits and so are, for example, the anomalous magnetic moment of the electron (known to more than 15 decimals). The entanglement correlation, however, that is the key to quantum computing follows different patterns. This is not only because inherently we have a rather short state lifetime involved in quantum computing; at most a lifetime that is of the length of the computation as opposed to the very long lifetimes of electrons, protons or atoms that are relevant for the super-precision quantum results. There is also the problem of identical preparation of the quantum state that depends on experimental equipment and the experimentalist. Accuracy for the correlation measurement of entangled pairs in the singlet state is at best around 1% while more complicated correlations such as the Greenberger-Horne-Zeilinger type have been reported with less than 10% accuracy only. The nanostructure specialist and experimentalist is usually well aware of the limitations in accuracy when determining probabilities to find a particle or when examining problems in electronic transport such as tunnelling which often can not even be estimated or experimentally reproduced within a factor of two. Thus there are two realms of accuracy when it comes to quantum mechanics; and entanglement problems do not belong to the accurate realm. For example, if the final measurement that determines the result consists of three Zeilinger triples, there is a 10% chance for the result to be wrong. Or, as directly found in [1], the result of a very simple quantum computation was false 10% of the time. Note that there exists no possibility to assess the correctness in cases where the outcome is not either a priori known or can not be obtained by ordinary computational means.

In addition there exists the vexing problem of quantum coherence. The wave functions that are involved in the calculations, and are subject to various “preparations” or time developments while passing quantum gates, need to stay coherent through this process. Coherence does not appear to be much of a problem in quantum optics experiments. Here it is the difficulty to achieve fast switching and detection of photons. The preparation involves switching of Kerr cell’s, for example, while the measurement involves avalanche photo-diodes both not even in the league of high speed nano-scale transistors. If instead of quantum optics nanostructures and charge carriers or excitons are involved in the entanglement experiments, then dephasing through phonon interactions are of importance. The electron-phonon interaction rates vary greatly depending on temperature and can be extremely long at extremely low temperatures (milli Kelvin). However, already at the temperature of liquid Helium the interaction time constants may be as short as nanoseconds and are below picoseconds at room temperature. In addition they depend on geometry and neighbouring materials (remote phonon scattering). This certainly means that in addition to all the other problems the problem of extremely low temperature operation is added for most possible implementations of quantum computers. The accuracy or reliability of accurate final measurements represents still a major problem even if the temperatures are lowered.

Cellular automata on the other hand do not rely necessarily on quantum coherence. They may, as shown in Fig. 1 largely depend on electrostatic effects and therefore may be less sensitive to any questions of quantum coherence. The reliability and accuracy of measurements may also be that of electrostatic problems and has been shown to be promising although still facing major challenges.

It is therefore concluded that from a purely theoretical view the special property of non-local quantum effects on which all special effects of quantum computation are based is questionable and not trusted by a large number of respectable physicists and mathematicians. The engineer attempting the construction of a quantum computer can rely on the results of quantum mechanics but can not draw on any substantive error analysis as they can in problems of electrostatics and electro-dynamics. The reasons for the large errors in the final measurements of Zeilinger triples, for example, are not known and do not have a theoretical basis because the nature of the quantum non-locality, if it exists, is not understood. What is it, for example, that keeps entangled pairs instantaneously and precisely correlated over large distances? Because this science question has not been answered improvement of deviations can not be achieved by engineering. Thus, a theoretical “quantum computer science” may exist but certainly there does not exist any form of quantum computer engineering.

Cellular Automata based on electrostatics or even Einstein local quantum electrodynamics, on the other hand, are scientifically understood and can therefore be engineered. This author can not assess the differences in the computational possibilities based on quantum computers and Cellular Automata sufficiently well to determine whether any actual needs can be found in certain applications that are forcing us at all to attempt to create a quantum computer instead of pursuing fruitful ideas related to Cellular Automata.

To finish on a positive note, however, the attempts to build quantum computers by using nano-structures may well lead to a more detailed understanding of what entanglement itself really is and therefore provide important clues for the interpretation of quantum mechanics itself.

References:

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