5-22-2014

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Recommended Citation

F. Matthew Mihelic "Implications of the Landauer limit for quantum logic", Proc. SPIE 9123, Quantum Information and Computation XII, 91230B (22 May 2014); https://doi.org/10.1117/12.2048531

Implications of the Landauer Limit for Quantum Logic

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ABSTRACT

The design of any system of quantum logic must take into account the implications of the Landauer limit for logical bits. Useful computation implies a deterministic outcome, and so any system of quantum computation must produce a final deterministic outcome, which in a quantum computer requires a quantum decision that produces a deterministic qubit. All information is physical, and any bit of information can be considered to exist in a physicality represented as a decision between the two wells of a double well potential in which the energy barrier between the two wells must be greater than kT·ln2. Any proposed system of quantum computation that does not result in such a deterministic outcome can only be considered stochastically as a probability distribution (i.e. a wave function). An example of such determinism in a quantum logic system is theorized to exist in the DNA molecule, where the decoherence of quantum decision results in an enantiomeric shift in the deoxyribose moiety that is appropriate to the Landauer limit.

Key words: quantum logic, Landauer limit, DNA, enantiomeric shift, double well potential

1. THE LANDAUER LIMIT

The existence of the Landauer limit has important implications for the theoretical consideration of quantum logic, and for the development of functional quantum computing. The Landauer limit might be thought of as the lowest energy at which a bit can exist, but that's not exactly right. The physicist Rolf Landauer is known for having shown that 'all information is physical' and how it is that the physicality of any bit of information exists as a decision between the two wells of a double well potential in which the energy barrier between the two wells must be greater than kT·ln2. [1] This meant that the energy consumption in a computational system comes about due to information erasure, rather than due to information generation as had been previously thought. Landauer showed how a "bit" of information could not exist unless that bit required an energy of at least kT·ln2 to erase or "randomize" it (also known as the "Landauer limit"), and this means that if a bit is considered as a double well potential with an energy barrier separating the two choices of a quantum decision, that energy barrier is kT·ln2 (which at 25 °C is approximately 0.0178 eV/bit). This is essentially the lowest energy at which the double well potential of a deterministic bit can exist, and because all qubits (or quantum bits) are essentially bits with superimposed information, this can also be considered as the lowest energy at which the double well potential of a quantum decision (or measurement) can exist. If a situation exists in which the energy barrier of a double well potential is less than kT·ln2, then that situation cannot be considered as a deterministic bit and consequently cannot be considered as a situation in which a deterministic quantum decision can be made, and such a situation can only be considered statistically as a probability distribution, and hence as a wave function. This is because in order for the proverbial "collapse of the wave function" to occur, a double well potential energy barrier of at least kT·ln2 must

Quantum Information and Computation XII, edited by Eric Donkor, Andrew R. Pirich, Howard E. Brandt,
Michael R. Frey, Samuel J. Lomonaco, Jr., John M. Myers, Proc. of SPIE Vol. 9123, 91230B
· doi: 10.1117/12.2048531

exist and be surmounted. So the definition of a deterministic bit or qubit necessitates that it entails a double well energy potential barrier appropriate to the Landauer limit (i.e. > kT·ln2).

So for any "bit" of information to exist, it must be associated with a physicality (i.e. a physical change in a system) that takes at least kT·ln2 of energy to erase or randomize it, and this means that it must be associated with a double well potential separated by an energy barrier of at least kT·ln2. The entropy associated with the stochasticity of a theoretical physicality represented by a double well potential with an energy barrier of less than kT·ln2 separating the two wells would preclude a deterministic decision, and thus any such theoretical physicality can only be described stochastically. Since all qubits are bits with superimposed information, all qubits are subject to the same limitations as bits. Thus, any physical change in a system that might require an energy level of less than kT·ln2 can only be considered stochastically, while a physical change in a system that requires an energy level of greater than kT·ln2 can not only be thought of statistically, but can also be thought of deterministically as well. Such an understanding of the nature of deterministic information might be used to resolve the seeming paradox between the stochastic ideas of Niels Bohr and the deterministic ideas of Albert Einstein, since Bohr would be right when considering systems with situations that operate at energy levels below the Landauer limit, while Einstein would be right when considering systems with situations of information that operate at energy levels above the Landauer limit.

2. IMPLICATIONS FOR QUANTUM LOGIC

In quantum computing a qubit is generally conceptualized in terms of particle spin, with the spin direction (arbitrarily either "spin-up" or "spin-down") representing the one degree of freedom of a particular qubit. In a coherent state a qubit exists stochastically as a probability distribution, with respective probability amplitudes for the spin-up state (α) and the spin-down state (β), and in which $|\alpha|^2 + |\beta|^2 = 1$. [2] The spin direction of a qubit statistically depends upon its probability amplitudes until one of the probability amplitudes equals 1 (which would necessarily mean that the other probability amplitude would equal 0), which would imply a deterministic decoherence (i.e. measurement, i.e. quantum decision) that would necessarily be associated with a physicality change in the system necessitating an energy level of greater than kT·ln2. So if one of the probability amplitudes equals 1, then the other must equal 0, and the associated physical change in the system must be associated with an energy level of greater than kT·ln2. In such a system there can be no deterministic physical change in the system if one of the probability amplitudes is not equal to 1, or if there is a change in the physical system that does not require at least kT·ln2 of energy to make the change; therefore, a quantum decision of either spin-up or spin-down implies that one of the probability amplitudes is equal to 1 and the other is equal to 0, and that the energy associated with the qubit is at least kT·ln2. The energy of the deterministic qubit must be associated with a deterministic probability amplitude, which must be equal to 1 in a deterministic situation. A quantum computational outcome that does not involve a change in the physicality of the situation requiring at least kT·ln2 of energy to effect that change, is not deterministic and can only be appropriately conceptualized (and represented) as a probability distribution (with its concomitant associated entropy).

In the "spin current" of a spin-1/2 quantum logic system it is not necessarily the mass or the charge of the particle that is being coherently conducted, but rather it is the "spin state" of the particle, and that "spin state" necessarily includes both the spin direction and the spin-angular momentum associated with the particle. [3] In a quantum logic system it is not only the information associated with a particle's spin direction (e.g. the spin projection quantum number m_s) that is being coherently conducted, held and read in the system, but it is also the physicality associated with the particle's spin momentum (e.g. the magnetic quantum number m_ℓ) that must be concomitantly coherently conducted, held and read along with it as well. Physically, a spin direction cannot exist without a momentum, and it is the magnetic quantum number from which the spin-angular momentum, and consequently the orbital angular momentum of the resultant physical change in the system proceeds. In order for a deterministic bit to be declared or measured, and for the resultant decoherence to take place, that orbital angular momentum by which the system is affected must bring about a physical change in the system that requires an energy level of kT·ln2 to randomize it. So the conceptual architecture of a system of quantum logic must provide for a deterministic computational outcome that is derived from a physical change in the system that is effected by an energy level of greater than kT·ln2, and if that system of quantum logic is based upon qubits of particle spin, then the orbital angular momentum that is associated with the decoherence of such a particle affecting the system must provide for a physical change in the system requiring an energy level of greater than kT·ln2 to randomize it. In the end, a quantum logic system must produce a deterministic bit (or qubit) in order for that system to be of any computational utility, so any meaningful decoherence must produce a physical change in the system that is appropriate to the Landauer limit.

3. "NON-TRIVIALITY" AND "QUANTUM-TO-CLASSICAL TRANSITION"

So all qubits are bits, and all information is physical. All bits can be represented as a choice between the two wells of a double well potential, and the two wells of the double well potential that represent a bit must be separated by an energy barrier of at least kT·ln2, therefore any qubit must eventually have a physical expression that necessitates the expenditure of at least kT·ln2 to randomize it. If a double well potential exists that is separated by an energy barrier of less than kT·ln2 then it cannot be considered as a bit and it cannot be considered as a qubit, and all that it can be considered as is a probability distribution (which is sometimes termed a "wave function"). However, a qubit that is defined by a double well potential that is separated by an energy barrier of greater than kT·ln2 can not only be expressed as a wave function, but it can also be expressed as the deterministic choice between the two wells of a double well potential (and this is sometimes referred to as the "collapse of the wave function"). All bits and all qubits must meet the requirement of the Landauer limit to be of any deterministic value in quantum logic, so the Landauer limit might be used to provide a definition of a "nontrivial" quantum mechanical process or event. As such the Landauer limit can thereby provide a delineation of "quantum-to-classical transition" as a quantum logic system in a "universal quantum computer" transitions from the coherent quantum mechanical processing of information to an output of deterministic classical information. [4]

4. MODEL OF QUANTUM LOGIC IN DNA

An example of the Landauer limit delineating a quantum-to-classical transition can be found in a theoretical model of quantum logic taking place in the DNA molecule. It is a property of DNA that electrons can be coherently conducted along the pi-stacking interactions of the aromatic nucleotide bases. [5] [6] This coherent conduction is dependent upon the base pair sequence and the relative geometry of the base pairs, which means that DNA does not function as a long "quantum wire", but rather it exhibits segments of coherence that dynamically shift and overlap because the geometry of DNA in a living cell is constantly changing. It is another property of DNA that electrons moving longitudinally along the DNA molecule are subject to a very efficient spin filtering effect as the spin of the electron interacts with the helicity of the DNA molecule. [7] So in DNA there are two simultaneous quantum-related processes occurring in that electrons are being coherently conducted along a very efficient spin filter. These two simultaneous processes can theoretically provide the means by which an individual electron (or its spin state) can be deposited (or read) into a specific nucleotide, and thereby affect the deoxyribose moiety of that nucleotide.

In DNA the deoxyribose moieties are strategically situated between the information-containing nucleotide base pair sequence, and the phosphate backbone that provides topological structure for the DNA molecule. Deoxyribose is a cyclical five carbon sugar with a relatively "floppy" structure that permits a "pseudorotation" around various conformations. Two of the most important conformations around that pseudorotation cycle of deoxyribose are the C2-endo and C3-endo conformations, which are chiral enantiomers or stereoisomers, and as such their respective chiralities are determined by electron spin direction via spin-orbit coupling at a chiral center. As the deoxyribose moiety "flip-flops" between the C2-endo and C3-endo conformations it can induce a significant change in the geometry of the phosphate backbone that is attached at both the C3 carbon and the C5 carbon, and/or induce a significant change in the angle of the nucleotide base that is attached at the C1 carbon. [8]

The C2-endo and C3-endo conformations occupy the lowest points in the plot of the deformation energies around the pseudorotation of deoxyribose, and they are separated by a relatively low energy barrier of 0.6 kcal/mole. This energy barrier provides the separation of a double well potential delineating the symmetry between the C2-endo and C3-endo conformations, and such a symmetry occurring within the physicality of information (e.g. DNA) can be theoretically both logically and thermodynamically reversible. [9] When an electron interacts with the deoxyribose moiety its orbital angular momentum can overcome the 0.6 kcal/mole energy barrier, essentially "randomizing" it, and allowing the spin direction of the electron to determine the conformational selection between the C2-endo and the C3-endo conformations, and such selection would essentially constitute a symmetry break. The energy barrier of 0.6 kcal/mole converts to approximately 0.0260 eV/molecule, which is slightly more than the Landauer limit of 0.0178 eV/bit (at 25°C). [10]

So the shift of the deoxyribose moiety between the C2-endo and C3-endo conformations constitutes a symmetry break that is determined by electron spin direction and occurs across an energy barrier that is appropriate to the Landauer limit, which means that it meets the energy requirement of a bit and therefore a qubit. This "flip-flop" or "wiggle" between the C2-endo and C3-endo conformations can be considered as an elementary movement of topological quantum logic in which a four-bar linkage exhibits exactly one degree of freedom in a local move taking place within the larger linkage of the three-dimensional lattice structure of the DNA double helix [11], and such a conformational shift can induce a rotation in the bond between the C1 carbon of the deoxyribose moiety and the nucleotide base (called the N-glucosidic bond or the χ bond) that can be a rotation of up to 45°. Remember that the pi-stacking interactions of the aromatic nucleotide bases depend in part upon the relative geometry of those nucleotide bases, and changing that relative geometry will thereby interrupt the coherent conduction longitudinally along the DNA molecule. So it is a deterministic quantum decision of enantiomeric shift that breaks the longitudinal coherence of the system, and this depends upon the measurement of electron spin direction by the coherently conducting spin filter of the DNA double helix. Essentially there is a qubit involving enantiomeric shift in each nucleotide that is provided by the logically and thermodynamically reversible three-state [12] chiral symmetry between the C2-endo and C3-endo conformations. [13]

The system of quantum logic in the DNA molecule operates at room temperature because the precise design of the crystalline nanospace that is the three-dimensional double helix lattice structure of DNA, limits the degrees of freedom upon which entropic factors such as temperature or solvation can have any effect. [14] This directly relates to Erwin Schrödinger's assertion in his 1944 book entitled *What is Life?*, that the genetic material in the nucleus of the cell (which had not yet been determined at that time) had to be in the form of some sort of "aperiodic crystal" in order to support the quantum mechanical "leaps" that he reasoned are necessary for adaptation to occur in that genetic material. [15] With the significant influence of Schrödinger, Watson and Crick determined the structure of that "aperiodic crystal" to be the DNA double helix in 1953, but the quantum mechanical function of that genetic material envisioned by Schrödinger had heretofore not been elicited.

Enabled by quantum-to-classical transitional operations appropriate to the Landauer limit, the quantum logic system in the DNA molecule is scalable to millions of qubits. Adding more qubits to the system simply involves adding more nucleotide base pairs, and this can be done by their physical addition and/or by increasing the coherence distance longitudinally along the DNA molecule. Remember that the coherence of the DNA molecule must be considered in terms of segments of coherence that dynamically shift and overlap, rather than considering DNA as a sort of long "quantum wire". This is because the geometry of DNA in a living cell is constantly changing, and this dynamic topology has prompted consideration of conceptualizations of topological quantum logic in the DNA molecule. The model of quantum logic taking place in the DNA molecule can provide physical conceptualization of proposed formal domains of control of topological quantum logic. [16]

5. THEORETICAL PARALLELS

In 1982 Dr. Paul Benioff published a seminal paper in quantum computing entitled "Quantum Mechanical Hamiltonian Models of Turing Machines" in which he described a model of a quantum logic system, and the model of quantum logic taking place in the DNA molecule has significant parallels to the model described by Dr. Benioff. He described a quantum mechanical model "constructed here on a finite lattice of spin-1/2 systems", and "each component system will be modeled as a sublattice of spin systems". His model contained both "time-independent" and "time-dependent" aspects. The "time-independent" aspects, which parallel the nucleotide qubits interacting via a coherently conducting spin filter, "do not dissipate energy or degrade the system state as they evolve", "they operate close to the quantum limit", and are "time global". On the other hand, the "time-dependent" aspects, which parallel the topological conformational changes of the DNA phosphate backbone, "do not degrade the system state" and are "time local". [17]

Dr. Benioff envisioned that his theoretical model would have a separation of systems in which "... the systems whose configuration states determine which configuration change operations are to be used are different from the systems on which the configuration changes are carried out." [18] In DNA the information in the nucleotide base pair sequence that is physically arranged as a coherently conducting spin filter, determines selection for electron spin direction, while the topological conformational changes of the system are manifest in the geometric changes of the phosphate backbone. The deoxyribose moieties, which are strategically situated between the coherently conducting information of the nucleotide base pair sequence and the topological structure of the phosphate backbone, can thereby mediate the quantum-to-classical transition of information across a deterministic energy barrier that is appropriate to the Landauer limit.

With consideration of the conceptualization of the process of the system, Dr. Benioff stated the following:

> "Consider the evolution of a complex system spread out over a region of space. One intuitively expects that as the evolution proceeds, changes will occur in the states of the subsystems in one region with the states of systems in other regions remaining stationary. Then the changes will transfer to some other subsystems in another region and occur in the new region for some time with the states of the subsystems in the first region remaining stationary. When the transferrals occur and to which subsystems in which regions they occur, or whether or not the whole system changes at some point, depends on the details of the process." [19]

Certainly this statement intuitively parallels the concept that in DNA there are segments of coherence that dynamically shift and overlap as the geometry of the molecule changes per deoxyribose enantiomeric selections, and such selections between the C2-endo and C3-endo enantiomers can not only affect longitudinal coherence distances along the DNA molecule, but can also affect the topology of the phosphate backbone and thereby the geometry of the whole of the DNA molecule.

6. CONCLUSION

In conclusion, the Landauer limit can delineate the "schnitt" (or cut) of quantum-to-classical transition between the quantum coherent state and a deterministic qubit in a quantum logic system, and thereby provide a definition of "non-triviality" in quantum mechanical processes. The model of quantum logic taking place in the DNA molecule can serve as an example of this, in that enantiomeric shifts across an energy barrier appropriate to the Landauer limit in the deoxyribose moieties, allow nucleotides to act as quantum gates that mediate between the quantum mechanical processes taking place in the coherently conducting spin filter of the pi-stacked aromatic nucleotide base pair sequence, and the deterministic geometry of the phosphate backbone.

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