Quantum Exclusivity: Uniquely Non-Classical Information Processing

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On October 23, 2019, an article appeared in the prestigious science magazine *Nature* entitled ‘Quantum supremacy using a programmable superconducting processor’ [5]. In it, the authors reported that their quantum computer had successfully solved a computational problem related to random number generation in 200 seconds. The same computation, they estimated, would require 10,000 years to perform on the fastest classical supercomputer of the day. Simultaneously, the group in charge of the said supercomputer cast doubt on the claimed quantum prowess. They stated that, according to their calculations, their machine would take 2.5 days (not 10,000 years) to complete the computation in question, in a straightforward way and without any optimization [6]. Following these events, several other claims and counterclaims on the subject of quantum supremacy and its variants were advanced by other major players in the business of building quantum computers. The debate is still raging at the time of this writing. If all of this was not enough controversy, the authors of the *Nature* paper concluded by asserting that their quantum computer had, for the first time, violated the Extended Church-Turing Thesis according to which any computation by any computer can be *efficiently* simulated on a Turing Machine.

The aim of this paper is to set the record straight concerning previous work on the limitations of the Church-Turing Thesis and, by extension, on the Extended Church-Turing Thesis. Indeed, the failure of the Church-Turing Thesis to capture the totality of the vast and mostly uncharted expanse of the computational universe has been meticulously documented by the Parallel and Unconventional Computation Research Group at Queen's University since 2005 [2, 3, 4]. In order to remain within the context created by the continuing confusion over quantum supremacy, our exposition of previous work on computations that contradict the Church-Turing Thesis is limited to quantum information processing.

We analyze the relation between the quantum and the classical models of computation from the broad perspective offered by quantum mechanics. In this new framework established by the laws of quantum mechanics, the concept of information acquires new dimensions due to the principle of superposition of states. Quantum information is, consequently, qualitatively different from classical information, the latter becoming just a simple, particular case of the former. This generalization has two major implications. The one of most interest perhaps is that the postulates of quantum mechanics allow us to design conceptually novel tools for processing information, leading to a significant increase in computational efficiency. But this radical departure from the classical ways of treating information also results in the formulation of novel information processing tasks. These problems involve purely quantum mechanical features and cannot be translated into classical terms.

In this paper, *quantum exclusivity* is introduced as a more powerful property than quantum “supremacy”. Computations are described in this paper that can be carried out on a quantum computer but are impossible, *in principle*, on a Turing Machine. This contradicts the Church-Turing Thesis, whereby any computation that can be performed on any computing device can be simulated on a Turing Machine. By direct consequence, *because they cannot be carried out at all*, whether efficiently or inefficiently, on a Turing Machine, these *exclusively quantum computations* invalidate the Extended Church-Turing Thesis as well. A broader and more important consequence of this result is that the Principle of Universality in computation is also invalid. It is therefore a fallacy to claim that there exists a finite and fixed Universal Computer, be it the Turing Machine, the Random Access Machine, the Cellular Automaton, or any such “universal” model, capable of simulating any computation by any other computer.

The presentation of *exclusively quantum computations*, that is, computations that are possible to carry out only on a quantum computer, is framed in the context of parallel computation [1], in general, and parallelism on a quantum computer [7, 8, 9, 10], in particular. There are two reasons for this, namely,

1. Parallel computation is central to each one of the described counterexamples to the Church-Turing Thesis and the Principle of Universality in computation, and
2. While the information processing power of quantum computers derives in theory from their ability to execute a certain computation simultaneously on all terms of a quantum superposition, parallelism in this paper refers to the ability to act simultaneously on multiple qubits.

The paper begins by introducing the class of unconventional computational paradigms that violate the Principle of Universality. This is followed by a theoretical proof of nonuniversality in computation. Detailed examples are then provided of *evolving computations*, that is, *unconventional computational problems* in which a parameter of the computation changes with the passage of time. This is followed by the description of five concrete evolving computations that cannot be performed on any classical computer, but are capable of being carried out successfully *only* on a quantum computer on which operations are executed in parallel, specifically,
(i) computing the quantum Fourier transform and its inverse, (ii) quantum decoherence in computing the quantum Fourier transform, (iii) quantum error correction, (iv) measuring entangled quantum states, and (v) maintaining quantum entanglement.

These computational problems demonstrate the incompleteness of the Church-Turing Thesis and, as a consequence, the falsity of the Principle of Universality in computation. In each of these paradigms, the information is encoded and processed using quantum mechanical means. As well, in each case a parallel approach offers the only way of seeing the task accomplished. This proves that parallelism as a concept, transcends the boundaries imposed by a particular way of representing and transforming information. The computational problems addressed herein clearly demonstrate the value of a parallel solution for quantum computation and information, confirming the capital role played by parallelism in the theory of computation.

In conclusion, the properties of the physical level chosen to embody information in a computational model ultimately determine its computational capabilities and power. The limitations of the classical Turing Machine are therefore purely physical. So, is a machine that computes following the principles of quantum mechanics really more powerful than a computing device designed in accord with classical physics? This paper endeavors to prove that the answer is definitely affirmative. And the difference is made by those problems, defined in purely quantum mechanical terms, whose quantum solutions are *impossible to simulate classically*.

References

[1] S. G. Akl, *Parallel Computation: Models and Methods*, Prentice Hall (1997).
[2] S. G. Akl, Evolving computational systems, In: S. Rajasekaran and J. H. Reif (eds.), *Parallel Computing: Models, Algorithms, and Applications*, Taylor and Francis, pp. 1-22 (2008).
[3] S. G. Akl, Nonuniversality in computation: Fifteen misconceptions rectified, In: A. Adamatzky (ed.), *Advances in Unconventional Computing*, Springer, pp. 1{31 (2017).
[4] S. G. Akl, Unconventional computational problems, In: R. A. Meyers (ed.), *Encyclopedia of Complexity and Systems Science*, Springer, pp. 631-639 (2018).
[5] F. Arute, et al., Quantum supremacy using a programmable superconducting processor, *Nature*, 574, pp. 505{510 (2019).
[6] E. Pednault, J. Gunnels, D. Maslov, D., and J. Gambetta, On quantum supremacy, October 21, 2019. https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/
[7] M. Nagy, and S. G. Akl, On the importance of parallelism for quantum computation and the concept of a universal computer, In: C. S. Calude, M. J. Dinneen, G. Paun, M. J., Perez-Jimenez, and G., Rozenberg (eds.), *Unconventional Computation*, Springer, pp. 176-190 (2005).
[8] M. Nagy and S. G. Akl, Quantum computing: Beyond the limits of conventional computation, *International Journal of Parallel, Emergent and Distributed Systems*, 22, 2, pp. 123-135 (2007).
[9] M. Nagy and S. G. Akl, Parallelism in quantum information processing defeats the Universal Computer, *Parallel Processing Letters Special Issue on Unconventional Computational Problems*, 17, 3, pp. 233-262 (2007).
[10] M. Nagy and S. G. Akl, *Using Quantum Mechanics To Enhance Information Process*ing, Scholars' Press (2012).