Supercomputer Numerical Simulation of Astrophysical Processes

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***Abstract*—For the 2015 CURE summer experience my research focused on pure research in the mathematics of Monte Carlo Analysis and also pure research in stellar formation processes. These two primary lines of research are of great importance to NASA and JPL and the wider scientific community to answer basic questions in mathematics and physics. An overview of some of these can be found in my partner Tannaz Oskui's final report.**

***Index Terms*—Monte Carlo analysis, Quantum Computation, Stellar formation.**

I. Introduction

In addition to the two primary research directions of analytic and numerical computation a new dimension of possibility has opened up. Following the instructions of my mentor Dr. John Sepikas I was directed to explore this new avenue of quantum computing. Such research is barely in its infancy and is very long range but it does offer the promise of great capability. Further it complements nicely the traditional Monte Carlo methods in that the computing capability only makes the Monte Carlo more effective.

II. Quantum Computation

The following is a very primitive outline of how the research has evolved. Yuri Manian in 1980 is the first to propose the idea of quantum computing in the way it is currently thought of. In 1981 the great Richard Feynman, while exploring how to simulate the evolution of a quantum system on a classical computer, proposed the basic model of a classical computer. In a sense he was saying that you *need* a quantum computer if you really want to model quantum mechanics. In 1985 David Deutsch explains the first universal quantum computer which was the analog accomplishment of Alan Turing's Universal Turing Machine; just as the Universal Turing Machine can be used to simulate any other Turing machine so too can the Deutsch universal quantum computer simulate any other quantum computer. Thus the theoretical foundations of quantum computing could be established even if the technology to implement it did not yet exist.

During the 1990's the explosion in computing technology and fabrications techniques increased interest in the field. Also too was the experimental foundations for quantum entanglement which increased confidence that quantum computing technology could indeed be realized and it is quantum entanglement which is at the heart of current understanding of the method.

During the 2000's the first working low qubit (5-10) quantum computers were actually built. These were proof of concept models and very finicky but did demonstrate that the idea had gone beyond merely the theoretical speculation stage. Of note was the establishment of the first commercial quantum computing company, D-wave systems. While the quantum computers they built were specialized problem specific systems, and were not general purpose, they did push the field and establish new qubit levels.

In the 2010's a number of new research groups and commercial companies have come into existence with mixed success. The shear increase in these numbers though testifies to the recognition of the tremendous potential of the quantum computing approach. Further, the wide technical implementations from spintronics to ion traps to quantum optics show that the field is wide open to innovation and promise similar to that which occurred in classical computing in the 1980's and 1990's and wide open for someone like me to participate in!

III. Classical computation

To understand just how quantum computing can show such promise it is necessary to review how classical computers work. All classical computers can be logically considered as a CPU together with collection of register circuits that are N bits long. The CPU contains a clock circuit, to synchronize the overall equilibrium digital states all circuits, together with combinational circuits to perform arithmetical and logical computations, along with sequential circuits to make logical decisions and data transfer/memory operations.

With this classical conceptual computer architecture in mind a number of important things can be seen. First, is that every such classical computer can only make changes from one state to another at a rate no greater than the clock speed. This might be fast but it is still finite. Second, the total number of states per register that the classical computer can distinguish is 2^N. Third the evolutionary changes that can be made to these states are limited to only those hard wired into the circuit's instruction set. To change that would require a redesign of the circuits in the classical computer.

Classical computer architecture and their variants have been extremely successful for the constructing both general purpose systems and also specialized, high speed systems. But despite this success the problems encountered in modern astrophysics (and many other areas of science such as meteorology) are still way too large or long to be solved in a reasonable time.

IV. Supercomputers

The current best method for dealing with this is the advent of the supercomputer which divides up a problem over a finite number of CPU's, each with additional memory ideally. This current approach is the dominate paradigm in high end computing today. First, it does not require designing new fundamental elements such as radically different CPU's or memory. In fact, the CPU used in most supercomputers are the exact same INTEL CPU's used in common laptops and desktops, there are simply more than one of them being used in the supercomputer. That is what the prefix super really means. The comparison of the "speed" between supercomputers is also generally simply the number CPU's which is of the order of a 100,000 or more for the NASA Pleiades system. Second it is scalable with for example two supercomputers being capable to being combined into single larger system. A drawback however is the need for new developments in software (such as MPI) to manage the new capability and the performance improvement is not strictly linear with CPU number. Having N CPU's does not mean that a problem can simply be done in 1/N the time of a single CPU since a lot of cycles are needed for the communication between CPU's. This communication problem has been one the main focus of supercomputer development.

V. Computational Challenges

Even with the new supercomputers which have advanced many fields, they are *still* are not powerful enough. Again modern astrophysical problems are just too large and also, some problems are simply not able to be run in parallel. For example most recursive problems, such as computing Fibonacci numbers cannot proceed independently of previous steps. So any additional CPU's that a programmer might have available does no good since they cannot be put to work until the previous calculation is completed.

One potential solution to the speed up of supercomputers is to literally speed them up with faster clock speeds and smaller transistors in the integrated circuits. This was part of the approach with early supercomputers in the 60's when hardware was much more expensive and of low density in terms of transistor density. With the general recognition of Gordon Moore Law's that there is a doubling in the number of components in circuits every two years it would be reasonable to expect that this approach would make an important contribution to computer speed. That has indeed been the general case but a fundamental physical limit is approaching in that the size of the circuit elements are now approaching that of a single atom and of course cannot go further. Thus the consideration of a new approach in the construction of a quantum computer.

VI. Solution through Quantum Mechanics

The need to employ more and more quantum mechanical analysis into the electrical theory of classical circuits has stimulated the development of the technical capability that would in part allow quantum computers to be realized physically. But more importantly the complete paradigm shift in their use is what has given them their computational power. For quantum computers in a sense takes parallel processing to the limit by using the very conceptual nature of Quantum Mechanics to do mathematics in a way that is very similar to Monte Carlo calculations.

It is the Copenhagen Interpretation of Quantum Mechanics that give quantum computers that large parallel computing quality. In this interpretation the nature of reality is that *before* the measurement of a physical system is taken, it is in sense in all possible measurable states *at the same time*. It is the act of measuring that forces or "collapses" the system into the state that is actually observed. This process is the "computation" part of a computer. The way it is programed is to arrange the quantum computer's physical system in such a manner that the solution to a desired problem is a high probability state that the system collapses into. Note the parallel with classical Monte Carlo solutions, in that the solution is only highly probably and not guaranteed, as it would be in Quasi-Monte Carlo computations. But as the quantum computer in a sense, tries all possible guesses including the right one at the same time, the effective parallel speed can be beyond what a current supercomputer can do.

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References

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