The Current State and Potential of Quantum Computing

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***Abstract* – In the wake of the recent purchase of a quantum computer by Google and NASA, this synthesis paper examines relevant articles surrounding the architecture and potential applications for quantum computing. The article also explains the principles of quantum computing necessary for such analysis.**

***Index Terms* – Quantum computing, emerging architectures, D-Wave processors, Google.**

INTRODUCTION

On the 25th of May in 2011, D-Wave Systems Inc. sold their first quantum computer to Lockheed Martin for ten million dollars. Six months later, the University of Southern California became the first academic institution to study quantum computing using a production grade quantum processor [1]. Almost exactly two years after their first sale, D-Wave Systems made their second sale of their next release, the D-Wave Two, to a joint venture between Google and NASA [2]. The promise of quantum computing is a revolutionary advance in computing speed via the complete reimagining of conventional processors. Is this forecast to be believed? A synthesis of various sources on the nature, architecture and implementation of quantum computing leads to the conclusion that quantum computing has a very strong (if currently unrealized) potential, but is not without practical limitations.

I. THE NATURE OF QUANTUM COMPUTING

Four principal sources will be used to summarize the necessary background on quantum computing. Michel Le Bellac provides a concise introduction to the main quantum computing ideas and techniques in his text, *A Short Introduction to Quantum Information and Quantum Computation* [3]. Michael Nielsen and Isaac Chung explore these topics in greater depth in *Quantum Computation and Quantum Information* [4]. Leszek Jaroszyński simplifies the physics behind quantum computing in his article "Introduction to Quantum Computing" [5]. Finally, D-Wave Systems maintains a tutorial containing useful information on quantum computing [6].

In a classic processor, bits are represented as either a zero when the capacitor is uncharged or as a 1 when the capacitor is charged. Yet between the charged and uncharged states, there are intermediate states where 10^4 to 10^5 electrons are displaced [3]. A quantum bit, or *qubit*, can contain all of these intermediate values via a quantum phenomenon known as a *linear superposition*. Particles can exist in two states at once; qubits (unlike classical bits) can have the value of zero and one at the same time. However observation or measurement of the qubit will force its random collapse from the superposition state to one of its basis states, i.e., zero and one [4]. In general, for *n* number of classical bits only one of 2^n values can be represented. As a qubit can represent two values at the same time, *n* qubits can represent 2^n values *simultaneously*. But as a series of qubits will collapse to only one of those 2^n values if observed, they are not useful in expanding data storage, but they can be useful in algorithms which can manipulate qubits without actually measuring or interacting with them [5]. As measurement disturbs the quantum state of the qubits, the end results are only probabilistic [5]. Even though the quantum computer returns multiple random answers, it can be taught the correct patterns via machine learning [6]. This manipulation can occur by the application of electric or magnetic fields, as the quantum mechanics operating inside the computer evaluates options which will allow the qubits to settle into the correct basis states to solve a particular algorithm. Essentially, the quantum computer learns and refines its pattern of qubit manipulation.

Besides superpositioning, the other quantum phenomenon necessary to understand quantum computing is *entanglement*. Two qubits, no matter how far they are separated, can become entangled into a single entity that can be manipulated. The amount of information available in multiple, entangled qubits grows exponentially with the number of qubits, whereas the information increase contained in bits only grows at a linear pace [3]. When two qubits are entangled, there is a correlation between the quantum state of one and the quantum state of its partner. Qubits can be processed through quantum circuits (known as quantum logic gates) which can evaluate a function f(x) for many different values of x simultaneously [4] in a principle known as *quantum parallelism*.

II. Quantum Computer Architectures

There are several different implementations of quantum computers which can be based on photon, coherent light, electrons, or current in specialized junctions [5]. Specific architectural design principles, techniques and limitations will be synthesized from research performed by Dimitry Solenov and colleagues as summarized in "Two-Qubit Gates in Semiconductor Quantum Dots using a Photonic Microcavity" [7]. D-Wave Systems describes their approach to quantum computing in their published architecture document [8], and Nicola Jones reveals some of the controversy surrounding the D-Wave Two in her review paper, "Computing: The Quantum Company," [9] which contains very specific references [10,11,12,13,14] on the quantum aspects of the D-Wave processors. Jacob Aron's review, "Controversial Quantum Computer Aces Entanglement Tests" presents more positive evidence on the D-Wave Two's quantum abilities [15].

A quantum computer can be constructed by expansion from a two-qubit gate system, provided five criteria are met:

- Availability of long-range switchable physical interaction between qubits;
- Quantum gates can perform an operation on one qubit based on its partner's state;
- Operations perform sufficiently faster than the rate of decoherence;
- A universal set of gates can be constructed;
- Gate design is scalable to multi-qubit systems [7].

Solenov, et.al. suggest that entanglement only occurs in today's photon-based optical cavities between nearest-neighbor qubits or in environments where no heat is exchanged between a system and its environment. They further contend that realistic quantum computing architecture requires distant qubits to entangle [7]. This observation is consistent with the mathematics which enable quantum information to exponentially grow with the number of qubits that can entangle. Limiting entanglement to nearest neighbors severely curtails the exponential increases in quantum computer efficiency to a more linear progression. The research at the Naval Research Laboratory has resulted in a design that can accommodate distant qubits that are manipulated with controlled laser frequencies. This design also claims to preserve fidelity from decoherence by reducing the times the qubits are in an excited state [7]. *Decoherence* is the interaction of qubits with the environment which blurs their superpositions and introduces errors [3].

The D-Wave Two creates circuits of eight qubits in a lattice so that each qubit is coupled to four other qubits internal to the circuit and to two qubits from adjacent circuits. Readout devices are connected, but do not record the qubits' values until after computation finishes [8]. In this way, quantum mechanics principles are preserved; however as the D-Wave Two is not accommodating distant qubits, its design must include supercooling. The D-Wave Two cools the processor to 20mK, which is approximately 100 times colder than interstellar space [8]. The refrigeration technology to accomplish this requires a significant physical footprint in a data center.

Controversy remains high on whether the D-Wave computers will be able to fulfill the promise of quantum computing, or whether they are even a quantum computers at all. Researchers at USC, an affiliate of D-Wave Systems Inc., acknowledge that "it is reasonable to ask whether this manufactured, macroscopic (~1 mm) [D-Wave One] system of artificial spins behaves quantum mechanically" [10]. Their experiments centered on *quantum annealing*, which is a way to find the lowest possible ground state of a system with multiple relative minimums [10]. Further research from USC seems to indicate such annealing is occurring. When running Monte Carlo simulations of easy and hard problems, the success probabilities on the D-Wave One closely resemble the expected probabilities from a simulated quantum annealer [11]. However, Smolen and Smith, from the IBM T.J. Watson Research Center, have demonstrated that a classical model can lead to the same annealing behaviors, and thus conclude "the evidence presented does not demonstrate the presence of quantum effects" [12]. Their findings were independently confirmed by Lei Wang and colleagues using a similar model [13].

Aron evaluates the D-Wave Two against two other expected aspects of quantum computing. He postulates that this processor's quantum credentials were originally suspect because D-Wave did not implement quantum logic gates [15]. Classical processors implement logic gates and many established quantum computing text books (including the two reviewed in this paper [3,4]) presuppose their presence in a quantum computer. Nicola Jones has stated that the quantum gate model is based on more established theory and has stronger academic support [16]. Aron, however, focuses more on entanglement. He notes that while entanglement cannot be measured while the D-Wave computer is in operation, D-Wave Systems have measured the energies of the qubits which conform to the quantum expectations of entangled qubits [15]. D-Wave's results were independently verified by the Information Sciences Institute using mathematical models. However, Aron also observes that the adiabatic model used by D-Wave depends on absolutely no heat exchange. Thus they might not be able to realize the exponential gains in quantum computing that have been predicted for systems that run at absolute zero [15]. Recall that the D-Wave computer runs at 20mK, although loading the digital to analog converters raises chip temperature to about 400 mK [17].

Additionally, qubits are very susceptible to interference from nearby internal or external components. As mentioned above, operations on a quantum computer must be significantly faster than the decoherence rate. Researchers from D-Wave Systems and the California Institute of Technology have demonstrated that localized magnetic impurities in the vicinity of qubit wiring are a key source of noise [14]. To overcome this challenge, a large number of qubits could be added to increase the probability of obtaining a correct answer (quantum information scientist Andrew Landahl suggests the ideal is 1 billion [18]) – or intensive error correction algorithms would need to be in place.

III. The Promise of Quantum Computing

Eleanor Rieffel and Wolfgang Polak discuss the projected domain areas for quantum computing in "An Introduction to Quantum Computing for Non-Physicists" [19]. The potential of quantum computing is envisioned by Russian physicist Michel Dyakonov in "State of the Art and Prospects for Quantum Computing" [20]. Finally, Google's rationale for launching a quantum computing center will also be reviewed [21].

Rieffel echoes one key potential area for quantum computing – the factoring of integers. As of the year 2000, the most efficient factoring algorithm was developed by Lenstra and Lenstra, but in 1994, Peter Shor created a quantum algorithm for factoring n-digit numbers [19]. Shor's algorithm, if implemented, could be very useful for breaking cryptographic codes [20] and could usher in a new area of more advanced quantum cryptography. Another area of opportunity is the simulation of quantum systems. One such application would be the efficient solving of quantum problems of strongly interacting particles [20], which might have broad applicability in chemistry and physics. Dyakonov skeptically remarks that after 15 years of imagining the potential of quantum computing, these are the only two application areas suitable for quantum information processing [20].

However, others have a more optimistic viewpoint. Search problems that take the form of "find some x in a set of possible solutions such that statement $P(x)$ is true" might also be good candidates for quantum computing [19]. These would include database searching, sorting, the coloring of regions in a graph, and artificial intelligence applications. Engineers Kristen Pudenz and Daniel Lidar have recently developed a machine learning approach using quantum optimization to learn the various operations of piece of software and then identify software errors [23].

Google's director of engineering, Hartmut Neven, explains why Google purchased the D-Wave Two. Google wants to use quantum computing to build better models of the world and make better predictions via machine learning [21]. One of the newer Google mobile applications is Google Goggles, which enable the user to retrieve information from a search using a photograph taken from a mobile phone. Neven remarks that Google has already created several quantum algorithms such as recognizers (which would be employed in Google Goggles). That particular efficient algorithm is especially useful when a mobile device is running low on power. Perhaps closer to realization is the use of quantum computing when searching dirty data. Google has developed a quantum algorithm to teach the processor to recognize mislabeled data [21], which would greatly enhance the accuracy and relevance of its search algorithms. Google believes quantum computing can be used in speech recognition, web searching, protein folding and many more areas [21].

IV. Conclusion

The true potential for quantum computing is not yet known. Will it be limited to a small domain of problems as espoused by Dyakonov, or limited only by the imagination of computer scientists? An interesting observation comes from Nielson and Chung who remark that one of the biggest challenges is for computer scientists to design algorithms in a non-classical manner [4]. This requires a new way of thinking and a comprehensive re-imagining of computational methodologies. To take full advantage of quantum computing, classical algorithms (such as the one for factoring) need to be reformulated to take advantage of quantum techniques.

Quantum computing does not need to be limited to a niche set of problems; nor must it be considered the only acceptable answer to a particular solution domain. Classical computing is a proven entity and, perhaps, sufficiently optimized for some operations when compared to the cost of quantum computing. Even Google has acknowledged that the very best results have come from a mixture of classical and quantum computing [21].

Yet the physical challenges remain. Adiabatic quantum computing, such as that employed by D-Wave Systems, will likely never be cost justified for the average computing needs. Other forms of quantum computing have not been implemented beyond a very small number of qubits. There are many physical problems yet to be solved as described in the final source to be included in this synthesis. Quantum computer scientists from key worldwide research institutes presented their design to overcome the capably described challenges that lie ahead for quantum computing in “Layered Architecture for Quantum Computing” [22]. Such challenges include the difficulty of moving data in a quantum processor, the difficulties in moving beyond nearest-neighbor qubit coupling, the implementation of a distributed quantum computing model, dealing with decoherence and fault tolerance [22]. Due to the probabilistic nature of quantum calculations, lack of robust error corrections could impede their reliability. These researchers summarize the current state of quantum computing well, “Designing a quantum computer requires viewing the system as a whole, such that tradeoffs and compatibility between component choices must be addressed.” [22].

At the moment, beyond the D-Wave implementations (whose value have yet to be demonstrated), there are many quantum computer designs and many theorized value propositions for quantum algorithms, but no conclusive evidence to demonstrate practicality. The current state of non-adiabatic quantum computing is limited to a collection of design theories, and adiabatic quantum computing remains prohibitively expensive. However, the theory of quantum computing continues to offer hope that a new evolution of processors will make a difference in computational operations within the next decade.

V. REFERENCES

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