Quantum Computing Meets the Real World

Kristen L. Pudenz(✉)

Advanced Development Programs,
Lockheed Martin Aeronautics Company,
Fort Worth, TX, USA
`kristen.l.pudenz@lmco.com`

1 Practical Quantum Information Processing

Quantum information processing as a scalable experimental pursuit has experienced significant progress in recent years. Multiple laboratories at large research organizations have constructed working systems with multiple interacting qubits, focused on the implementation of small-scale computational problems or the demonstration of quantum error correction techniques. This stage of development is particularly interesting because the engineering issues related to controlling multiple quantum systems in a noisy environment are being clarified as the various systems progress, illuminating where the best hopes for quantum computation may lie. These practical pathways are not always the same as what has been predicted in the closed-system theoretical context, so creative algorithmic thinking is needed to unlock the potential of the real devices.

2 Models and Implementations

2.1 Circuit Model

The circuit model is the first scheme proposed for a quantum computer, and the closest to the architecture and operation of classical computing system. In a circuit model computation, the qubits are initialized into some quantum state, then operated on by a series of discrete gates, which may introduce quantum effects such as entanglement into the system. Many of the canonical quantum algorithms were developed for the circuit model of quantum computation.

Several circuit model quantum information processing systems are currently under development. IBM recently announced a four-qubit system based on superconducting technology; the interactions between their four qubits were designed for the purpose of state preservation on two of the qubits, while measurement of the other two allows the detection of an arbitrary quantum error [1]. The National Institute for Standards and Technology (NIST) has been working on quantum computation using trapped ions for many years, and has been able to generate entangled states of at least six atoms in the laboratory [2].

© Springer International Publishing Switzerland 2015
C.S. Calude and M.J. Dinneen (Eds.): UCNC 2015, LNCS 9252, pp. 66–70, 2015.
DOI: 10.1007/978-3-319-21819-9_4

2.2 Adiabatic

Most of the recent efforts to construct a scalable quantum processor, however, have focused on the adiabatic model of quantum computation (AQC). AQC involves initializing a set of qubits to a known state, then slowly and continuously changing the parameters of the experimental Hamiltonian. If the noise is low enough and the changes are sufficiently slow, the state of the qubits at the end of the computation will represent the low-energy state of an entirely different energy function than that which initialized the computation [3]. Both the circuit model and the adiabatic model are universal for quantum computation, and a translation with polynomial overhead exists for mapping circuit-model quantum algorithms to adiabatic target energy functions [4].

The best-known implementation of the adiabatic model is the D-Wave Systems quantum optimization processor. Their commercially available quantum chips have grown in size from 128 to over 1000 superconducting qubits, which interact via a fixed local connectivity structure [5]. Google is also developing a superconducting quantum information processing system based on the adiabatic model. Their most recent chip has nine qubits fabricated in a row, allowing users to study dynamics of chained quantum systems or do limited error correction [6]. Other groups working on experimental AQC systems include the University of Maryland (trapped ions) [7] and Sandia National Laboratories (superconducting) [8].

2.3 Limitations

None of the currently available experimental systems is a universal quantum computer; each has its own limitations. Coupling between qubits is difficult for superconducting systems because of space and routing limitations on the chip. All of the superconducting implementations have a specific connectivity structure that is much more sparse than a complete graph connecting all qubits; most are limited to nearest-neighbor interactions. Of the superconducting circuits, the IBM chip is the only one to incorporate all of the coupler types necessary for universal quantum computation, but currently is still limited to state preservation rather than computation. The ion trap implementations have more flexibility in the interactions available to them because all of the ions reside in the same trap and can be coupled with laser pulses. However, these systems face a serious scalability hurdle because the number of ions that a trap can hold is limited, so a way to move ions between traps while preserving their state must be developed and integrated.

3 Applications

3.1 Factoring

Shor's algorithm for factoring numbers is the most famous example of an application for quantum computers [9]. The algorithm is attractive because it offers an exponential quantum speed advantage over the best known classical algorithm and it solves a cryptographic problem that is widely used. It may not be the first application to be realized on a large scale, however, because it demands much of a quantum information processor. A device to solve the factoring problem must be able to implement universal interactions between qubits, and be extremely low-noise in order to preserve small variations in quantum states. Other, more flexible applications will be needed to take advantage of the initial generations of quantum information processors.

3.2 Quantum Simulation

The application that inspired the concept of a quantum computer was the simulation of quantum systems, once it became clear that solving the Schrodinger equation using classical computers becomes intractable very quickly as the system size increases [10]. The idea is to build a quantum system that is controllable and measurable in the laboratory, yet will naturally undergo the same processes as the system we wish to study. Of course a universal quantum computer can simulate an arbitrary quantum system, but perhaps of more immediate interest is the idea of a special-purpose quantum simulator, constructed to emulate a particular system or class of systems. This idea is particularly appealing because the constraints that hamper the construction of a universal quantum computer also apply to natural systems (particularly locality of interactions and restrictions on the number of particles that may interact significantly at once). If such a quantum simulator is built for the right quantum system, it may become the first great success for quantum computing.

3.3 Optimization

The largest and most functional quantum processor currently in existence, the D-Wave chip, is an optimizer by design. It uses the adiabatic model to solve an Ising spin glass (or, equivalently, a quadratic binary optimization) problem, finding the configuration of spins that minimizes the energy of the system. Because the adiabatic model is probabilistic and the process occurs in a system with noise, approximate solutions may be generated in addition to or, under certain conditions, in lieu of the global optimum [11]. This will also be true for the other adiabatic systems under development that were discussed in Sect. 2.2. Though many efforts have been made to develop applications for [12–14] and characterize the performance of the D-Wave family of processors, whether and for what type of problem these systems can offer a genuine quantum speed-up is still an open question [15,16].

3.4 Error Correction

Efforts are also beginning to implement error correction for quantum information systems, which will be an essential component of any quantum computer operating at large scale in a real environment, and therefore must be a concern for any group seeking to implement quantum computation. The circuit model system at IBM and the adiabatic system at Google are addressing the problem directly in their small-scale devices, designing from the ground up to implement a robust quantum error correction scheme known as the surface code [1,6]. D-Wave has not incorporated error correction in the design of their systems, but there are user-side constructions that provide some amount of error suppression and correction [17,18], which would also be applicable to future adiabatic implementations.

4 A Path Forward

The new generation of quantum computing systems is producing novel open questions for the field at a rapid pace and creating opportunities for work which will have a real impact on computation. Of particular importance among these open problems is the creation of new algorithms for practical devices which are useful at small scales, robust to noise, and capable of taking advantage of the special features of implemented systems (e.g. the distribution of approximate solutions returned by adiabatic devices). Such development should keep in mind the capabilities of classical computing, and use the quantum processor as a complement and enhancement to the resources we already have available to us. In this way, classical and quantum algorithms will advance together, each providing feedback to the other, to the overall enhancement of useful computation.

References

1. Corcoles, A. D., et al.: Demonstration of a quantum error detection code using a square lattice of four superconducting qubits. Nature Commun. 6, 6979 (2015)
2. Leibfried, D., et al.: Creation of a ‘six-atom Schrodinger’ cat state. Nature **438**, 639–642 (2005)
3. Farhi, E., et al.: Quantum computation by adiabatic evolution (2000). arXiv preprint quant-ph/0001106
4. Aharonov, D., et al.: Adiabatic quantum computation is equivalent to standard quantum computation. SIAM Rev. **50**(4), 755–787 (2008)
5. Johnson, M.W., et al.: Quantum annealing with manufactured spins. Nature **473**(7346), 194–198 (2011)
6. Kelly, J., et al.: State preservation by repetitive error detection in a superconducting quantum circuit. Nature **519**, 66–69 (2015)
7. Kielpinski, D., Monroe, C., Wineland, D.J.: Architecture for a large-scale ion-trap quantum computer. Nature **417**, 709–711 (2002)
8. Blume-Kohout, R.: Robust, self-consistent, closed-form tomography of quantum logic gates on a trapped ion qubit (2013). arXiv preprint quant-ph/1310.4492
9. Shor, P.W.: Algorithms for quantum computation: discrete logarithms and factoring. In: 1994 Proceedings of 35th Annual Symposium on Foundations of Computer Science, pp. 124–134. IEEE (1994)
10. Feynman, R.P.: Simulating physics with computers. Int. J. Theor. Phys. **21**(6), 467–488 (1982)

11. Amin, M.H.S., Love, P.J., Truncik, C.J.S.: Thermally assisted adiabatic quantum computation. Phys. Rev. Lett. **100**(6), 060503 (2008)
12. Denchev, V., Ding, N., Neven, H.: Robust classification with adiabatic quantum optimization. In: Proceedings of the 29th International Conference on Machine Learning, pp. 863–870 (2012)
13. Rieffel, E.G., et al.: A case study in programming a quantum annealer for hard operational planning problems. Quantum Inf. Process. **14**(1), 1–36 (2015)
14. Santra, S., et al.: MAX 2-SAT with up to 108 qubits. New J. Phys. **16**(4), 045006 (2014)
15. Troels, R.F., et al.: Defining and detecting quantum speedup. Science **345**(6195), 420–424 (2014)
16. Hen, I., et al.: Probing for quantum speedup in spin glass problems with planted solutions (2015). arXiv preprint arXiv:1502.01663
17. Pudenz, K.L., Albash, T., Lidar, D.A.: Error-corrected quantum annealing with hundreds of qubits. Nature Commun. **5**, 3243 (2014)
18. Pudenz, K.L., Albash, T., Lidar, D.A.: Quantum annealing correction for random Ising problems. Phys. Rev. A **91**, 042302 (2015)