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Why quantum adiabatic computation and D-Wave computers are so attractive?

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Because of the possibility that improves our computational capability dramatically, in the past two decades quantum computation has been attracting more and more attentions. Particularly, in recent years remarkable progresses have been made for theoretical researches and experimental implementations in this area, which will probably bring us quantum computer able to beat best classical computer in just a few years.

When studying quantum computation, the historical experiences people gained from developing digital computers play an important role. For example, following the idea of designing processors with circuits composed by logical gates, the concept of quantum circuit was proposed, where the logical gates are replaced by quantum gates. Using the language of quantum circuit, the first bunch of successful quantum algorithms that reveal the power of quantum computation were introduced, including Shor's algorithm [1] and Grover's algorithm [2,3].

Meanwhile, for classical computation it is well-known that besides the circuit model there are several other theoretical models like the Turing machine model and pi-calculus model, and they have the same computational power with circuit. Similarly, for quantum computation some non-circuit theoretical models with the same power also exist, and among them one-way quantum computation and quantum adiabatic computation (QAC) are two instances that have been studied extensively.

Then one may ask a natural question: since the computational power of these non-circuit quantum models are not stronger, why do we need to study them? Actually we have at least two good reasons for this.

Firstly, it has been known that finding interesting and powerful new quantum algorithms is a hard task, and the list we have now is not long. Nevertheless, different models offer us different insights on quantum computation and allow us to develop different intuitions about this hard task. For example, the manner in which QAC works is so different from quantum circuit that by using this new model people have studied the power of quantum computation on some problems that have never been tried before.

Secondly, the equivalency between these theoretical models only means they have the same computational power in some sense, which does not imply anything on physical implementations. It has been well-known that realizing large-scale quantum computation is notoriously difficult, thus which model is the most realistic one for future physical implementation is a central problem in quantum computation and is far from settled. Due to the above two reasons, for now it is an extremely important topic to fully characterize these theoretical models. In this paper, we will focus on QAC.

We now briefly introduce how QAC works, which was proposed by Farhi et al. [4]. Suppose we have a computational problem to solve. For this, we introduce a quantum system, and at the beginning the quantum state is the unique ground state of some initial Hamiltonian, which is usually chosen to be easy to prepare. Next we choose a final Hamiltonian, about which an interesting fact is that though the solution of the problem is unknown, it is possible to construct a final Hamiltonian such that its unique ground state encodes the solution. After this, control the parameters of the system to make the Hamiltonian vary slowly. Then quantum adiabatic theorem [5,6] says that if the evolution is slow enough, the actual final state will be very close to the ground state of the final Hamiltonian, which means that we can obtain the solution and solve the problem by measuring this final state. As a computational task, the running time needed by the evolution, the time complexity of the algorithm, is what we care about most. According to the quantum adiabatic theorem, it can be estimated roughly as $O(\Delta_{\min}^{-2})$, where $\Delta_{\min}$ is the minimal gap between the lowest two eigenstates of the Hamiltonian.

It has been found out that QAC has the full power of quantum computation. Firstly, van Dam et al. [7] proved that the adiabatic computation can be efficiently simulated by quantum computers based on quantum circuits. Later, Aharonov et al. [8] showed that standard quantum computation can also be efficiently simulated by adiabatic computation. Therefore, quantum adiabatic computation is polynomially equivalent to the standard model of quantum circuit.

After proposed, QAC has been utilized to reproduce some famous quantum algorithms, including the one for the Deutsch-Jozsa problem [9,10] and quantum search algorithm [11]. Furthermore, as mentioned above this new model allows people to study the performance of quantum computation on some problems that are hard to try in the model of quantum circuit. For example, QAC algorithms for 3-SAT, an NP-complete problem, have

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been studied extensively. It should be pointed out that though many new QAC algorithms can be proposed by following the standard procedure, the time complexity is usually hard to find out, as this essentially requires us to solve the challenging problem of estimating the minimal spectral gap. In most cases, this cannot be done analytically, and people can only observe the performance of the algorithm on small scale cases by numerical simulations [12].

Besides the new insights for quantum computation, a major advantage of QAC is its quantum properties beneficial to physical implementations. Due to the fact that any quantum system, including quantum computers, has to interact with its environment, quantum information is very fragile, which makes decoherence the most significant obstacle in building large-scale quantum computers physically. To overcome this difficulty, fault tolerant protocols for quantum computation have been proposed, but they are very costly, which results in a high requirement for the precision of quantum operations. In this situation, if somehow alternative protections can be provided for quantum computation, it will be really valuable. Interestingly, in QAC such a phenomenon can be seen.

As mentioned, if a QAC algorithm has a sizable energy gap, the running time will be short. In fact, this gap also leads to another consequence, that is, the quantum computer exhibits robustness against decoherence. Particularly, if we run the QAC algorithm at a temperature lower than energy gap, the interactions between the computer and environment will not induce transitions between the eigenstates, which implies that the system is kind of robust to thermal noises. Here, we set Boltzmann's constant $k_B = 1$, then temperature has units of energy. This kind of robustness of QAC is thought of as a great advantage over the quantum circuit model, and has attracted a lot of attention. By numerical simulations, Childs et al. [13] investigated the effect that QAC resists decoherence, and their results verified that QAC algorithms remains robust as long as the temperature of the environment is not too high. Besides, they also found that QAC is robust against unitary control errors.

A breakthrough on QAC was made by D-Wave, a Canadian company, which released the world's first commercially available quantum computer in 2011. This quantum computer, named the D-Wave One, performs QAC based on superconducting qubits. Undoubtedly, this news immediately attracted worldwide attentions. In fact, the D-Wave machine is not a universal quantum computer, but uses a special type of QAC, quantum annealing (QA), to solve certain classes of hard combinatorial optimization problems [14]. The QA uses quantum tunneling to get speed up compared with the simulated annealing (SA). In the last several years, the qubit number in D-Wave machines increased by 16 times, from 128 to 2048, corresponding to greatly decreasing of the energy gap $\Delta_{\min}$. However, the environment temperature of the systems only decreased by two times. As we discussed in the last paragraph, the QAC algorithm is robust against thermal noises only when the minimal energy gap $\Delta_{\min}$ is larger compared with the environment temperature energy. Therefore, the temperature in the D-Wave machine seems not low enough. In the last few years, there has been a debate on whether the D-Wave machine is really quantum, and whether computational speed up from quantum tunneling exists or not.

Despite the above controversies, as the computational power greatly increased in the past several years, quite a few famous companies and laboratories have bought the D-Wave machines and tested them. Particularly, the quantum feature during the computational processes was confirmed in 2013 [15]. In 2016, researchers from Google used D-Wave 2X to perform QA [16], and found that the speed of QA is about 10^8 times faster than both SA and quantum Monte Carlo algorithm. Because of these studies, more and more people tend to believe that QA in the D-Wave machine really has quantum accelerations. Now, the D-Wave machines are tried in many practical problems. For example, researchers from Los Alamos Laboratory in USA used D-Wave 2X to perform unsupervised machine learning algorithms for analyzing large datasets, such as facial images [17]. Volkswagen Group also used D-Wave 2000Q to optimize the route of 10,000 Beijing taxis. They found that it was possible to dissolve the traffic jam problem (https://www.volkswagenag.com/en/news/stories/2017/03/the-beginnings-of-a-quantum-leap.html).

Though the D-Wave machines have achieved so many commercial successes, the lack of quantum error correction is still a big drawback. In order to make sure the computation is reliable, the future large-scale quantum computers based on QAC should have to include extra fault tolerant protocols [18].

Conflict of interest

The authors declare that they have no conflict of interest.

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