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# Quantum Computing Systems: A Brief Overview

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A classical simulation of quantum systems demands enormous computational resources. The dimension of underlying Hilbert space scales exponentially with the number of participating elements ($N$), requiring a $2^{2N}$ size of calculation matrix for a unitary operation, for example, $2^{100} \approx 10^{30}$ for only $N = 50$. With the increase of $N$, the first obstacle to encounter is in fact the deficiency of computer memories. A straightforward resolution is to use a quantum computer, a calculating device that operates with the principle of quantum mechanics. During the last twenty years, quantum computing once considered as theoretical exercise has become an important field of research in modern physics. At the forefront of quantum information technology, quantum computing has emerged as a new engineering field with broad interest not only in physics but also in computer science, electronics engineering, and mathematics.

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## I. INTRODUCTION

Quantum computer is a device that processes arbitrary computational algorithms by harnessing quantum mechanical properties such as coherent superposition, entanglement, and non-locality. Its performance is expected to exceed the computing capability of today's and future digital computers. There are three types of quantum computing schemes theoretically proposed: the circuit-based model where operations are executed in succession, the adiabatic model that was designed for optimization problems, and measurement-based cluster-state computation [1]. The building block of a quantum computer is a two-level quantum system called physical qubit, which carries fundamental information unit, also called as qubit, in a superposition of Boolean states of 0 and 1. Quantum circuits constructed with a set of at least two one-qubit rotations and a two-qubit entanglement can perform universal computation, where on-demand entanglement is the key ingredient to control a quantum system of $N$ qubits.

Quantum information stored in a physical qubit is not stable. During calculation, undesired interactions among qubits and dephasing within surrounding cause the superposition to decohere into either 0 or 1, and hence, error-correction processes are necessary for a fault-tolerant logical qubit. Quantum error corrections can be employed to remove faults influenced by a single qubit decoherence, at the expense of additional physical qubits. The number of physical qubits is estimated to be to more than 10,000 per logical qubit for typical vacuum quality and gate fidelity in laboratories. Scaling up a quantum system with as-many physical qubits that are entangled becomes experimental ambition and principal challenge while building such a device is still the ultimate goal.

Technically, DiVincenzo's five criteria [2] (well-characterized qubits, qubit initialization, long coherence, universal gates, qubit-specific measurement) are considered as inevitable conditions for candidate physical qubits. A number of rival approaches such as photons [3], trapped ions [4], neutral atom [5], spins in solid state [6], semiconductor quantum dots [7], superconductors [8], and NV-centers in diamonds [9] can all demonstrate

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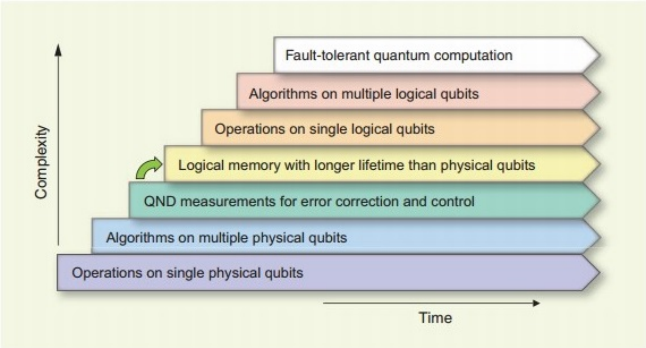


Fig. 1. (Color online) Seven development stages of a quantum computing system. The image is from Ref. [11] with permission of the publisher.

basic quantum operations, but until now a quantum computer that outperforms digital computers has not been created. In some of such systems, small-scale qubit quantum computers that are capable of implementing simple quantum algorithms have been built [10]. However, to build a medium-size quantum computer, a total of seven stages of technical requirements as shown in Fig. 1 must be satisfied. The first two stages correspond to the above-mentioned DiVincenzo prerequisites [11], the third stage refers to the quantum error correction (QEC) capability, and the fourth stage demands amplification of the coherence time through the error correction processes. By accepting the concurrent restrictive weakness, the remaining steps are to implement fault-tolerant quantum computing pertaining to qubit quality within reach, affordable gate operation fidelity, and all aforesaid. Presently, comprehensive operational structures that demonstrate the ability or at least provide a plausible progress to correct errors through quantum-feedback control are trapped-ion systems, Rydberg atomic assemblages, and superconducting circuits [12–15]. In this article, we present an overview of the working principles and current activities of these three quantum computing systems as follows. We postpone the discussion on other quantum systems like semiconductor quantum dots, defects in solid materials, and topological materials, till they achieve meaningful progress toward scaling.

## II. TRAPPED ION SYSTEMS

Ion-trap quantum computers use a vacuum device known as Paul trap [16] that binds ions using the electrostatic repulsive force ($z$-direction, for example) and the dynamic stabilization ($xy$-direction) produced by RF oscillating electric fields. As many as about 50 ions can be lined up to form a 1D crystal with a lattice constant of about 5 - 10 μm and a trapping potential of about 1 K of depth. The single-qubit coherence time more than 10 minutes has been reported, for example, in $^{171}$Yb$^+$ ion sympathetically cooled in $^{138}$Ba$^+$ ion bath [17, 18], making trapped ions suitable not only for computation qubits but also for quantum memories. When the kinetic energy of the ions is lessened by laser cooling to about the energy difference of the qubit two levels (*e.g.* the spin state basis), the oscillation of all ions as a whole (only $z$-directional motion) is also confined to two levels via the strong coupling of the ionic crystal. Optionally and inversely, the spin states of individual ions can be controlled by external optical fields or radio frequency waves. In this case, since the motion of individual ions in the ionic crystal is bound by the movement of the center of mass, the Cirac-Zoller CNOT gate can control a two-qubit quantum logic device constructed out of distant trapped ions [19]. Quantum simulation using quantum annealing, quantum Fourier transform, and three-qubit QEC have been also reported [12,20,21].

As the number $N$ of ions in the ionic crystal increases, the movement of the center of mass slows down, and higher-order motions intervene. The result is that the crystal vibrates faster placing a practical limit to the maximum number of engaging qubits. The ion trap quantum computers based thereon can in principle only be built-up from one-dimensional ion arrays restricted to the geometry of the Paul trap. Therefore, to dramatically increase the number of mutually repulsive qubits, alternative schemes or novel apparatus designs is indispensable. The first experimental device exploits a surface electrode ion-trap. The fabrication therein makes use of a semiconductor MEMS processed by cutting or attaching a one-dimensional ion array that relies on the concept of a T-junction. This quantum charge-coupled device (QCCD) utilizes programmed electrodes to shuttle ions. However, it is currently technically challenging to transfer a large number of ions at high speed using electrodes on a semiconductor surface [23], in particular when they convey fragile quantum information. The second technique has been carried out through the quantum network approach that connects two independent strings of ions in an entangled state using a pair of entangled photons [17]. Following this, it is rather difficult to control the state of communication qubits of each ion registor by directly applying an entangled photon pair. Therefore, a post-selection method is considered after indistinguishable detection of photon pairs through Hong-Ou-Mandel interferometer [22]. For the reasons delineated, trapped ions can be entangled through a photonic quantum communication channel to realize a long-distance entanglement between qubits [23,24].

Quantum computing research with ion trap systems is led by a small number of research groups in the United States and Europe. National Institute of Science and Technology (NIST) has been ahead in the field of quantum computing research using ion traps. Consistent progress has been contributed by David Wineland of NIST (Boulder, Nobel laureate) and Chris Monroe of JQI (NIST-Gaithersburg and University of Maryland). Kim Jungsang at Duke University, who is originally from

Korea has launched with the Monroe's group an ion-trap quantum computing joint venture, IonQ. In addition, Sandia National Laboratories is conducting research subjected to MEMS-based surface electrode ion trap. Rainer Blatt at the University of Innsbruck, Austria, is one of the forerunners in ion-trap quantum computer research and has experimentally reported the entanglement of 14 qubits. In UK, NQIT (Networked Quantum Information Technologies) research collaboration has planed to deploy 20 ion-trap quantum computer modules with 20 qubits, named Q20:20, into a quantum network to run a total of 400 ion qubits. Related research in the other regions lags significantly behind. Studies in Asia are less active than those in North America and Europe, and are mainly focused on theories. Kim Ki-hwan of Tsinghua University, China is the principal investigator of the Ion-Trap Quantum Computing Research Team, and CQT in Singapore has clustered atom- and ion-based experimental teams. Research activity in Korea and Japan is less active like elsewhere.

## III. SUPERCONDUCTING CIRCUITS

Most design concepts and fabrications in conventional semiconductor electronics provide primarily utilitarian functions in processing quantum integrated circuit called superconducting qubit. Such non-linear and non-dissipative element getting the name of Josephson tunnel junction can be practically assembled with two overlapping superconducting thin films. The flux in a circulating current is quantized mimicking resonant modes in an L-C oscillating circuit [11]. A superconducting qubit system made with Type-I superconductor such as aluminum typically requires a working temperature of few mK so that the thermal noise (1 K is comparable to 20 GHz) is less than the qubit transition frequency (5 - 20 GHz) which must be much less than the threshold energy required to break a Cooper pair (100 GHz).

In a Josephson device, the flux state is the superposition of ground state 0 and excited state 1. Through various electrical circuit structures with varying tunnel junction inductance and capacitance values, the charge on an isolated superconducting clump, the current phase-drop, and the energy levels of a single junction can be quantized and used to store information in addition to the flux. When radio frequency waves couple such a superconducting qubit system, single qubit manipulation can be achieved in 5 - 50 ns while a two-qubit gate would require 50 - 500 ns per operation. The performance of individual superconducting qubit system depends on the circuit design aiming to minimize dissipation in all metallic parts and dephasing by coupling with the environment during quantum processing. In recent years, the coherence time over 100 μs ($Q = 10^6$) has been achieved [25].

Unlike atoms or ions, Josephson tunnel junctions are artificial resonators so they are intrinsically not identical. Characterization of individual superconducting qubits with high precision is therefore essential in order to coherently manipulate the qubit state with high fidelity, and to suppress cross-talk with adjacent superconducting qubits that could lead to dephasing and random errors. Recently, it has become possible to detect and correct errors by measuring the parity of qubits arranged in a square lattice and then processing with the quantum error recovery protocol called the surface code model [13, 26]. This error correction technique corresponds to the fourth stage in Fig. 1, which implies that we might be able to construct logical qubits that can overcome the decoherence time of a physical qubit by using multiple physical qubits.

In 2011, Canadian-based D-Wave Systems Inc. had astonished the world by announcing the launch of superconducting quantum computer. D-Wave One, consisting of 128 superconducting qubits, was followed by D-Wave Two with 512 qubits and then D-Wave 2X with more than 1000 qubits. Although the quantum annealing method of these machines was claimed to efficiently handle optimization problems such as the protein folding problem that conventional computers can not solve [27], that controversial machine is genuinely not a universal quantum computer because the complete control over the quantum states of all single qubits was not permitted. In addition, the energy spectral analysis has shown that eight entangled qubits are used [28] but quantum speed-up has yet been fully confirmed [29].

The study of superconducting qubit system in North America is unique in that industries as well as academic and public research institutes collectively participate in quantum research. IBM, Microsoft, Alcatel-Lucent, D-Wave Systems, and Google have already assembled research teams to undertake the complexity in quantum computing. IBM has developed superconductor systems, providing their sixteen and twenty qubit fully-programmable quantum computers available as a cloud service. D-Wave Systems has already developed and marketed multiple-qubit quantum annealers utilizing their six-qubit D-Wave Orion chips. Microsoft and Alcatel-Lucent were studying other solid-state qubits such as topological qubits appearing as local maxima of conductance at both ends of a 2D electron chain. Nevertheless this natural fault-tolerant stratagem expected to diminish the need for error corrections has not been yet realized. Google Quantum AI Lab recruited John Martinis and his team from California State University (UC-Santa Barbara) to pursue incorporating attainable surface-code quantum error correction into quantum memories and gate operations [30]. Research activities elsewhere including in Korea are less active than those in North America.

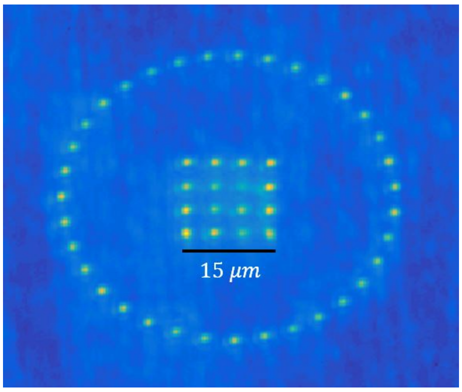


Fig. 2. (Color online) Rydberg atomic assemblage. Rubidium atoms are trapped and arranged with optical tweezers to form a zero-entropy arbitrary array and then entangled through Rydberg energy excitation [34].

## IV. RYDBERG ATOMIC ASSEMBLAGES

Neutral atom qubits with Rydberg interactions for quantum computing [31,32] is scarcely recognized in contrast to trapped ions or superconducting circuits. In spite of that, the advance of laser spectroscopy has assisted fulfilling technical requirements for quantum computing and is currently promoting this approach to the fourth stage, *i.e.* the QEC. In the other physical systems, as a result of increasing number of qubits, two-qubit CNOT elements and QEC were typically developed in succession. On the contrary, in the Rydberg atomic system, the QEC based on the $N$-qubit quantum non-destructive measurement (QND) [14] and the development of CNOT logic devices [33] progressed independently. To some extent, the quantum computing research using Rydberg atoms is still in its infancy with respect to the ion trap research that is now focusing on increasing the number of qubits and the superconductor research that heads for improving the qubit stabilization and quantum error-correction. Recent experiments have shown that capturing single atoms at a distance of about 10 μm by using optical tweezers [33], and then rearranging them in an arbitrary lattice structure can be rapidly achievable [34]. At this stage, it is therefore relatively easy to expand the number of atomic qubits as in Fig. 2. Besides the scalability that makes quantum computing research using neutral atoms more attractive, the possibility for multi-qubit gate implementation via dipole blockade ensures the Rydberg atom approach as one of a few viable quantum computing technologies.

A high-energy Rydberg state causes an atom to swollen like a balloon. Since the radius of an atom is proportional to the square of principal quantum number $n$, for an electron with $n = 100$, the size of the Rydberg atom is in order of μm. The coherence time that scales with $n^3$ would be close to 1 μs, and the interaction potential $U_{\rm int}$ increasing as $n^{11}$ could easily reach 25 THz in frequency. If the laser line-width is less than $U_{\rm int}/\hbar$ then all excitations above the Rydberg state for other atoms within the so-called Rydberg dipole blocking distance (0.1 to 10 μm) are blockaded. This phenomenon suggests that a two-qubit CNOT quantum device (Jaksch scheme) is plausibly implementable [35].

Although one-qubit manipulation and two-qubit CNOT gates are enough to build a universal quantum computer, the error correction algorithms would be much less complicated with multiple-qubit quantum logic gates. The competency to precisely measure the mode of microwave resonator has been unprecedentedly amplified to some extent using Rydberg atoms [36]. With a high-Q resonator, a photon lifetime will be relatively long and the Fock state can be nondestructively determined by measuring the state of the Rydberg atom [14]. The quantum feedback control of the Rydberg atom manifests that it is possible to instantaneously probe and preserve the photon number states in the resonator. In return, by passing a Rydberg atom through the resonator, three-qubit QEC has been realized [37–39].

Atomic transparency to optical field induced within Rydberg blockade volume has been widely employed. Quantum repeater, a device that extends secure quantum communication over distance, is one example that can be attained via super-radiant single photon generation [40]. It is well known that hundreds of atoms in a space of a few μm could be excited into the $N$-qubit W-state, an entangled multi-partite quantum state, through cooperative absorption of a single photon by Rydberg dipole blocking [41]. Thereby, when a Rydberg atom is transited to another excited state with high spontaneous emission rate, a single photon of a superradiance emission process is generated in an instantly phase-matched direction [42]. This means that atomic ensembles and a cooperative single-photon absorption-emission process of the $N$-qubit quantum registers based on various Rydberg energy levels could be combined into a quantum repeater [43].

On a global scale, much work on the Rydberg atomic system has been pioneered by Mark Saffman of the University of Wisconsin. Rydberg CNOT quantum logic devices were first demonstrated with a relatively low two-qubit gate fidelity of 0.75, but in the past few years research mainstream has been conducted toward beyond 100 qubit Rydberg atomic systems utilizing optical tweezers [44–46]. Quantum computing with Rydberg atoms seems to be relatively inactive in Europe, while many research groups including Immanuel Bloch and Gerhard Rempe of the Max Planck Institute in Germany are energetically conducting basic research on Rydberg atom systems.

## V. REMARKS

The development of quantum computing systems is expected to solve the current technical limitations of digital computers based on semiconductor integrated circuits. First, the number of units that can be operated exponentially increases as the number of unit devices increases. That is, the $N$-bit digital memory represents only one number at a time in the range of 1 to $2^N$, but the $N$-qubit system can simultaneously represent $2^N$ numbers. Therefore, a large amount of information can be processed in parallel without increasing the degree of integration of the devices. Second, since the computation of a quantum computer is based on a unitary operation during which no heat is input or loss, so the total amount of energy used for particular computation is finite and anticipative. Last but not least, the amount of computation for quantum simulation of a real-world quantum system is supposed to be possible by using a quantum computer because it transcends the performance of digital computers in principle. Furthermore, new discovered phenomenology through rigorous calculations when modeling future nanoelectronic elements and new drugs could lead to novel devices, disruptive technologies, and more efficient medical treatment.

We have briefly outlined trapped ion systems, superconducting circuits, and Rydberg atomic assemblage, chosen as system candidates for beyond small-scale quantum computing. Notably these systems have already achieved massive entanglements and are expected soon to meet with the capability of quantum error corrections. A quantum computing research on trapped ions with qubit number of $N = 400$ is under development, and a superconducting circuit commercial system with $N = 1156$ is being pursued, although the entanglements in these systems are still insignificant and less than 20 qubits can be fully operated through quantum logic circuits. However, the recent explosive quantum interest shown by North American industry is motivating the existing academics to rethink their earlier judgment about the coordinates of technology development cycle of quantum computing research.

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## REFERENCES

[1] T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe and J. L. O'Brien Nature **464**, 45 (2010).
[2] D. P. DiVincenzo, Fortschritte der Physik (Progress of Physics) **48**, 771 (2000).
[3] J. L. O'Brien, Science **318**, 1567 (2007).
[4] P. Schindler *et al.*, New J. Phys. **15**, 123012 (2013).
[5] D. Weiss and M. Saffman, Phys. Today **70**, 44 (2017).
[6] D. D. Awschalom *et al.*, Science **339**, 1174 (2013).
[7] M. Veldhorst *et al.*, Nature **526**, 410 (2015).
[8] J. M. Gambetta, J. M. Chow and M. Steffen, NPJ Quantum Inf. **3**, 2 (2017).
[9] L. Childress and R. Hanson, MRS Bulletin **38**, 134 (2013).
[10] Timeline of quantum computing (2018, June 13) Retrieved from https://en.wikipedia.org/wiki/Timeline_of_quantum_computing.
[11] M. H. Devoret and R. J. Schelkopf, Science **339**, 1169 (2013).
[12] J. Chiaverini *et al.*, Nature **432**, 602 (2004).
[13] J. Kelly *et al.*, Nature **519**, 66 (2015).
[14] C. Sayrin *et al.*, Nature **477**, 73 (2011).
[15] C. Ottaviani and D. Vitali, Phys. Rev. A **82**, 012319 (2010).
[16] R. Blatt and D. Wineland, Nature **453**, 1008 (2008).
[17] L-M. Duan and C. Monroe, Rev. Mod. Phys. **82**, 1209 (2010).
[18] Y. Wang *et al.*, Nat. Photon. **11**, 646 (2017).
[19] F. Schmidt-Kaler *et al.*, Nature **422**, 408 (2003).
[20] J. Chiaverini *et al.*, Science **308**, 997 (2005).
[21] T. Monz *et al.*, Phys. Rev. Lett. **106**, 130506 (2011).
[22] M. Jachura and R. Chrapkiewicz, Opt. Lett. **40**, 1540 (2015).
[23] C. Monroe and J. Kim, Science **339**, 1164 (2013).
[24] D. Hucul, I. V. Inlek, G. Vittorini, C. Crocker, S. Debnath, S. M. Clark and C. Monroe, Nat. Phys. **11**, 37 (2015).
[25] A. Megrant *et al.*, Appl. Phys. Lett. **100**, 113510 (2012).
[26] A. D. Córcoles *et al.*, Nat. Comm. **6**, 6979 (2015).
[27] A. Perdomo-Ortiz *et al.*, Sci. Reports **2**, 571 (2012).
[28] T. Lanting *et al.*, Phys. Rev. X **4**, 021041 (2014).
[29] A. Cho, Science **344**, 1330 (2014).
[30] R. Barends *et al.*, Nature **508**, 500 (2014).
[31] M. Saffman, T. G. Walker and K. Mølmer, Rev. Mod. Phys. **82**, 2313 (2010).
[32] M. Saffman, J. Phys. B: At. Mol. Opt. Phys. **49**, 202001 (2016).
[33] L. Isenhower *et al.*, Phys. Rev. Lett. **104**, 010503 (2010).
[34] H. Kim, W. Lee, H-G. Lee, H. Jo, Y. Song and J. Ahn, Nat. Comm. **7**, 13317 (2016).
[35] D. Jaksch *et al.*, Phys. Rev. Lett. **85**, 2208 (2000).
[36] S. Haroche, Rev. Mod. Phys. **85**, 1084 (2013).
[37] C. Ottaviani and D. Vitali, Phys. Rev. A **82**, 012319 (2010).
[38] M. Martinez-Dorantes, W. Alt, J. Gallego, S. Ghosh, L. Ratschbacher, Y. Völzke and D. Meschede, Phys. Rev. Lett. **119**, 180503 (2017).
[39] M. Kwon, M. F. Ebert, T. G. Walker and M. Saffman, Phys. Rev. Lett. **119**, 180504 (2017).
[40] R. A. de Oliveira *et al.*, Phys. Rev. Lett. **90**, 023848 (2014).
[41] W. Dr, G. Vidal and J. I. Cirac, Phys. Rev. A **62**, 062314 (2000).
[42] T. Wang *et al.*, Phys. Rev. A **75**, 033802 (2007).
[43] E. Brion, F. Carlier, V. M. Akulin and K. Mølmer, Phys. Rev. A **85**, 042324 (2012).
[44] M. Endres, H. Bernien, A. Keesling, H. Levine, E. R. Anschuetz, A. Krajenbrink, C. Senko, V. Vuletic, M. Greiner and M. D. Lukin, Science **354**, 1024 (2016).
[45] D. Barredo, S. de Léséleuc, V. Lienhard, T. Lahaye and A. Browaeys, Science **354**, 1021 (2016).
[46] H. Kim, Y. Park, H-S. Sim and J. Ahn, Phy. Rev. Lett. **120**, 180502 (2018).