Expectations and Prospects for Innovation in Quantum Technology

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Abstract

NTT laboratories have been engaged in basic research on various quantum-related technologies, including quantum information, since the mid-1980s before research on quantum computers took off. The Feature Articles in this issue present the latest global trends in quantum technology and NTT's research portfolio regarding quantum technology. In addition to quantum computing, quantum sensing and quantum networks are also extensively discussed from both experimental and theoretical perspectives.

Keywords: quantum computer, quantum sensing, quantum internet

1. Trends in quantum technology

The first "quantum-computer boom" was triggered by the development of Shor's algorithm in 1994, which drew attention to the potential threat to the security of the information technology (IT) society in which public-key cryptography is widely used. Numerous important advances, particularly in academia, have been made including the demonstration of qubit operation in various physical systems and the development of theory of quantum error correction. Around 2010, the technical difficulties in implementing those advances as a quantum computer became widely recognized and excessive expectations began to subside.

However, in 2011, the sudden announcement by D-Wave Systems of their development of a dedicated machine for solving combinatorial optimization problems (called a *quantum annealer*) by using a completely different technology called *quantum annealing* came as a surprise to all concerned. The significant improvement in performance of superconducting qubits around 2014 prompted IT companies such as Google, IBM, and Microsoft to enter into full-scale research and development of quantum computers and triggered a second quantum-computer boom, which has since continued as venture capital investments continue to increase.

Facing the added perspective of security, research and development of quantum technologies, such as quantum computers, quantum security, and quantum sensing, is in the midst of fierce global competition. Around 2015, Europe, the U.S., and China began to significantly expand government support under their quantum technology strategies. Although a few years behind them, Japan formulated the "Quantum Technology and Innovation Strategy" in 2020 [1] and the "Vision of Quantum Future Society" in 2022 [2], which aims to create new industries and business opportunities and address social issues on the basis of quantum technology. In response to this action, the Quantum STrategic industry Alliance for Revolution (Q-STAR) [3] was established in 2021 with the aim of making Japan a "quantum technology innovation-oriented nation," and Q-STAR is accelerating efforts to implement quantum technology in society.

2. Fundamental characteristics of quantum nature and application areas

As shown on the left side of **Fig. 1**, the world we live in is described by classical mechanics represented by Newtonian mechanics, i.e., a world that can be actually observed and touched. In contrast, as shown on the right side, the quantum world represented by the behavior of atoms and electrons is defined by

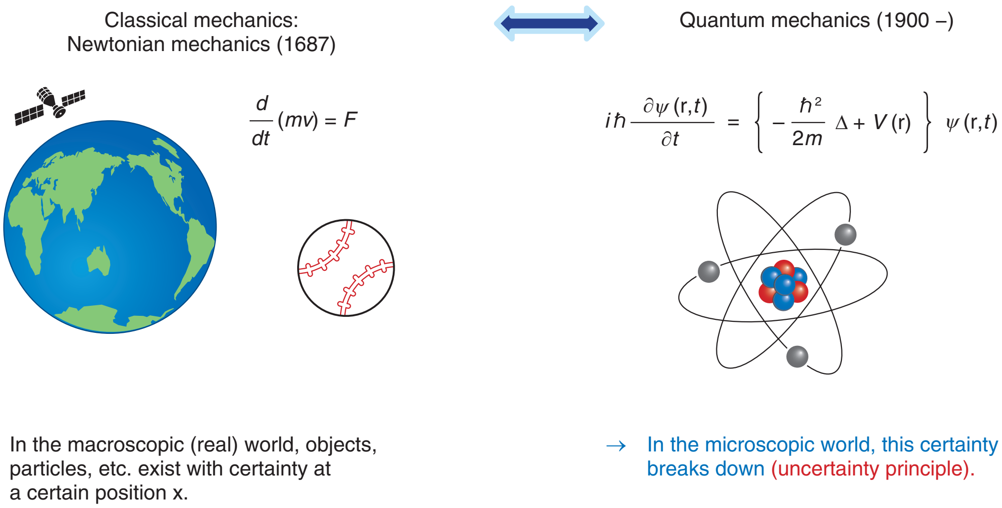

Fig. 1. Contrast between the real (classical) world and quantum world.

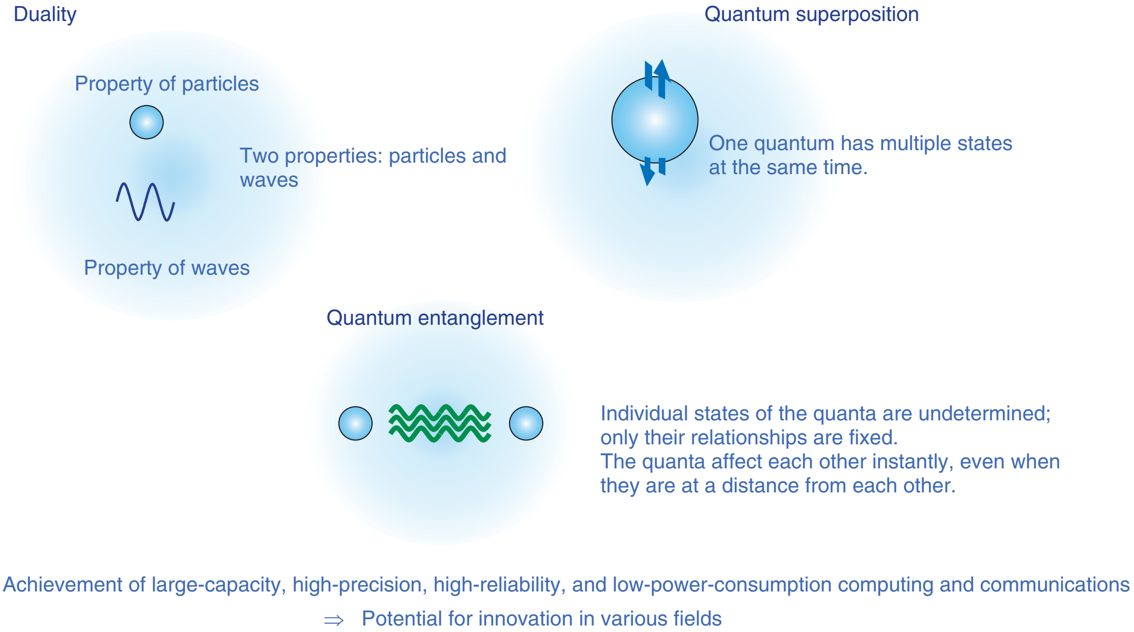

Fig. 2. Three characteristics of quantum behavior.

mathematical expressions that represent waves with existence probability under the laws of quantum mechanics, therefore far from our common sense and experience. There are various types of quanta, including extremely small ones, such as atoms and electrons, as well as light and relatively large superconducting quantum circuits; however, as shown in **Fig. 2**, regardless of the type, they all share the same characteristics of *duality*, *quantum superposition*, and *quantum entanglement*. Duality is the simultaneous possession of two properties: property of particles and property of waves. Quantum superposition enables two values, "0" and "1," to be held in a single state, as illustrated in the figure with the upward arrow (corresponding to "0") and downward arrow (corresponding to "1") side by side. Quantum

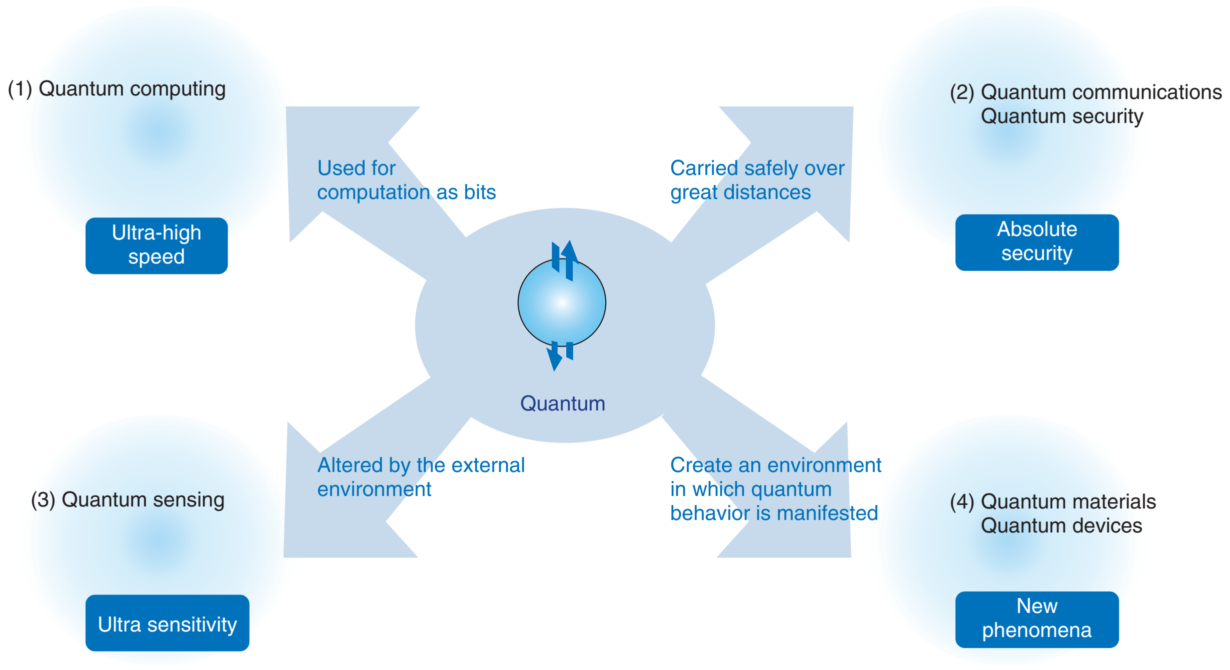

Fig. 3. Four application areas of quantum technology.

entanglement is a phenomenon in which the individual states of two quanta are undetermined, but the relationship between them is fixed in a way that even if the quanta are far apart, they can instantly affect each other when one is measured, even if they are at the other ends of Earth or even at opposites sides of the universe. In 1935, Einstein and other researchers published a paper arguing that the spooky behavior of quantum entanglement could not be sufficiently explained; therefore, quantum mechanics is incomplete. After 80 years of debate among many theorists and experimentalists, in 2015, it was finally concluded that quantum entanglement is real. Note that the 2022 Nobel Prize in Physics was awarded for significant work concerning this quantum entanglement controversy. The hope that harnessing these three quantum wonders will lead to technologies that achieve high-capacity, high-precision, high-reliability, and low-power-consumption computing and communications is drawing attention to the potential for innovation in a wide variety of fields.

The four main application areas of quantum technology—as shown in **Fig. 3**—are (i) quantum computing, which uses quanta as bits for high-speed computation; (ii) quantum communications and quantum security, which guarantee safety by using the property that quanta cannot be duplicated; (iii) quantum sensing, which uses the quantum sensitivity to the external environment to execute highly sensitive detection; and (iv) quantum materials, which create environments in which quantum behavior is manifested, and quantum devices, which use functions unique to quanta.

3. Recent progress in application of quantum technology

3.1 Quantum computers

Quantum computers can be broadly classified as two types: gate-based quantum computers, which can run a variety of algorithms and be used as general-purpose computers, and Ising machines, which are dedicated solvers for solving combinatorial optimization problems. Several companies have announced commercial gate-based quantum computers that are based on superconducting and ion-trap systems, but they can currently solve only small-scale problems. Various other approaches, such as using neutral atoms, photons, and semiconductor quantum dots, are also being researched and developed. In contrast, Ising machines have reached the practical application level of solving real problems of a certain scale. NTT reported that its coherent Ising machine called LASOLV™ can solve combinatorial optimization

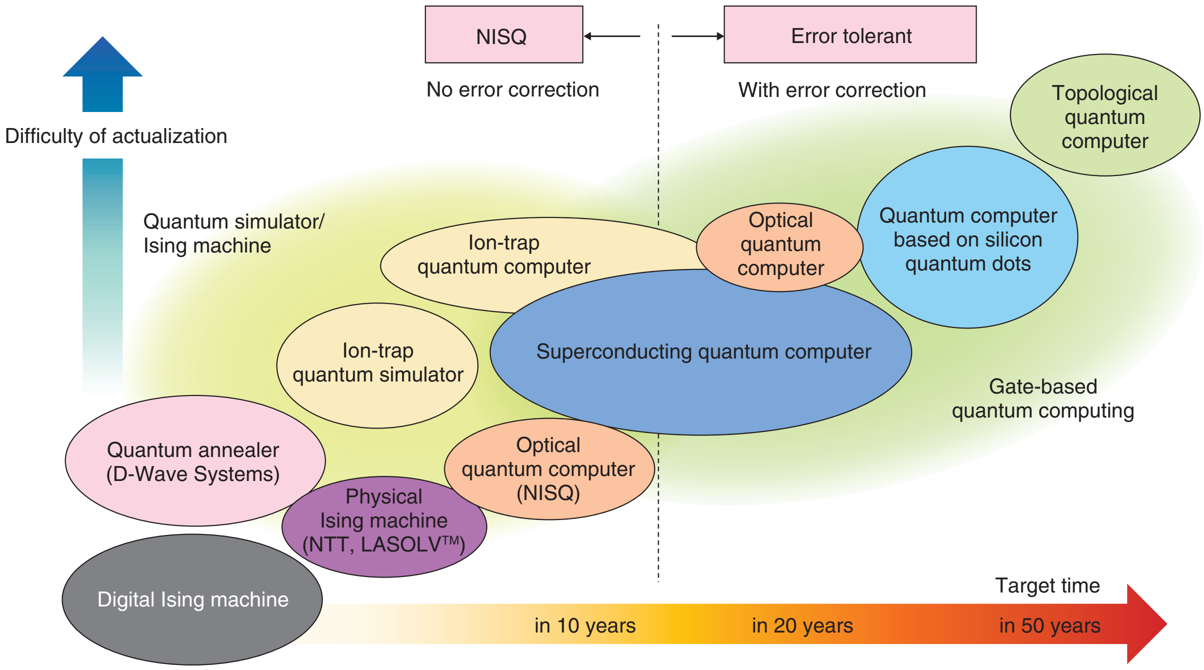

Fig. 4. Overview of quantum-computer development.

problems (maximum cut problems) of a 100,000-node graph 1000 times faster than a digital machine [4]. Annealing machines to solving combinatorial optimization problems using digital technology have also been commercialized by several Japanese companies, which are thereby giving Japan a strong presence in this field.

The development of quantum computers is illustrated on the basis of NTT's own indexes in **Fig. 4**. The current gate-based quantum computer is called a noisy intermediate-scale quantum computer (NISQ), namely, a quantum computer that cannot be scaled up due to noise, and its applications are limited by its lack of error-correction capability. To implement quantum error correction, a large number of qubits (several dozen to ten thousand) are combined to form a single logical qubit, which requires large-scale integration and connection between qubit chips via a quantum network. Many technical challenges, such as the enormous size of the refrigerator and the complexity of the control system, must also be overcome. Under these circumstances, it is still unclear which quantum bit will be the most favored approach. Superconducting qubits are not suitable for integration of 1000 qubits or more owing to their large element size; accordingly, silicon qubits based on semiconductor processing technology are promising for achieving higher integration. Optical quantum systems—which can place a large number of qubits on a time axis—are also being studied. Topological quantum computers, which are protected by the inherently stable property of matter called *topology*, thus do not require error correction, are also attracting attention. On top of these developments in hardware, research and development of quantum algorithms, which exploit the high speed of quantum computers, is also continuing apace.

3.2 Quantum communications and quantum security

Since the Ministry of Internal Affairs and Communications took the lead in launching the world's first quantum-cryptography testbed called the TOKYO QKD network in 2010, Japan has possessed world-class technological capabilities in quantum-cryptography communications, and verification experiments for genome information, electronic medical records, financial transactions, etc. using the TOKYO QKD network are underway. China has established a 2000-km-long quantum-cryptography network stretching from Shanghai to Beijing, and is further extending it by using satellites. Since quantum cryptography requires the use of extremely weak light, namely, a single photon (the smallest unit of light), the transmission distance of quantum cryptography is limited due to transmission loss in optical fibers, and that limit is thought to be about 100 km for actual use.

Post-quantum cryptography (PQC), a cipher that cannot be solved even by a quantum computer, is under development, mainly in the U.S., and hybrid schemes combining quantum cryptography and modern cryptography such as PQC are also being developed. Quantum relay technology is an essential element of the quantum internet, and quantum memory to retain the received quantum state is being actively researched. All-photonic quantum repeaters, which do not use quantum memory, are also being demonstrated.

3.3 Quantum sensing devices and materials

One type of quantum sensing is diamond nitrogen-vacancy (NV) centers, in which quantum effects exist even at room temperature, and are expected to be used to detect magnetic fields and temperature with higher sensitivity than possible with conventional sensors. Applying quantum sensing to medicine and drug discovery is also being investigated, and technologies for real-time observation of drug efficacy using magnetic resonance imaging by combining materials containing isotope-controlled elements and nuclear-spin hyperpolarization technology are rapidly emerging.

Other developments include quantum inertial sensors based on atom-wave interferometers, which theoretically offer ten orders of magnitude higher performance than fiber-optic gyroscopes, and ultra-high-precision clocks (optical lattice clocks). Quantum devices, including single-photon and entangled-photon light sources, highly sensitive photodetectors, single-electron devices, and spin Seebeck devices and quantum materials, including diamond NV centers, quantum dots, topological materials, and atomic-layer materials, have attracted attention.

4. Future prospects for quantum technology

As mentioned above, the creation of a quantum computer that can surpass current digital computers in terms of computational power is still a long way off; even so, quantum cryptography and quantum sensing are expected to be implemented in society in the near future if the cost issues can be overcome. It is envisioned that there will be a demand for quantum connections between quantum computers and between quantum sensors and quantum computers, which will require a network capable of transmitting quantum states, that is, a quantum internet. The current structure of the Internet, however, cannot handle quantum states, so innovative infrastructures such as the IOWN (Innovative Optical and Wireless Network) All-Photonics Network will become increasingly important. Quantum computing is also important from the perspective of energy consumption in the IT industry because, in principle, it is energy-neutral computing.

The Feature Articles in this issue discuss an optical quantum computer [5], quantum-information technology with superconducting qubits [6], an optical lattice-clock network [7], fast algorithms for quantum computers [8], high-performance quantum-key distribution [9], and the all-photonic quantum internet [10] as representative examples of NTT's quantum technology.

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