Provisional translation

【Moonshot Goal 6】

R&D concept of “Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050.”

February 2020
Revised in June 2022
Ministry of Education, Culture, Sports, Science and Technology

1. Moonshot Goals

Within the Moonshot Goals (decided on January 23rd, 2020, by Plenary session of Council for Science, Technology and Innovation), the Ministry of Education, Culture, Sports, Science and Technology (“MEXT”), with Japan Science and Technology Agency (“JST”) as a research and development promotion agency, will undertake research and development activities for achieving of the following Goal.

＜Moonshot Goal＞

“Realization of a fault-tolerant universal quantum computer [1] that will revolutionize economy, industry, and security by 2050.”

・Achieve the large-scale integration required for fault-tolerant universal quantum computers by 2050.

・Develop a certain scale of NISQ computer[2] and demonstrate the effectiveness of quantum error correction by 2030.

2. Direction of research and development

Based on the discussion and proposal made in the Moonshot International Symposium (held in December 17, 18, 2019), direction of research and development at present is shown as follows.

---

[1] In this plan, “fault-tolerant universal quantum computer” refers to a general-purpose digital quantum computer with a capability of converting any quantum state to a desired state (universal) with a guarantee on sufficiently high accuracy (fault-tolerant) that can be used in various applications.

[2] The NISQ (Noisy-Intermediate Scale Quantum) computer is a small- to medium-scale quantum computer without an error correction function.

(1) Area and field to promote challenging R&D

While it is said that the progress of conventional computers is reaching its limits, it is important to be able to respond to the explosion of various information processing demands for the realization of Society 5.0. The key is to realize a fault-tolerant universal quantum computer that will revolutionize our economy, industry, and security.

In order to realize a fault-tolerant universal quantum computer, it is necessary to promote research and development of hardware, software, networks, and related quantum technologies shown in FIG. 1 widely and to integrate them appropriately. These are the areas and fields for challenging R&D to be promoted in Moonshot Research & Development Program.

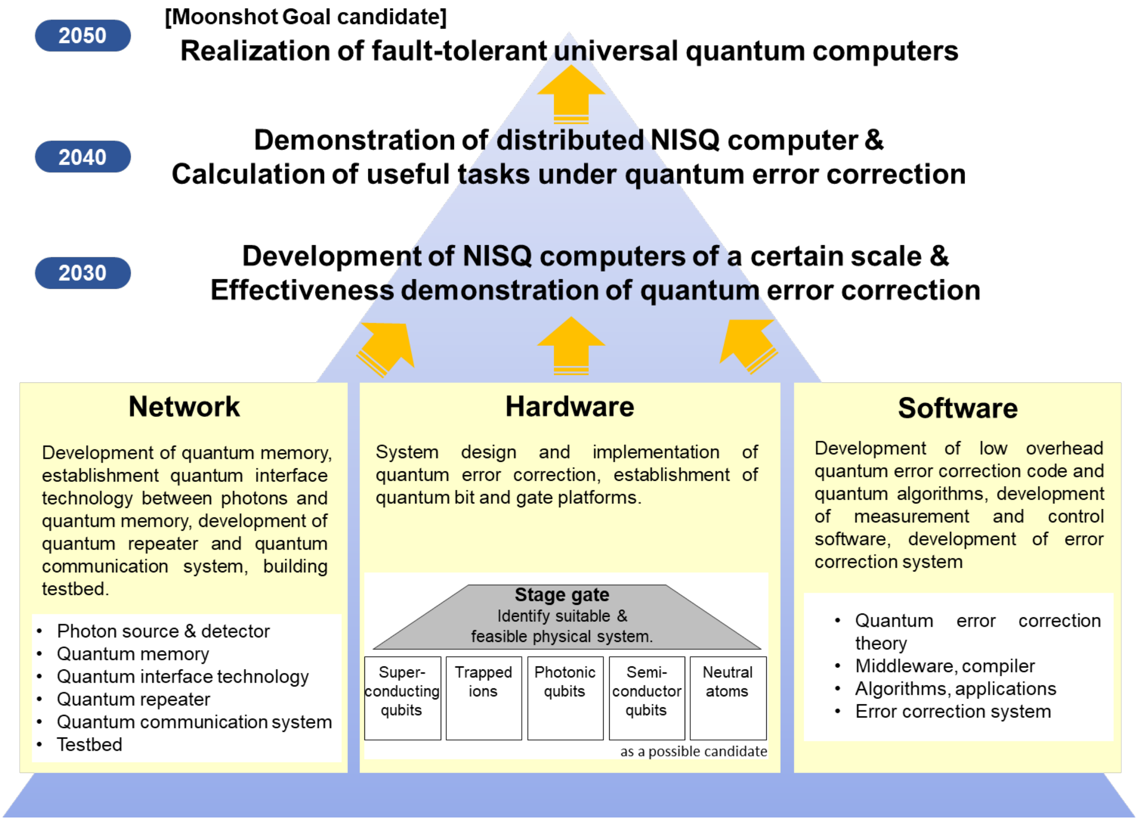

Fig. 1 Main fields and areas of R&D that is required for Realization of a fault-tolerant universal quantum computer

(2) Research subject for realization of MS Goal

The image in Fig.1 is the area and field for challenging R&D to be promoted under the Moonshot Research & Development Program. R&D that contribute to the achievement of this MS goal ”realization of a society in which human beings can be free from limitations of body, brain, space, and time” should proceed. In order to have the most effective and efficient countermeasure, the most cutting edge scientific trends shall be researched and used for R&D.

Specifically, we will conduct R&D on hardware such as a qubit / quantum gate infrastructure, software such as that for quantum error correction theory, and networks such as quantum interfaces.

Regarding R&D on hardware, along with the superconducting qubit method, we will proceed with R&D in parallel on multiple promising methods including optical qubits, ion traps, semiconductor qubits, etc. At an appropriate time, such as at a stage gate, we will determine the most suitable method from the viewpoint of feasibility and possibility of upscaling.

In conducting R&D, various sources and types of knowledge and ideas will be adopted, stage gates will be established. And evaluation will be conducted to promote R&D to achieve Goal.

In addition, from the viewpoint of smoothly implementing research results in society, a system that enables researchers in various fields to participate in ethical, legal, and social issues will be considered.

(3) Direction of research and development for realization of the Goals

○ By 2030

・Develop a certain scale of NISQ computer and demonstrate the effectiveness of quantum error correction.

○ By 2050

・Achieve the large-scale integration required for fault-tolerant universal quantum computers.

To realize a fault-tolerant universal quantum computer by 2050, we will first develop a certain scale of NISQ computer and demonstrate the effectiveness of quantum error correction. On top of that, it is necessary to demonstrate a distributed processing type NISQ computer and calculate useful tasks under quantum error correction, and work on a large scale. Thus, the target by 2030 is to develop a certain scale of NISQ computer and effectively demonstrate quantum error correction. Fig. 2 shows how to proceed with R&D to achieve the Moonshot target by realizing the R&D concept.

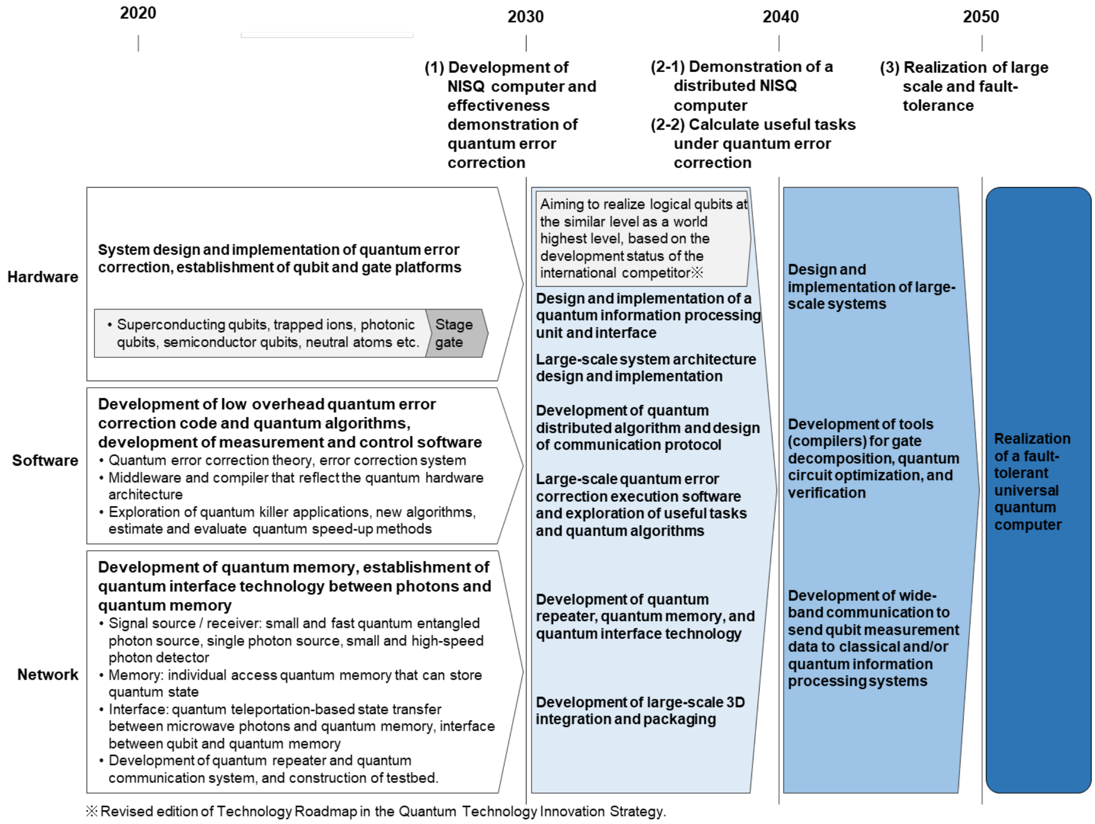

Fig. 2 The R&D process toward the realization of a fault-tolerant universal quantum computer

＜Reference : Analysis for realization of the Goals＞

Summary of content which is analyzed in the Initiative Report presented in Moonshot International Symposium is shown, as follows:

(1) Structure of research fields and technologies

The quantum computer is a representative example of quantum technology that manipulates, controls, and utilizes quantum mechanical properties such as quantum coherence and quantum entanglement.

Figure 3 presents a panoramic view of quantum technology. This includes the four main areas: quantum computing and simulation, quantum measurement and sensing, quantum cryptography and communication, and quantum materials, as well as the areas of common principles and common tools that deepen and enable them, and common quantum technology platforms that include new scientific discoveries and new technologies that will become the seeds for new quantum science and technology developments that cannot be covered by the above areas alone.

In developing a fault-tolerant universal quantum computer, in addition to the above, it is necessary to combine various technical elements such as materials, microwave technology, process technology, design, and peripheral circuit technology developed for semiconductor integrated circuits and so, challenging R&D is required.

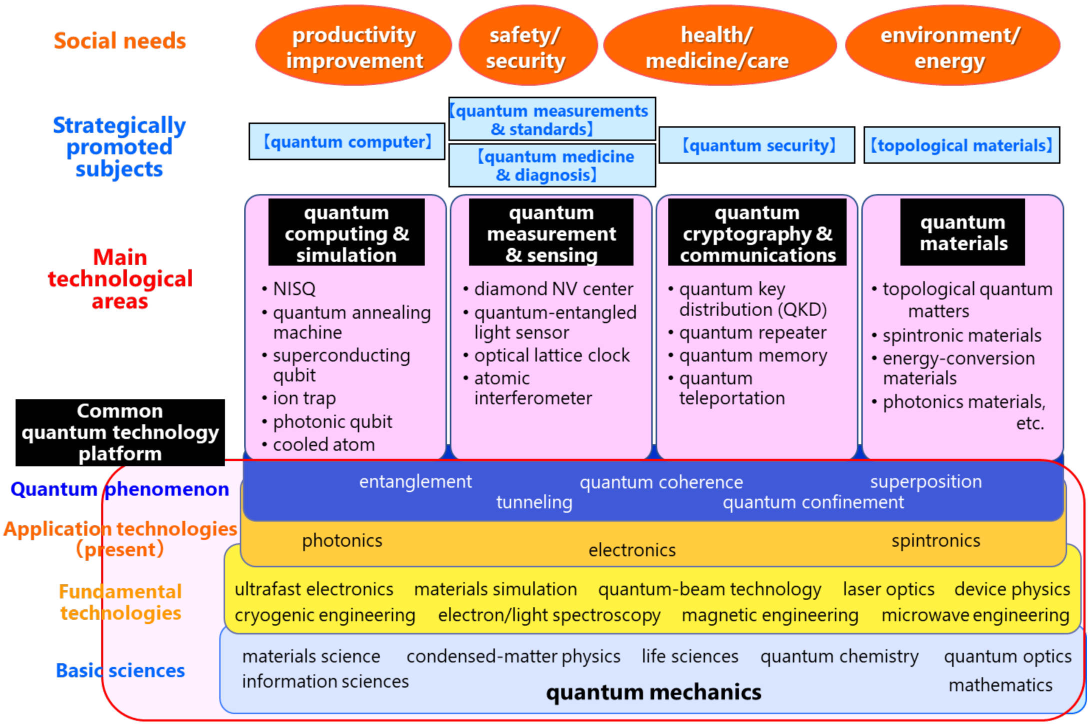

Fig. 3 The structure of research fields and technologies mainly related to a fault-tolerant universal quantum computer

(Source) Japan Science and Technology Agency, Center for Research and Development Strategy, "(Strategic Proposal) Quantum 2.0 ~Towards new horizons of quantum applications ~", CRDS-FY2019-SP-03, 2019. *(in Japanese)*

(2) R&D trends in related fields①Patent Map

The similarity of 4,088 related patents was evaluated using topic models and mapped on a two-dimensional plane by applying manifold learning (Fig. 4) to assess the development status of quantum technology to date. Based on the similarity of the patent documents, 30 clusters are indicated by dotted lines, and "quantum computer," "quantum bit and gate," "quantum communication and cryptography," and "quantum device" are identified as additional global structures.

The "quantum computer" category includes 173 patents and clusters for "quantum information processing unit" and "superconducting quantum computers." The "quantum bit and gate" category also includes patents for quantum computer applications.

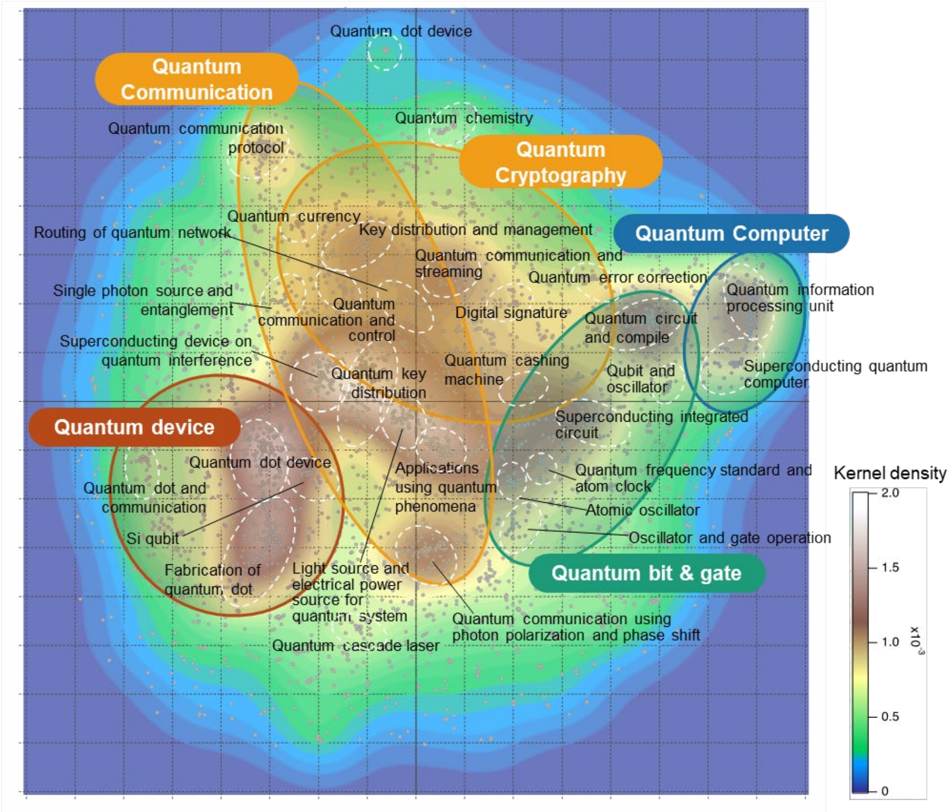

Fig. 4 Patent map related to quantum technology (kernel probability density estimation)

(Source) Japan Science and Technology Agency, Center for Research and Development Strategy, "(Research Report) Quantum technology 2.0 in the world patent map", CRDS-FY2018-RR-04, 2019. *(in Japanese)*

In Fig. 5, the 29 years from 1990 to 2018 are divided into six periods, and the number of patents applied for within each period is plotted by technology area.

Although the 2015 to 2018 timeframe is shorter compared to other the periods mentioned, this period represents the highest number of patents in all technology categories.

In particular, very active patent/publication activities are observed in the "Quantum communication and cryptography" category in the patent map, represented by the "Quantum key distribution" area. Multiple patents have also been pursued in the "Quantum computer" category, such as "Quantum information processing unit," "Quantum circuit and compiler," and "Superconducting integrated circuits."

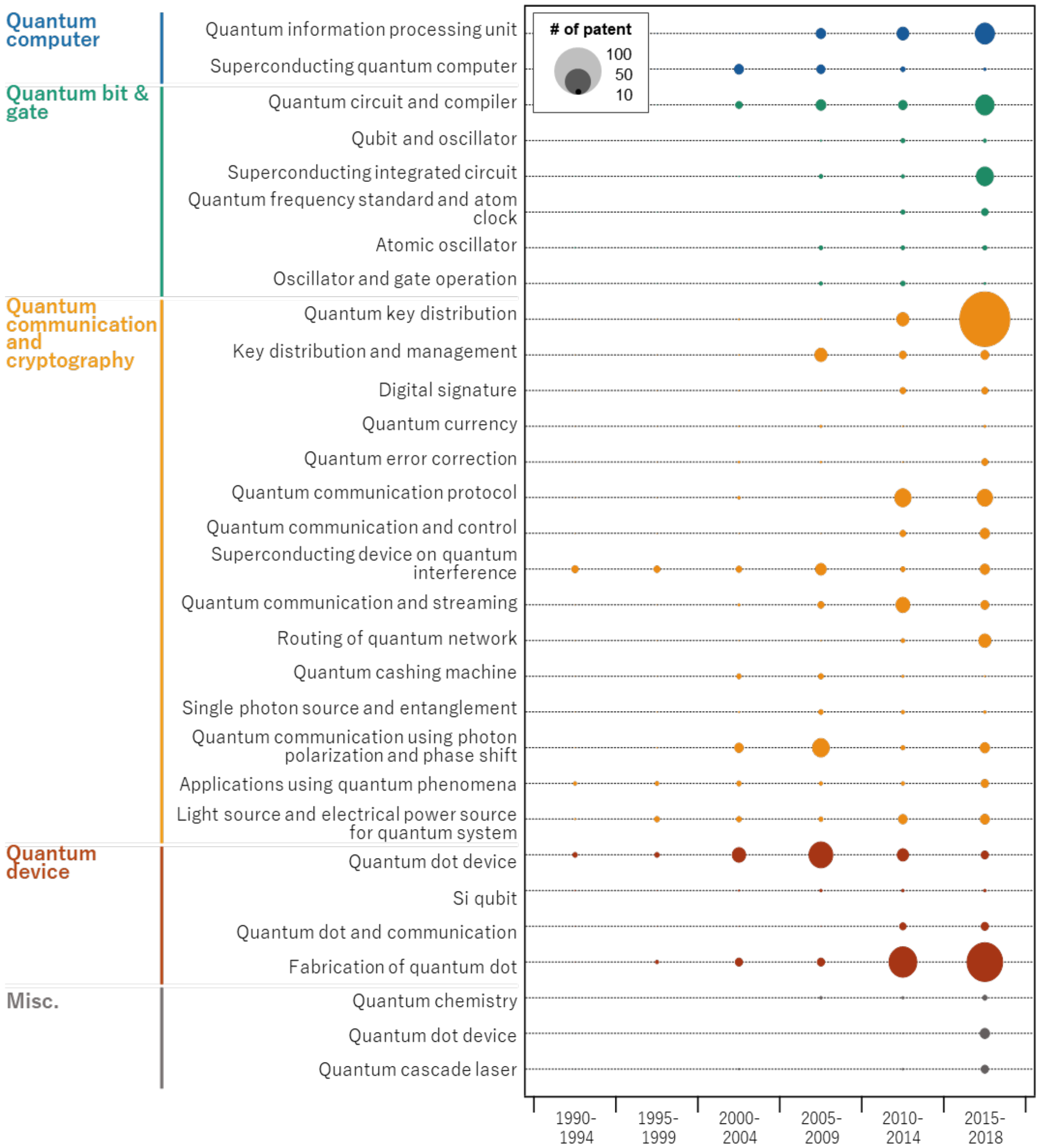

Fig. 6 Trends in the number of patents related to quantum technology

(Source) Japan Science and Technology Agency, Center for Research and Development Strategy, "(Research Report) Quantum technology 2.0 in the world patent map", CRDS-FY2018-RR-04, 2019. *(in Japanese)*

② Trend in the number of academic papers

The macroscopic trends of papers related to quantum technology were investigated using the Scopus database.

Papers/proceedings/reviews that contain "quantum computer," "quantum communication," "quantum sensor" or "quantum sensing," and "quantum simulation" or "quantum simulator" in the title, abstract, or keywords were extracted and the annual changes in the number of publications are shown in Fig. 6.

The results indicate that the activities of the quantum technology research community have become more dynamic around the globe. In particular, papers on quantum computers began to increase in 1994, and inflection points are observed in 1999 and 2010, where the rate of increase in the number of documents changed noticeably. The publication of superconducting qubits by Nakamura and Tsai et al. appeared in 1999, and papers on superconducting qubits began to increase from this year forward.

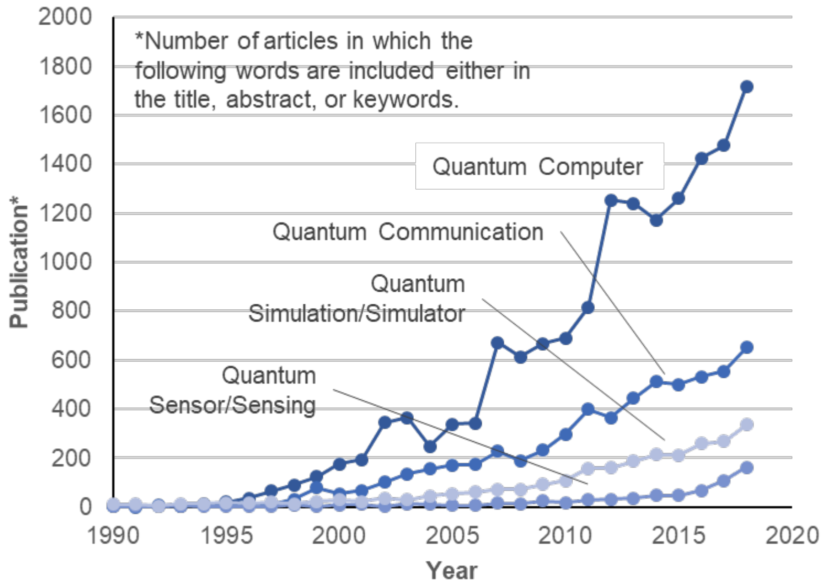

Fig. 6 Trends in the number of quantum technology-related papers

Furthermore, within documents containing "quantum computer" as the general category, documents that explicitly contain terms related to computer science (algorithm, software, compiler, programming, architecture, instruction, device, and network) were extracted and the annual trends are shown in Fig. 7. From the viewpoint of hardware and software, as compared to "device" and "algorithm," there are relatively few papers on "software" and "compiler," which are essential for computers. As a whole, the publishing trend is one of increase; in particular, the increase in the slope beginning in 2010 is a behavior common to many technology categories.

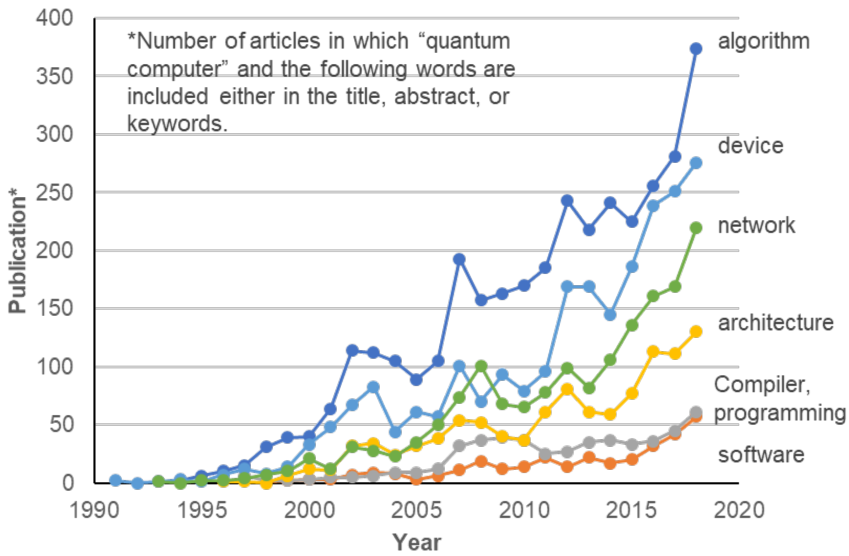

Fig. 7 Trends in the number of quantum computer-related papers

③ Trend in the number of qubits

The annual trends of qubits numbers and presenters published from 2014 to date are plotted in Fig. 8. The main focus of the current quantum computer research and development community is the implementation of quantum error correction codes and the realization of medium-scale quantum computers. There are also efforts to use NISQ computers, which have become feasible in terms of hardware, for some computational tasks, such as the demonstration of quantum supremacy (generally more than 50 qubits and the accuracy of the gate error rate must be less than 0.1%) and quantum/classical hybrid algorithm trials. Overall, the effectiveness of quantum error correction code verification and the execution of computational tasks represent an important milestone leading to the ultimate goal of fault-tolerant universal quantum computers.

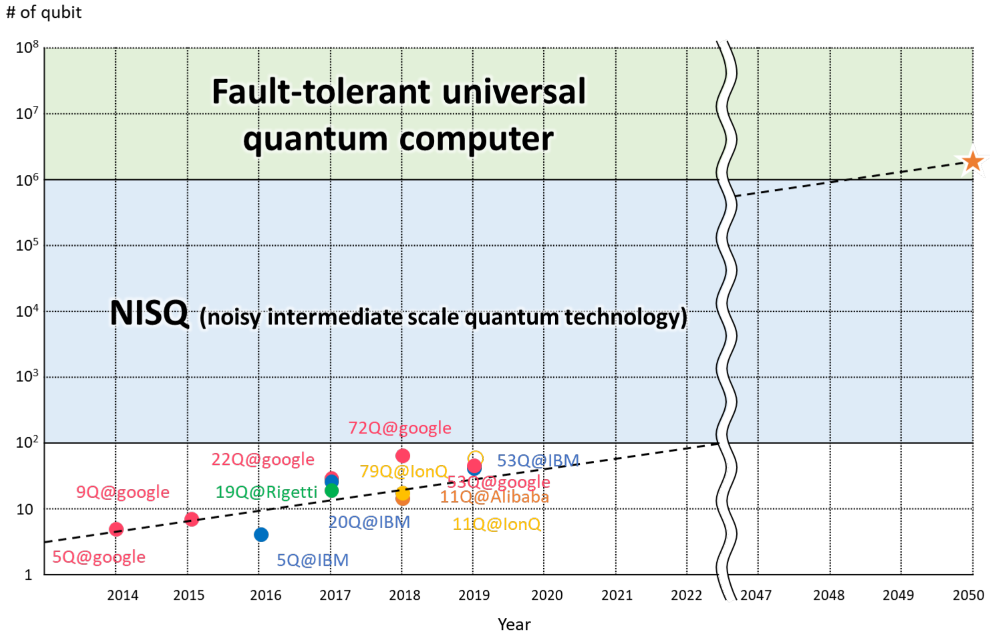

Fig. 8 Quantum version of Moore's Law

(3) Strengths of Japan, trends in global research community

In carrying out research and development, in order to collaborate and share roles with overseas research institutions, it is important to promote specific cooperation with countries and regions such as the United States and Europe that have high levels of research dedicated to quantum technology, taking account of Japan's strengths, competitiveness, and the pros and cons of international R & D collaboration. Therefore, the effort status regarding domestic and international research and development of hardware, software, and networks in Japan and overseas is summarized as follows.

①Hardware

Overseas, led mainly by global IT companies and universities, the United States is strong in both hardware and software, and research and development of superconducting qubits and trapped ions is in progress by multiple teams. China is following the superconducting qubits method within industry, academia, and the government, and development competition is intensifying. Overall, quantum gates have been realized overseas in all qubit implementation methods.

As for domestic efforts regarding superconducting qubits, Japan was the first country in the world to conduct a successful experiment (in 1999) involving controllable qubits [17], and although the research studies are led by world-class researchers, it is necessary to overcome engineering issues to achieve multi-qubits, including the associated design and architecture, such as miniaturization of qubits, wiring, and elimination of irregularities in bit accuracy. Regarding trapped ion qubits, the number of researchers in Japan is very small; therefore, it is particularly important to develop and secure researchers to focus on this area. At the same time, it is recognized that basic research such as the establishment of a qubit control method based on an understanding of many-body physics is also necessary. With regard to photons, research aims at a universal photon quantum computer that enables error correction by generating large, stable qubit entanglement in a looped optical circuit at room temperature. The silicon quantum dot system is well-matched to conventional CMOS circuit technology and is expected to be compatible with the existing, abundant CMOS technology platforms toward the development of quantum computers. The implementation of high-fidelity 2-qubit gates is one of the key research areas currently in progress.

② Software

In the United States, both software and hardware development has been promoted, mainly in universities and global IT companies. A project supported by the US National Science Foundation has begun research on practical-scale quantum computer systems and trapped ion architectures. Various IT companies have released quantum software development platforms and have expanded their open source software libraries. Furthermore, Europe announced the Quantum Software Manifesto in 2017, and is conducting integrated research on hardware and on quantum software, developing quantum software and algorithms, as well as developing new communication protocols.

In Japan, research on quantum information theory and algorithm is being carried out at universities and national research institutes. Quantum computer emulators have been developed by universities and start-up companies and have been publicly released and are available for use. Furthermore, having entered into user license agreements with hardware development companies, start-up companies are working on software development and consultation, aimed toward social implementation. Although the number of domestic researchers and engineers is not enough, there are excellent Japanese researchers with a high international reputation, have research achievements such as a fault-tolerant theory.

③ Networks

Overseas, research and development related to quantum networks has been carried out, such as establishing the Quantum Internet Alliance in Europe and systematically conducting experiments on inter-city quantum communication. China also succeeded in satellite-to-ground QKD experiments using artificial satellites.

In Japan, the Tokyo QKD Network, a test bed with a total length of approximately 100 km, was built in 2013, and its operation and evaluation are ongoing to lead the world in integration with distributed storage, etc. A Japanese research team has succeeded in an experiment to generate entanglement between cooled atomic quantum memory and a communication wavelength photon for the first time, which has received worldwide attention. A single photon source using a diamond NV center or the like, for which Japan has high fabrication capabilities, has also attracted attention. As a basic technology for quantum repeaters, successful transfer of information has been achieved without the possibility of eavesdropping while maintaining the quantum states of photons using carbon isotopes in diamond as the quantum memory and applying the principle of quantum teleportation. In addition, a demonstration experiment of an all-photonic quantum relay has succeeded for the first time in the world.