Moonshot International Symposium
December 18, 2019

# Working Group 6

## Creating innovative non-traditional sciences and technologies based on quantum and related phenomena

## Initiative Report

## Contents

## *EXECUTIVE SUMMARY*

The progress of semiconductor circuit technology, computer architecture, software and algorithms over the last few decades has been remarkable, and this has been the driving force behind the realization of today's information society. Toward the realization of Society 5.0, the demand for the computers, deep learning and combinatorial optimization methods will increase explosively. Although computer performance has been improving for over half a century with the increase of the scale of integration (Moore's Law), it is widely believed that computer progress in such a conventional style will soon come to a limit.

Even assuming that the present supercomputers continue to progress at the same rate as now, a number of important computational tasks are known to be difficult or impossible to perform using current style supercomputers. The recent research of quantum computers, however, tells us that many of such difficult tasks can be efficiently calculated by using a large-scale "fault-tolerant universal quantum computer". It is expected that fault-tolerant universal quantum computing is applicable to important but difficult tasks such as new material development, discovery of new chemical synthesis methods, development of new drugs, optimization of logistics and traffic, and financial engineering.

In Working Group 6 (WG6), based on the Area and Vision goals set by the Visionary council, the Moonshot (MS) Goal candidate, “22) General-purpose quantum computer network” was adopted as a starting point for further study. The members of WG6 have reviewed and discussed this goal from various perspectives, considering societal demands and urgency toward developing quantum computers, global trends in research and technical challenges, such that this goal will be accepted by many as a viable goal achievable by 2050.

As a result, WG6 proposes the following MS Goal:

- **Realize a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050**

WG6 further specified the following intermediate milestones for the realization of fault-tolerant universal quantum computers.

- Establish technology to arbitrarily control a practical noisy intermediate-scale quantum (NISQ) computer with a certain scale of qubits (approximately 100 qubits), conduct error correction empirical research to derive lower error-rate logical qubits, and demonstrate the effectiveness of quantum error correction by 2030.
- Develop a secure distributed NISQ computer connected by a quantum communication network and execute calculations that are difficult to perform using current modern computers. Furthermore, execute various quantum algorithms that contribute to useful tasks with quantum computers that implement quantum error correction by 2040.
- Achieve large-scale integration required for fault-tolerant universal quantum computers by the year 2050.

Diverse research and development are required to accomplish these milestones, and it is extremely important to develop and possess the core technologies in Japan from the perspective of Japan’s “Quantum Technology and Innovation Strategy”. WG6 identified core technologies that should be developed in terms of hardware, software, and networks. Moreover, research and development efforts to realize fault-tolerant universal quantum computers will generate many scientific and technological spin-offs, as in the case of the Apollo project.

By the year 2050, a society based on quantum technology is expected to be established, where combinations of quantum technologies such as quantum computers, quantum sensors, quantum communication and cryptography, and conventional information technology are used frequently. It is expected that fault-tolerant universal quantum computers will cooperate with conventional classical computers to solve problems and create new services that take advantage of the characteristics of both systems. Meanwhile, various quantum technologies such as early medical diagnosis through quantum IoT using quantum sensors and quantum computers, protection of corporate proprietary information through blind quantum computation using quantum computers and quantum cryptography, and real-time monitoring of infrastructure through quantum sensor networks using quantum sensors and quantum communications, will be utilized according to societal needs. Quantum technology as represented by fault-tolerant universal quantum computers will lead to an entirely new information society following the introduction of the internet and cloud services.

# I. VISION AND PHILOSOPHY

## 1. The Moonshot「Area」「Vision」 for setting MS「Goals」 candidate

The visionary council, which consists of various experts, has proposed the following 3 Areas, 13 Visions, and 25 examples of Moonshot (MS) Goals that the Moonshot Research and Development Program should aim for. The aim is to set ambitious targets and concepts for a social agenda that are difficult to tackle but will have profound impact once resolved. (See Fig. 1)

Working Group 6 (WG6) discusses the following area, vision, and example out of the 3 Areas, 13 Visions, and 25 examples that were proposed by the visionary council as the MS Goals candidate.

**[Area]**

*Exploring frontiers with science and technology.*

**[Vision]**

*Measuring, computing, and visualizing unexplored spaces.*

**[Example of MS Goal candidate to be used as reference]**

*22) General-purpose quantum computer network*

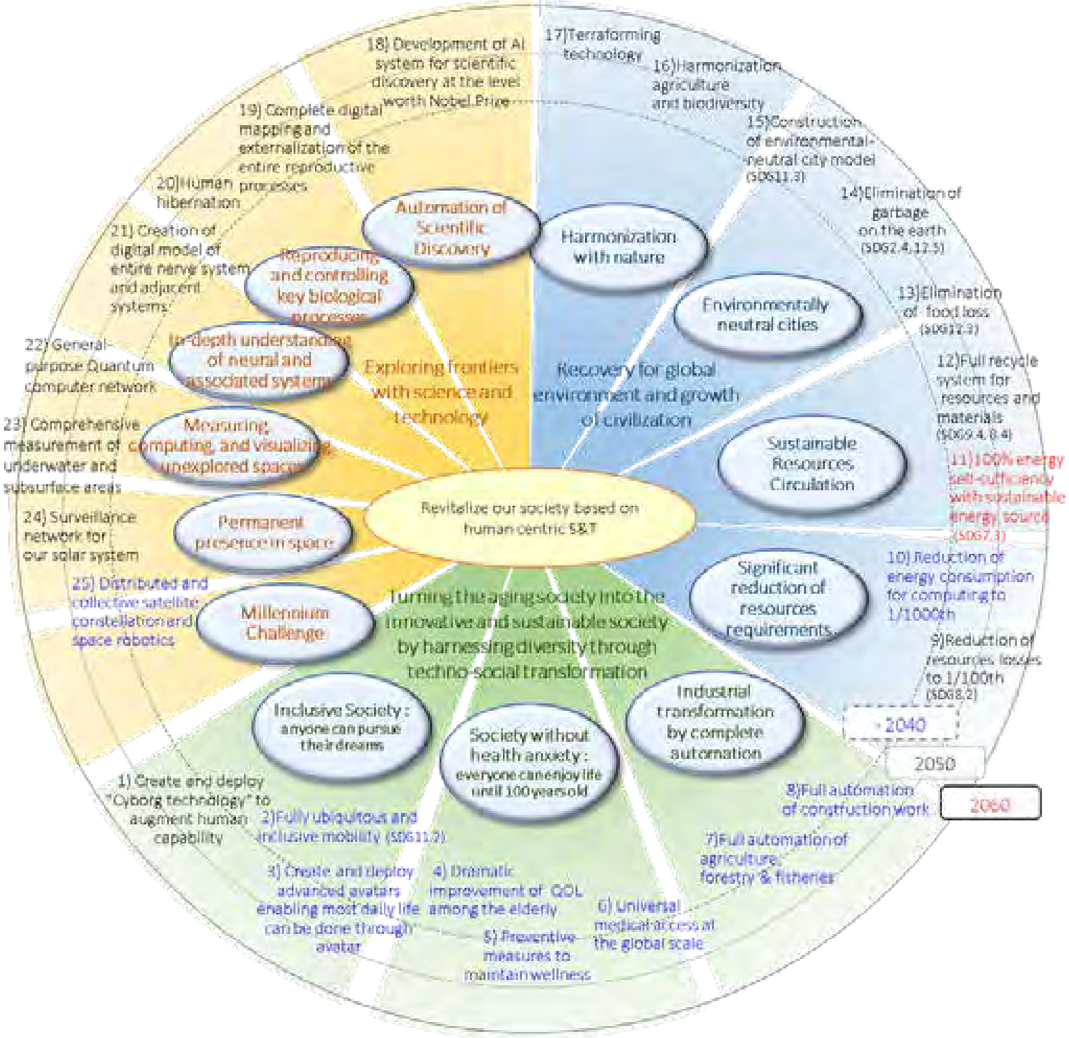

Fig. 1 Future visions and 25 MS goal examples

## 2. Concept of MS Goal candidate

### 2.1. MS Goal candidate

Realize a fault-tolerant universal quantum computer[1] that will revolutionize economy, industry, and security by 2050

### 2.2. Target (Expected milestones and Research and Development activities)

The following candidates are considered as intermediate milestones toward the realization of fault-tolerant universal quantum computers.

- Establish the technology needed to arbitrarily control a practical NISQ computer with a certain scale of qubits (approximately 100 qubits) and enable quantum communication among NISQ computers, conduct empirical research on error correction techniques to derive lower error-rate logical qubits, and demonstrate the effectiveness of quantum error correction by 2030.
- Develop a secure distributed NISQ computer connected by a quantum communication network and execute calculations which are difficult to perform using current modern computers and execute various quantum algorithms that contribute to useful tasks using quantum computers that implement quantum error correction by 2040.
- Achieve the large-scale integration required for fault-tolerant universal quantum computers by the year 2050.

The research and development necessary to realize the above milestones can be mainly classified into three areas of hardware, software, and networks. From these viewpoints, the following candidate areas for research and development may be considered.

The research and development required to realize these goals is diverse, and it is extremely important to develop and possess core technologies in our country from the perspective of the "Quantum Technology and Innovation Strategy". From the viewpoint of hardware, software, and networks, the following core technologies should be developed under this program.

- Hardware
  System design and implementation of quantum error correction, establishment of quantum bits and gate platforms, etc.
- Software
  Development of low overhead quantum error correction code and quantum algorithms, development of measurement and control software, etc.
- Network
  Development of quantum memory, establishment of quantum interface technology[2] between photons and quantum memory, etc.

It is not realistic for Japan or this program to cover all these activities independently and to conduct all this research and development. Therefore, it is essential to incorporate the results of other projects and to collaborate and share roles with private companies and overseas research institutions. To this end, it is necessary to evaluate Japan's strengths and competitiveness in a timely and appropriate manner while adhering to the national strategy, and to reflect on the appropriate results in research and development under this program.

### 2.3. Concept

The progress of semiconductor circuit technology, computer architecture, software and algorithms over the last few decades has been remarkable, and this has been the driving force behind the realization of today's information society. Toward the realization of Society 5.0, the demand for the computers, deep learning and combinatorial optimization methods will increase

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[1] In this report, "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] Quantum interface technology refers to the transcription (and reverse transcription) of quantum memory or qubit states involving communication using photons (also called quantum media transformation).

explosively. Although computer performance has been improving for over half a century with the increase of the scale of integration (Moore's Law), it is widely believed that computer progress in such a conventional style will soon come to a limit.

Even assuming that the present supercomputers continue to progress at the same rate as now, a number of important computational tasks are known to be difficult or impossible to perform using current style supercomputers. Quantum computation is based on a completely different principle from classical computers, and is expected to perform the above tasks in a realistic time. However, today’s small-scale quantum computers are affected by errors, and have a limited ran go applications. The recent research of quantum computers, tells us that many of such difficult tasks can be efficiently calculated by using a large-scale "fault-tolerant universal quantum computer". It is expected that fault-tolerant universal quantum computing is applicable to important but difficult tasks such as new material development, discovery of new chemical synthesis methods, development of new drugs, optimization of logistics and traffic, and financial engineering.

By the year 2050, the arrival of a society based on quantum technology is expected, where combinations of quantum technologies such as quantum computers, quantum sensors, quantum communication and cryptography, and conventional information technology are generally available. At that time, it is expected that fault-tolerant universal quantum computers will be used in cooperation with conventional classical computers to solve problems and create new services that take advantage of the characteristics of both systems. Meanwhile, various quantum technologies, such as early medical diagnosis through quantum IoT using quantum sensors and quantum computers, protection of corporate proprietary information through blind quantum computation using quantum computers and quantum cryptography, and real-time monitoring of infrastructure through quantum sensor networks using quantum sensors and quantum communications, will be utilized according to specific needs. Quantum technology represented by fault-tolerant universal quantum computers will help establish an entirely new information society.

The realization of fault-tolerant universal quantum computers is a challenging issue that requires a time scale of approximately 20 to 30 years due to the technical difficulties involved, but if this goal can be achieved, it is expected to have an extremely large economic and social impact, including possible applications involving peripheral quantum technology. Therefore, it is inevitable that global research and development trends related to quantum computer development will head toward this goal. In other words, this goal is “inspiring” because it can provide shared values, both at home and abroad, with a medium- to long-term perspective.

Moreover, the realization of fault-tolerant universal quantum computers is expected not only to create new industries and accelerate new scientific discoveries, but to bring about greater changes than the development of IT has brought to society. Based on this recognition, that innovative results in quantum computers will bring about cutting-edge technologies, governments and companies in several countries are already actively engaged in research and development. The realization of fault-tolerant universal quantum computers, which is the goal of this project, will make it possible to realize imaginative ideas that seem to be contrary to common sense and will promote a shared vision among many citizens. In this regard, this goal is “imaginative.”

Furthermore, although the realization of fault-tolerant quantum computers is an unprecedented and ambitious target that requires the elucidation of new phenomena and technological developments, there are already a certain number of technical ideas that can be used to objectively examine its feasibility, and we are at the stage where we can explore this possibility. In addition, because various spin-offs of other quantum technologies that can be put into practical use are assumed to be generated already during the process of research and development, it should be possible to verify the achievement status through their social returns. For the reasons discussed above, this goal is “credible”.

## 3. Why Now?

Quantum technology is an extremely important technology with the potential to dramatically improve future economy, industry, and security by enabling high-level control of phenomena unique to quantum mechanics, such as quantum entanglement and quantum coherence, and by achieving a performance that surpasses conventional technologies [1].

In the United States, Europe, and China, research and development and social implementation efforts in this field are being rapidly promoted through considerable government investments [2-5]. On October 23, 2019, the Google team published a paper in *Nature*, an English scientific journal, stating that they have achieved quantum supremacy [6]. While paying attention to ever-improving global trends, it is now necessary for the scientific community to pioneer frontiers in quantum technology based on each country's strengths and international competitiveness in anticipation of future social innovation.

Among the many quantum technologies to be explored, the focus on quantum computers is particularly high. The dramatic improvement in the performance of computers resulting from semiconductor microfabrication technology is approaching its technical and economic limits, and improvements in performance due to the increase in the number of transistors is no longer possible as it was in the past (the limit imposed by Moore's Law). In contrast, in response to the explosive increase in the amount of information brought about by the advent of the digital society, there are situations in which existing technologies do not represent a practical option for fulfilling computing needs such as big data processing, image/video processing, deep learning, and combination optimization. Development of quantum computers that can continue to improve computing performance in the future by using new calculation principles, algorithms, architectures, devices, etc., without relying only on microfabrication technology, is urgently needed. This is to respond as soon as possible to the growing social expectations for the utilization of large-scale data that are difficult to handle using current technology and from the viewpoint of computer science.

Because currently available small-scale quantum computers (NISQ) have no error correction function and it is difficult to obtain reliable results for practical large-scale calculations, their return on investment is limited. In contrast, although there are various technical problems in realizing a fault-tolerant universal quantum computer that can solve useful problems in industrial applications, there is no particular reason to prevent its development [7]. If reliable quantum computing is realized, the social and economic impacts will be immeasurable, and the long-term return on investment will be very high.

In light of this, it is important to begin research and development of fault-tolerant universal quantum computers as soon as possible.

## 4. Changes in industry and society

By the year 2050, the use of quantum technology, including quantum computers, will generate innovations in various fields and is expected to change existing social systems. As the paradigm shift toward a knowledge-intensive society progresses and the importance of utilizing large-scale data continues to increase, fault-tolerant universal quantum computers are expected to be capable of solving various social problems and in turn function as powerful tools that will lead to stronger industrial competitiveness.

As shown in Fig. 2, the realization of fault-tolerant universal quantum computers is expected to contribute to the creation of new values over a wide range of industrial and social fields, including material development, energy, drug discovery, finance, transportation and logistics, and weather [8]. Specifically, the following outcomes are expected:

- Materials Development
  Acceleration of discoveries that maximize the performance of existing and new materials through detailed functional analysis
- Energy
  Development of the energy-saving nitrogen fixation and highly efficient artificial photosynthesis methods through high-precision quantum chemical calculations.
- Drug Discovery
  Facilitation of the discovery of new drugs through powerful simulations and provide cost reductions through streamlined workflows
- Finance
  Addressing short-term portfolio optimization and long-term risk analysis through quick, energy saving large-scale calculations
- Transportation/Logistics
  Streamlining of the supply chain and scheduling through optimization problems such as traveling salesman problem
- Weather
  Improvement of weather forecast accuracy through large-scale simulations, boosting of early warnings, corporate price, and trading strategies

These impacts are relevant to and able to contribute on the perspectives of the other Working Groups, such as WG2, WG4, WG5, etc. Therefore, WG6 will have close information exchange under the whole Moonshot framework.

Summarizing these expected outcomes, the following three examples can serve as future visions brought about by the use of quantum technologies including quantum computers.

- Dramatical improvement in productivity by strengthening industrial competitiveness through technological innovation so that we can overcome rapid aging and a declining working population.
- Realization of the health and longevity of the population through innovative medical care and health management in response to the arrival of a super-aging society.
- Ensuring the safety and security of society through advanced risk analysis and the creation of a security environment to take full advantage of the rapidly growing digital information era.

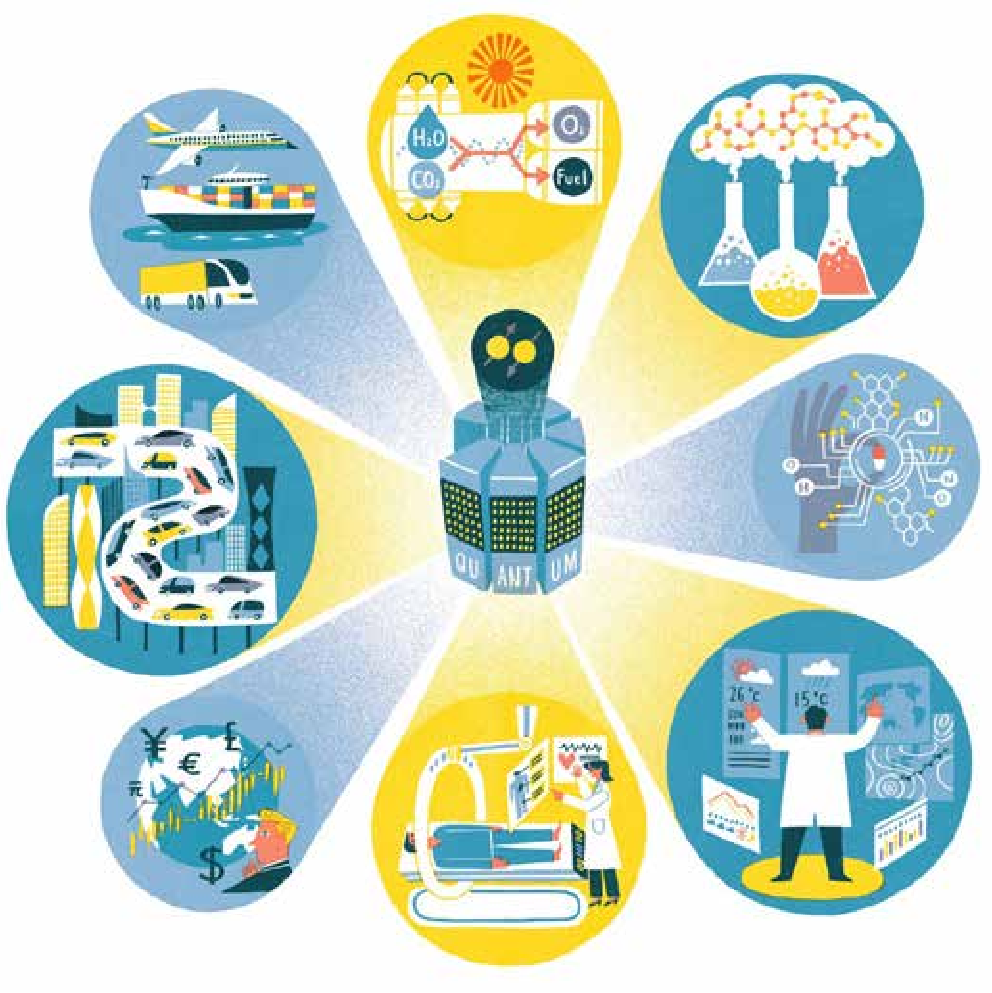

Fig. 2 Vision of a society

Furthermore, the realization of fault-tolerant universal quantum computers can fundamentally contribute to Sustainable Development Goals (SDGs) by dramatically increasing human computing power. For example, the Harbor Bosch method, which uses high temperature and high pressure, is currently said to account for several percent of the world's energy consumption; therefore, if an energy-saving nitrogen fixation method that mimics bacterial biosynthesis is developed, it will represent a major step forward in solving global energy and food problems. Additionally, if the high-efficiency photosynthesis mechanism of plants is elucidated such that high-efficiency artificial photosynthesis mimicking it becomes possible using only the abundant elements on Earth, it will lead to the development of technology that can simultaneously achieve $CO_2$ reduction, $O_2$ production, and solar energy utilization, which will contribute to the resolution of current environmental and energy issues.

On the other hand, there are concerns that future large-scale quantum computers will be capable of breaking the RSA cryptography currently used widely on the internet and the hash function used in virtual currencies such as Bitcoin [9]. However, a significant amount of research and development has already been carried out regarding countermeasures against attacks by quantum computers, and in view of the possibility that existing public key cryptography will be neutralized, replacement with secure public key cryptosystems (anti-quantum computer cryptography) is expected to progress in the future. Moreover, compromising a secure virtual currency requires brute force calculations (it is unlikely that such types of secure systems will be immediately disabled by a quantum computer), and such systems are expected to evolve to address the risks brought about by the computational capabilities of quantum computers.

In the future, it will be necessary for various stakeholders (such as researchers, engineers, user and supplier companies, individual users, policy makers, universities, etc.) to discuss what type of social system should be built for the common benefit of the population and humankind in general. Even if an ideal fault-tolerant universal quantum computer is realized, it is unlikely that all (modern) universal digital computers will be replaced with fault-tolerant universal quantum computers, and it is presumed that both types will solve problems and create new services using their respective characteristics. Given that it will take approximately 30 years to achieve this goal, it should be possible to fully assess social and industrial changes, including any negative impacts. It is important to understand the strengths and weaknesses of quantum computers as research and development in this area progresses, and to integrate and develop conventional information processing technologies and quantum technologies in ways that are beneficial to society.

## II. STATISTICAL ANALYSIS

### 1. Structure of the MS Goal

The realization of fault-tolerant universal quantum computers is a goal that no country has achieved as of yet. To achieve this extremely challenging goal, it is necessary to promote research and development by improving overall quantum technology. Figure 3 shows the structure of the MS Goal candidate. Toward achieving this goal, we identified "development of NISQ computers of a certain scale" and "effectiveness demonstration of quantum error correction" as the milestones by 2030. It is assumed that MS Goal candidates are reached by widely promoting the research and development of hardware, software, and networks; assessing each step in progress, and integrating it properly. In addition, the realization of fault-tolerant universal quantum computers is expected to generate many scientific and technological spin-offs during the process of research and development, as in the case of the Apollo project [10].

Regarding the necessary hardware for realizing a fault-tolerant universal quantum computer, various methods such as superconducting qubits, trapped ions, photon, silicon quantum dots, etc. are considered as promising candidates[3]. Overall, for the realization of a fault-tolerant universal quantum computer, it is important to determine, in the early stages, the advantages/disadvantages and possibilities of those physical systems and to conduct research and development regarding computer architecture design. This Moonshot program thus will utilize stage-gate management on those hardware proposals by examining engineering feasibility and scalability and will identify the shortest and the most credible technology path to the fault-tolerant universal quantum computer.

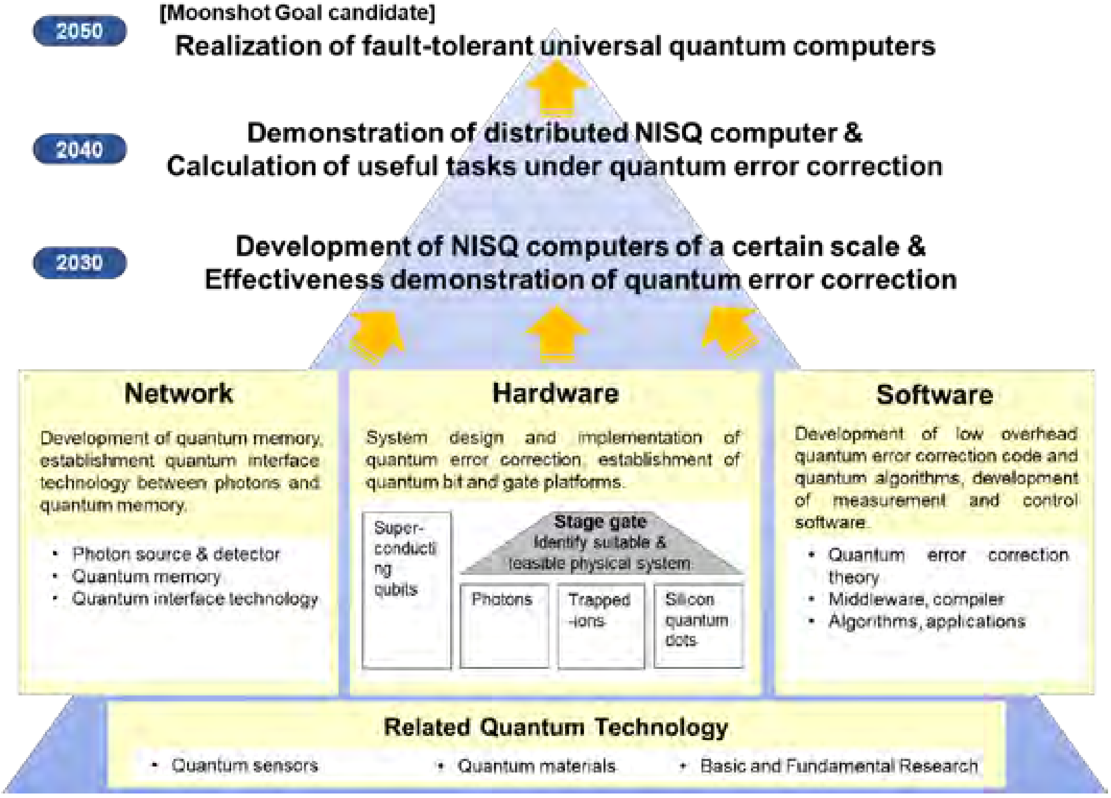

Fig. 3 Structure of MS Goal candidate

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[3] Among these physical systems, in the "Quantum Technology and Innovation Strategy" for Japan, superconducting qubits are considered the priority technology, and should be promptly promoted with particular emphasis, while trapped ion, photon, and silicon quantum dot technologies are considered fundamental and should be steadily promoted as long-term prospects [2].

## 2. Science and Technology Map

### [Panoramic view of quantum technology]

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

Figure 4 presents a panoramic view of quantum technology [11]. 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, 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. For the integration of qubits, which is one of the tasks related to the hardware requirements for quantum computers, many related technologies must also be scaled up to achieve a distributed architecture that operates by connecting many qubits through quantum communication. Therefore, contributions by experts in various fields are essential.

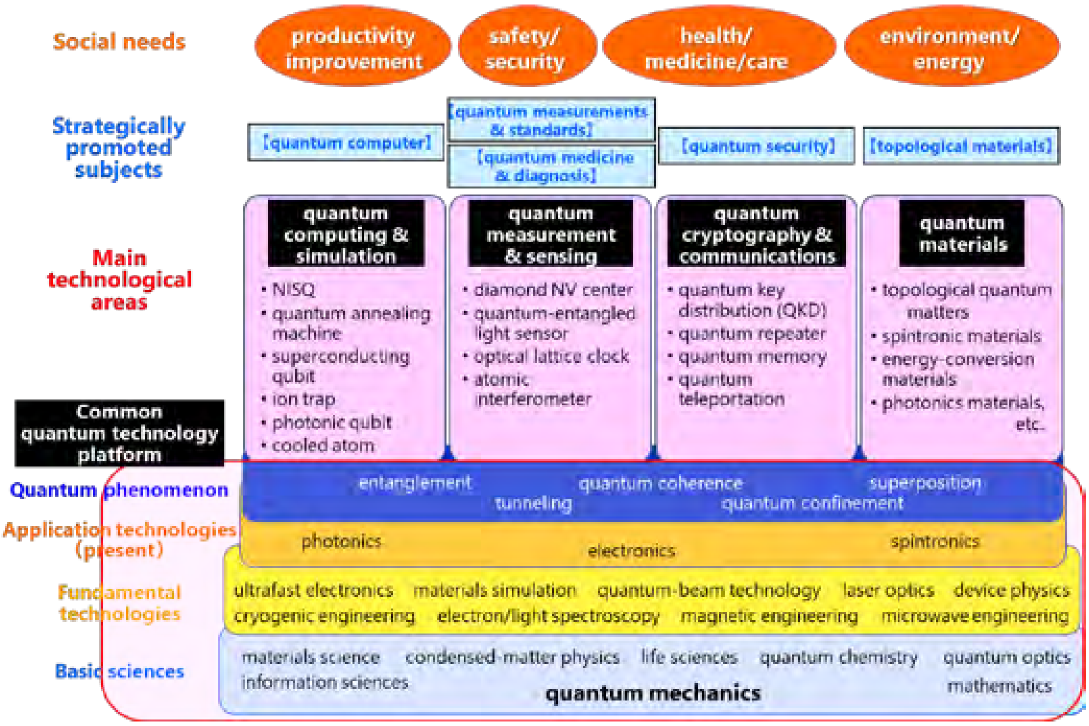

Fig. 4 Panoramic view of quantum technology [11]

### [Patent 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. 5) 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 [12].

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.

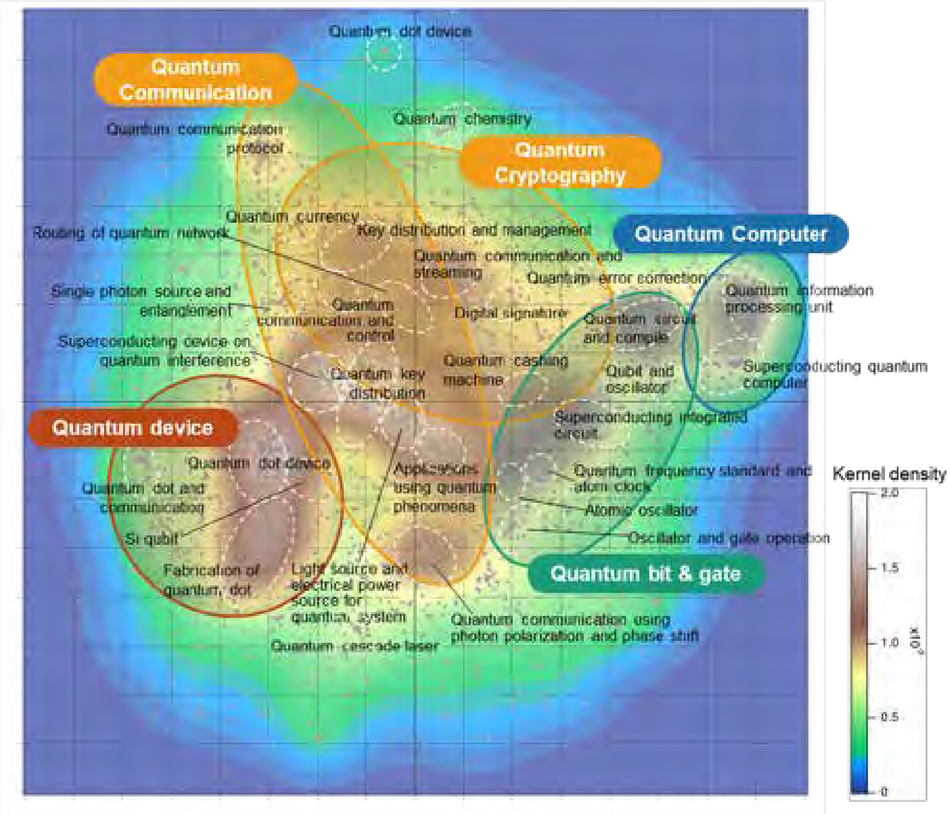

Fig. 5 Patent map related to quantum technology (kernel probability density estimation) [12]

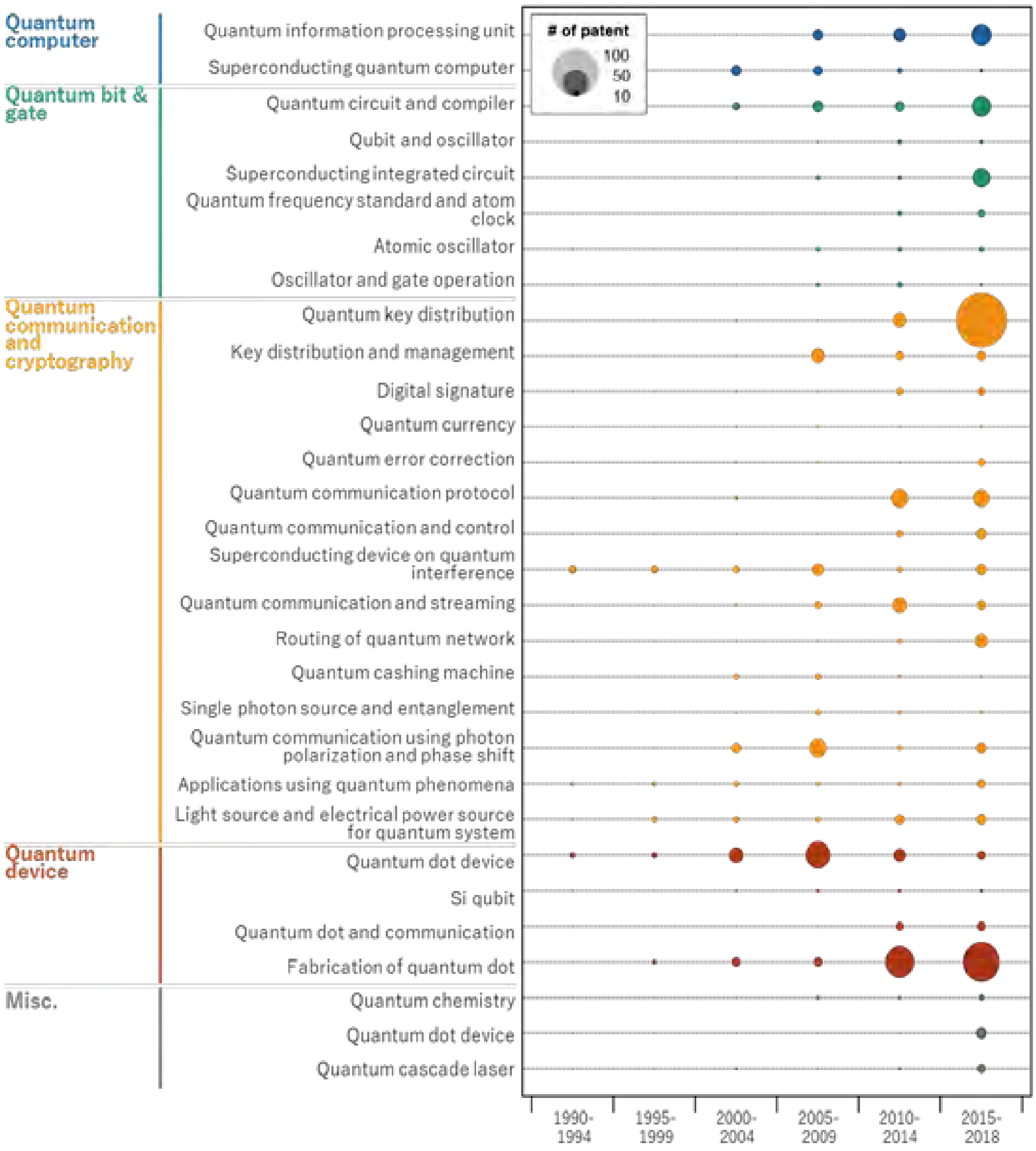

Fig. 6 Trends in the number of patents related to quantum technology [12]

In Fig. 6, 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. During 1990-94, quantum research was almost inconspicuous except for the areas of “Superconducting device on quantum interference” and “Quantum dot devices (partial quantum information processing unit).” In addition to the announcements of ultra-high-density coding, quantum cryptography experiments, etc., beginning in 1992, a number of important research achievements in quantum information science were published, including a paper by Bennett et al. on quantum teleportation (1993) and a paper by Shor on a prime factorization algorithm (1994), but did not result in any patents. From 1995 to 1999, the “Superconducting device on quantum interference” area continued to exhibit high density. Although it was a period when spectacular achievements continued in quantum information science research such as the generation of quantum entangled photon-pairs (1995), the Bose-Einstein condensation in cold atoms (1995), Grover's search algorithm (1996), the proposal of fault-tolerant quantum computation (1996), the quantum teleportation experiment verification by Zeilinger et al. (1997), nuclear magnetic resonance (NMR) quantum computation (1997), and the superconducting qubits proposal and experiments by Nakamura and Tsai et al. (1999), no upsurge was observed in the number of patents.

From 2000 to 2004, extremely high interest emerged in the “superconducting quantum computer” area of the “Quantum computer” category. In addition, an upsurge in the areas of “Quantum circuit and compiler” and “Quantum communication using photon polarization and phase shift” becomes apparent. During this period, significant progress took place in the quantum electronics field centered around superconducting devices, such as the solid single photon source (2000) and diamond nitrogen-vacancy (NV) center qubits (2004), as well as the observation of Rabi oscillations in superconducting phase qubits by Martinis et al. (2002), and the Quantum Electrodynamics (QED) circuit experiment in a resonator proposed by Schoelkopf et al. (2004), which is also reflected in the patents granted during this timeframe, at least to some extent. This was a period when applications for patents related to such concepts as the quantum cryptography network operation experiment by DARPA (2003) and the announcement of a commercial quantum cryptography key distribution device by MagiQ (2003), etc. increased, in addition to the progress on basic research in the field of quantum cryptography/quantum communication. However, an accumulation of patents in the category “Quantum communication and cryptography” is not present.

In addition to hot research areas such as "Superconducting quantum computer," "Quantum circuit and compiler," "Quantum communication using photon polarization and phase shift," "Quantum dot device," and “Superconducting device on quantum interference,” significant accumulation becomes apparent in the “Quantum key distribution” area of the “Quantum communication and cryptography” category between 2005 and 2009. Along with a decrease in the number of publications in the “Superconducting quantum computer” area, patents in the “Quantum information processing unit” area increased. The most prominent areas of technology in 2010 to 2014 were the "Quantum communication protocol," "Quantum communication and streaming," and "Quantum key distribution." In this timeframe, a demonstration experiment involving quantum key distribution was conducted using the Tokyo quantum key distribution (QKD) network in Japan (2010). 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.”

**[Trends in numbers of 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. 7.

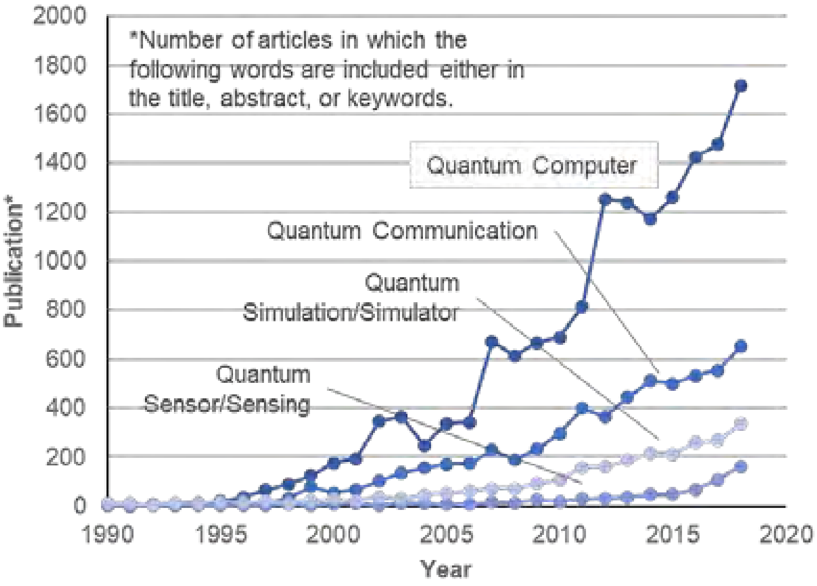

Fig. 7 Trends in the number of quantum technology-related papers

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.

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. 8. 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. From the above, it can be stated that quantum computer research and development has entered a critical phase.

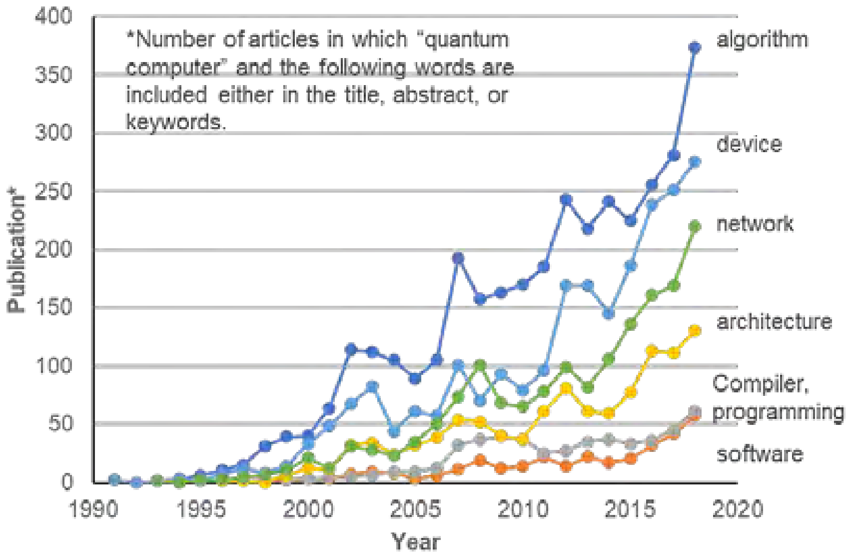

Fig. 8 Trends in the number of quantum computer-related papers

**[Trends in the number of publications associated with qubits]**

Recent advances in research on superconducting circuits have led to the anticipation of the realization of fault-tolerant universal quantum computers, and research and development investments are increasing worldwide. However, it is recognized that achieving large-scale hardware with the number of qubits necessary to execute large-scale quantum algorithms such as prime factorization and search will require several decades [13, 14].

The annual trends of the number of papers involving qubits[4] published from 2014 to date are plotted in Fig. 9.

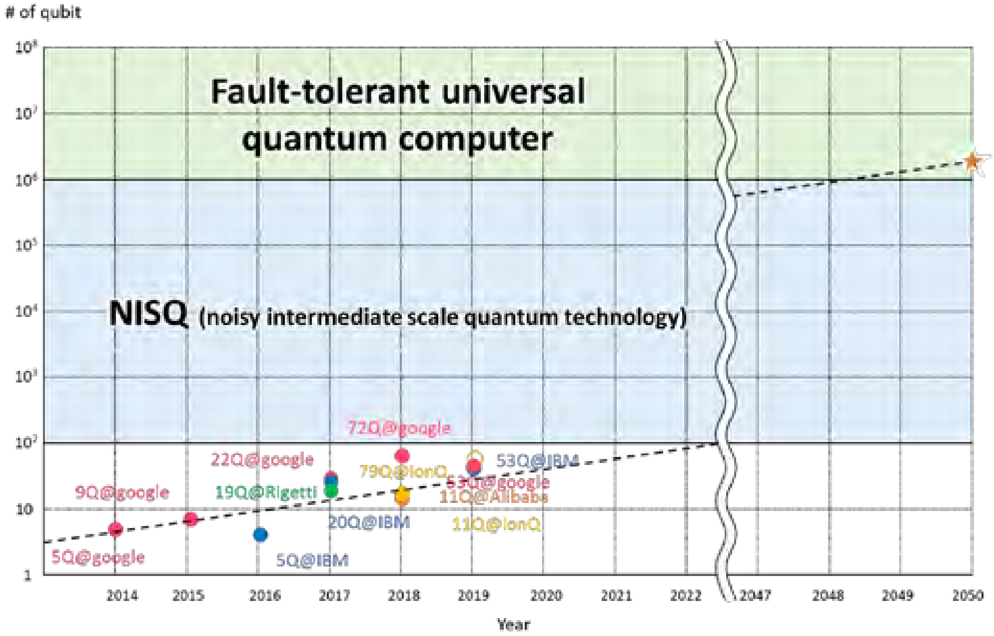

Fig. 9 Quantum version of Moore’s Law

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 [15]. 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 [16]. It can be stated that in the superconducting qubits and trapped ion qubit systems, where research is progressing in terms of the number of qubits and the fidelity of quantum gate operations, the implementation of quantum error correction codes corresponds to the fourth stage of the seven stages of quantum computer development.

To attract continuous research and development investments in quantum computers from the private sector toward the realization of fault-tolerant universal quantum computers, it is important to show in a convincing manner that NISQ computers are capable of performing computational tasks with market value and that the technology surpasses classical computers in some way. In this sense, the demonstration of quantum supremacy can be considered as a starting point to apply the quantum version of Moore's Law successfully, which will highlight the benefits of developing large quantum computers to perform industrially useful tasks.

**[Effort status involving related fields]**

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

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[4] The number of qubits is a measure that represents the computing performance of a quantum computer; however, an improvement in the number of qubits alone does not necessarily signify an improvement in performance. Furthermore, the numbers shown in Fig. 9 are only the number of qubits that have been announced, and do not consider whether a computer using these numbers has been successfully manufactured or operated.

international research and development of hardware, software, and networks in Japan and overseas is summarized as follows.

### (1) Hardware

Regarding hardware, methods using superconducting qubits, trapped ion qubits, photon qubits, silicon quantum dots, etc., are being considered for gate-based quantum computers, and the current mainstream trend is the research and development of superconducting qubits and trapped ion qubits. With respect to any of these methods, the development of hardware that enables quantum control and scalability (large scale integration) is the major issue. The realization of fault-tolerant, gate-based quantum computers is expected to take time, and NISQ computers in particular are attracting attention [15]. Although various methods to implement fault-tolerant quantum hardware have been studied in various countries, no definitive method has yet emerged. 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 [18]. 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 [14].

### (2) Software

With regard to quantum software, it is currently expected that the realization of a fault-tolerant gate-based quantum computer will take time, and therefore software development for NISQ is the mainstream trend; however, because hardware design guidelines have not yet been established, it is necessary to construct an optimal architecture for various hardware (implementation methods for quantum circuits, preprocessing optimization, etc.). In addition, solutions for logical bit operation problems (modeling, high-speed programming, etc.), development of quantum languages and compilers (error correction theory, etc.), development of applications taking advantage of quantum supremacy, and improvement of user environments are current issues. [19, 20].

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 [21]. Various IT companies have released quantum software development platforms and have expanded their open source software libraries [22]. 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 [23]. 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 there are several talented Japanese researchers with a high international reputation, the number of researchers, engineers and teachers is currently not sufficient as a whole. Utilizing past research achievements, including fault-tolerant theory, verification of algorithms with quantum supremacy, search for applications that enable quantum acceleration, and development of hardware verification tools are expected to emerge as the research progresses.

### (3) Networks

Quantum communication represents the technologies that realize ultra-high efficient communication, which include quantum repeaters for long-haul transmissions. A large number of quantum information processing nodes are connected to realize a wide-area quantum cryptography network, cloud quantum computing, etc. Because it is necessary to carry information using weak single photons and transmit them at regular intervals, a technology to deliver them stably across long distances is not yet existent (currently the limit is approximately 100 km), and therefore, long-distance transmission is an issue [24]. In addition, technologies such as quantum repeater/memory for networking quantum computers and the like remain undeveloped.

Furthermore, quantum cryptography is expected to protect the communication of important information by using encryption communication technology that cannot be decrypted by any computer. Challenges include wide-area quantum cryptography networks connecting cities, the sophistication of operating technology, and strengthening the security of relay nodes.

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 2010, to lead the world in integration with distributed storage, etc. A Japanese research team has succeeded in an experiment to generate entanglement between quantum memory and a communication wavelength photon for the first time, which has received worldwide attention [25]. 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 [26]. In addition, a demonstration experiment of an all-photonic quantum relay has succeeded for the first time in the world [27]. It is necessary to continuously improve the performance of the quantum devices constituting the quantum network.

# III. SCENARIO FOR REALIZATION

## 1. Realization of Goals

A fault-tolerant universal quantum computer, as indicated by Di Vincenzo's criteria, must be designed to have sufficient scalability, programmability, and capability to perform universal quantum computations for a long period of time. In addition, the preparation of the software infrastructure, such as programming languages and various libraries, is indispensable. At present, there are various approaches toward realizing a fault-tolerant quantum computer.

Overall, for the realization of a fault-tolerant universal quantum computer, it is important to determine, in the early stages, the advantages/disadvantages and possibilities of a physical system realizing various qubit gates, such as superconductivity, trapped ions, photons, silicon quantum dots, and diamond NV centers, and to conduct research and development regarding architecture design. Moreover, it is necessary to conduct hardware and software development in parallel, such as simultaneously achieving integration of qubits and highly accurate operation of quantum gates, the development of a new method for error correction codes that reduces the required number of physical qubits, the development of middleware software, the development of a new algorithm to reduce the specific gate operations that increase costs under quantum error correction, etc. In addition, implementation of computational models other than quantum circuit models[5] is worth considering as an alternative approach to fault-tolerant universal quantum computers.

Figure 10 shows the milestones for achieving the MS Goal candidate. To achieve the realization of fault-tolerant universal quantum computers by 2050, it is important to ensure that the following milestones are achieved in a certain term, as described below. Regarding the hardware for realizing a fault-tolerant universal quantum computer, various methods such as superconducting qubits, trapped ions, photon, silicon quantum dots, etc. are considered as promising candidates. To determine the possibilities of those physical systems and to conduct research and development regarding computer architecture design, this Moonshot program thus will utilize stage-gate management on those hardware proposals by examining engineering feasibility and scalability and will identify the shortest and the most credible technology path to the fault-tolerant universal quantum computer.

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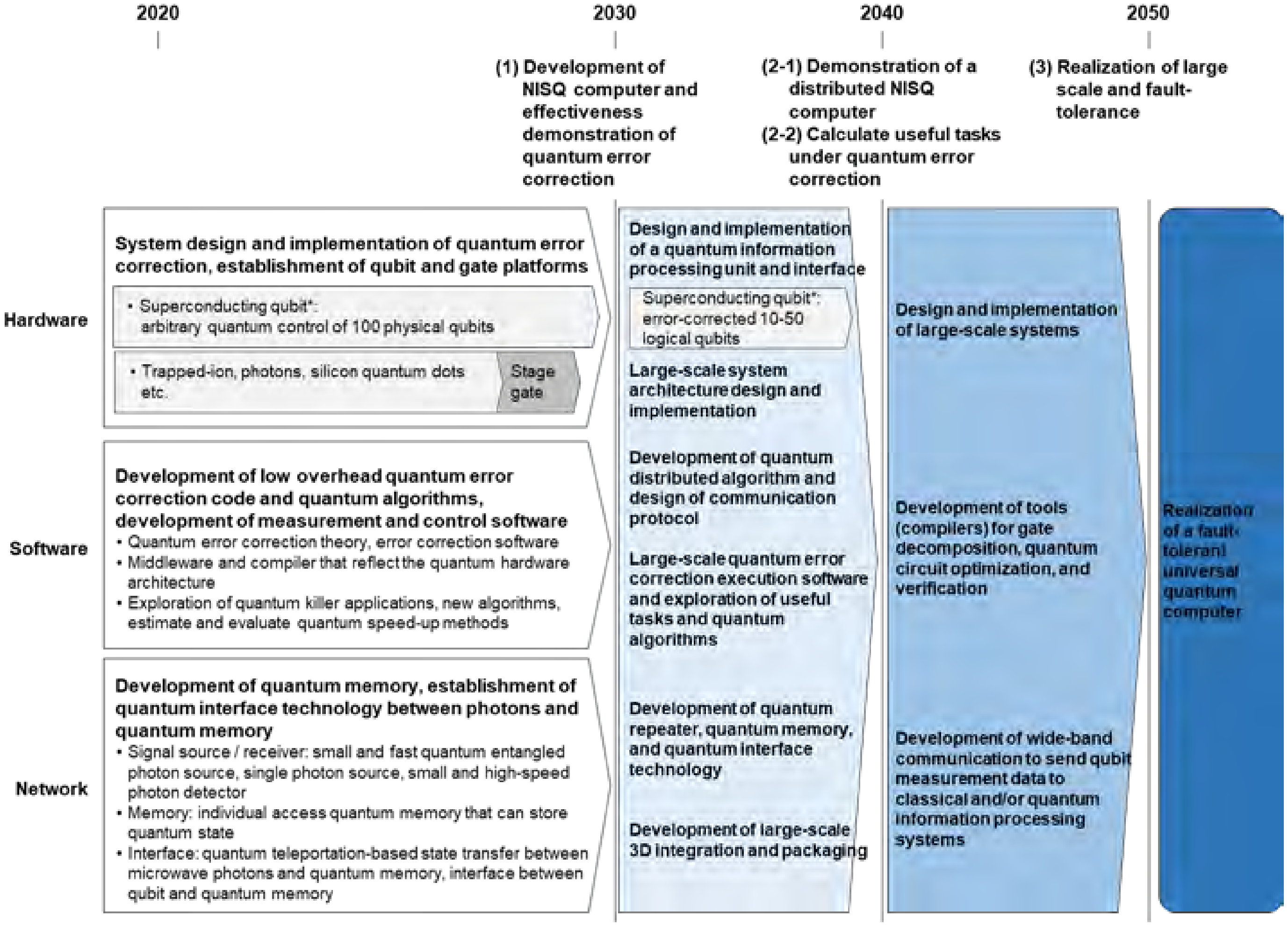
[5] Several models have been proposed as quantum computation models, and a quantum circuit model (a model that computes by applying quantum gates to qubits, also known as a gate-based model) is a typical example. In addition, quantum computation models that can be imitated efficiently (in polynomial time) such as adiabatic quantum computation models and measurement-based quantum computation models (one-way quantum computation models) are known. In these quantum circuit models, there is a point at which the amount of quantum entanglement increases or decreases during the calculation, which increases the difficulty of control, but in measurement-based quantum computation, the maximum amount of quantum entanglement is given in the initial state. It can be said that this measurement-based model is more realistic in that quantum entanglement only decreases as the computation progresses.



*Excerpt from Technology Roadmap "Gate-based quantum computer (Superconducting qubit)" in the Quantum Technology Innovation Strategy[2].

Fig. 10 Milestones for the realization of a fault-tolerant universal quantum computer

### (1) Development of NISQ computers of a certain scale, and effectiveness demonstration of quantum error correction (by 2030)

The experimental verification that execution of calculations is possible with a system error rate lower than the original error rate by configuring a logical qubit from a number of physical qubits using a quantum error correction code is an extremely important step toward the realization of fault-tolerant universal quantum computers [7]. In physical systems such as superconductive and trapped ions systems, a one-dimensional system with several qubits has been reported to achieve a gate error rate below the threshold required for quantum error correction, but there have been no reports in regards to achieving a gate error rate below a threshold in a two-dimensional system with at least several tens of qubits [7, 16].

To achieve this milestone, we will establish a NISQ-level quantum bit and gate platform and examine and select a quantum error correction code taking into consideration hardware design and implementation. The choice of quantum error correction code determines the system architecture of fault-tolerant universal quantum computers, including physical systems, qubit layout, error correction protocol, and control electronics and optics [28].

Because the overhead required for quantum error correction depends on the error rate of the individual physical qubits, a highly accurate control and implementation method to achieve an error rate below the threshold depends on quantum error correction codes. In a superconducting qubit system, a method for implementing a two-dimensional topological code by arranging qubits in a two-dimensional lattice, a cat code in a hybrid system combining a superconducting qubit and a cavity, etc., will be facilitated to prove the effectiveness of the quantum error correction scheme. The implementation of a superconducting qubit system will be based on the results of the Quantum Leap Flagship Program (Q-LEAP).

In the trapped ions system, high-precision gate operation technology and ion shuttle technology will be established, and the effectiveness of quantum error correction will be demonstrated by implementing topological color codes. In systems using photons and hybrid systems with diamond NV centers, etc., we will establish the technology to create a large-scale cluster state with high probability and implement a topological quantum error correction code with a measurement-based quantum computation model, and demonstrate the effectiveness of the quantum error correction method [18, 29].

**[Examples of research and development themes required to achieve this 2030 milestones]**

- Hardware: System design and implementation of quantum error correction, and establishment of quantum bit and gate platforms, etc.
- Software: Development of low overhead quantum error correction code and quantum algorithms, development of measurement and control software, etc.
- Network: Development of quantum memory, establishment of quantum interface technology between photons and quantum memory, etc.

### (2) Demonstration of distributed NISQ computer and calculation of useful tasks under quantum error correction (by 2040)

#### (2-1) Demonstration of distributed NISQ computer

The environment in which the physical system to be mounted is placed, such as a dilution refrigerator for the superconducting qubits system, a vacuum chamber for the trapped ion qubits system, and an optical workbench for the photonic system, has some physical size restrictions. The limiting value varies depending on the physical system to be implemented, but large-scale integration requires a distributed system configuration in which multiple small- to medium-scale systems are connected using quantum communication [30-32]. Therefore, to realize a large-scale fault-tolerant universal quantum computer, it is necessary (while realizing each quantum information processing module as a small/medium-scale system by using superconductivity, trapped ions, photons, silicon quantum dots, etc.) to establish short-range quantum channel technology that enables quantum entanglement and quantum teleportation between such systems. Miniaturization of quantum information processing modules is also required with the aid of existing technologies such as semiconductor integrated circuits and optical chips. Facilitate existing tools, knowledge, and technology in industry is essential to achieve this milestone.

At the same time, it is necessary to develop distributed quantum algorithms, new error correction codes, quantum communication protocols, etc., that execute fault-tolerant quantum computation while communicating using quantum information. Use of photons is considered to be promising for quantum communications among quantum information processing units/modules, but the conversion efficiency of the interface (quantum teleportation-based state transfer) between physical systems of quantum information processing units/modules and photons used for quantum communication is an extremely important factor.

**[Examples of research and development themes required to achieve this 2040 milestones]**

- Hardware: Design and implementation of quantum information processing units and interfaces
- Software: Development of a distributed quantum algorithm, design of the communication protocols
- Network: Development of quantum relay system using a hybrid architecture consisting of all-photonic quantum repeaters and quantum memory, establishment of quantum state transfer technology

### (2-2) Useful calculation tasks under quantum error correction

Quantum computers with 10 to 100 logical qubits with an implementation of quantum error correction are expected to be capable of executing quantum algorithms that calculate various useful tasks. Frequently appearing subroutines such as phase estimation, quantum Fourier transform, probability amplitude amplification, the Harrow-Hassidim-Lloyd (HHL) algorithm, and combinations of these subroutines should be possible to execute at will [33]. However, there is a limit to the data and problem size that can be input to qubit systems at one time, and new quantum/classical hybrid methods such as effective divide-and-conquer methods are required to increase these limits.

**[Examples of research and development themes required to achieve this 2040 milestones]**

- Hardware: Design and implementation of large-scale system architecture
- Software: Development of large-scale quantum error correction execution software, search for useful calculation tasks and algorithms
- Network: Development of large-scale three-dimensional assembly and packaging

### (3) Realization of large-scale/fault-tolerance (by 2050s)

Increasing the scale of fault-tolerant quantum computers requires tens of thousands of times of performance improvement in terms of operation accuracy and implementation accuracy from the current state of the art, and it is difficult to determine when such progress will be made [5, 6]. At present, it is too early to determine how to realize a fault-tolerant quantum computer based on one particular method. The various physical systems, such as superconducting qubits, trapped ions, photons, silicon quantum dots, and diamond NV centers, have different advantages/disadvantages, which make it difficult to estimate the timing involved in developing reliable fault-tolerant universal quantum computers. Overall, the general idea would be to scale up systems by providing units/modules of physical systems that implement the qubit/gate architecture, including peripheral electronics and optics, and devising the interfaces. As the scale increases, stable system operation, repair/replacement in the event of a failure, concealment/virtualization of system level operation variations, and responses to problems unique to large-scale systems will also be required.

Furthermore, as it is difficult to debug a large-scale quantum program, it is important to develop a method for verification by segmentation.

**[Examples of research and development themes required to achieve this 2050 milestones]**

- Hardware: Design and production of large-scale systems
- Software: Development of tools (compilers) for gate decomposition/quantum circuit optimization/verification
- Network: High-speed and large-capacity communication for transmitting qubits measurement data to quantum and classical information processing systems

## 2. Remarks

When specifying research and development areas that will contribute to the realization of this MS Goal candidate, it is required to clarify the implementation details so that the themes do not overlap with existing research and development projects, and therefore waste resources. In particular, it should be noted that the research and development contents are different from the ongoing Quantum Leap Flagship Program (Q-LEAP) by the Ministry of Education, Culture, Sports, Science and Technology, as the project target is completely different from this program[6]. That is, the research and development of the fault-tolerant universal quantum computer with millions or more qubits differs from that of an NISQ computer with 100 qubits in terms of the system design level. Moreover, the Q-LEAP flagship project assumes a superconducting qubits method for achieving the target and does not include other methods such as trapped ions, photon and silicon, and network technologies (quantum memory, quantum repeaters, etc.) in its scope. On the other hand, from the viewpoint of exploring various possibilities, this program does not limit the methodology of hardware implementation to the superconducting qubits system, but broadly supports alternative quantum bit and gate platforms to potentially achieve fault-tolerant quantum computation. In this program, for the superconducting qubits systems (while taking the achievements of Q-LEAP into account), the lead should be taken in research and development based on a long-term view toward the realization of fault-tolerant universal quantum computers.

For promoting methods for research and development, as there is no hardware that has an overwhelming technical advantage in terms of error rate and scalability at this time, it is inadvisable to proceed with projects that focus on hardware development limited to particular qubits systems. Therefore, when implementing an actual research and development project, multiple hardware systems that potentially achieve fault-tolerant quantum computation should be promoted simultaneously. In contrast, for software research and development, certain areas are recognized to be appropriate to proceed with research and development independently of the hardware-specific requirements of various quantum computers. Therefore, it is desirable to carry out projects focused on software development with regards to common aspects involving both hardware and networks. To achieve the MS Goal candidate, it is important to conduct management by narrowing down the research at various stages and by integrating multiple projects; such s role should be taken by the program director(s) who supervise the program managers.

In promoting actual research and development, it is important to obtain the participation of private companies. Currently, many of the technologies, know-how, and human resources needed to create a fault-tolerant universal quantum computer system exist in private companies; therefore, industry-government-academia collaboration among universities, public research institutions, and private companies at a deep level is important from early stage [5]. Because it is difficult to provide all full-stack technologies at a high level using a single research team or project, it is also essential to cover gaps in the project in the form of joint research with startups and overseas research teams, mutual provision of technology, utilization of open sources, etc. In addition, promoting the participation of private companies and the continuity of research and development in terms of technology transfer and possible commercialization should be fully considered from the beginning of the project implementation. In particular, investment from the private sector is significantly insufficient compared to the currently assumed market size [34], and whether private investment will expand in the future with government research and development investment as an incentive will greatly affect the timing for realization of fault-tolerant universal quantum computers.

At the same time, because the realization of fault-tolerant universal quantum computers is expected to have a major impact on our lives and on society in general, it is necessary to continue to discuss Ethical, Legal, and Social Issues (ELSI).

## IV. CONCLUSION

In WG6, out of 25 related examples of moonshot goals presented at the Visionary Council, the goal: “22) General-purpose quantum computer network” was discussed and is considered to be a suitable starting point. In reviewing the requirements, discussions have been presented from various perspectives, including an overview of international trends and the status of projects currently being conducted in Japan, thereby clarifying the expected milestones for research and development, and the discussion of spin-offs expected during the process of research and development, to promote the acceptance of this MS Goal candidate by many people as an

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[6] Specifically, Q-LEAP aims at social implementation of NISQ computers with 100 qubits by 2030, while this program aims to realize a fault-tolerant universal quantum computer by 2050.

accomplishable goal by the year 2050.

Based on the above discussions, WG6 proposes the “Realize a fault-tolerant universal quantum computer that will revolutionize economy, industry and security by 2050” as a viable MS Goal candidate.

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