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Quantum Computer Research and Development Strategy

to Drive the Information Society

April 8, 2019

THE ENGINEERING ACADEMY OF JAPAN
The Quantum Computer Research and Development Strategy Project

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EAJ is an organization that was established for the purpose of contributing towards the development of all aspects of engineering and scientific technology and is composed of members who are leading engineers in industry, university, and government fields. Project teams that use the wealth of experience and knowledge of our members and their wide-ranging network play a key role in promoting investigation proposal activities along with extensive cooperation from outside members. After summarizing the results of these activities, with regards to the direction society should take, we propose leading and creative measures to such as government agencies, legislature, industry, academic societies and research institutes with the aim of implementing such measures into society.

The **Quantum Computer Research and Development Strategy to Drive the Information Society** project concerns quantum computers, which are expected to be the next generation of computers, and are receiving large-scale investment for research and development in Europe and the United States. The project has investigated the current development situation and technical issues towards creating quantum computers, and has been considering policy proposals for Japan. Recently, a draft of this report was summarized and peer reviewed by the Policy Proposal Committee and then examined by the EAJ Council before the final version was confirmed. Therefore, the Council decided to release it as a report from EAJ. We hope that the report will be used extensively.

The research results for the Engineering Academy of Japan “The Quantum Computer Research and Development Strategy to Drive the Information Society” project are summarized and presented in this report.

The Engineering Academy of Japan
The Quantum Computer Research and Development Strategy to Drive the Information Society project

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Summary

As the limits of semiconductor miniaturization become apparent, the Moore's law of semiconductor integrated circuits, which has supported the improvement of computer performance up to now, cannot be expected to provide the way to deliver high performance of computers. In addition, as the amount of information to be processed increases, the limitations of the Neumann-type computing method are becoming apparent. On the other hand, the demand for higher performance computers in the advanced information society is increasing, and there is a need for innovation in computing technology. In this context, quantum computers are expected to be a candidate for technological innovation in computing, as they perform operations based on a principle completely different from that of conventional computers. For this reason, the United States, China, and Europe are competing with each other in launching large-scale national research and development programs for the development of quantum computers. Japan has made important contributions in the process of forming the concept of quantum computation, and while it is not inferior to other countries in the accumulation of basic research, it lags behind in the development of applications. For this reason, we make the following recommendations.

(1) It is necessary to develop a prototype quantum computer and to establish a center to promote the development of the necessary technologies. The existence of these prototypes is also important as operational verification machines for evaluating the effectiveness of individual technologies. The development of quantum computers at the above center should be carried out through collaboration among researchers in a wide range of technical fields, including materials science, quantum physics, electronics, and computer science.

(2) It is also important to support research on quantum computing software, including basic architecture and algorithms. Unlike the development of devices, which requires accumulation of basic technologies, research into new basic architecture and algorithms for quantum computers can be conducted with free ideas and is now at a stage of rapid development.

(3) In the long term, it is important to develop the next generation of human resources, and a system for this purpose must be established. Many twists and turns are expected in the research and development toward the realization of quantum computers. To survive the competition in quantum computer development, it is necessary to have the strength to continue research from a long-term perspective, and human resource development is the key to this.

(4) The United States, China, and Europe (Germany and the United Kingdom) are moving forward with national programs for quantum technologies, such as quantum computing, communications, and sensing with a duration of 5 to 10 years and an annual budget of more than 10 billion yen. In order for Japan to compete with these countries in the field of quantum technology research and development, it will be necessary to invest a budget of the same scale. Considering that the development of quantum computers is a core issue in the quantum technology, it is necessary to establish a national plan for research and development of quantum computers with an annual budget of more than 5 billion yen.

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Chapter 1: The background and objective of this project

With the advent of the Internet of Things (IoT) era and the emergence of Artificial Intelligence (AI), the massive amount of information that the world produces on a daily basis is about to be put to good use, bringing tremendous benefits to our lives. We are now in the process of realizing such an advanced information society. In order to realize such an advanced information society, it is necessary to have high-performance computers that can process large amounts of data and produce useful information beyond human knowledge. However, Moore's Law, the path of miniaturization of semiconductor devices that has led to the high performance of computers, is beginning to show its shadow, and it is necessary to renew the basic architecture of computers in order to realize the enormous computing power demanded by the times. Under such circumstances, expectations are rising for quantum computers as computers that can perform complex and advanced calculations that are practically impossible to perform with current computers. The concept of a quantum computer was first proposed in the 1980s, and since then, many fundamental results have been accumulated in various aspects, such as basic computing architecture, algorithms, and computational circuit elements and their integration, in order to realize the concept and make it work effectively. During this period, Japanese researchers have made significant contributions to the development of these technologies. In contrast to conventional digital computers (also called classical computers as opposed to quantum computers), which perform operations by applying logic gate operations to bits represented as binary values of 0s and 1s, quantum computers create superposition states of 0s and 1s called qubits, and use them to perform computing operations by utilizing quantum phenomena such as entanglement and interference between multiple qubits. By creating a computing method that can effectively utilize such qubit operations, a quantum computer will be able to instantaneously perform operations that are enormous for a classical computer. However, the aforementioned quantum state can easily be destroyed by minute electromagnetic noise coming from the outside world in various forms or thermal noise caused by the operating temperature, making it impossible to perform the desired operation. In order to reduce such noise, it is necessary to operate at cryogenic temperatures, but even under such conditions, it is not easy to precisely control the subtle quantum coherence phenomena[1] that appear in superconducting devices and perform qubit operations. It was thought that it would take several decades of technological development to achieve quantum operations that surpassed conventional computing technologies. However, with the advancement of circuits using superconducting devices to perform qubit operations, the development of peripheral electronic technology to control these circuits, the development of quantum error correction methods, and the creation of new arithmetic methods to perform advanced information processing with qubit circuits, the realization of quantum computers has suddenly come into view. The commercialization of a quantum annealing machine[2], a special form of quantum computer, by Canada's D-Wave System in 2011 has raised expectations for quantum computers that go far beyond the capabilities of conventional computers.

In response to this situation, globally operating IT companies such as IBM, Google, and Intel have begun research and development of quantum computers using superconducting qubit circuits, and recently, Chinese IT companies including Alibaba and Huawei have also begun research and development. Inspired by these developments, many venture companies have been established in various countries to develop quantum

[1] Quantum coherence phenomena and time: The physical state of things in quantum mechanics (the quantum state) is displayed using a wave function. Quantum coherence refers to the superposition of a wave function that corresponds to two or more states of the same particle (quantum). This state is easily destroyed by disturbances from external sources, which causes the wave to lose coherence. The time in which coherence is lost is referred to as the quantum coherence time.

[2] Quantum annealing machine: Based on the theory of reaching the lowest energy state of an Ising model advocated by Kadowaki and Nishimori of the Tokyo Institute of Technology, the company constructed a calculation method to enable the above process to be performed as a quantum computer. It demonstrates the strength of the machine when solving optimization problems such as the traveling salesman problem.

computers. In the U.S., Europe, and China, large state-funded research and development projects are underway in anticipation of the potential of quantum computers in the future information society. In Japan, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) has launched a large-scale research program called Q- LEAP[3], and JST's CREST, PRESTO, ERATO, and other research programs on quantum computers have also been launched.

As mentioned above, there are high expectations for the realization of quantum computers, but the technological barriers are high, and many technological innovations are expected in the future, and there is a possibility that completely new basic design concepts, algorithms, computing circuits, and related supporting hardware will be created. In this sense, the winner of the race for the development of quantum computers has not yet been decided, and it is now necessary to establish a research and development system in which Japan can firmly participate and play a leading role in the development race, which is expected to be a long one. The technological barriers to the realization of quantum computers are high, and it will be difficult for Japan to achieve this goal alone. Japan should firmly look overseas, demonstrate its strong presence by communicating its high R&D capabilities, build powerful partnerships with other countries, and accelerate research and development.

Three major technological areas are necessary for the realization of quantum computers. The first is the integration of basic elements called qubits to enable operation as a qubit integrated circuit. This requires knowledge of quantum mechanics and materials science to understand and control the operation of qubits, and knowledge of electronics to build integrated circuits. The second is the development of quantum computer software at various levels to operate qubit integrated circuits by developing arithmetic methods to suit the purpose of the application. Here, knowledge of computer science is required. The third is to build a computer system as hardware, starting from the implementation of the qubit integrated circuit in a special environment (cryogenic refrigerator in the case of superconducting qubits, ultrahigh vacuum chamber in the case of ion trap qubits), to the construction of high-speed electronic circuit technology at room temperature to control the input and output of information. This requires engineering in a wide range of fields, including microwave engineering, ultrafast electronic technology using semiconductors, and low-temperature packaging technology. In particular, for the input/output of information between a qubit integrated circuit locating at cryogenic temperature and a control circuit at room temperature, it is desirable to execute as many control operations as possible on an ultrafast electronic circuit in a low-temperature environment such as helium temperature (4.2 K) in order to suppress the inflow of heat, reduce the delay in the input/output wiring cable, and execute high-speed control. As mentioned above, the realization of a quantum computer will require the cooperation of researchers and engineers from a wide range of specialized fields. In Japan, support for the development of qubit integrated circuits and quantum computer software has begun under the National Research Program. In addition to the above, it is urgent to support the development of the third technological area, which will become increasingly important as the level of integration of qubits increases, and to develop a symbolic quantum computer prototype as a national policy. In order to do this, it is necessary to establish a center for the realization of quantum computers where researchers and engineers in the above-mentioned wide-ranging fields of expertise can gather and collaborate, and it is desirable to increase the presence of the center in Japan as a contact point from overseas for the development of quantum computers.

In this report, Chapters 2 and 3 describe the reasons why quantum computers are needed and the

[3] Q-LEAP: The "Photonics Quantum Leap Flagship Program", which aims for a non-continuous solution (quantum leap) making full use of quantum science and technology (photonics and quantum technology). Implements the flagship project and fundamental research in each field of technology under the theme of quantum information processing, quantum measuring and sensing, and next-generation lasers. The research period will be for 10 years from FY2018 to 2027.

fields of application where they are expected to be applied, Chapter 4 describes the current status of development in Japan and overseas, Chapter 5 describes the specific details of research and development and the issues that need to be addressed, and finally Chapter 6 provides recommendations for measures to ensure that Japan plays a leading role in this field, which are summarized in Chapter 7.

Chapter 2: The reason why quantum computers are necessary

We are surrounded by many sensors in our living space and the places where we work, and both a variety and large volume of data (Big Data) is collected as required, and then those data are sent to the Cloud. Ultra-fast computers in the Cloud analyze large-volume complex data and then provide us with new information services. The so-called IoT/AI era has arrived but the volume of data we need to handle is increasing exponentially. Those data are expected to reach 40 zettabytes (ZB) [2-1] in 2020. An ultra-high performance computer will be required to handle this large volume of data. However, this will become difficult as high-performance of semiconductor integrated circuits reaches the miniaturization size of less than 10 nanometers, something which has been the driving force for the increase in high-performance of computers. The limitations of the conventional von Neumann architecture computer are also becoming apparent in terms of information processing speed and power consumption due to the increase in the volume of information being handled. Meanwhile, the market shows a strong demand for an increase in computing capability and it will be difficult to meet this demand simply by means of semiconductor miniaturization. We need to introduce to the market a design concept that surpasses the conventional von Neumann computing architecture. Quantum computers are based on a completely new computing method. It has already been mathematically proven that quantum computers are incomparably faster at processing data for specific problems, and are expected to represent computers that do not use the von Neumann architecture. This does not mean that quantum computers can provide solutions at high speed for any kind of problem. In the future, conventional von Neumann architecture computers will surely continue to be responsible for most information processing. However, quantum computers are considered to play the role of supporting conventional computers as accelerators for problems that are difficult to perform on conventional computers, such as advanced AI processing and scientific computation required for designing complex materials.

As mentioned earlier, expectation is high for quantum computers but it is necessary to control vulnerable quantum phenomena that appear in solids to achieve quantum computers. Realizing such a computer is considered to be a long way off. However, in 1999, qubit operation corresponding to basic arithmetic operations of a quantum computer was proven by controlling quantum phenomena in superconductor circuits [2-2], and since then we have increased the quantum coherence time of qubits that show potential as quantum computers by an order of magnitude 5, from several nanoseconds to several hundred microseconds. Furthermore, when the Canadian company D-Wave Systems, Inc. commercialized the quantum annealing machine in 2011, this ignited a development race for quantum computers.

Being able to draw a definite picture of a quantum computer in this way means that our expectations are about to come true for computers that do not use the von Neumann architecture leading a future information society. However, we face numerous technical issues as stated in Chapter 5 to achieve this, and it is expected that the road ahead will be long. Europe and the United States is ahead in developing quantum computers but we are just at the starting point of a long road so we believe it is necessary to accelerate Japan’s research and development in this area and develop our presence overseas.

[Reference]

[2-1] “Digital information volume for the entire world will reach 40 zettabytes in 2020”, https://www. itmed ia.co.jp/enterprise/article/1212/12/news049.html

[2-2] Y. Nakamura et. al., “Coherent control of macroscopic quantum states in a single-Cooper-pair box”, Nature Vol. 398, pp786-788 (1999).

Chapter 3: Fields to which quantum computers are expected to be applied

Currently, there are two major areas of application where quantum computers are expected to be used from the perspective of information processing [3-1]. The first is quantum system simulation represented by quantum chemical calculations while the second is quantum machine learning. Both of these are versatile calculations, and there are a great many industrial fields where they can be applied such as material and manufacturing, chemical and drug development, ICT, medical treatment, entertainment, gaming, and services (Fig. 3-1). This chapter looks at promising application fields from the perspective of computing methods.
In addition, we have the Shor's computing algorithm [3-3] as an innovative one that was mathematically proven to be effective. If we achieved a quantum computer that uses this computing algorithm, it would allow us to quickly decode the current RSA encryption, which uses the difficulty of factoring the product of large prime numbers to secure data. In order for this cryptanalytic threat to become a reality, an error-tolerant quantum computer with more than several million qubits would be required, which at present is expected to be a long way off.

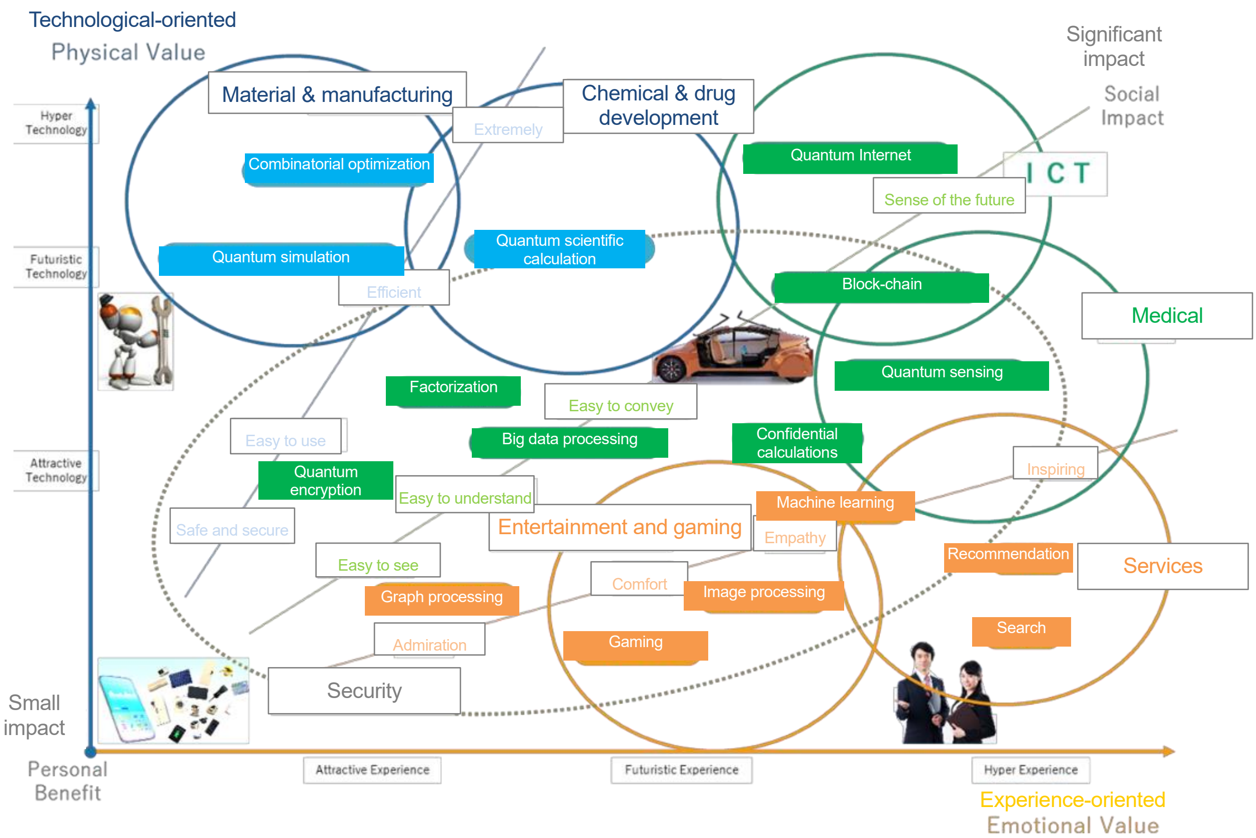

Fig. 3-1: Quantum computer applications
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3-1. Quantum chemical calculations

Numerical material simulation plays an important role not only in scientific research but also in many industrial situations. In particular, numerical material simulations are important for the physical properties of compounds and the dynamics of systems, because it is difficult to predict the properties of complex material systems analytically from the basic equations given by partial differential equations called Schrodinger equation.

In the case of quantum many-body systems where many electrons interact with each other, the number of physical states to be treated increases exponentially with the number of electrons and spin orbitals, and the difficulty of numerical simulations increases drastically. Since the Hamiltonian describing the system is huge, approximate solutions such as DFT (density functional theory) and CC (coupled cluster theory) are usually used instead of exact diagonalization.

As pointed out by Richard Feynman [3-4] when he said "If you want to efficiently simulate nature that obeys quantum mechanics, you must create a computer that operates on the rules of quantum mechanics", the fact that it is difficult to efficiently calculate quantum many-body systems using classical computers (conventional von Neumann architecture computers) and the fact that it is possible to exponentially accelerate this calculation if we have a quantum computer are inextricably linked. In the problem of finding the energy eigenvalues of a quantum system, it is known that the phase estimation method can be faster than the best classical arithmetic methods known today [3-5]. This method places high demands on hardware performance, such as the number of qubits and the precision of quantum gate operations, and should be regarded as an computing method that can be run on an error-tolerant quantum computer[4], which is expected to appear in the long term.

Based on the premise that hardware (NISQ machine[5]) can be realized in the near future, quantum-classical hybrid computing methods that operate on such hardware have been actively studied in recent years [3-6]. VQE (Variational Quantum Eigensolver), which executes the variational method on a quantum computer, is known as a typical computing method, and demonstrations on superconducting qubits have been reported [3-7]. This method consists of a quantum operation part to obtain the energy expectation value by quantum gate operations including variational parameters and observations, and a classical optimization part to minimize the energy expectation value by changing the variational parameters. It also has desirable properties for NISQ machines, such as no need for auxiliary qubits and robustness against systematic errors, but a large number of observations are required to achieve high accuracy in the solution.

Excited states can be calculated in a similar framework, and methods such as penalizing the overlap with the ground state [3-8], using excitation operators [3-9], and subspace search VQE [3-10] have been proposed. The accurate determination of the energy eigenvalues of excited states is a promising application of quantum computers to show their superiority over classical conventional methods, and is being vigorously studied all over the world.

3-2. Quantum machine learning

Machine learning is a universal technology that has an impact on industrial applications. If it were possible to perform machine learning tasks efficiently on quantum computers, this would create vast market opportunity. With quantum machine learning, we expect efficient recognition of patterns that are hard to recognize with classical computers [3-11]. Unlike the simulation of quantum material systems introduced in the previous section, the problem setting itself in this case has nothing to do with quantum mechanics, but quantum computers can efficiently calculate eigenvalues and singular values of huge matrices by utilizing the linear algebraic structure of quantum mechanics.

Machine learning using quantum computers first appeared in quantum computing methods by Harrow, Hassidim and Lloyd (called the HHL algorithm), which can solve specific linear equations at an exponentially

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[4] Error-tolerant quantum computer: A digital quantum computer that encodes many physical qubits into logical qubits using quantum error correction codes, and can perform large-scale calculations with guaranteed accuracy.

[5] NISQ (Noisy Intermediate-Scale Quantum): An approximate quantum computer with no error tolerance at the small to medium scale.

high speed. There are now many proposals for quantum computing methods that are assumed to run on error-tolerant quantum computers, such as quantum support vector machines, quantum ridge return, and quantum deep-learning. Although the hardware performance required by these methods is not yet attainable on current NISQ machines, vigorous research on data input/output and resource estimation is underway to make it possible.

For machine learning tasks as well as quantum chemical calculations, quantum-classical hybrid computation methods that are expected to run on NISQ machines in the near future are attracting attention. A typical example is the Quantum Approximate Optimization Algorithm (QAOA), which solves combinatorial optimization problems with quantum circuit models [3-12]. Researchers at Rigetti Computing demonstrated how to formulate a classification problem, which is one of the machine learning tasks, as a weighted MAXCUT problem and find the optimal solution using QAOA [3-13]. The idea of using quantum states as a feature space is similar to Quantum Circuit Learning (QCL) [3-14], which uses variational quantum circuits for supervised machine learning, and a method for optimizing classical support vendor machines by estimating kernel functions on a quantum computer [3-15]. The recent AI boom has stimulated research in these areas, and there are high expectations for the application of NISQ machines.

[Reference]

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[3-15] Vojtěch Havlíček et.al., “Supervised learning with quantum-enhanced feature spaces”, Nature 567, 209 (2019).

Chapter 4: The current development situation

4-1. History of quantum computers to date

The history of quantum computers dates back to 1980, when Benioff showed that quantum systems can perform calculations without consuming energy [4-1], and in 1982, Feynman speculated that quantum operations might be exponentially more effective than classical calculations [4-2]. Earlier, in 1959, Feynman gave a lecture at the California Institute of Technology, in which he famously said, "There's plenty of room at the bottom" [4-3]. In 1985, Deutsch defined the quantum Turing machine [4-4], and in 1989, the quantum computing circuit was invented [4-5]. In the 1990s, Deutsch and Jozsa's "Deutsch-Jozsa arithmetic method" [4-6], Vazirani and Bernstein's "Universal quantum Turing machine" [4-7], and the quantum Turing machine "Universal quantum Turing machine" [4-8] were introduced. In the 1990s, Deutsch and Jozsa proposed the "universal quantum Turing machine" [4-6], and Vazirani and Bernstein proposed the "quantum Fourier transform" [4-7], but the most impactful of all was the "Shor's method" presented by Shor at Bell Labs in 1994 [3-3]. When a quantum computer using this arithmetic method was realized, the RSA cryptosystem, which currently uses the difficulty of prime factorization to guarantee security, could be broken in a short time, and this led to widespread interest in quantum computers from both academia and industry. Subsequently, "quantum error correction computing method" by Steane and Shor [4-8, 4-9], "Grover's arithmetic method" by Grover [4-10], and "quantum annealing method" by Hidetoshi Nishimori and others [4-11] were proposed. Although theoretical and circumstantial evidence that a quantum computer that is intrinsically faster than a classical computer is possible was presented in this way, and the so-called first quantum computer boom began, at that time it was thought to be technically very difficult to create hardware that could actually operate a quantum computer.

In 1999, Yasunobu Nakamura, Jaw Shen Tsai, and their colleagues at NEC demonstrated that a quantum gate (one qubit) could be realized with a solid-state device for the first time in the world using a superconducting circuit [4-12]. In 2008, Wineland showed that individual ions can be laser-cooled and captured [4-13], and research on ion-trap quantum computers that manipulate ions in individual quantum entangled states has progressed. However, the number of qubits and the error rate required for hardware by the error correction code theory were unrealistic, and there was no technical prospect for improving the processing capacity, so the boom gradually faded away.

In the 2000s, several new error-correcting code methods were discovered, and the error threshold was relaxed from 0.01% to about 1%, but the technical barriers to developing an error-tolerant quantum computer remained high. In 2011, D-wave Systems [4-14] announced a machine that claimed to be the "world's first commercial quantum computer". The first machine (D-wave One) had 128 qubits, and the second machine (D-wave Two), with 512 qubits, was announced in 2013, and Google, NASA, and others have purchased and begun testing it, triggering a rekindling of the quantum computer boom. Subsequently, D-wave 2X (1024 qubits) was announced in 2015, followed by D-wave 2000Q (2048 qubits) in 2017.

In 2014, the Martinis group at the University of California, Santa Barbara (UCSB) achieved a breakthrough in quantum computing with high precision qubits (1 qubit gate fidelity of 99.92%, 2 qubits 99.4%, and measurement fidelity 99%), and succeeded in operating a five-qubit quantum computer with nearly feasible error correction [4-15]. The lifetime (coherent time) of superconducting qubits has improved by about five orders of magnitude in less than 20 years due to the accumulation of various technologies such as charge noise suppression, electromagnetic field mode confinement by resonators, dynamic decoupling, and dilution of surface and interface effects in the devices.

The result by Martinis et al. satisfies the threshold of 1% error rate required for quantum error correction by surface codes, and means that an error-tolerant quantum computer can theoretically be realized if the system is scaled up. This resulted in removing the psychological barrier against the possibility of a quantum computer which held back companies and investors, as well as researchers. As a result, Google began supporting research by hiring the Martinis Group in the same year of 2014, sparking the second quantum computer boom.

The second boom was characterized by the fact that it entered the engineering phase of "how to build a quantum computer". Actually, Google, IBM as well as Rigetti Computing, a venture company, are competing in a development race to make a quantum computer with the superconducting qubit method. Intel, together with QuTech, a quantum technology research institute founded by Delft University of Technology in the Netherlands, have also joined the race using superconducting and semiconductor qubit methods. Furthermore, other venture companies aiming to make a quantum computer using different methods from those above have appeared such as IonQ with the ion-trapped method and Xanadu with the photonic method. Microsoft is also jointly researching with several universities both in the USA and in countries outside the USA based on a research plan called Station Q in order to develop a new qubit method that is topologically protected, referred to as a Majorana fermion, in addition to research and development on quantum computing algorithms and software for quantum computers.

As for the hardware for a quantum computer, an integrated circuit with 20 qubits of superconducting qubit technology has been confirmed to work, and an integrated circuit with 50-70 qubits has been completed (Google, Intel + QuTech, and IBM) and is under evaluation. It is expected that 100 qubits will be achieved in the next few years. However, even if the number of qubits is increased, the performance cannot be achieved if the operation accuracy is low, so it is necessary to pay attention to the operation accuracy as well.

On an actual quantum computer, if computing operations continue for a long time even if the error in each individual qubit is small, the error will accumulate and unfortunately yield an incorrect computing result. Small-scale quantum computers containing this type of error were referred to by Dr. John Preskill of the California Institute of Technology as "Noisy Intermediate-Scale Quantum computing: NISQ" in 2018 [4-16]. Prior to this in 2012, Preskill proposed the term "quantum supremacy". This is said to be where quantum computers have capability of exceeding classical computers at calculating when integration level of qubit reaches around 50. In addition to the US companies mentioned above, many researchers and engineers mainly in Europe, China, and Japan are currently competing in research and development to aim for "quantum supremacy".

Figure 4-1 summarizes the history of quantum computer development as described above

1980s: Concept of quantum computers proposed in the USA (Feynman, Benioff and Deutsch)
1994: Prime factorization algorithm from Peter Shor
*Can instantaneously decode the current RSA encryption (scientific societies and industry focus their attention on quantum computers)
1995: Quantum error correction codes from Peter Shor
1998: Quantum annealing theory from Nishimori and Kadowaki
1999: Superconducting qubits from Nakamura and Tsai, et al.
*Achieved first qubit in a solid-state device, presents the possibility of integration
From 2011: Quantum annealing machine commercially available from D-Wave System Inc. (Canada)
"D-Wave one" (128 qubits in 2011), "D-Wave two" (512 qubits in 2013)
2013: Google buys "D-Wave two" and establishes "Quantum AI Lab"
2014: UCSB Martinis achieves high fidelity qubit *Quantum error correction can be applied

	Google hires UCSB Martinis Group
2017:	IBM announces a processor with 20 qubits, begins Cloud-based service
	D-Wave Systems Inc. releases "D-Wave 2000Q" (2048 qubits)
2018:	Google announces the start of "Bristlecone" a processor with 72 qubits
	Alibaba starts a Cloud-based service using an 11 qubit processor
	IBM starts to commercialize "IBM Q System One" (20 qubits)
	IonQ announces a device equipped with 160 qubits, operation is 11 qubits

Intensification of the quantum computer development race throughout the world

(Fig. 4-1) The history of development for quantum computers

4-2. The quantum annealing method and quantum gate method

As mentioned in the previous section, quantum annealing machines were the first to be commercialized in 2013, but recently, the mainstream of research has focused on the practical application of quantum computers using quantum gate systems. It has been mathematically proven that quantum gated computers have an overwhelming advantage over classical computers for several problems. In contrast, the advantage of quantum annealing depends on the problem to be solved, and the mathematical advantage has not been completely proven. D-Wave System, a Canadian company, has taken the lead in quantum annealing, and is in the process of developing a machine with more than 2000 qubits, applying it to various applications, and demonstrating its effectiveness. In quantum annealing, a quantum state starting from the ground state of a transverse magnetic field is transformed over infinite time (or more precisely, evolved over time under the conditions of the adiabatic theorem) to the quantum state corresponding to the desired optimal solution (the solution to the combinatorial optimal problem to be solved). However, existing quantum annealing machines perform the above quantum state transition in finite time instead of infinite time. Therefore, it is highly likely that we are not in the ground state, but in a heat-distributed state at a finite temperature. The faster we try to get a solution to a problem, the more likely it is that we will reach a solution that is not necessarily optimal. However, conversely, by running this state many times, sampling of the thermal distribution state can be performed and an optimal solution may be inferred. In recent trends, there are efforts to adopt quantum mechanical many-body interactions as quantum fluctuation[6] instead of transverse fields. It is also known that quantum annealing has the versatility that gate-type quantum computers have been aiming for [4-17], and there is a possibility that the development of quantum annealing and quantum gate systems will move in the same direction. Since both methods have similar requirements at the computational element stage and the implementation stage, we will discuss the quantum gate method below, assuming that the evolution of the quantum annealing method will be pursued as a research topic for quantum software.

4-3. The state of research fund investment and the development situation in Japan and overseas

[USA]

In the USA, the National Science and Technology Council (NSTC) published "A Federal Vision for Quantum Information Science" in 2009. In response to this, the National Science Foundation (NSF) started the

[6] Quantum fluctuation of other than transverse magnetic field: In quantum annealing, a simple constant transverse magnetic field is applied as quantum fluctuation in addition to the Ising model but the transverse magnetic field is replaced with a more complex magnetic field.
https://quantum.fixstars.com/introduction_to_quantum_computer/quantum_annealing/ising_model/theory/

“Interdisciplinary Faculty Program in Quantum Information Science” (4 million dollars per year (2015), a scientific research grant worth tens of millions of yen per project). In the “10 Big Ideas for Future NSF Investments” report announced in August 2016 by the NSF, “Quantum Leap” was listed as one of the six research ideas and “Growing Convergence Research at NSF” was listed as one of the four process ideas. In response to this, “Quantum Leap” was set as an area to support in relation to convergence research in August 2017, and three projects were selected. Even after this, public offering for the area of “Quantum Leap” continues, and projects such as “Transformational Advances in Quantum Systems” and “Engineering Quantum Integrated Platforms for Quantum Communication” have been selected. Public offering started for Quantum Leap through the Early-Concept Grants for Exploratory Research (EAGER) plan, and ten areas for study are shown for the application of quantum computers to quantum chemistry.

In 2018, the Office of Science and Technology Policy (OSTP) and the Subcommittee on Quantum Information Science (SCQIS) from the NSTC Scientific Committee released a report entitled “National Strategic Overview for Quantum Information Science”. At the same time, both the United States Department of Energy (DOE) and the NSF announced that they would provide funding to the Quantum Information Science (QIS) research and development plan. The above national strategy emphasizes support for basic research and the DOE will invest 218 million dollars over a 2 to 5 year period from now for 85 projects conducted by universities and national research institutes in terms of such as building and using cutting-edge quantum testing platforms. Meanwhile, the NSF plans to contribute 31 million dollars to fields such as quantum sensing, computing technology, and quantum communication.

Furthermore, in December of the same year, the National Quantum Initiative Act was passed, which will invest $1.25 billion in quantum technology research over five years starting in 2019. The National Quantum Coordination Office, which will be established under the OSTP, will put together a comprehensive strategy and basic plan, including research results, consolidation of expertise, and human resource development, with China and Europe, which have been strengthening this field, in mind.

[Europe]

In Europe, QuTech was established at Delft University of Technology in the Netherlands in 2013. In the following year, the Dutch government positioned quantum technology as one of the four "National Icons" of science and technology diplomacy, and announced a major government investment in the research promotion initiative. In 2016, the Quantum Manifesto was published by a number of researchers, including QuTech researchers. In response, the European Commission published a roadmap for the Quantum Flagship project within the framework of Horizon 2020, defining the focus areas of quantum communication, quantum simulation, quantum computing and quantum sensing, as well as two emerging areas of European interest: quantum software and quantum control. In the fall of 2018, the 20 issues selected for the Quantum Flagship will be announced, and one billion euros will be invested over 10 years.

Within Europe, the German government has been active in quantum technology, investing about €650 million in a five-year plan starting in 2018 called "Quantentechnologien - von den Grundlagen zum Markt" (Quantum Technology - From Basic Research to the Market). In the UK, the UK National Network of Quantum Technology Hubs has been launched under The UK National Quantum Technologies Programme (£270 million budget over five years), which has been underway since 2014. In the UK, the UK National Network of Quantum Technology Hubs was launched in 2014 under The UK National Quantum Technologies Programme, which has a budget of £270 million over five years.

[China]

China's basic policy on science and technology, the "Outline of the National Medium- and Long-Term Science and Technology Development Plan 2006-2020," places "quantum control" as one of the major scientific research areas. In 2015, the Chinese Academy of Sciences (CAS), in collaboration with the IT company Alibaba, established the Quantum Computation Laboratory to conduct advanced research in quantum information science and the development of quantum computers. With a budget of about 500 million yen/year, the two organizations have set the following research plans, utilizing the technological strengths of both organizations.

- Improve quantum chemistry simulation using quantum computers to the level of the world's fastest supercomputer (as of 2015) by the year 2025.
- By 2030, develop a general-purpose quantum computer (prototype) with 50 to 100 qubits, and establish technology for mass production of integrated circuits for quantum computers. Realize general-purpose quantum computing functions, from the design and manufacture of the physical layer to the proprietary development of arithmetic method execution, and apply them to serious and substantial problems such as big data processing.

The company is actively pursuing research and development, including the provision of an 11-qubit quantum computer to the cloud in 2018. It is also building a $10 billion national laboratory for quantum information science on 37 hectares (about 4 million square feet) of land in Hefei, Anhui Province (scheduled to open in 2020). It has two major research goals: quantum metrology and building a quantum computer, both of which are efforts to support both defense/military activities and civilian development.

[Japan]

Quantum technology, including quantum information processing, in Japan has moved forward with sporadic research and development in the form of individual research plans incorporated in fields such as nanotechnology and life-science. However, quantum technology has not made progress in an integrated manner with the support of policy measures based on a mid- to long-term perspective. In August 2017, the Quantum Science and Technology Committee in the Ministry of Education, Culture, Sports, Science and Technology announced the “New Promotion Measures for Quantum Science and Technology (Photonic and Quantum Technology)”, which emphasizes quantum information processing, quantum measurement and sensing, ultra-short pulsed lasers, and next-generation laser processing as fundamental technologies with strengths that will become the core of new value creation in the "ultra-smart society. As for research investment plans, JST's CREST "Creation of an Innovative Quantum Technology Platform Based on Advanced Control of Quantum States," PRESTO "Quantum State Control and Functionalization," and ERATO "Nakamura Macroscopic Machines Project" were launched in 2016. In 2018, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) launched the Quantum Leap in Advanced Photonics (Q-LEAP) Flagship Program, which aims to achieve a quantum leap in quantum science and technology (photonics and quantum technology). In Q-LEAP, networked research centers have been formed in the three areas of quantum information processing (mainly quantum simulators and quantum computers), quantum measurement and sensing, and next-generation lasers under the R&D management of the program director (PD). Although three projects have been adopted: research and development of superconducting quantum computers, creation of innovative sensor systems through advanced control of solid-state quantum sensors, and a center for advanced laser innovation, the current budget scale is an order of magnitude smaller than overseas.

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Chapter 5: Research and Development Issues

Quantum computers are known to have several quantum computation methods that can efficiently compute specific problems such as factorization and search, and are also expected to be used in quantum chemical simulations and machine learning, as described in Chapter 3. At present, however, the hardware for all of these methods is not yet developed enough to perform practical-sized computations. The development goals for qubit integrated circuits, which will be the core of the hardware, are high integration of qubits, implementation of quantum gates with high fidelity and high operability, and implementation of quantum error correcting codes to achieve large scale, but it is expected to take 20-30 years to develop a large-scale quantum computer with quantum error tolerance [5- 1, 2, 3]. The perspective of software and basic computer design (architecture) is also still lacking for its development [5-4]. On the other hand, as mentioned in Chapter 3, there has been a recent movement to develop NISQ machines that do not implement error-correcting codes, in order to make quantum computers more practical in the near future.

The realization of these quantum computers will require research and development in three technical areas: quantum software (5-1, 2, 3), qubit integrated circuits (5-4), and quantum computer systems (from the hardware aspect) (5-5). Figure 5-1 shows the hierarchical structure of the basic design for an error-tolerant quantum computer (Figure 5-1). In the figure, the upper level corresponds to the quantum software and the lower level corresponds to the qubit integrated circuit. In the following, we will discuss the R&D issues sequentially from the upper level to the lower level.

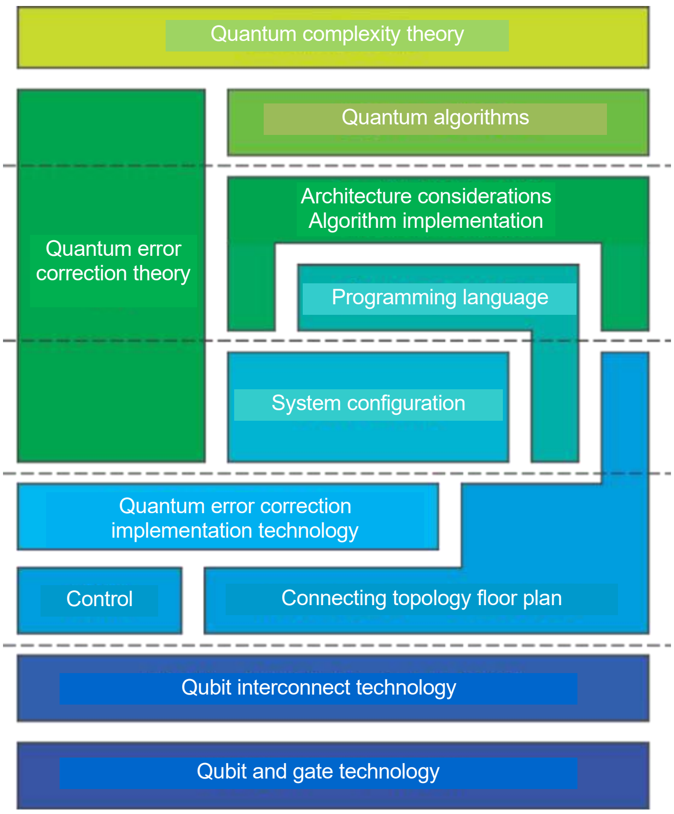

Fig. 5-1 Hierarchical structure of error-tolerant quantum computers
(Excerpt from reference source [5-1])

5-1. Software development

As the hardware implementation technology advances, the importance of software to maximize the information processing capability is also increasing. To support software development for quantum computers, programming languages, libraries, compilers, debuggers, and high-performance simulators are required as backing. At present, it is necessary to consider computation methods and programming from the viewpoint of the lower level of quantum circuits, which hinders cooperation between experts in fields such as quantum chemistry and machine learning and developers of quantum computation methods who have experience with quantum information. It is important to expand the ability to formulate and express problems and constraints from the viewpoint of software, which is located at the upper level of the hierarchy, and to translate them into machine language and relate them appropriately to hardware and simulators for verification [5-5].

Several software development platforms, including quantum programming languages and compilers [5-6], as well as simulators and libraries [5-7], have already been proposed, but further improvements in abstraction to higher levels, verification, and optimization are expected to significantly reduce the barriers faced by developers of quantum computation methods. It is also important to consolidate common subroutines such as phase estimation, Grover search, quantum walk, variational method, matrix product operation, and quantum information processing-specific operations (transformation of measurement basis, teleportation, etc.) as mathematical functions and libraries [5-8].

In the short term, with quantum-classical hybrid computation using NISQ machines in mind, it will be possible to develop quantum software more efficiently if an integrated development environment is created in which quantum programs can be called from existing programming languages and frameworks. Such an environment will also be effective in expanding the base of the quantum computer field.

5-2. Basic design of system (from the aspect of software)

The basic design concept of a quantum computer becomes more and more important as the scale of hardware increases [5-9]. The most important factor influencing the basic design of a quantum computer is the quantum error correcting code. The layer structure differs greatly between the case with and without error correction, and how to structure it is an important theme in the basic design. It is impossible to scale up the current 5-50 qubit NISQ machine to a 1 million qubit system without changing the basic design concept. There are many decisions to be made and designed under the complex conflicting relationships of gain and loss, such as the granularity and abstraction of components, interfaces between elements, instruction flow between classical and quantum parts, and interfaces between quantum and classical parts. Rather than aiming at the mature layered structure of current computers from the beginning, some directions have been proposed to seek a basic architecture specialized for each application area to some extent [5-10].

In an error-tolerant quantum computer, the choice of the quantum error-correcting code scheme not only determines the system configuration and the interrelationship of each element, but also has a profound effect on the state of implementation at lower levels, such as the physical arrangement and connectivity of qubits. A promising error-correcting code for superconducting qubit systems is a two-dimensional surface code, which is one of the topological quantum error-correcting codes [5-11]. This code operates on multiple qubits arranged in a two-dimensional square lattice, has a high permissible error threshold of about 1%, and requires only two qubit gates in the nearest neighbor qubit for error detection and correction, which makes it easy to implement in hardware. Another advantage is that if each side of the two-dimensional square lattice is extended as it is, the sign distance, which is a factor determining error tolerance, becomes large. However, if the qubits are simply placed on a two-dimensional plane and the wiring is also mounted on the same plane, it will inevitably be difficult to connect to the qubit in the center, so three-dimensional mounting technology such as TSV (Through Silicon Via) or flip chip bonding is required inevitably.

The error correction speed is an important factor for the computing performance of error-tolerant quantum computers. In specific terms, a physical qubit measurement is performed to detect errors, the measurement results are analyzed, and then a control signal to correct the error must be sent back to the qubit. The volume of data at this time depends on the number of qubits and the module clock frequency. For a full-scale error correction quantum computer that can decode currently-used codes, it has been estimated that it will be necessary to transfer and analyze data at a dozen petabytes per second [5-12], something which is very difficult for classical information processing to do.

5-3. Quantum circuit optimization and compiler

As a long-term R&D element to be solved in the basic design of a quantum computer, in addition to the abstraction of physical bits into logical bits by error correcting codes described above, the abstraction aspect of gate operations is also important. First of all, gate operations of continuous quantities (e.g., rotation operations) appearing in quantum arithmetic methods written in quantum circuits need to be decomposed into discrete operations of finite precision, and although there are arithmetic method proposals [5-13] that perform optimal gate decomposition according to precision, compilers that perform optimization are not yet developed.

Furthermore, it is necessary to decompose these gate sequences into gate sequences that are described by quantum error correcting codes. There are several proposals for optimizing the entire system, including optimization to avoid certain gates that are difficult to operate on surface codes, as well as proposals for magic state functional units that optimize the entire system, including the countless quantum circuits needed to create a magic state[7] to enable the use of such gates [5-15]. In the future, we will also need tools to verify that the optimized quantum circuit is equivalent to the original quantum circuit.

5-4. Qubit and integrated circuits

To date, qubit integrated circuits, which are considered to be promising for realizing quantum computers, consist of basic elements based on superconductivity and ion trap phenomena. These have already been integrated to 100 qubits or less, and their operation as qubit arithmetic circuits has been demonstrated. In the future, Si qubit integrated circuits [5-16] and optical qubit circuits [5-17], which can be operated at room temperature and are based on a Japanese original idea, are also expected to be developed.

Although Si qubit integrated circuits are still at the stage of realizing operation of a few qubits, they have advantages over the preceding superconducting qubit integrated circuits, such as longer coherence time and applicability of Si integrated circuit manufacturing technology, which will be a great advantage in improving the processing capacity of the system. Intel is also paying attention to the potential of silicon qubits, and is working with QuTech on a spin qubit system based on Si, in parallel with superconducting qubits.

The current status of these candidate devices is summarized in Figure 5-2, using gate fidelity and gate speed as scales. The gate fidelity is 99%, but the closer the fidelity is to 100%, the easier it is to apply error correction codes. The higher the gate speed, the faster the operation can be performed, and it is also an important parameter in determining the depth of the operation, i.e., how many operations can be performed within the quantum coherence time. The basic concept of the optical qubit arithmetic circuit is still in the proof-of-concept stage, and there are many unknowns regarding its characteristics.

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[7] Magic state: Some logic quantum gates cannot be implemented directly on the quantum error correction code. Using this special assist state called magic state enables us to configure a group of logic quantum gates required for general-purpose quantum computations from only logic quantum gates that can be implemented on the quantum error correction code.

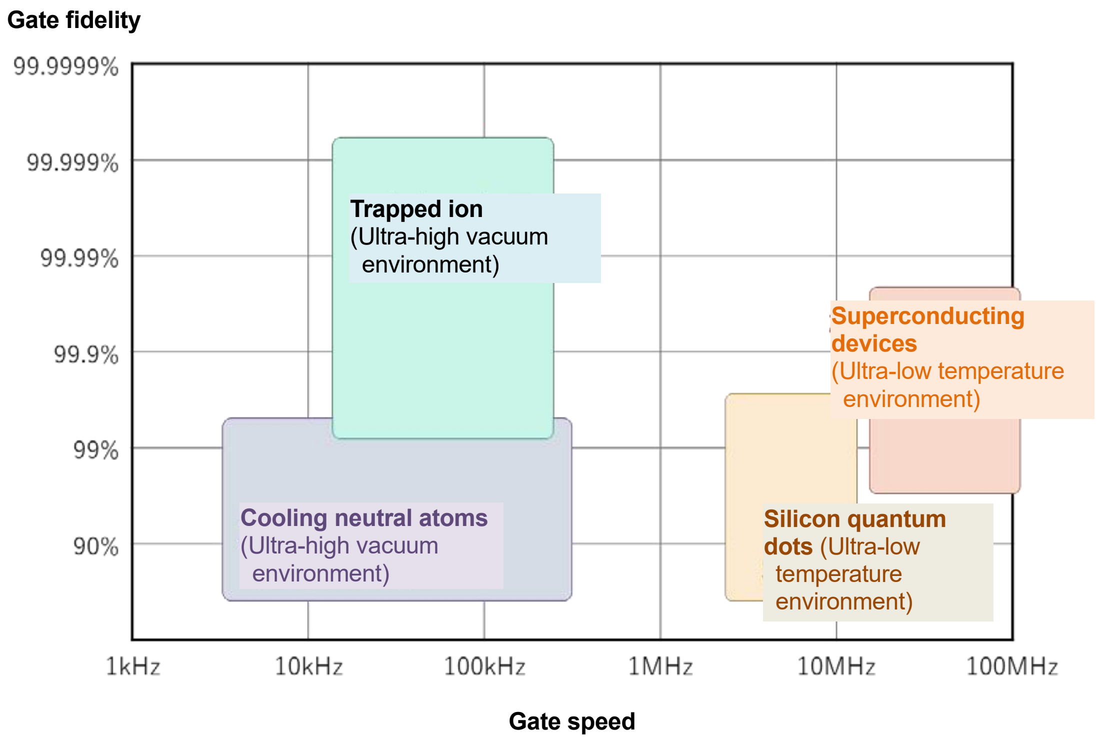

Fig. 5-2. Comparison of qubit realized system
(Edited and included after receiving permission from reference source [3-2])

In these qubit circuits, it will be important to improve the basic properties such as the degree of integration as a qubit, the quantum coherent time, and the fidelity of quantum gate operations. The degradation of quantum coherence in superconducting qubit devices can be attributed to material defects in the integrated circuits where the devices are integrated, and the identification, control, and isolation of such defects will require the involvement of researchers in materials science. Three-dimensional packaging of the integrated circuit is also an important issue for efficiently feeding microwave pulses to the qubit device. On the other hand, the implementation of quantum error correction ideas on integrated circuits will require collaboration between electronics engineers and computer scientists.

In addition, silicon quantum dot integrated circuits are implemented within a cryogenic dilution refrigerator and gate operation is performed using microwave pulses, the same as for superconducting qubit integrated circuits. Therefore, apart from related devices, technology such as peripheral electronic technology that includes hardware system implementation and microwave control circuits can be discussed in the same way as quantum computers that use superconducting qubits, which are the premise of this report. Meanwhile qubit devices that use trapped ions and cooling atoms do not require an extremely low-temperature environment. Instead, they require an ultra-high vacuum operating environment. Since gate operation also uses laser light pulses, the way the system is implemented will be completely different. In this report, we will proceed with discussing on the premise of superconducting computers, which are technologically ahead in the development of a computer system. However, we also believe that the pursuit of possibilities for qubit elements other than superconducting ones as integrated circuits should progress in parallel.

5-5. Quantum computer systems (from the aspect of hardware)

In this section, we will discuss the technical issues of hardware that accompany the increase in the number of qubits. As long as we use the system technology that is currently available, we can expect to see systems with up to 1,000 qubits, but new technology will be required for larger systems.

・Small-scale systems (1,000 qubits or less)

In addition to circuit technology to improve the error tolerance of qubits, technology to create an environment that minimizes the disturbance of electronic signals in the surrounding area, such as packages, will be important. It is necessary to make structural improvements, such as securing the distance from the parts that may be the source of signal disturbance and forming shielding, while improving the signal disturbance tolerance of qubits by making full use of related device technologies for high quality and three-dimensional structures that reduce defects in the materials that make up related devices, which are considered to be one of the causes of electronic signal disturbance. In addition, as the number of bits increases, the number of qubit control lines increases. The conventional method of routing control lines from the periphery of the two-dimensional plane is likely to be insufficient. A structure that directly connects to the qubit from above and below in three dimensions will be necessary. Furthermore, the number of interconnections with room temperature facilities will be expanded by using microwave wiring with low thermal conductivity and wide bandwidth, and by using refrigeration technology with higher refrigeration capacity. It will also be necessary to reduce the amount of wiring required for interconnection by multiplexing signals. In addition, it will be necessary to improve the circuit technology of the room temperature control side.

・Large-scale systems (More than 1,000 qubits)

The implementation and circuitry of qubit control will be a major constraint on large-scale systems. Therefore, the qubit control function must be implemented in hardware at low temperatures below helium temperature (4.2 K). Progress in cryogenic electronics technology is needed to make this possible. Cryogenic CMOS integrated circuits, cryogenic high-frequency circuits, and superconducting SFQ (Single Flux Quantum) circuits are candidates as related devices. In terms of implementation, optical interconnection technology is expected to enable information exchange between room temperature and low temperature areas with large capacity and low heat inflow. As the scale of the system increases, there is concern about the size of the facility, which is determined by the refrigerator. For this, parallelization, which is common in classical computers, may become important. Firstly, it is necessary to research the software and basic architecture for the parallelization, but advanced interconnection technology between computers is also expected to increase its importance with the increase of the system scale.

In addition, when considering a system that can realize quantum error correction technology with practical performance, integration of qubits and the error rate in the current qubit circuits are two opposing sides of the same coin, and a breakthrough in qubit devices themselves is necessary. In the future, we hope to realize the ultimate error-tolerant quantum computer with less redundancy, such as a qubit using Majorana fermion, which is said to be an error-free qubit.

5-6. The quantum computer research and development roadmap computer

Figure 5-3 shows the performance and technology trends of quantum computers that can be expected in the future, in terms of the number of qubits and the error rate of qubits.

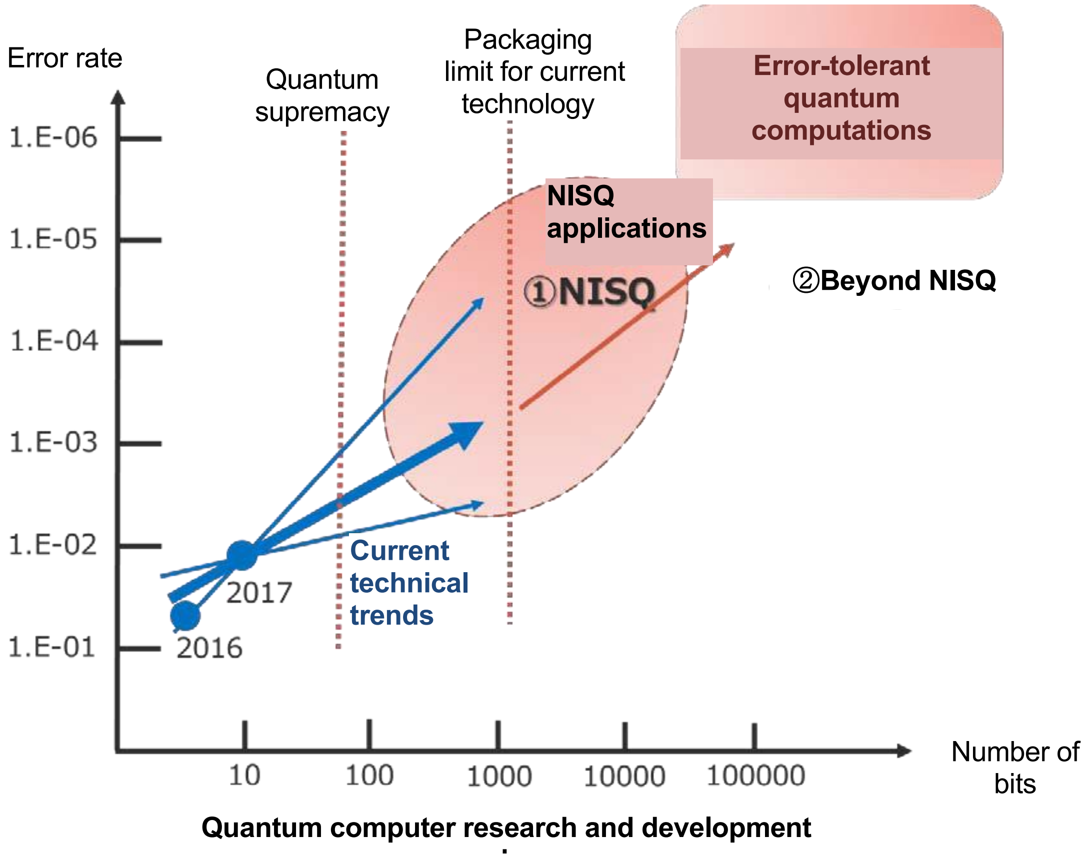

Fig. 5-3. Quantum computer research and development roadmap

At present, the first milestone in research and development is the realization of quantum supremacy[8]. There is still room for debate on the point as to what indicates the achievement of quantum supremacy. However, an integrated circuit that operates at a very low error rate with at least 50 bits or more is required for the hardware. Based on technical trends during the last two to three years, it is possible that we will achieve quantum supremacy during 2019 at the earliest. This is a significant step for quantum computers, but it is only an intermediate milestone and we still have a long way to go before quantum computers show practical advantages. The current mainstream concept of technological development beyond the realization of quantum supremacy is the realization of NISQ machines (shown as ① in the Fig. 5-3). The system is assumed to be NISQ, and hardware and application technologies are developed as a set. While increasing the degree of integration, it is essential that we build qubit elements that aim to reduce the error rate, design low-electromagnetic noise environments, and research materials to increase the quantum coherence time. We will probably need high quality manufacturing lines used in semiconductor mass production technology as the degree of integration increases. First of all, we should aim to accumulate system technologies in the 100 to 1000 bit class, and realize the system specifications required by NISQ application technologies, arithmetic methods, and basic architecture. After that, when the scale of integration and the error rate reach a certain level through the introduction of new technologies, the technology for applying error-tolerant quantum operations will become a reality. Another

[8] Quantum supremacy: When a quantum computer that has the capacity to calculate on a level not possible for a conventional computer. An important milestone for experimental demonstration using specific problem settings. At first, the threshold to achieve quantum supremacy was estimated to be about 50 qubits. However, recently this is said to be 90 qubits due to progress in classical calculation methods and improved computer performance.

approach is to continue to accumulate the number of qubits without considering NISQ, aiming for an error-tolerant quantum computer (② in the Fig. 5-3). For this purpose, it is hoped that a revolutionary idea will be born that will enable error-tolerant quantum operations to be realized.

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Chapter 6: Policy required for quantum computer development

In this chapter, we will make a series of recommendations on the measures that need to be taken to realize a quantum computer, including (1) building a prototype quantum computer as a flagship of national policy, (2) establishing a research and development center that integrates different technology fields and can serve as a contact point for Japan's relevant fields from overseas, and (3) developing young human resources who can carry out the research and development of quantum computers, which are expected to take time to put to practical use.

6-1. The importance of building a quantum computer prototype

Figure 6-1 shows the three technological fields required to achieve a quantum computer.

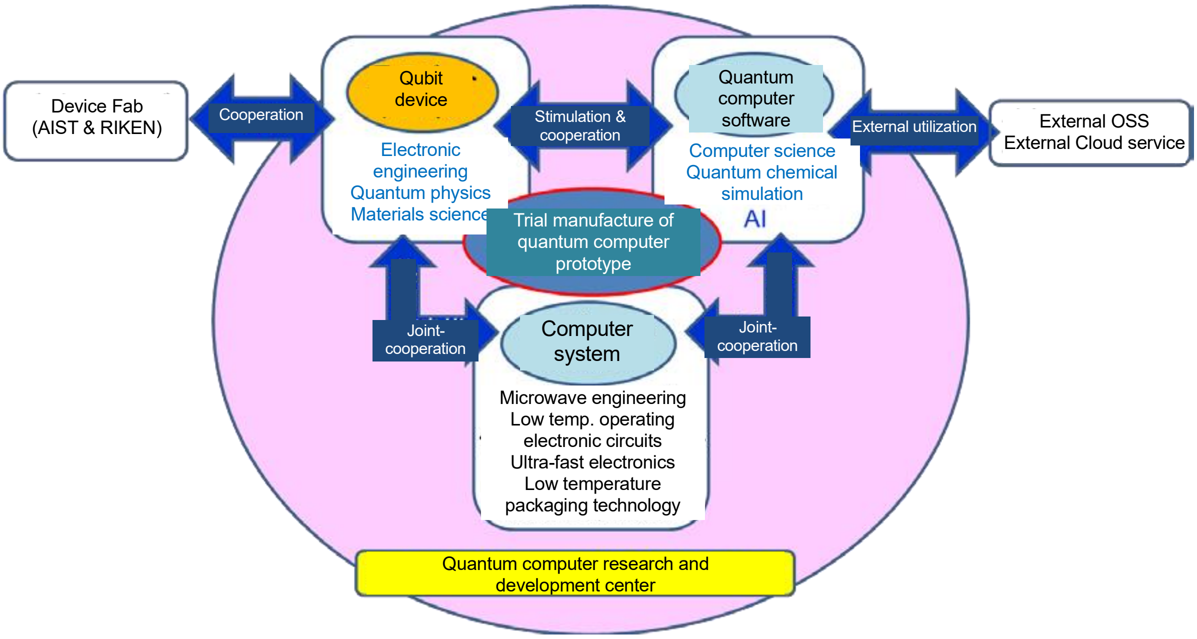

Fig. 6-1: The three technological fields required to achieve a quantum computer at research and development center

Qubit operation was first demonstrated using superconducting circuits in Japan, and research at the circuit level is in the most advanced group in the world. It would be natural to use superconducting qubits as components since Japan has accumulated research at a basic level on these type of qubits. However, it is not clear which method will win out in the end for qubit operation circuits so we believe it is important to work on other candidate circuits up to a basic level of research. At this stage, improvements of basic characteristics such as degree of integration for qubit operation circuits, quantum coherence time, and the fidelity of quantum gate operation will be important. As discussed in section 5-5, improving the quantum coherence time would also require the involvement of materials science researchers. Furthermore, generating ideas for quantum error correction and implementing them onto integrated circuits would require the cooperation of scientists from quantum physics, electronic engineering and computer science.

The second technical area is the research of software to run quantum computers. In this technical area, computer scientists will play a central role. In order to develop useful applications of quantum computers, software development environments such as high-speed simulators, libraries, compilers, etc., must be developed so that users can try various experiments on their own. In addition, the development of control software (middleware and firmware), which is needed closer to the hardware, and software for quantum error correction, which has a significant impact on the basic architecture of integrated circuits, is an important issue. At the same time, in the near future, it will be important to pursue the possibility of NISQ without error correction in both basic research and application development [3-2]. In the development of software and application technologies, it will be necessary to use cloud services provided by overseas quantum computers. However, the internal structure of a quantum computer is kept secret, and it can only be used in a given environment, and the use of the results obtained from it is bound by contract. It is essential to have Japan's own quantum computer, and to have a system in which hardware and software researchers can work together to promote research.

The third area of technology is the construction of computer systems. It is necessary to send high-speed microwave pulses from an electronic device at room temperature through many wires to a qubit integrated circuit in a dilution refrigerator at cryogenic temperatures (10-20 milli Kelvin). To perform quantum error correction, the qubit readout results are sent to a measurement device at room temperature, where error correction is performed, and then sent back to the qubit integrated circuit at cryogenic temperature. In order for the qubit integrated circuit to operate as expected, complex high-speed signal processing must be performed outside the qubit integrated circuit. This requires the development of microwave multiplexing circuits, the implementation of compact integrated circuits that eliminate high-frequency noise, the three-dimensional implementation of the many input/output wires connected to the integrated circuits, and the development of cryogenic cooling systems that eliminate the inflow of heat from room temperature as much as possible. In order to avoid heat inflow and delays in input/output wiring, it will also be important to develop CMOS integrated circuits or superconducting SFQ circuits which operate under cryogenic environment such as helium temperature (4.2K) to control input/output signal. Thus, this technological field will require a great deal of engineering knowledge and collaboration with various component and measurement equipment manufacturers. These manufacturing technologies are areas in which Japan excels, and we believe that Japan, with its large number of component manufacturers, has a chance to gain a competitive edge.

6-2. The necessity for a unifying research and development center

Research and development in the three technological areas described in 6-1 are not independent, but are highly interrelated. In fact, since the operation of qubits is completely different from that of classical computers, computer scientists will be required to have basic knowledge of quantum physics in the development of compilers. In the development of quantum error correction, which is a major obstacle in the development of quantum computers, the error correcting code scheme to be devised will function only after it is implemented on an integrated circuit. This will require collaboration between researchers in computer science, quantum physics, and electronics. Close collaboration between researchers of qubit integrated circuits and the computer systems will also be necessary. In order to efficiently and densely deliver microwave signals from the outside via coaxial wiring to the integrated circuit, compact packaging with a three-dimensional modular structure is necessary. Here, close collaboration between electronics researchers, microwave engineering researchers, and module packaging researchers is necessary. In order to efficiently carry out these developments, a center for quantum computer research and development is needed, as shown in Fig. 6-1, where the development of a quantum computer prototype as a flagship of national policy should be promoted. The development of qubit integrated circuits should also be executed at the same center. The role of the computer system is important not only in providing the developed integrated circuits to the quantum computer system, but also in providing the operating environment for the development of the integrated circuits. However, since the evolution of the basic architecture of computers has a great impact on the development of related devices and computer systems, it is important that discussions related to the basic computer architecture can be coordinated at any times in the center. In research on quantum software, there are many situations where we have no choice but to use cloud services and open source software provided by leading overseas companies, but invention of new computing methods can only be demonstrated with cooperation from the hardware side. In this sense, the collaboration at the above centers is extremely important. The development of qubit integrated circuits also requires collaboration with related equipment prototyping and manufacturing sites within or outside the same center.

The following is a list of representative overseas research centers for quantum computing for reference.

(1) Institute for Quantum Computing (Canada)

- Established within the University of Waterloo (Canada) with donations from Mike Lazaridis, the founder of Blackberry, in 2002, opened a Quantum-Nano Center in 2012. Collaborates on quantum theory subjects with the Perimeter Institute of Theoretical Physics on the same campus.
- 31 faculty members, 43 postdoctoral researchers, 140 students (as of June 2018)

Investment from the Canadian government is 15 million dollars over a 3-year period from 2018

- They have a wide-range of research themes such as spintronics, photonics, superconducting qubits, quantum material, quantum optics, ion trapping, quantum encryption, quantum software, and quantum systems
- Already created 12 startup companies relating to quantum computers

(2) QuTech (Netherlands)

- Established by Delft University of Technology, TNO and industrial partners. Totally, 180 staff members with 30 faculty members as core members (as of December 2017).
- The three major research themes are error correcting quantum computation, quantum internet & network computation, and topological quantum computation.
- In 2015, Intel invested 50 million dollars over a ten year period towards quantum computing research. Microsoft supports research on topological quantum computing.

(3) University of Science and Technology of China

- The Chinese Academy of Sciences, Alibaba, University of Science and Technology of China, and Zhejiang University are cooperating in the research of quantum computers. Alibaba’s quantum computer, which provides Cloud services, is set up in the University of Science and Technology of China (Shanghai).
- A national laboratory for quantum information is being constructed within the University of Science and Technology of China in Hefei City (the total cost of investment including research funds is 76 billion yuan or over 1 trillion yen).

6-3. The necessity of developing young human resources for the next generation

Since the research and development of quantum computers is a new field that is advancing rapidly, there are only a limited number of people who can play a central role in the research. Moreover, there are many technical issues that need to be addressed before quantum computers can surpass the performance of conventional classical computers and be accepted in the market. In order to achieve this, it is important to foster young researchers who can carry out long-term research. In particular, the research and development of software for quantum computers is a technical field that is rapidly increasing in importance alongside the progress in the integration of qubit operating circuits, and there is little accumulated research to date and only a limited number of researchers who can carry out such research, making the fostering of young researchers an urgent task. In this field, it is necessary to have a system that can recruit not only researchers who specialize in computer science, but also talented researchers who specialize in theoretical physics and mathematics. Fortunately, there are a small number of researchers who can play a leading role in the field of quantum software, and it is hoped that talented young researchers will grow by conducting research under them. In order to avoid placing a heavy educational burden on researchers who play a central role in research, it will be necessary to enhance staff to support education.

It is desirable to make effective use of the R&D centers described in section 6-2 for the development of young researchers. Research and development of quantum computers requires specialists in a wide range of technical fields, such as quantum mechanics, materials science, electronics, and computer science, and it is important to provide an environment in which researchers in the above diverse fields can meet and discuss freely. The creation of important ideas related to quantum operations, such as new quantum error correction, requires close discussions with shared goals between software researchers and system researchers of computer hardware. In addition, it is hoped that Japan's research centers, as a national policy, will increase their presence in overseas research communities and attract excellent overseas researchers, thereby creating a stimulating and attractive environment for young Japanese researchers to interact with top-class overseas researchers.

Chapter 7: Summary

As the limits of semiconductor miniaturization become apparent, it is no longer possible to expect high performance in accordance with Moore's law for semiconductor integrated circuits, which has supported the improvement of computer performance up to now. In addition, as the amount of information to be processed increases, the limitations of the Neumann-type arithmetic method are becoming apparent. On the other hand, the demand for higher performance computers in the advanced information society is increasing, and there is a need for innovation in computing technology. In this context, quantum computers are expected to be a candidate for innovation in computing technology because they can perform operations based on a completely different computing principle from conventional computers (classical computers), and depending on the given problem, they can provide solutions to problems that are virtually impossible to solve with classical computers. For this reason, the United States, China, and Europe are competing with each other in launching large-scale national research and development programs for the development of quantum computers. Japan has made important contributions in the process of forming the concept of quantum computing, and is not inferior to other countries in the accumulation of basic research, but lags behind in recent applied development research. For this reason, we make the following recommendations.

(1) It is necessary to develop a prototype quantum computer as a national policy, and to form a center to promote the technological development necessary for this. (1) Development of a prototype quantum computer as a national policy, and the formation of a center to promote the development of the necessary technologies for this purpose. The development of an actual prototype will enhance Japan's presence in the world, and attract funds, information, and talented human resources. The existence of these prototypes is also important as operational verification machines that can evaluate the usefulness of individual technologies. The development of quantum computers at the above center should be carried out through collaboration among researchers in a wide range of technical fields, including materials science, quantum physics, electronics, and computer science.

(2) It is also important to support research on quantum software, including basic computing architecture and application algorithms. Unlike the development of devices, which requires accumulation of technology, research on new basic computing architecture and algorithms for quantum computers can be conducted with free ideas, and is currently at a stage of rapid development. New ideas have the power to change the direction of research on quantum computers, including related devices and hardware systems. Also, the developed quantum software will be meaningful only when it is implemented in a quantum computer. In order to make the most of the value of the software developed, it will be important to develop Japan's own prototype quantum computer as described in (1) above.

(3) In the long term, it is important to develop the next generation of human resources, and a system for this purpose must be established. Many twists and turns are expected in research and development toward the realization of quantum computers. In order to survive the competition in quantum computer development, it is necessary to have the strength to continue research from a long-term perspective, and human resource development is the key to this. At the same time, it is also important to conduct basic research to generate new ideas from a long-term perspective.

(4) As mentioned in section 4-3, the United States, China, and Europe (Germany and the United Kingdom) have begun to implement national programs for quantum technology with a duration of 5 to 10 years and an annual budget of more than 10 billion yen. In order for Japan to compete with these countries in the field of quantum technology research and development, it will be necessary to invest a budget of the same scale. Considering the fact that the development of quantum computers is a core issue in quantum technology, we believe that it is

necessary to establish a national plan for research and development of quantum computers with an annual budget of more than 5 billion yen.

<Reference material> Deliberation progress

1. Individual discussion was conducted with the committee and then information collected to firmly establish the proposal outline.

April 11, June 7, and August 6, 2018: Discussion with Professor Yasunobu Nakamura at the University of Tokyo
April 16, May 9, and July 4, 2018: Discussion with Professor Jaw-Shen Tsai at the Tokyo University of Science
May 11, 2018: Discussion with Professors Tadashi Ishihara, Akira Furusawa and Tatsuya Okubo at the University of Tokyo
May 22, 2018: Discussion with Professor Yasuhiko Arakawa at the University of Tokyo
June 4, 2018: Discussion with Professor Kohei Ito at Keio University
June 22, 2018: Discussion with Professor Hidetoshi Nishimori at the Tokyo Institute of Technology
August 9 and 21, 2018: Discussion with Professor Keisuke Fujii at Kyoto University

June 6 and 27, July 25, December 19, 2018, February 18, March 14 and 19, and April 11, 2019: Project leader and secretary discussion

2. Participated in academic societies and research meetings to collect information.
[In Japan]

- The 65th JSAP Spring Meeting (March 17-20, 2018@Waseda University)
  Symposium “Current Situation and Future Perspective for Quantum Computers and Simulation”
- 73rd Annual Meeting of the Physical Society of Japan (March 22-25, 2018@Tokyo University of Science)
  Symposium “New Developments in Physics Brought About by Topology”
- The Physical Society of Japan 2018 Autumn Meeting (September 9-12, 2018@ Doshisha University)
  Symposium “Diversified Quantum Computers”
- The 79th JSAP Autumn Meeting (September 18-21, 2018@Nagoya Congress Center)
  Symposium “Current Situation and Future Perspective for Quantum Computers and Simulation”
- The 66th JSAP Spring Meeting (March 9-12, 2019@Tokyo Institute of Technology)
- 74th Annual Meeting of the Physical Society of Japan (March 14-17, 2019@Kyushu University)
  Symposium “Developments in Devices Based on Superconducting Phase Physics”

[Overseas]

- American Physical Society (APS) March Meeting 2018（2018.3.5-9, Los Angeles, USA）
  Sessions:”Scaling Superconducting Circuits”,”Progress in Quantum Computing Implementations”,”Scaling up Quantum Computer”,”Architectures for Semiconducting Quantum Computing”
- 2018 IEEE International Electron Devices Meeting (2018.12.1-5, San Francisco, USA), Focus Session: “Quantum Computing Devices”, etc.
- Quantum for Business (Q2B) 2018（2018.12.10-12, Mountain View, USA）
- American Physical Society (APS) March Meeting 2019 (2019.3.4-8, Boston, USA),Sessions:”Semiconducting Quantum Computing with Donors”,”Applications of Noisy Intermediate Scale Quantum Computers”, “Quantum Computing with Open Quantum Systems”

3. Members and observers of the quantum computer project gathered together to discuss quantum computer research and development strategies and this was firmly established in a report outline.

・Conference: Quantum Computer Research and Development Strategy Investigative Commission
・Date: August 21, 2018 3:00 PM - 5:30 PM
・Venue: JST 2F Conference Room

4. Submission of the final draft report and its deliberation

1) January 28, 2019: The project leader gave a report to the Policy Proposal Committee concerning the progress and results of the project. It was then decided that a final draft report may be submitted summarizing the project with consideration for comments from the committee.
2) April 8, 2019: The final draft report was submitted to the Policy Proposal Committee and then the project leader explained the outline of the report at the committee. Several requests were made by the committee. As a result of the deliberation, further comments were requested from the committee concerning the details and after receiving these comments the corrected report was approved for escalation to the Steering Meeting.
3) On April 17, 2019: The project leader explained the content outline of the final report at the Steering Meeting, and as a result of the deliberation, the format of the final report was re-arranged before being approved for escalation to the Council.
4) May 15, 2019: the project leader explained about the outline of the final draft report that was distributed by email to Council members prior to the start of the Council meeting, and as a result of the deliberation, it was approved for public release.

If you wish to receive a copy of this document and its content, please contact the Secretariat at the Engineering Academy of Japan (public corporation).

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