Toward Creation of a System Architecture for Quantum Computers

Sumitaka Sakauchi

Abstract

To achieve innovations in the era of the Innovative Optical and Wireless Network (IOWN), for example, predicting the future by Digital Twin Computing, a computing infrastructure that supports ultra-high-speed and ultra-large-scale computing is needed. This need has led to a growing interest in quantum computers, which execute operations in a completely different way than conventional computers. NTT Computer and Data Science Laboratories is engaged in both (i) theoretical research to create system architectures that maximize the capabilities of quantum computers and (ii) development of system and software technology for practical applications of quantum computers.

Keywords: quantum computer, Ising machine, quantum-computing system architecture

1. Necessity of renewing computing infrastructure for supporting IOWN

Promoting its concept called the Innovative Optical and Wireless Network (IOWN), NTT is striving to build a new network and information-processing infrastructure that overcomes the limits of current information and communication technology (ICT). In the IOWN era, we aim to provide a new service called Digital Twin Computing (DTC)—which will enable future prediction by combining the real world with the digital world—by optimally combining various ICT resources through Cognitive Foundation and connecting everything at high speed with light via the All-Photonics Network.

Future prediction by DTC requires a computing infrastructure that can process huge amounts of data and provide unimaginable accuracy and speed. To actualize the IOWN concept, we are considering speeding up arithmetic processing by using photonics-electronics convergence technology and considering radically switching to a completely new computing infrastructure using quantum computers, which have been attracting attention. Quantum computers are expected to exploit quantum-mechanical behavior to solve problems that are difficult for conventional computers to solve, such as prime factorization, optimization problems, and chemical simulations, at high speed. Our goal is to take advantage of these characteristics of quantum computers to implement unprecedented applications and provide new services.

2. What is quantum computing?

Research on quantum computers is thought to have started in 1985 with the proposal of a computational model called a "quantum Turing machine" by Oxford University physicist David Deutsch [1]. In 1994, Peter Shor, a mathematician at AT&T, a U.S. telecommunications company at the time, announced a quantum algorithm that could solve prime-factorization problems considerably faster than a classical computer with conventional central processing units [2]. That announcement attracted a great deal of attention, and various universities and companies began a race to develop various types of computers that apply quantum-mechanical behavior to computing. Two main types of such computers have been developed: the so-called quantum computer and its derivative, an Ising machine.

Quantum computers are expected to be used for tasks such as solving prime-factorization problems at high speed. Quantum operations are based on quantum bits (qubits), which can represent quantum-superposition states through their quantum nature. Various methods for creating qubits, such as using superconductivity, photons, and ion trapping, have been proposed, but the number of qubits that can be implemented is currently limited. In addition, errors are generated by noise, etc., and practical calculations require additional qubits for error correction. For example, it is said that prime factorization of 2048 bits requires 10^7 qubits with an error rate of 10^{-4} [3]. However, current quantum computers lack both scale and precision. Many companies and research institutes are therefore conducting basic research and development of multi-bit systems. However, a large-scale quantum computer called a fault-tolerant quantum computer (FTQC)—which can correct errors during calculation while executing prime factorization—has not yet been put into practical use. Even in the current situation in which the number of qubits is small, efforts to suppress noise by minimizing the circuit scale as much as possible and promote the development of useful computational applications before an FTQC is put into practical use are underway. Such research and development on a small-scale noisy intermediate-scale quantum (NISQ) computer is progressing.

The other type of quantum computer, an Ising machine, specializes in solving combinatorial optimization problems, namely, time-consuming problems for classical computers to solve, at high speed by using a statistical-mechanics model that represents the properties of magnetic materials called the Ising model. Unlike quantum computers that use qubits, an Ising machine has limited applications. However, having already been commercialized by several companies, it leads the competition in terms of practical use.

At NTT, we are conducting a wide range of research and development—from technologies related to Ising machines to technologies for enabling the development of quantum computers (NISQ computers and FTQCs). We developed an Ising machine called the LASOLV™ computing system, which executes operations using light. We are also promoting the development of its applications. Regarding quantum computers, we are researching optical quantum systems and superconducting systems as methods for implementing quantum-computing hardware. Regarding software, we are investigating methods and theories to achieve error correction and error suppression with higher performance and efficiency. On March 27, 2023, RIKEN started providing Japan's first quantum-computing cloud service through the national project Q-LEAP [4]. Participating in this project, NTT Computer and Data Science Laboratories is contributing to the implementation of control software for quantum computers.

A positioning map for an Ising machine, NISQ computer, and FTQC is shown in **Fig. 1**. An FTQC increases the range of problems that can be solved, but its relative difficulty of implementation is higher. With that difficulty in mind, NTT laboratories, considering implementation of an FTQC as our goal, are aiming to provide a practical computing infrastructure as soon as possible by researching and developing technologies to fill the gap from an NISQ computer to an FTQC called the "early-FTQC" as well as developing Ising machines and NISQ computers.

3. System-architecture technology for practical use of quantum computers

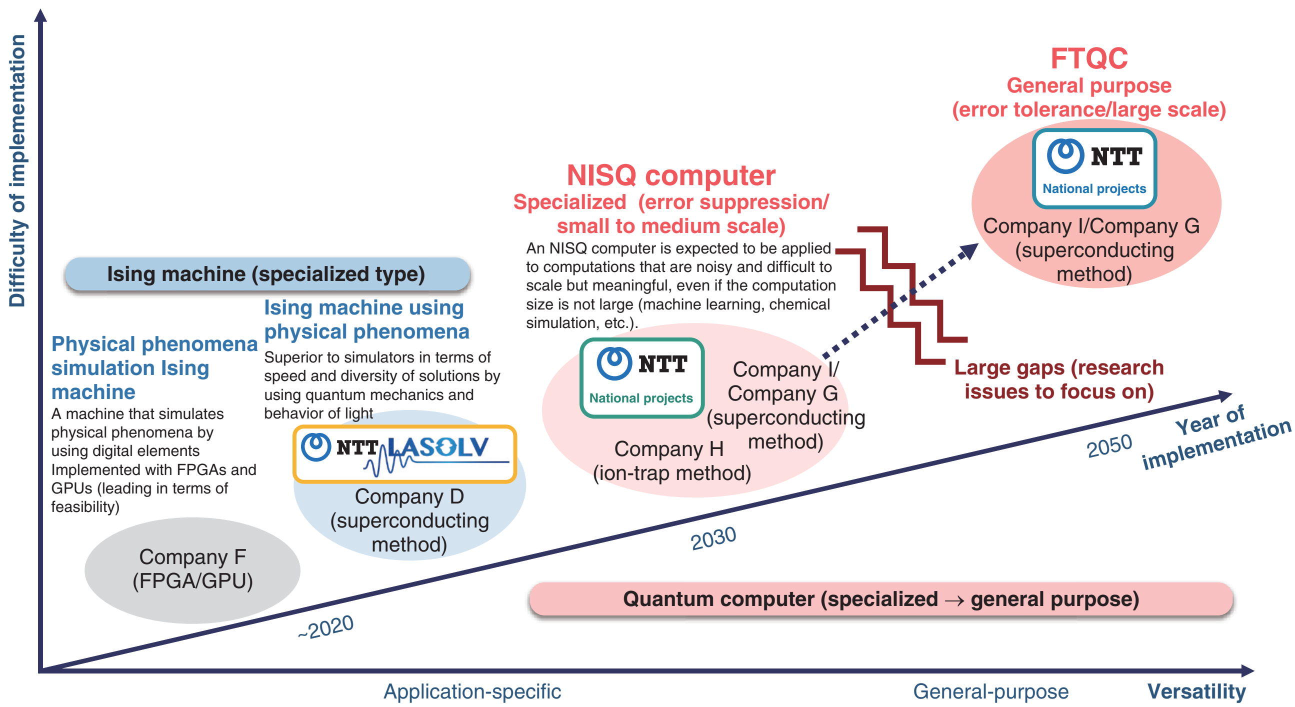
Various types of hardware have been proposed for implementing Ising machines and quantum computers. A research-and-development competition to establish a mechanism for controlling various types of hardware that enable quantum computing and executing meaningful applications, that is, establishing a quantum-computing system architecture, has also begun.

Various challenges facing the creation of system architectures to use quantum computers have been identified. To address these challenges, NTT Computer and Data Science Laboratories is engaged in research and development that combines physics and information science to explore the ideal architectural design and usage of a practical quantum computer (**Fig. 2**).

Challenge (1): Application development for quantum computers is difficult

A quantum computer solves problems by using specialized quantum algorithms. It is therefore necessary to study how problems in general form can be represented by complex quantum algorithms and converted into a form suitable for quantum computers. Since knowledge of quantum mechanics is also used, the hurdle is currently too high for general application developers.

To address this challenge, we are working to



FPGA: field-programmable gate array
GPU: graphics processing unit

Fig. 1. Position map for Ising machines and quantum computers.

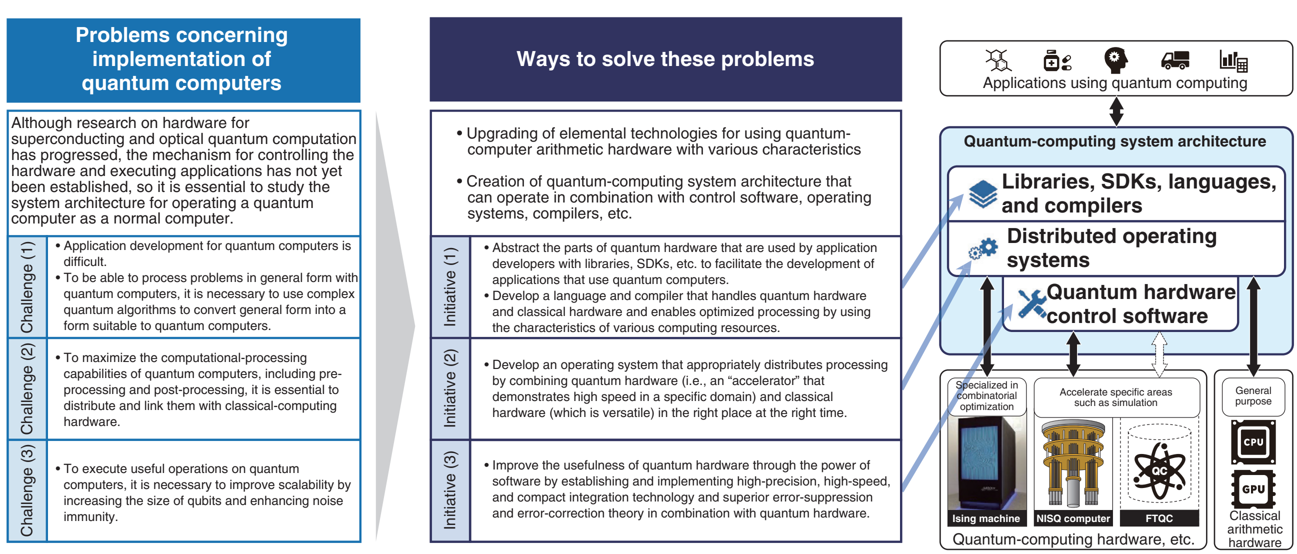


Fig. 2. Research and development toward creating a system architecture that uses quantum computers.

abstract the parts of quantum hardware that are used by application developers by implementing them as libraries or SDKs (software-development kits). Software development specialized for each type of quantum hardware is currently required, as was the case with assembly languages in the early days of classical computers. Therefore, we aim to construct instruction sets, intermediate expressions, high-level programming languages, and compilers that enable optimized processing by using the characteristics of each type of quantum hardware.

Challenge (2): Quantum computers demonstrate high speed only for certain applications

By using superposition states, quantum computers can be expected to dramatically speed up operations on many inputs at once, such as during prime factorization; however, they are not expected to be fast enough to replace all operations executed by a classical computer. In other words, a quantum computer acts as a kind of accelerator. To create value as an application, it is therefore necessary to consider a system that works well with a classical computer and maximizes the computing power, which is the advantage of quantum computers.

To overcome this challenge, we are investigating system architectures that combine various types of quantum computers and classical computers in a tightly coupled manner and distribute processing appropriately. We are pursuing research and development to materialize these architectures as distributed operating systems.

Challenge (3): To achieve useful quantum computation, increased scalability is needed

As mentioned above, quantum-computing hardware with various means of implementation is being developed; however, we have not yet reached the stage of conclusively proving quantum transcendence, in which a quantum computer can compute faster than a classical computer. One reason for this is the lack of the number of qubits needed to execute meaningful operations in quantum computers. Hardware-implemented qubits are also susceptible to noise, and to correct the errors due to that noise and execute operations, additional qubits are needed. The key challenges are therefore three-fold: expand the scale of the number of qubits, improve the accuracy of operations, and reduce the number of required qubits by improving the efficiency of circuits.

To address these challenges, while improving qubits through research and development of the quantum-computing hardware, we are working to improve the usefulness of hardware through the power of software by developing technologies for higher precision, higher speed, and more compact integration; improving scalability through inter-hardware communication; and establishing and implementing superior error-suppression and error-tolerance theories.

By overcoming each of these three challenges, we will create a system architecture that maximizes the capabilities of quantum computers.

4. Future developments

Quantum computers are expected to be able to solve problems that would take a very long time to solve with classical computers at ultra-high speeds. NTT Computer and Data Science Laboratories is developing technologies for creating the system architecture of quantum computers described in this article. Applications of these technologies range from an Ising machine, which is leading in terms of practical application, to NISQ computers and FTQCs, which will require further research and development.

References

[1] D. Deutsch, “Quantum Theory, the Church–Turing Principle and the Universal Quantum Computer,” Proc. R. Soc. Lond. A, Vol. 400, No. 1818, pp. 97–117, July 1985. https://doi.org/10.1098/rspa.1985.0070

[2] P. W. Shor, “Algorithms for Quantum Computation: Discrete Logarithms and Factoring,” Proc. of 35th Annual Symposium on Foundations of Computer Science (FOCS 1994), Santa Fe, NM, USA, pp. 124–134, Nov. 1994. https://doi.org/10.1109/SFCS.1994.365700

[3] C. Gidney and M. Ekerå, “How to Factor 2048-bit RSA Integers in 8 Hours Using 20 Million Noisy Qubits,” arXiv:1905.09749. https://doi.org/10.48550/arXiv.1905.09749

[4] Press release issued by RIKEN, National Institute of Advanced Industrial Science and Technology, National Institute of Information and Communications Technology, Osaka University, Fujitsu Limited, and NTT, “Japanese joint research group launches quantum computing cloud service—Opening access to Japan’s first superconducting quantum computer,” Mar. 24, 2023. https://group.ntt/en/newsrelease/2023/03/24/230324a.html

Sumitaka Sakauchi
Vice President, Head of NTT Computer and Data Science Laboratories.

He received a B.S. in physics from Yamagata University in 1993, M.S. in physics from Tohoku University, Miyagi, in 1995, and Ph.D. in systems and information engineering from the University of Tsukuba, Ibaraki, in 2005. He joined NTT in 1995 and conducted research on acoustics, speech, and signal processing. He is currently engaged in the management of the research and development for computer science and data science. He received the Paper Award from the Institute of Electronics, Information and Communication Engineers (IEICE) in 2001, and Awaya Kiyoshi Science Promotion Award from the Acoustical Society of Japan (ASJ) in 2003. He is a member of IEICE and ASJ.