The Arrival of a New Era in Quantum Information Processing Technologies

Hiroshi Yamaguchi and Tetsuomi Sogawa

Abstract

Research on quantum information processing has progressed astoundingly in the past several years. Concepts totally different from before such as adiabatic computation, quantum measurements, and topological states have been introduced, expanding the possibility of applications. This article introduces recent developments in quantum information processing and discusses NTT's research achievements as examples of the advances in this field.

Keywords: quantum information processing, quantum computing, quantum key distribution

1. Introduction

In the last ten years, the application of quantum information processing technologies has expanded to areas outside of our own field of specialty. In our work, we are often asked about quantum computing by non-specialists. When we began research on quantum technologies at NTT, we had to start by answering the question, "What does 'quantum' actually mean?" Now, however, we are more often asked, "I know the background story. How far have you progressed?" There have been times when news about quantum information processing would suddenly pop up when we were watching television or listening to the radio. When watching science-fiction movies, we would be surprised when a character suddenly uttered a line about "quantum teleportation." It seems that the subject of quantum information processing technologies has already spread widely from the realm of specialists to the general public.

NTT's research on quantum information processing goes back more than 30 years. We joined NTT about 30 years ago, and it is no exaggeration to say that our research career has unfolded alongside the development of quantum technologies in the NTT laboratories (NTT Labs). When research began at NTT, the usual answer to the question about when quantum computers would be put to practical use was "at least 30 to 50 years." Initially, quantum computing technologies were immature, and we think they gave the impression at the time that although the field was interesting theoretically, putting the technologies into practical use was not a simple matter.

However, astounding progress has been made in quantum computing over the last several years. When we first began our research, we had, in all honesty, a negative assessment of the possibility of practical quantum computing. When we look at the state of affairs now, however, we seriously think that it just might be possible that it will be used. Five years ago we contributed an article on quantum computing to the NTT Technical Review [1]. Re-reading the article again, we are struck by how far the field has advanced since then. In the US and Europe, world-famous companies have made large investments in the research and development (R&D) of quantum information processing technologies. It is truly an unexpected state of affairs.

How, specifically, has quantum computing progressed? The Feature Articles in this issue present the advances in this field. While one cannot understand all the latest quantum information technologies in 30 minutes just by reading these articles, we think one can understand the atmosphere in which these amazing technologies are continually developed based on new concepts. As a foreword to this issue, we wish to give an overview of these technologies and explain the new ideas behind them.

2. Adiabatic computation

It can be said that a major impetus of quantum computing research was the effort to achieve high-speed factorization to break RSA (Rivest-Shamir-Adleman) cryptography. This claim actually demonstrates the weakness of quantum computing. That is, the mention of factorization indicates that the problems that can be solved at a high speed by quantum computing are very limited. The number of proven high-speed algorithms, including those for simple and trivial problems, is extremely small. Consequently, no matter how much improvement there is in hardware development for quantum computing, it is unlikely that quantum computers will entirely replace the all-purpose personal computers we have today.

We refer here to the conventional method of quantum computation as *quantum gate computation*. In quantum gate computation, the solution to a problem is obtained by writing bit information to quantum bits (qubits) and then performing gate operations on them sequentially (called *unitary transformation* in quantum mechanics). This method is similar to the sequential computation carried out in computers today. While this is an easy-to-understand concept, bit information written in qubits must be correctly maintained and operated at all times. Thus, scaling up current hardware is not a simple matter.

In contrast to this approach, a computation method based on a completely different concept called *adiabatic quantum computation* has been proposed. In this concept, gate operations are not performed on each bit sequentially. Instead, the necessary answer is finally obtained by continuously changing the bit environment that makes up the computer (such as how bits are connected to each other). One of the biggest advantages of this method is its approach to perform calculations while constantly maintaining the lowest energy state.

The conventional gate computation approach involves the use of a high-energy excited state, and computational errors are produced by the transition to a low-energy ground state. Imagine quantum gate computation as passing a golf ball from person to person in a spoon relay. If there is just one little mistake, the golf ball falls to the ground. In other words, the computation fails.

In contrast, adiabatic computation continues in the manner of a soccer ball being kicked from person to person at ground level, where it cannot fall down. As a result, computation can be carried out without losing energy (called *energy relaxation* in technical terminology) (**Fig. 1**).

Another major advantage of adiabatic computation is that it can be applied to more problems than quantum gate computation. Although rigorous proof of its high-speed processing capability remains a future topic of research, adiabatic computation has been proposed as a method for handling many combinatorial optimization problems such as the traveling salesman problem and the knapsack problem, for which conventional computers require computation times that are exponential to the complexity of the problems.

The classical approach of obtaining a solution by changing the system while maintaining the lowest energy state—called simulated annealing—actually already exists. The proposed application of this method to quantum mechanistic conditions is called quantum annealing [2]. D-Wave Systems, a Canadian company, made news when it offered a commercial quantum computing product utilizing this approach. A joint research team that includes NTT Labs recently developed a quantum neural network that carries out the annealing using laser and optical fibers, and demonstrated a 2000-node calculation [3]. Although the use of an approach different from quantum annealing and the detailed roles of quantum mechanical superposition states should be clarified in the future, the experiment confirmed the high-speed capability (compared with the conventional computation) to solve a combinatorial optimization problem.

3. Quantum sensing technologies and experimental verification of quantum mechanical principles

As introduced in past articles of the NTT Technical Review, NTT Labs have developed various qubits to create quantum computers. Research on these qubits was conducted with multiplexing and circuit integration in mind and the assumption that in the future, it will be necessary to connect many qubits—several thousands and tens of thousands or more. The reason that developing a quantum computer is reportedly difficult is that it is not a simple matter to integrate such a large number of qubits.

However, there have been recent efforts to pioneer technologies that apply quantum computing without

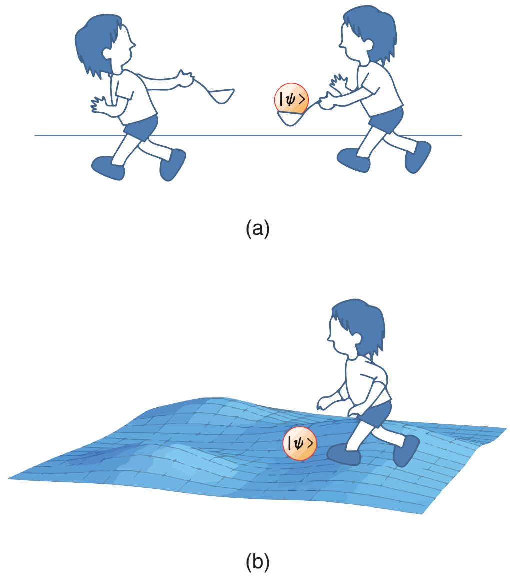

Fig. 1. Pictorial representation of (a) conventional quantum gate computation and (b) adiabatic quantum computation. Gate computation is similar to a spoon relay race. Superposition states in qubits ($|\psi>$ in the figure) are manipulated on sequentially. Because a high-energy excited state is used, calculations are not possible if error (energy relaxation) occurs when the ball is inadvertently dropped. The adiabatic computation (b) is equivalent to dribbling a ball while weaving through the dips in the ground. Computation is performed while constantly passing through the bottom of energy distribution.

using qubits or by using a small number of qubits. Until now, a linear progression of R&D was assumed for quantum information processing technologies. First, the problem of quantum key distribution would be tackled, and when that was successfully solved, the next step would be to tackle quantum computing. Integrating many qubits is essential in this linear development map.

However, nowadays there is growing awareness that quantum technologies can be used for a variety of goals that can be achieved with fewer qubits (**Fig. 2**). Quantum sensing technology is a representative example. The application of the superposition principle in quantum mechanics means that sensing technologies that are orders of magnitude higher in sensitivity than current technologies can be created. This technology exploits the strong interaction between qubits (the so-called quantum correlation) to create a state that is very sensitive to changes in the external environment.

Meanwhile, technologies to manipulate the quantum state and read it accurately have made great strides as a result of advances in quantum computing technologies. A new development is the use of these technologies to experimentally verify the principles of physics. In the past, because technologies to manipulate and detect quantum states were insufficient, it was impossible to experimentally answer questions involving the nature of physics, such as "To what size of objects can quantum mechanics be applied?" However, the technology has recently advanced to the point where accurate experiments could be carried out. In these Feature Articles, we introduce research on superconducting quantum circuits, which are applied to quantum sensing and the experimental verification of physical principles [4, 5].

4. Quantum cryptography and single photon manipulation

Quantum cryptography is a quantum information processing technology that is often discussed together with quantum computing. This technology is properly referred to as quantum key distribution. Rather than being an encryption technology, it provides solutions to everyday issues in encryption technology such as how to safely deliver a private key to the user. Disturbing a pure quantum state is an intrinsic part of the action of observing the state and cannot be avoided. Quantum key distribution secures the safe delivery of private keys by exploiting the fact that an act of

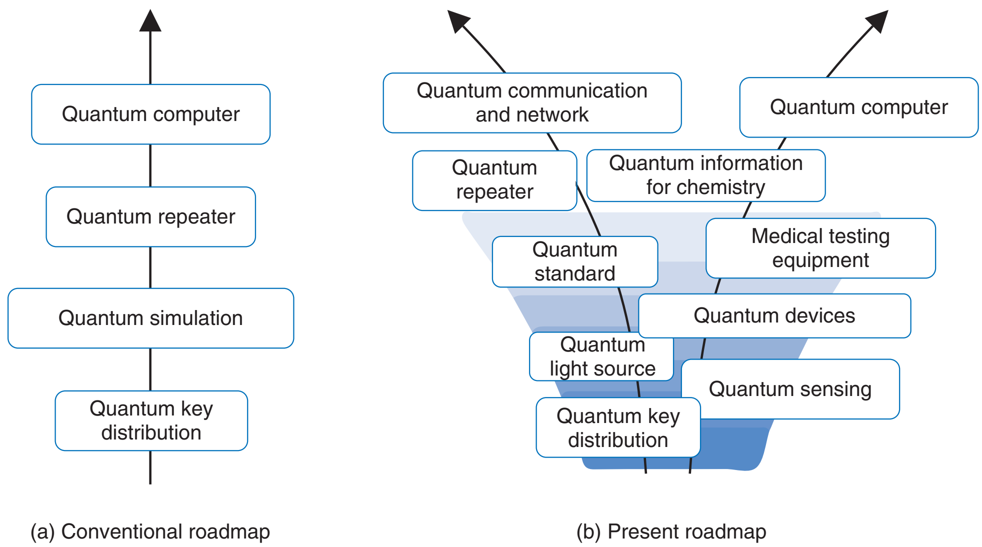

Fig. 2. Schematic showing the new expansion of quantum information processing. (a) The conventional roadmap shows a linear progression with the final goal of realizing quantum computing. (b) The current roadmap holds promise for the application of quantum technologies to a variety of fields, from quantum sensing to diagnostic tools.

eavesdropping during the stage of key distribution leaves an effect that cannot be fundamentally erased.

Compared with quantum computing, the prospects of quantum cryptography as a practical technology have always abounded, and in fact, experiments using optical fiber networks are being conducted in countries throughout the world. Although the technology is expected to be commercialized soon, there are still many challenges that must be solved, such as security proofs and the development of quantum repeater technologies. In this issue, we give an overview of the current state of quantum cryptography and challenges in its commercialization [6].

In addition to quantum cryptography, single photon generation technology also plays a critical role in quantum measurement and quantum computing. Quantum computing requires multiplexing. Thus, while the idea of manipulating a single quantum (photon) may sound contradictory, the question of to what extent each quantum can be manipulated with fine control is critical to carry out multiplexing in the future. Technology to finely control a single quantum (photon) is extremely important because a few quantum states play a critical role in quantum key distribution and quantum repeater technologies.

In this issue, we introduce the results of successfully controlling a wavelength of a single photon, which plays an important role in quantum information processing technologies. We accomplished this by applying the technique of cross-phase modulation, which is widely used in the field of optical communications, to a single photon for the first time [7].

5. Development of topological materials for quantum information processing

Finally, we touch on material research for topological quantum computers. The Nobel Prize in Physics in 2016 was awarded to three theoretical physicists at American universities for their theoretical discoveries of topological phase transitions and topological phases of matter. Topology is a discipline that seeks to understand the conditions of an object from the *connection* of things. Consider, for example, four shapes: a ball, coffee cup, donut, and wine glass. In topology, the size and curvature of a shape is not important. What is important is how connections are made. A coffee cup can be transformed into a donut by continuous deformation, as can a wine glass into a ball. However, to transform a donut (or coffee cup) into a wine glass (or ball), deformation of the former object by filling in its penetrating hole must be carried out somewhere. At this stage, the manner in which things are connected changes (**Fig. 3**).

In this way, it is known that different connection states, in other words, different topological states, appear not only in physical objects but also in a variety of physical systems. Electronics is a representative

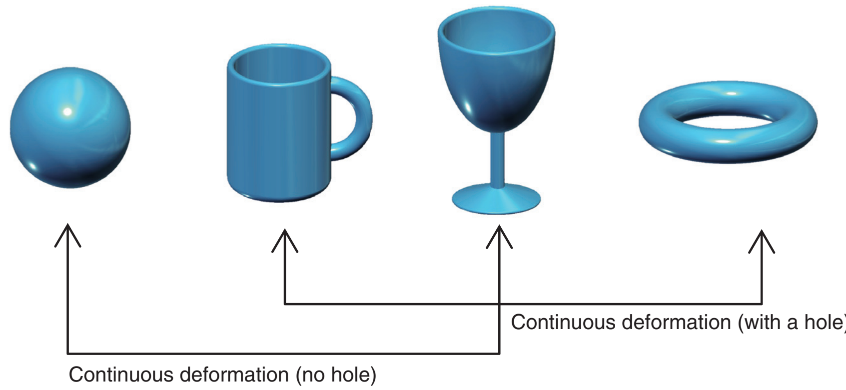

Fig. 3. Conceptual representation of topology. The ball and wine glass have completely different shapes. However, because they are connected through continuous deformation, they have the same topology. The cup and the donut have the same relationship. However, to transform the donut into the ball, for example, the penetrating hole in the donut must be filled in. Thus, it has a different topology, as it cannot be continuously deformed.

example. The Nobel Prize mentioned above demonstrates the extremely important role that electron states with different topologies play in solid-state physics. If it is possible to carry out quantum computing using such states, stable and highly accurate calculations can be performed since changes between different topological states do not occur easily.

Research on topological insulators applying the above findings has increased markedly in recent years. A topological insulator is a material in which electronic states with different topologies naturally manifest themselves due to the material's special properties. The heterostructure of two materials, indium arsenide (InAs) and gallium antimonide (GaSb), has attracted attention as an example of a topological insulator. NTT Labs have pioneered a method of crystal growth that dramatically improves the characteristics of this material. In this issue of the NTT Technical Review, we introduce the details of this research and discuss future prospects [8].

6. Conclusion

This article presented an overview of recent developments in quantum information processing and discussed NTT Labs' research achievements as examples of advances in this field. As mentioned in the Introduction, the progress in research on quantum information processing in the past several years has been astounding. New concepts such as adiabatic computation, quantum measurements, and topological states have been introduced, expanding the possibility of applications as a result of approaches that differ from conventional methods. In particular, while the adiabatic method has aroused debate about the extent to which quantum properties can be exploited in actual hardware, its future development is drawing attention because it solves computation problems with architecture different from the conventional computation architecture that uses quantum gates.

The most important properties of conventional digital computers are accuracy, which is achieved with binary encoding, and versatility, which is achieved with software. Originally, continuous analog values were encoded as digital information. Although inaccuracies generated in this process are ignored, calculations after encoding are executed without any mistakes. Also, the specifications of computation could be freely changed with software instead of being fixed in hardware. Present-day information processing technology has developed greatly based on the completeness and versatility of such a computational approach. However, we think the situation is gradually changing with the spread of the internet and the arrival of the big data era.

In the area of search technology, for example, how important is it to get a unique and rigorous answer to a search query? Rather, what is important is getting answers as quickly as possible from an extremely large number of choices in exchange for a modest level of certainty. In this way, adiabatic computation, which solves specific combinatorial optimization problems, has the possibility of truly being a powerful computing tool for a particular type of fuzzy problem. In this sense, the new technologies introduced here not only possess high-speed performance by exploiting quantum properties, they also have the possibility of changing how information processing technologies are fundamentally used.

Finally, while not introduced here, we would like to mention that great progress has also been made in the research on conventional gate model quantum computing hardware. We cannot predict which model of quantum information processing technology will change the world in the future, but we definitely wish to experience such a world beyond our wildest expectations.

References

[1] "Feature Articles: Quantum Computing," NTT Technical Review, Vol. 10, No. 9, 2012.
https://www.ntt-review.jp/archive/2012/201209.html

[2] T. Kadowaki and H. Nishimori, "Quantum Annealing in the Transverse Ising Model," Phys. Rev. E, Vol. 58, No. 5, pp. 5355–5363, 1998.

[3] H. Takesue, T. Inagaki, K. Inaba, and T. Honjo, "Quantum Neural Network for Solving Complex Combinatorial Optimization Problems," NTT Technical Review, Vol. 15, No. 7, 2017.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201707fa2.html

[4] K. Kakuyanagi, Y. Matsuzaki, H. Toida, H. Yamaguchi, S. Saito, and W. J. Munro, "Demonstration of Realism Violation on a Macroscopic Scale," NTT Technical Review, Vol. 15, No. 7, 2017.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201707fa4.html

[5] Y. Matsuzaki, K. Kakuyanagi, H. Toida, H. Yamaguchi, W. J. Munro, and S. Saito, "Coherent Coupling between 4300 Superconducting Flux Qubits and a Microwave Resonator," NTT Technical Review, Vol. 15, No. 7, 2017.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201707fa5.html

[6] K. Tamaki, "Implementation Security of Quantum Key Distribution," NTT Technical Review, Vol. 15, No. 7, 2017.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201707fa7.html

[7] N. Matsuda, "Lossless Wavelength Conversion of Single Photons," NTT Technical Review, Vol. 15, No. 7, 2017.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201707fa3.html

[8] T. Akiho, "Creating New Two-dimensional Topological Insulators for Fault-tolerant Quantum Computing," NTT Technical Review, Vol. 15, No. 7, 2017.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201707fa6.html

Hiroshi Yamaguchi

Senior Distinguished Researcher and Group Leader of the Hybrid Nanostructure Physics Research Group, NTT Basic Research Laboratories.

He received a B.S. and M.S. in physics and a Ph.D. in engineering from Osaka University in 1984, 1986, and 1993. He joined NTT Basic Research Laboratories in 1986. His current interests are micro/nanomechanical devices using semiconductor heterostructures. He has been a guest professor at Tohoku University since 2006. He is a fellow of the Institute of Physics and the Japan Society of Applied Physics (JSAP) and a member of the Physical Society of Japan, the American Physical Society, and IEEE (Institute of Electrical and Electronics Engineers).

Tetsuomi Sogawa

Vice President, Head of NTT Basic Research Laboratories.

He received a B.S., M.S., and Ph.D. in electrical engineering from the University of Tokyo in 1986, 1988, and 1991. He joined NTT Basic Research Laboratories in 1991. From 1999 to 2000, he was a guest scientist at Paul Drude Institute in Berlin, Germany, where he investigated acoustic spin transport phenomena in semiconductor quantum structures. From 2004 to 2006, he worked for the Council for Science and Technology Policy, Cabinet Office, Japan, as a deputy director for policy planning. His current research interests include fabrication technology of low-dimensional nanostructures, optical properties of quantum dots/wires and photonic crystals, spin-related phenomena, and surface acoustic wave application on nanostructures. He is a member of JSAP.