R&D Spirits

Opening the Door to Quantum Computers

Dr. Hideaki Takayanagi
Director,
NTT Basic Research Laboratories
NTT R&D Fellow

The key to revolutionizing information processing can be found in the quantum computer. In Japan, quantum computers are being heavily researched, and NTT Basic Research Laboratories are becoming a core site for this research. To learn about the current state of progress and future outlook of quantum computer research, we sat down with Dr. Hideaki Takayanagi, the head of quantum computer research at NTT Basic Research Laboratories and an NTT R&D Fellow.

Performing astronomically large calculations instantly using the basic principle of quantum mechanical uncertainty

Editor: Dr. Takayanagi, what exactly is a quantum computer, the subject of your research?

Takayanagi: The conventional computer operates on the basis of Newtonian mechanics, which means that it conforms to classical mechanics. We call it a "classical computer" for this reason. In contrast, a quantum computer operates on the basis of uncertainty, a key feature of quantum mechanics, where "the movement of an object can be determined only as a probability." In other words, while a bit can be clearly expressed as either a 0 or 1 in a classical computer, a quantum computer is concerned with the probability that a 0 or 1 state exists. Consequently, a single data element might simultaneously be 0 and 1, that is, it may take two different states at the same time, as long as it is not observed. This is called superposition. Since n elements result in 2^n states, we can see that 100 elements in a quantum computer could represent 2^{100} states simultaneously. This ability to represent a huge number of states should make it possible to perform massively parallel computing in which ultra-high speeds are achieved on the whole as opposed to each individual element running at high speed. This is the general principle behind the quantum computer.

E: Why are quantum computers receiving so much attention at this time?

T: In 1994, it was shown that unique factorization could be solved in an extremely efficient manner by an algorithm discovered by Peter Shor of AT&T. This discovery had a major impact on the information sharing society. To put this in perspective, existing encryption technology is based on the fact that it is impossible for all practical purposes to uniquely factor a 100-digit or larger integer. Just a 20-digit integer, for example, would take about 10,000 years to uniquely factor using today's fastest computers. A quantum computer, however, could solve the same problem in 1/1,000,000 of a second, which would clearly shake the foundation of encryption technology. This, in turn, would have grave effects on Internet business and national defense, which explains the sudden interest in quantum computers. I would like to point out here that quantum computers are not expected to replace classical computers—they will supplement them.

E: What could be done with quantum computers?

T: First of all, it would be natural to consider applications in information communications since this is the field in which research on quantum computers has flourished. One example is quantum encryption. If

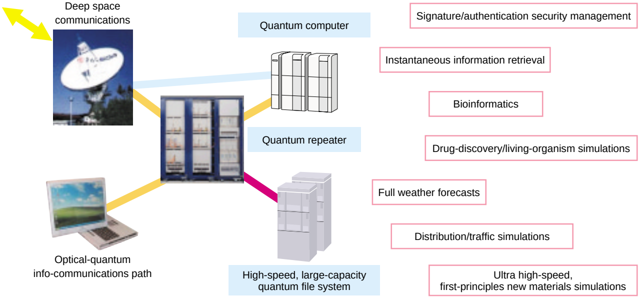

Fig. 1. Future quantum computer society.

current encryption schemes can be solved by quantum computers, new encryption schemes must be developed based on quantum mechanics. Research has already begun on applying to encryption the phenomenon of superposition in which one element can take on two different states simultaneously. On a broader scope, the extent to which such a property might be used in the world comes down to an algorithmic problem, so no one really knows. If research in this area progresses, we might see a variety of applications. For example, quantum computers might be used in simulations concerning distribution, drug discovery, and living organisms, in bioinformatics, and in the preparation of full weather forecasts. If such applications come true, we might see a future society that is very dependent on quantum computers. In any case, it will take several decades of R&D before such applications can be realized (Fig. 1).

Successful reading of quantum bits—a milestone in achieving real quantum computers

E: Please give us an overview of this research and its current state of progress.

T: At NTT Basic Research Laboratories, we are currently focusing our research efforts on quantum-bit molecules, optical-quantum bits, and superconducting loops. Quantum bits, by the way, come in various types such as solid, gas, and ion, but as we anticipate that they will be integrated in the future, we are limiting our studies to solid-state quantum bits to which LSI technology can be applied. To be honest, we have not yet reached the stage of a real quantum computer, but I can say that we have been successful in constructing a single quantum bit using a superconducting loop. We have shown that producing current in a 1-µm × 0.5-µm aluminum superconducting loop under certain conditions can result in clockwise and counterclockwise currents flowing simultaneously (Fig. 2). A superconducting loop, while small by everyday standards, is large compared to atoms and molecules. Nevertheless, constructing a quantum bit at this scale is highly significant. The ability to read the state of a quantum bit by a “one-shot” measurement is also an outstanding achievement that I don’t think has been reproduced yet anywhere else in the world.

E: What are some technical issues in this regard?

T: I would say progress in nanotechnology and ultraprecise measurement technology. Although the quantum computer has been around for some time in terms of basic principles, a successful one has yet to be constructed despite the best efforts of many researchers. This is not only because it has been impossible to fabricate on a very small level but also because it has been impossible to exclude noise during measurements. It is said that the quantum mechanical super-

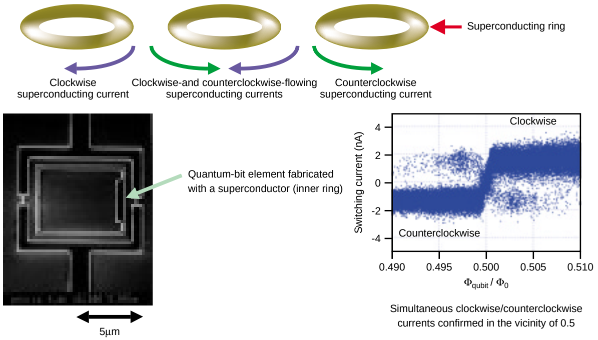

Fig. 2. Quantum-bit elements.

position state that I mentioned earlier can be maintained indefinitely as long as no observation is made, and conversely, that this state will be destroyed if an observation is performed. Noise cannot help but be measured, however, and the simple addition of noise can destroy a quantum bit. Reducing noise in measurements is therefore a major issue. Some progress has been made here on entering the 21st century, and research on quantum computers has likewise advanced to some degree.

E: What kind of form do you think quantum computers will take three or five years down the road?

T: In about five years, we may reach the stage of practical quantum computers for quantum encryption. For example, we may see small, several-bit quantum computers for quantum encryption/decryption in networks. On the other hand, 100-bit and 1000-bit quantum computers are still a long way off. We, of course, are involved in basic research, and cannot easily venture into such applications. For this reason, we feel a bit awkward when asked what kind of results we expect in 3- or 5-years time (smiles). The president of NTT understands our predicament well, but in general, research is now expected to produce results quickly. If we push out results too fast, though, we may experience the same fate as Bell Laboratories. Basic research, in particular, needs to take a long view of things.

E: What are some international and domestic trends in quantum computer research?

T: The country that is expending the most effort on quantum computers is the United States, and there is also considerable research in Europe and Australia. In Asia, there is noticeable activity in the IT nations of Singapore and Japan. Quantum computer research in Japan is being led by the private sector, however, and several projects are proceeding in a nearly independent manner. This is why I have promoted the establishment of a government-level project for some time, and just this year a move in that direction appeared centered on the Japan Science and Technology Corporation. Perhaps I will be asked to cooperate.

Expanding into international activities as a recognized authority on quantum computers

E: What kind of research have you personally been involved in over the years?

T: In graduate school, I was researching SQUIDs (Superconducting Quantum Interference Devices), which means that I was already studying quantum bits. This research, however, did not actually concern the quantum computer but was rather a pursuit of high-sensitivity detectors. After entering NTT, my research in this area expanded into superconducting Josephson devices, and as part of this research, I demonstrated, for the first time in the world, that the Josephson effect could be achieved by combining a semiconductor and superconductor to form a superconducting transistor. After that, superconductivity research at NTT was unfortunately scaled down, but three researchers including myself remained in this area, and I went on to do a lot more basic research in superconductivity.

E: Why did you begin researching quantum computers?

T: As I mentioned, the backbone of my current research goes back to my university days, and my interest in the quantum computer began during my time as a guest researcher at the University of California, Berkeley in 1988 and 1989. Quantum mechanics for someone studying physics is the most correct interpretation of the physical world at this time, and as such, is the ultimate area of study. One of my desires was to find out how far and in what way quantum mechanics could be used. That was my first encounter with computational principles and other phenomena in relation to quantum mechanics. Later, a more specific encounter with the quantum computer concept occurred in 1996 when I was invited to an international NATO conference in Curacao. Although I was actually giving a presentation on another subject, this conference marked the first time that I began discussing quantum computer theory with other researchers. I found it utterly fascinating.

E: Are you involved in any international activities related to your research at this time?

T: Actually, I am involved in many international activities and have been making about 5 to 10 overseas trips a year. I could never say that I don't enjoy these trips, as any place that brings together many leading researchers from around the world is quite stimulating. I have been a member of the organizing committees for various conferences including the 10th International Conference of Narrowgap Semiconductors, 23rd International Conference of Low Temperature Physics, and 15th International Conference on Electronic Properties of Two-Dimensional Systems. I have also been involved with various joint research programs with overseas researchers, including two major programs sponsored by the New Energy and Industrial Technology Development Organization (NEDO). I have been a research partner first in Sweden and France and later in Germany and the United States. I have since entered into a joint-research contract with Delft University of Technology in the Netherlands and am also involved in programs in Switzerland, Italy, the United Kingdom, and Denmark. From this spring, moreover, I will be a guest professor at Nanjing University in China, and I think I may be able to do some joint research there as well. As you can see, I have been involved in all sorts of activities up to now, which can certainly be stressful, and recently, I think I have become a bit disoriented as a result (smiles). I am therefore trying to make one long overseas trip a year so that I can devote more time to research without having to think of other duties. Everyone asks me if that is possible, but if I declare that I am going somewhere, it usually happens.

E: It has been said that you are a candidate for a Nobel prize. What is your personal reaction to this?

T: Well, I have attended Nobel award ceremonies twice and have been an invited speaker at Nobel symposiums three times. Looking back at those times, I remember that many symposium speakers were Nobel-prize recipients and that the staff of the Nobel Foundation were saying that much attention was being given to Japan. Perhaps that is why I have been considered a candidate. At the same time, I know that obtaining a Nobel prize is not that easy. It is nevertheless a great honor even to be mentioned as a candidate. If I were to receive a Nobel prize, however, it would be for past accomplishments and not for my current research on quantum computers. As my past research has been successfully completed, my main concern now is my present research.

Expanding beyond its corporate framework, NTT is becoming a core research site for quantum information processing in Japan

E: What direction would you like your research to take in the years to come?

T: First of all, I would like to be involved in research for the rest of my life. This is also the wish of NTT. In fact, receiving the title of NTT R&D Fellow means exactly that, and the reality is that you gradually move from pure research to management of research. As a result, I have been able to develop an eye for the "big picture," and with this in mind, I would like to make a sincere suggestion as to how I might promote basic research in Japan and quantum computer research in particular. At present, Japan is in the early stages of quantum computer research and even the government is starting to become involved. Since I am also involved in national research in various forms, I feel I can add to this momentum and spur on this research. At the least, I would like to be one of the people providing a driving force behind this research.

E: In the light of many and varied international activities, how do you think NTT is viewed overseas?

T: NTT Laboratories on the whole and Basic Research Laboratories in particular have received high praise. While it would be presumptuous to say that we might take the place of Bell Laboratories, whose fortunes are declining, it is widely acknowledged that NTT deserves to be noticed as a major private research institution. The number of papers published by NTT in such periodicals as Science and Nature is impressive for Japan and proposals for joint research are being received constantly.

E: As a manager of one of the NTT Laboratories, what are your hopes and challenges for the future?

T: The scale of quantum computer research at NTT is the largest in the nation, I believe. Nevertheless, we cannot do everything alone and joint research and information exchange are absolutely necessary. Even though this is private-sector research, we cannot get around the fact that this field is not very competitive within Japan. Against this background, my aim is to make Basic Research Laboratories a center of excellence for quantum information processing in Japan. These laboratories have been very open from the start, but I would like make it even easier for people to come and go. My challenge as a manager is to create an environment conducive to such openness.

E: Dr. Takayanagi, what is it like to work at NTT Laboratories?

T: Since I am not familiar with all aspects of NTT Laboratories, I can't say in general, but with regard to Basic Research Laboratories, freedom in research is good, the caliber of people is high, and funding is sufficient. I don't think you could find a place as well rounded as these laboratories elsewhere in the world. There is also little interpersonal friction. Basic research, moreover, is primarily an individual pursuit, and for independent-minded researchers, Basic Research Laboratories is a place where they can demonstrate their abilities. At the same time, a wonderful environment might also be the cause of overly nice behavior in young researchers, and I would rather see more researchers who have the guts to give me a good fight when needed. I actually like that type of researcher very much.

Interviewee profile

■ Career highlights

1975 B.S. from the University of Tokyo, Dept. of Basic Sciences
1977 M.S. from the University of Tokyo, Graduate School of Arts and Sciences
1977 Joined Musashino Electrical Communication Laboratory, NTT
1987 Ph. D. (science) from the University of Tokyo
1988 Guest Researcher in the department of physics at UC Berkeley (one year)
1995-present Guest Professor at Tokyo University of Science
1996 Guest Professor at Delft University of Technology (Netherlands)
1997 Guest Professor at Chalmers University of Technology (Sweden)
1998 Guest Professor at Denmark University of Technology
2000 NTT R&D Fellow
2003 Concurrent Professor at Nanjing University (China)
2003 Guest Professor at the University of Tokyo

■ Major awards

1986 NTT R&D Headquarters Award
1994·1996 NTT Basic Research Laboratories Award
2000 Nissan Science Award
2003 Superconductor Science and Technology Award

■ Committee memberships and other posts

Research coordinator in NEDO Grants for International Joint Research (1997-1999)
Organizing committee member of the Satellite conference to LT22 (Göteborg, 1999)
Organizing committee member of the 10th International Conference of Narrowgap Semiconductors (Kanazawa, 2001)
Organizing committee member of the Int. Symposium on Superconducting Device Physics (Tokyo, 2001)
Organizing committee member of the 23rd International Conference of Low Temperature Physics (2002).
Organizing committee member of the 15th International Conference on Electronic Properties of Two-Dimensional Systems (Nara, 2003)
Chair of the Int. Symp. on Mesoscopic Superconductivity (Atsugi, 2000)
Chair of the Int. Symp. on Mesoscopic Superconductivity and Spintronics (Atsugi, 2002)
Research member of NEDO Grants for International Joint Research (2000-2002)
Adjunct member in the Quantum Phase Electronics Center, the University of Tokyo (2001-)
Committee member of the Atom, Molecule and Optical Science, Science Council of Japan (2001-2004)
Committee member of the Fundamental Physical Standards, Science Council of Japan (2002-2003)
Member of the University Evaluation Committee in National Institution for Academic Degrees (2002)
Technological Committee member in NEDO (2002-)
Research Leader of the CREST, JST (2002-2007)
Guest Researcher of the Nanoscience Special Project in Tsukuba University (2003-2005)

■ Publications

B. J. van Wees and H. Takayanagi, "The superconducting proximity effect in semiconductor-superconductor systems," in Mesoscopic Electron Transport, ed. by L. L. Shon *et al.*, (Kluwer, Dordrecht, 1997) p. 469.
H. Takayanagi, "A mysterious boundary between a superconductor and a normal conductor," Kyoritu Shuppan, Tokyo, 2000 (in Japanese).
"Towards the controllable quantum states," ed. by H. Takayanagi and J. Nitta, World Scientific, Singapore, 2003.